XCIX CONGRESSO NAZIONALE

Relazione Generale Sezione IVa

PHYSICAL PROCESSES OCCURRING DURING AN EARTHQUAKE: WHAT CAN WE LEARN FROM MODELS OF SEISMIC SOURCES?

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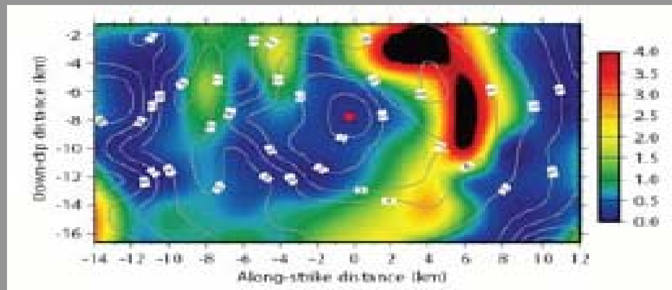
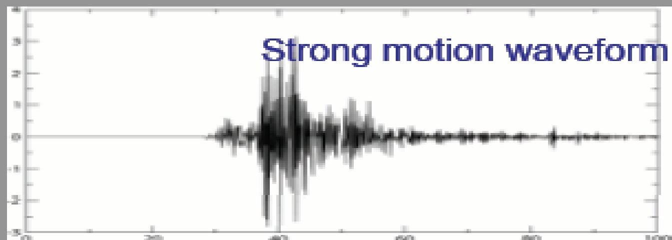
Seismologists need traction

- ✓ To apply fracture mechanics on mathematical planes representing the fault surfaces;

- ✓ To numerically simulate the spontaneous rupture nucleation, propagation, healing and arrest in dynamic earthquake models;



- ✓ To model seismic wave propagation in the surrounding medium;



- ✓ To predict ground shaking.

Stochastic or deterministic?

- ✓ Stochastic (or statistic) models: several aspects of the phenomenon under study are out of range, and they are replaced by unknowable, and hence random, processes, whose behavior cannot be predicted exactly but can be described in probability terms:

  - Gutenberg–Richter law

  - Omori law

- ✓ Deterministic (or physical) models: aim to understanding (and hence to predict) all the details of the considered phenomenon which does not include random components.

Central issues

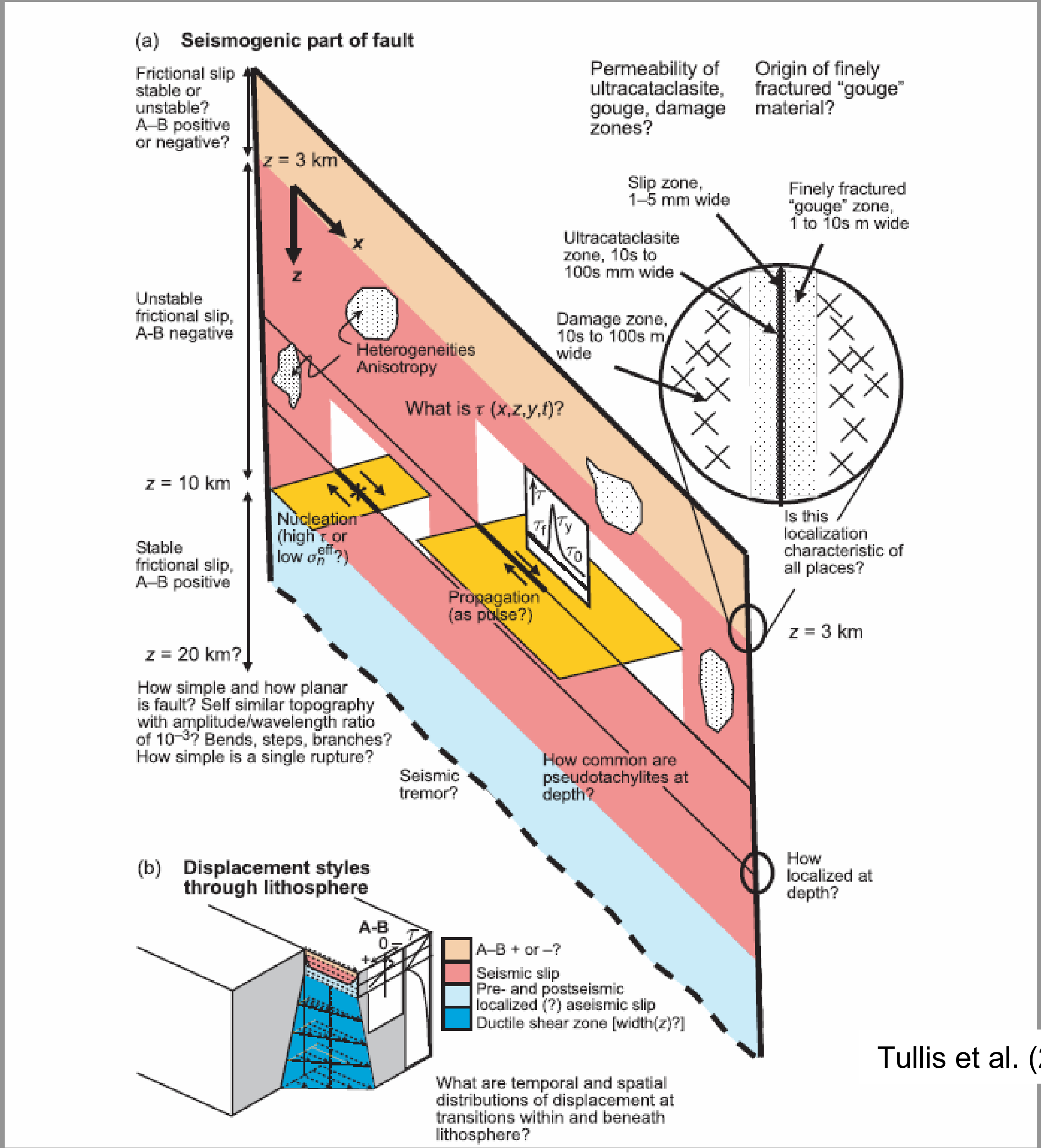
- Quantitative (instrumental) seismology is a relatively juvenile discipline

- Contrary to other fields of science, we can not plan <u>natural</u> (i.e., at real–world scale) experiments (like biology, chemistry, etc.)…

- … and we do know the PHYSICS, i.e., what are the exact equations which completely describe the complex fault systems (on the contrary, climatologists, e.g., know the equations to be solved through numerical experiments)…

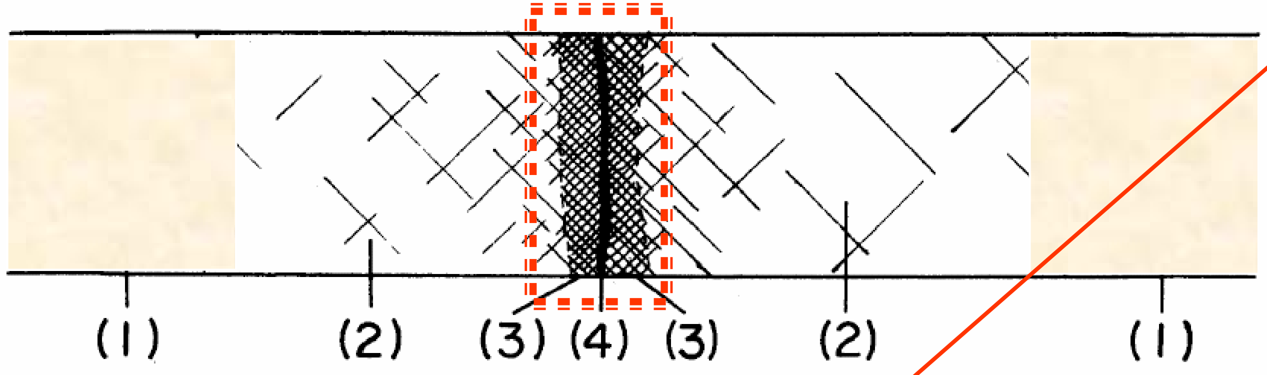
- … and we do not know the initial conditions.

Fault models



Tullis et al. (2007, *MIT Press*)

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.

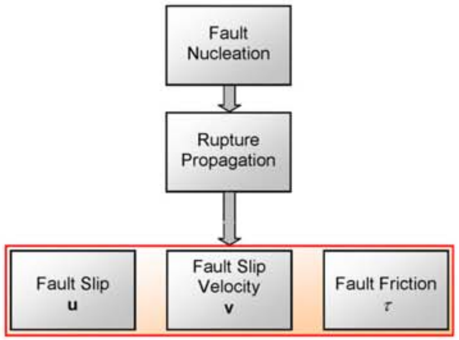
30 - 100 m
(Damage ≈ *highly cracked rock*)

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

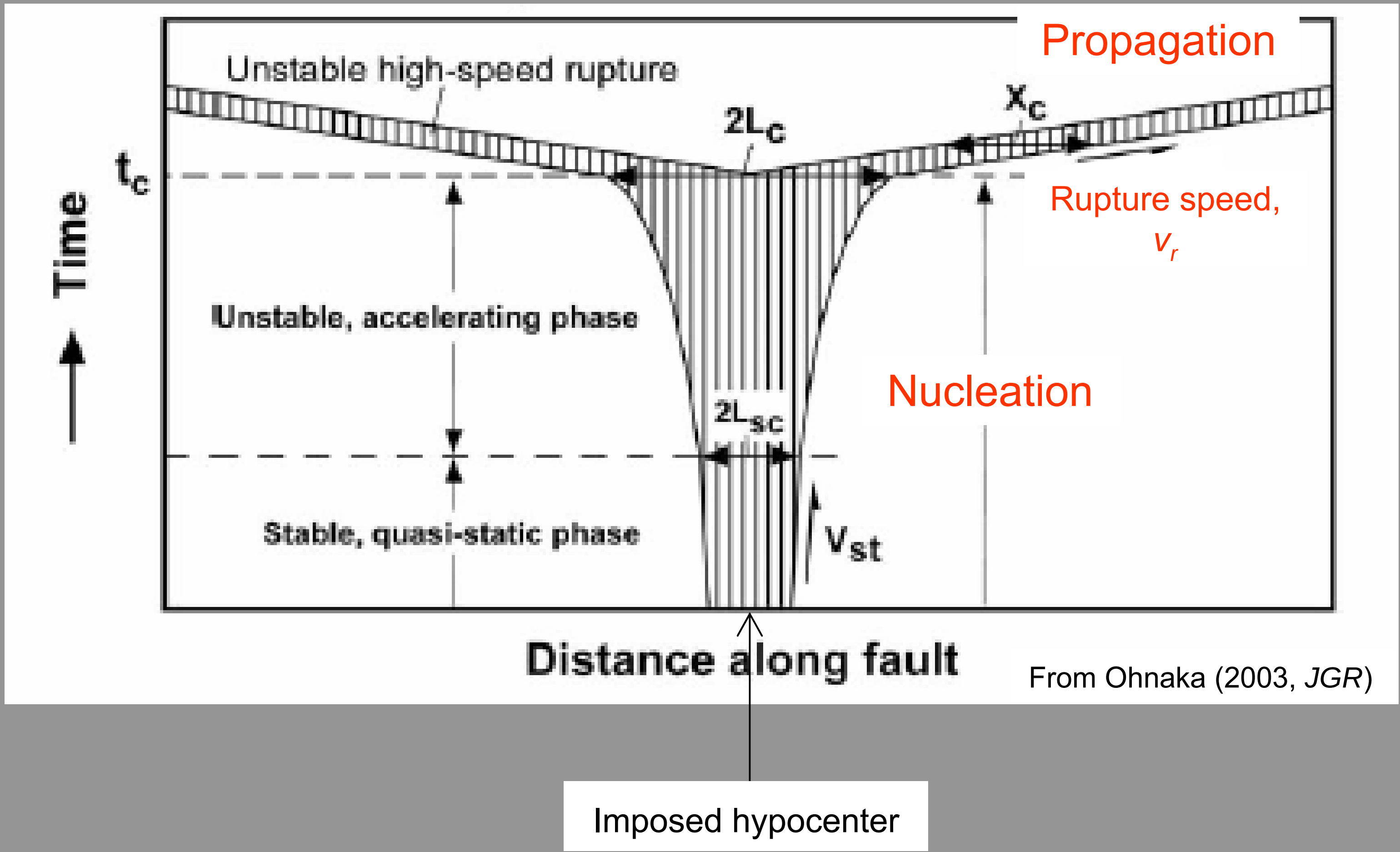
10s - 100s mm
(containing the ***principal slipping zone***, *which* is *much thinner*, typically < 5 mm)

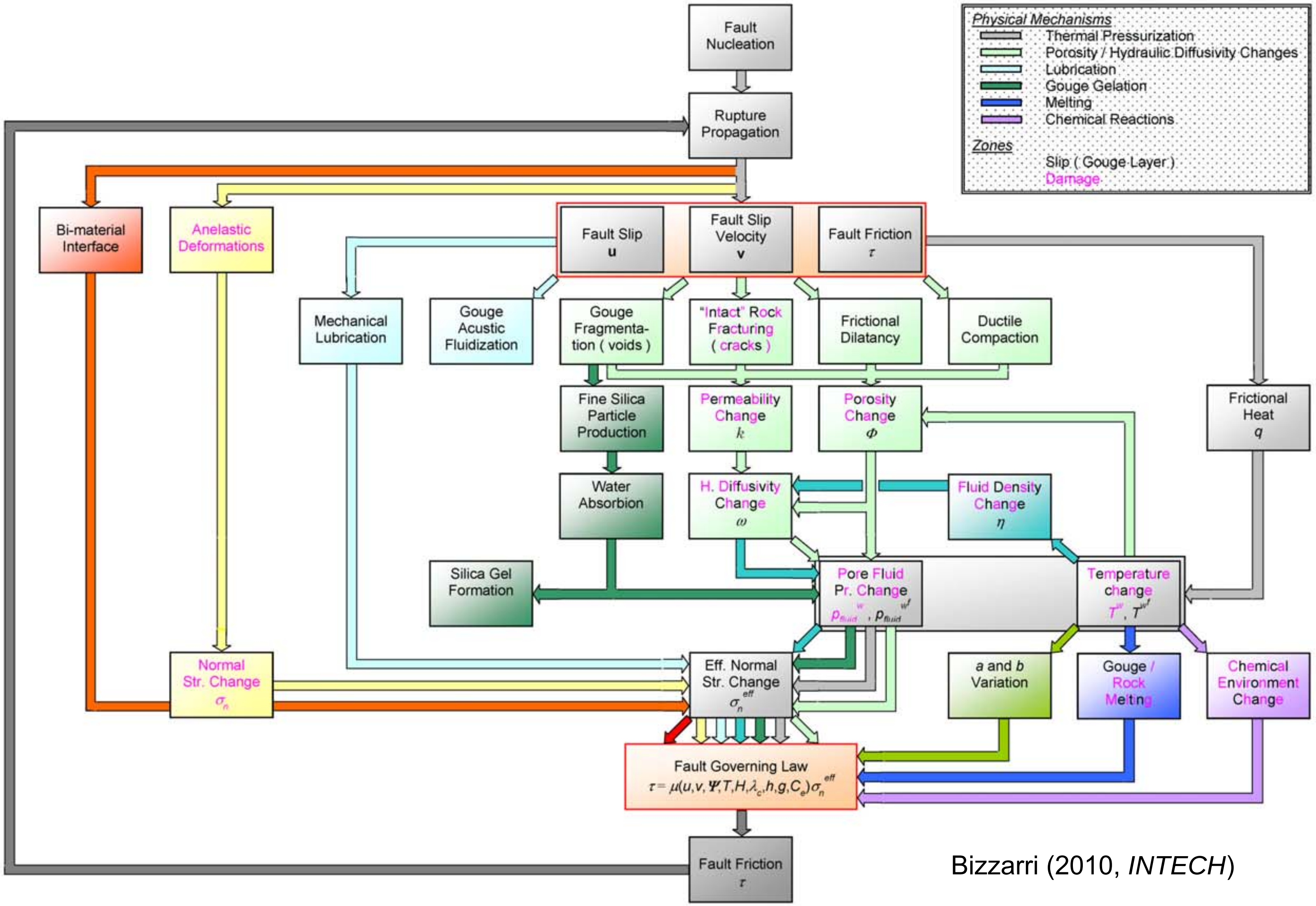
Chester et al. (1993, *J. Geoph. Res.*)
Sibson (2003, *BSSA*)
Chester and Chester (2004, *SSA, SCEC meetings*)

Physical Phenomena in Faulting



Sketch of an expanding bilateral rupture





Bizzarri (2010, *INTECH*)

Fracture Criteria & Constitutive Laws

- In full of generality we can express the constitutive (or governing) as:

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

where:

1st – order dependencies

u is the slip (i. e. displ. disc.) modulus,

v is the slip velocity modulus (its time der.),

$\Psi = (\Psi_1, \ldots, \Psi_N)$ is the state variable vector,

T is the temperature (related to ductility, plastic flow, melting and vaporization),

H is the humidity,

λ_c is the characteristic length of surface (accounting for roughness and topography of asperity contacts),

h is the hardness,

g is the gouge (accounting for surface consumption and gouge formation),

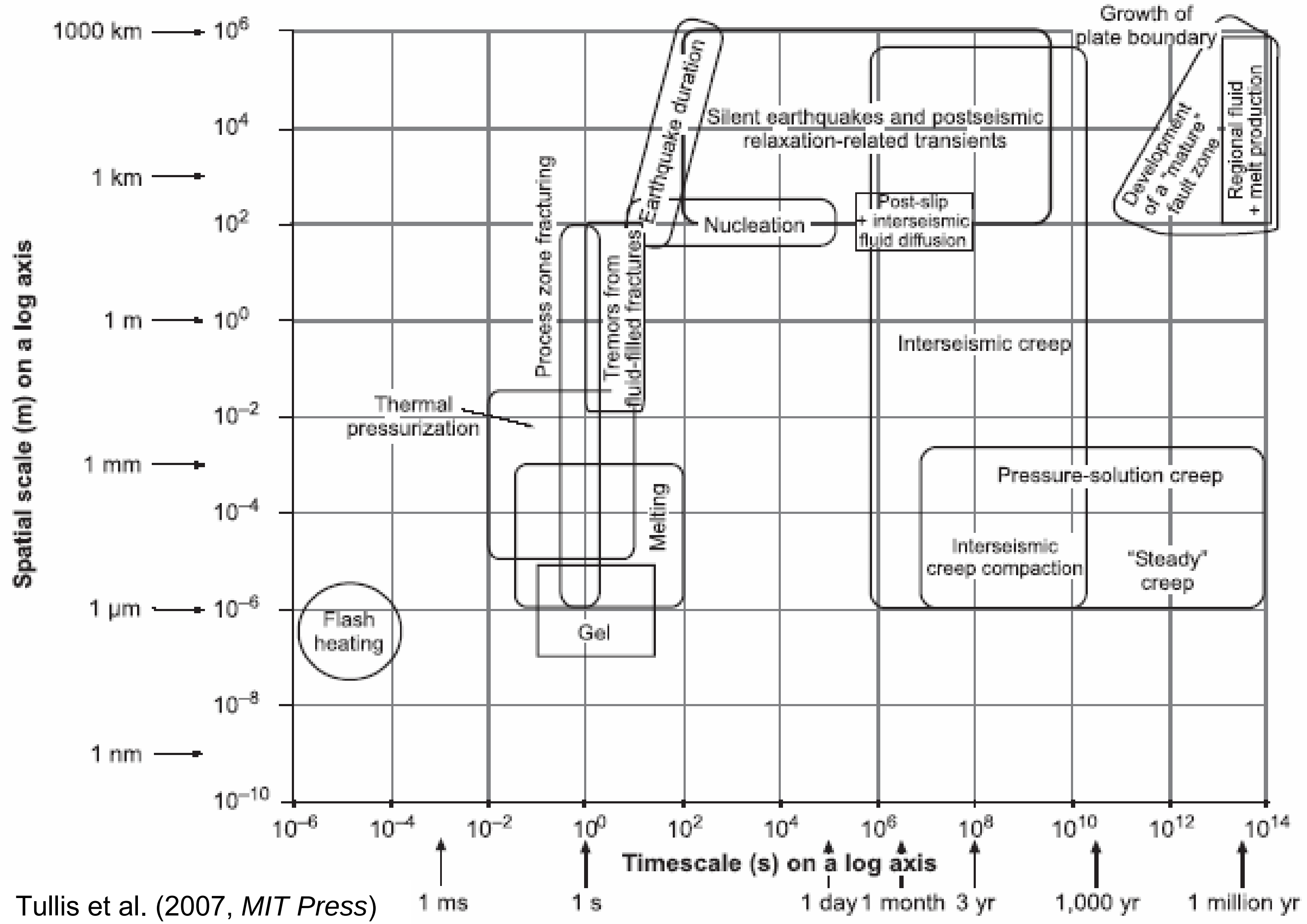
C_e is the chemical environment

Occam's razor

- ✓ We follow the logical principle of simplicity (i.e., the Occam' s razor):

The simplest way to describe the fault complexity is to **start from the beginning** (i.e., from the canonical formulations of the governing equations) and then **add** to the model **one by one** all additional phenomena until the empirical (instrumentally recorded) evidence can be explained.

Spatial and temporal scales



Tullis et al. (2007, *MIT Press*)

Towards real – world conditions

u_{tot} ~ several m

v ~ several m/s

σ_n^{eff} = 100 – 200 MPa

Classical laboratory

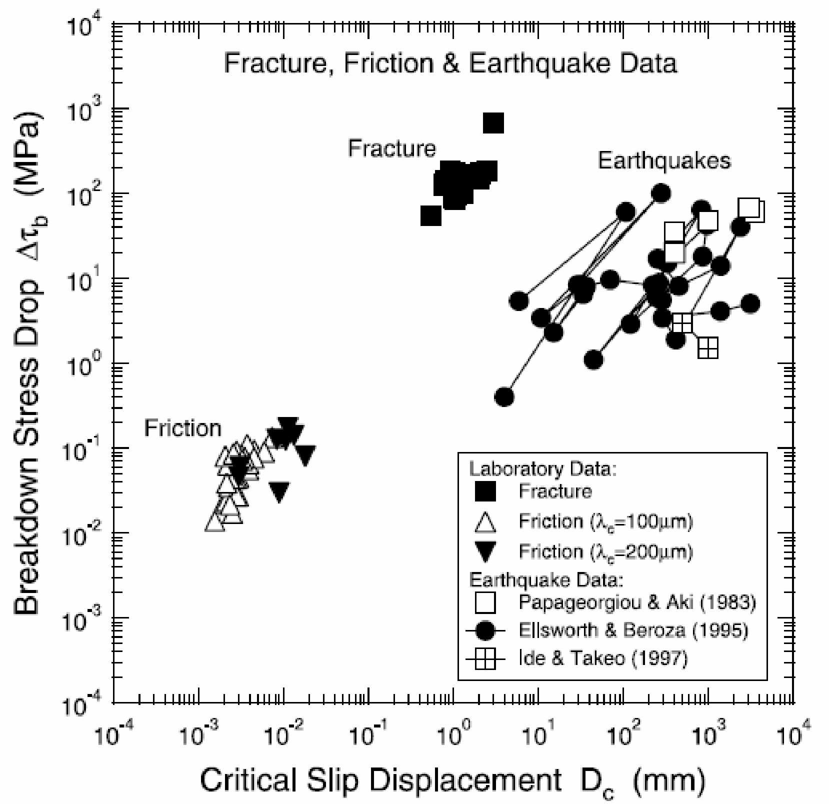
stick – slip experiments

(Dieterich, 1981)

u_{tot} up to 1.4 mm

v up to 25 μm/s

σ_n^{eff} = 10 MPa



From Ohnaka (2003)

High velocity rotary friction apparatus

u_{tot} = infinite

v = 0.1 μm/s – 10 m/s

σ_n^{eff} < 20 MPa

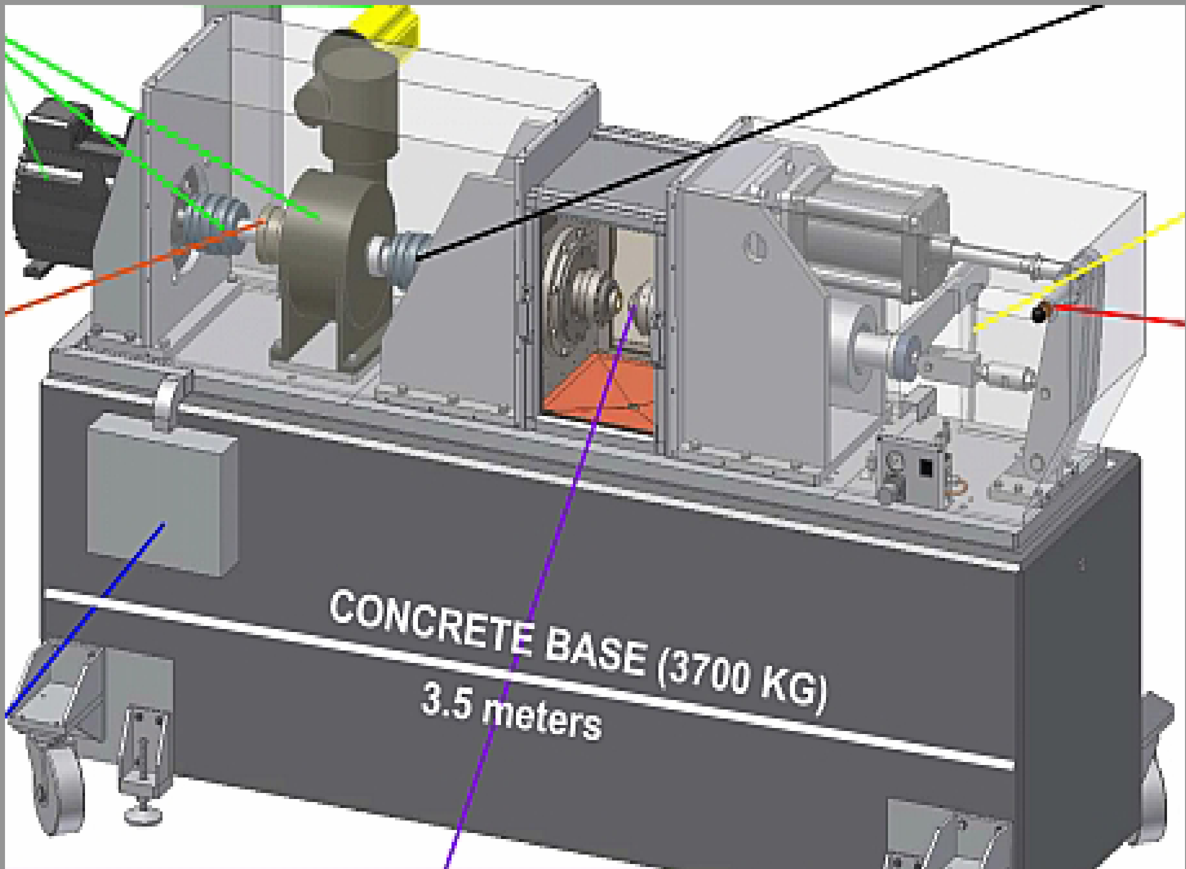
Shimamoto and Tsutumi (2004, *Str. Geol.*)

High velocity rotary friction apparatus @ INGV

u_{tot} = infinite

v = 1 μm/s – 9 m/s

σ_n^{eff} < 70 MPa



Niemeijer et al. (2009, *AGU Fall Meeting*)

Statement of the problem and methodology

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

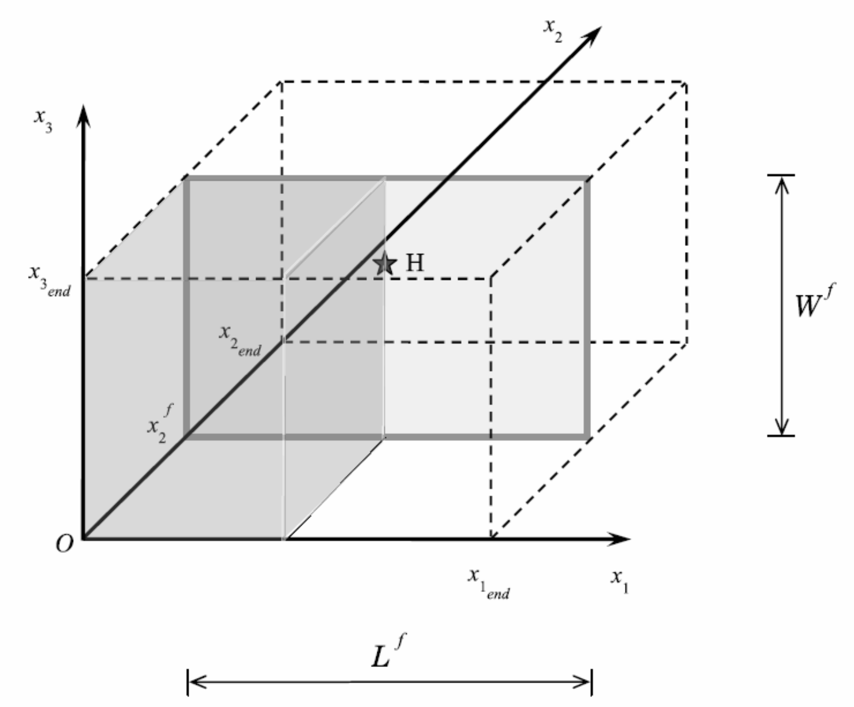
$$\rho \ddot{U}_i = \sigma_{ij,j} + \cancel{f_i}$$

We consider a *truly* 3–D problem, for which the solutions are in the form **u** = ($u_1(x_1,x_3,t)$, 0,$u_3(x_1,x_3,t)$), and so on

The fault plane Σ can be governed by different constitutive laws

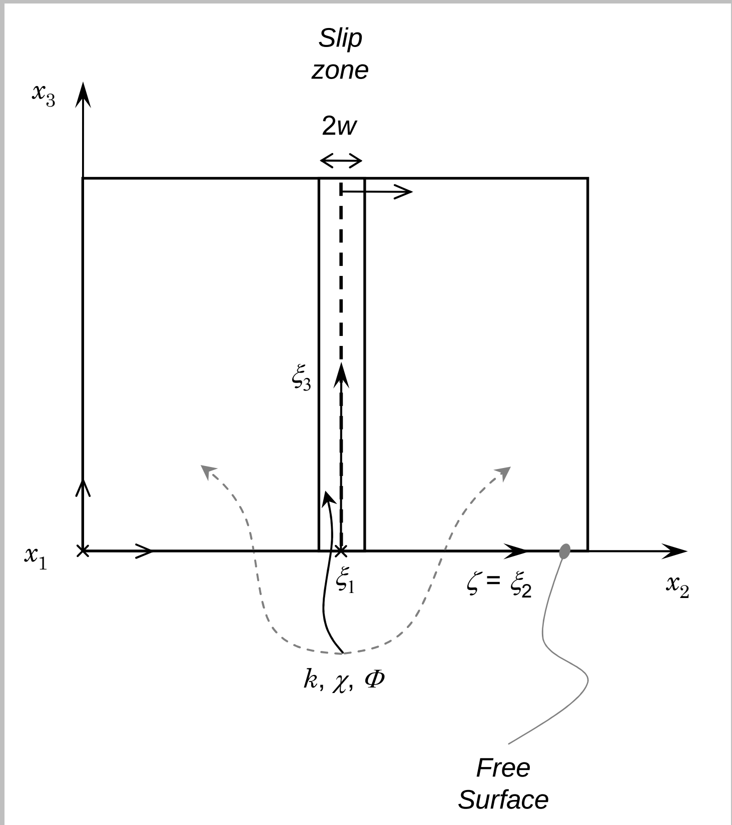
The solution of the elasto–dynamic problem is obtained numerically, by using 2nd–order accurate, finite–difference code

Bizzarri and Cocco (2005, *Ann. Geophys.*); Bizzarri and Spudich (2008, *JGR*)



I. Thermal pressurization of pore fluids

Mathematical background



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:

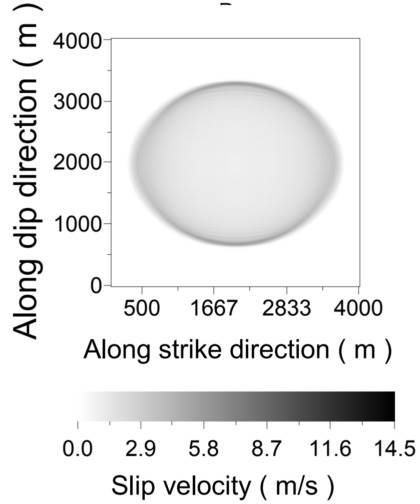
$$T^{w^f}(\xi_1,\xi_3,t) = T_0^f + \frac{1}{2\,cw(\xi_1,\xi_3)}\int_0^{t-\varepsilon} \mathrm{d}t' \,\mathrm{erf}\left(\frac{w(\xi_1,\xi_3)}{2\sqrt{\chi(t-t')}}\right)\tau(\xi_1,\xi_3,t')v(\xi_1,\xi_3,t')$$

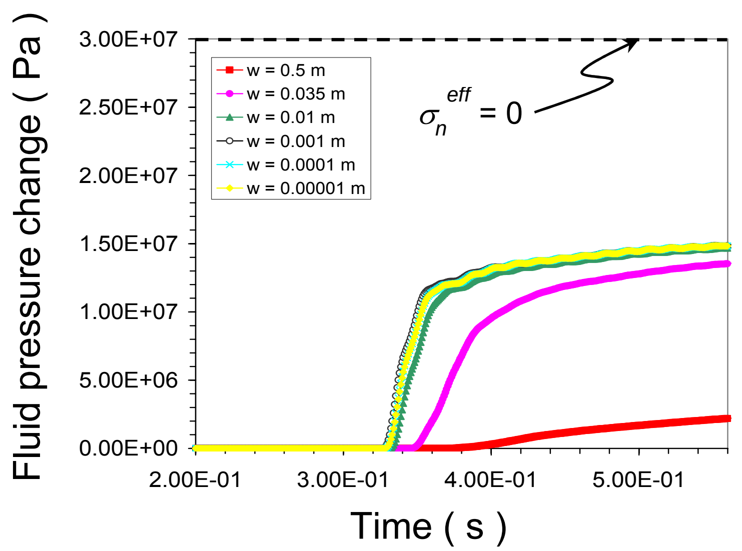
$$\tilde{p}_{fluid}{}^{w^f}(\xi_1,\xi_3,t) = p_{fluid_0}{}^f + \frac{\gamma}{2\,w(\xi_1,\xi_3)}\int_0^{t-\varepsilon} \mathrm{d}t' \left\{ -\frac{\chi}{\omega-\chi}\,\mathrm{erf}\left(\frac{w(\xi_1,\xi_3)}{2\sqrt{\chi(t-t')}}\right) + \frac{\omega}{\omega-\chi}\,\mathrm{erf}\left(\frac{w(\xi_1,\xi_3)}{2\sqrt{\omega(t-t')}}\right)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

Bizzarri and Cocco (2006a, 2006b, *JGR*)

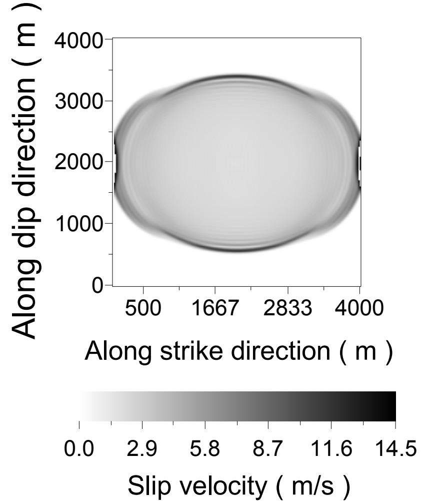
Results with SW law

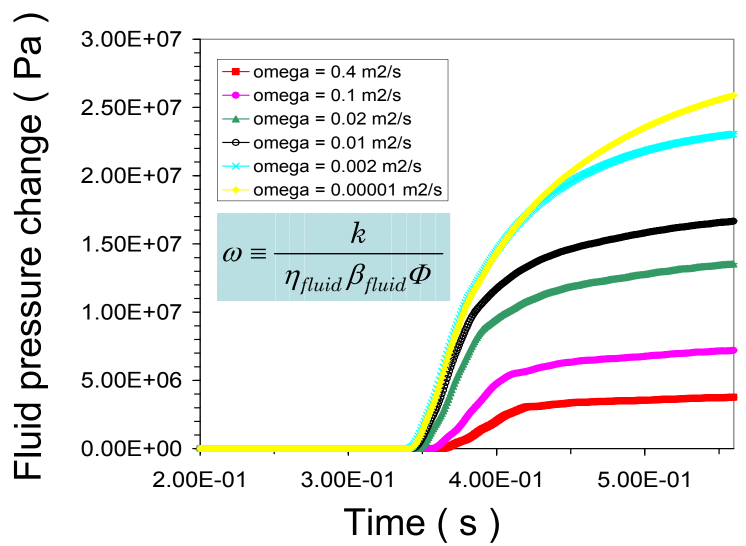
Dry fault (σ_n^{eff} = const)



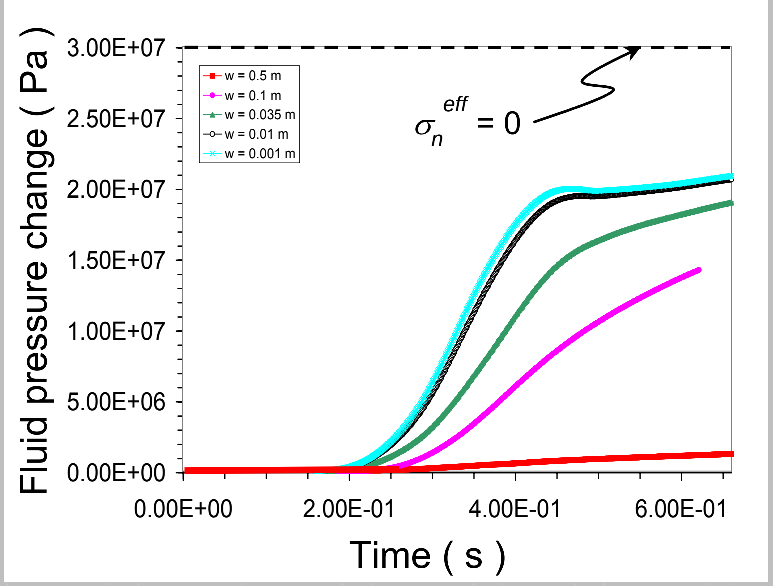


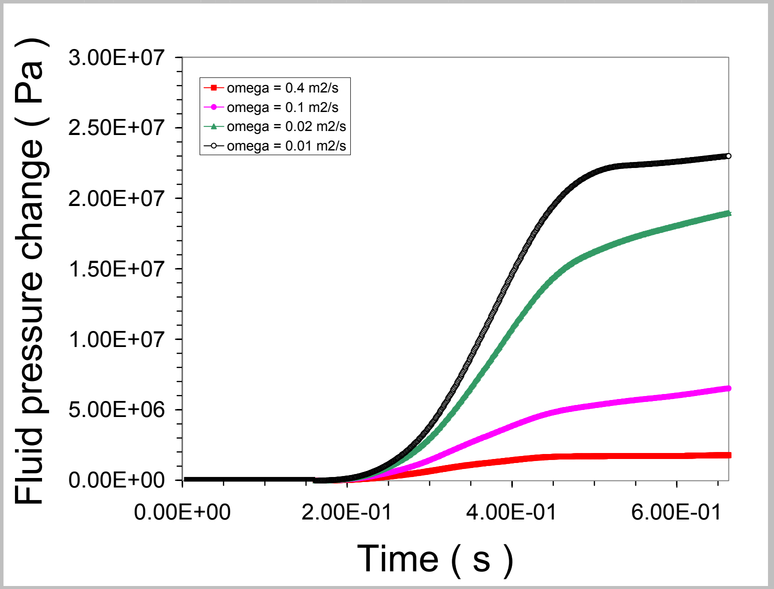
Wet fault (σ_n^{eff} varies)



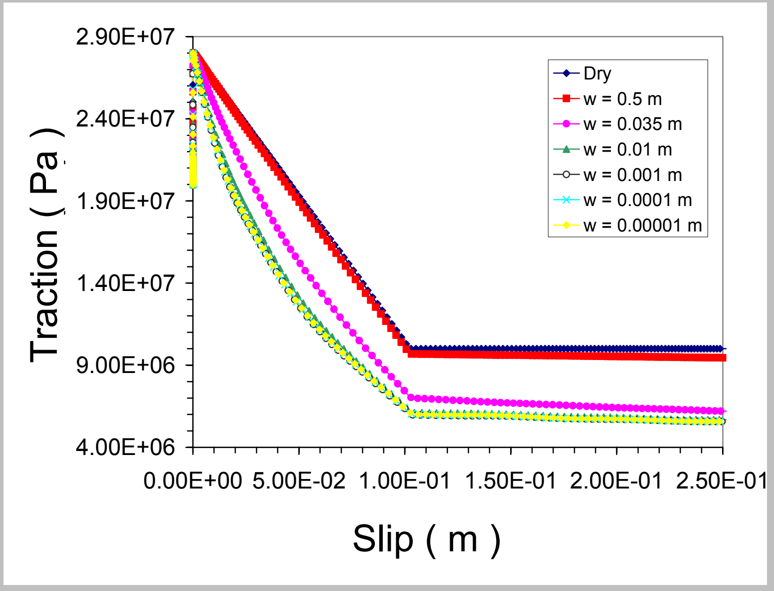


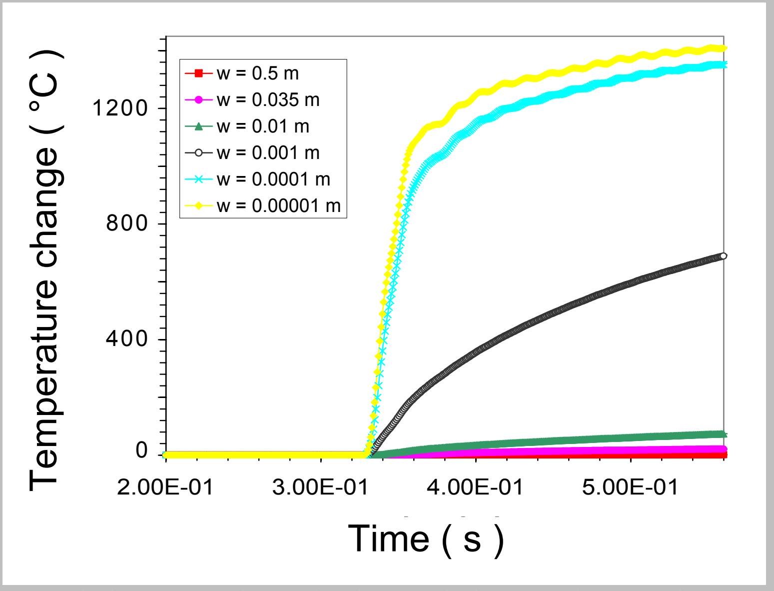
Results with DR law

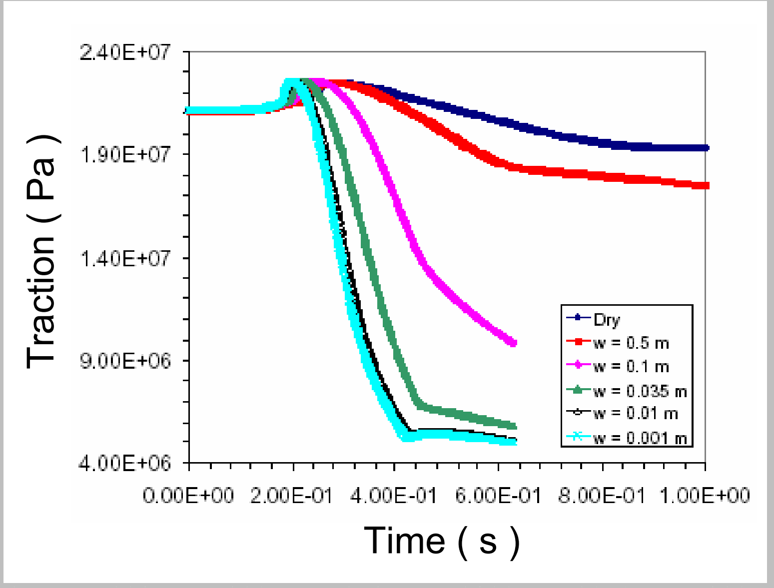


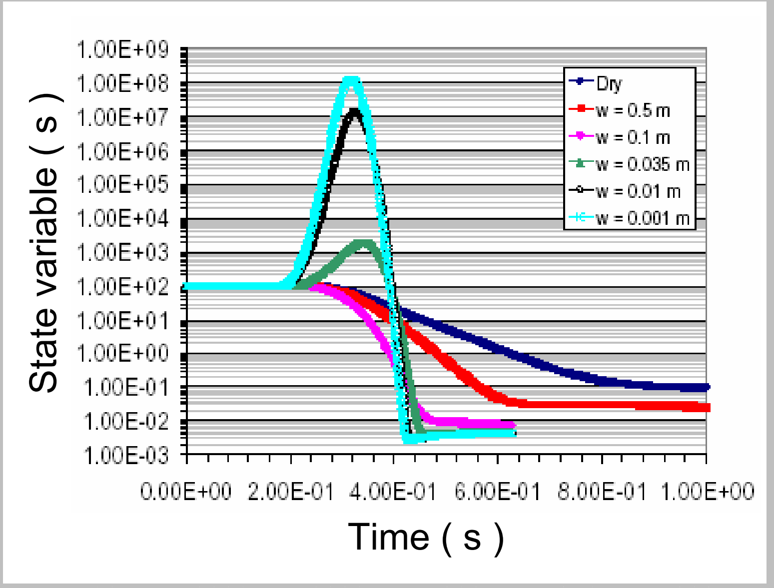


The breakdown zone









II. Flash heating of micro – asperity contacts

Mathematical background

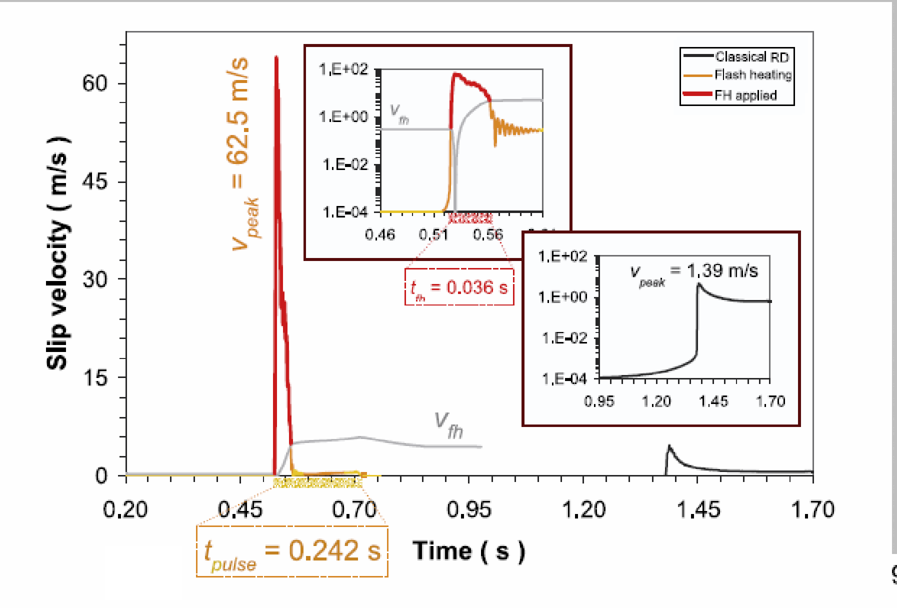
RUINA – DIETERICH WITH FLASH HEATING

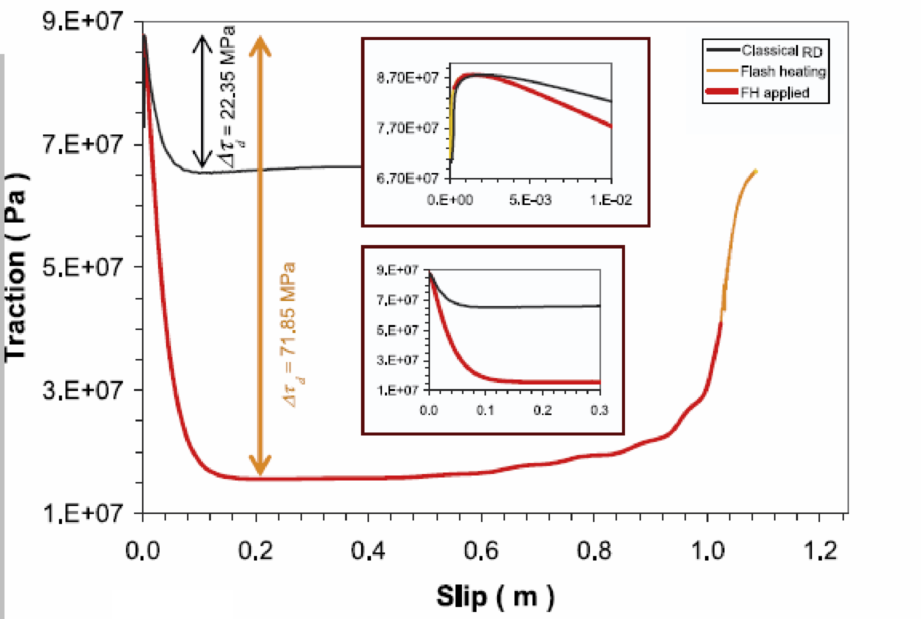
$$
\begin{cases}
\tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v} \right) + \theta \right] \sigma_n^{\,eff} \\[2ex]
\dfrac{\mathrm{d}}{\mathrm{d}\,t}\theta = \begin{cases} -\dfrac{v}{L}\left[\theta + b \ln\left(\dfrac{v}{v_*} \right) \right] & , v \le v_{fh} \\[2ex] \boxed{-\dfrac{v}{L}\left[\theta + b \dfrac{v_{fh}}{v} \ln\left(\dfrac{v}{v_*} \right) + \left(1 - \dfrac{v_{fh}}{v} \right)\left(a \ln\left(\dfrac{v}{v_*} \right) + \mu_* - \mu_{fh} \right) \right] \quad , v > v_{fh}} \end{cases}
\end{cases}
$$

where $v_{fh} = \dfrac{\pi\chi}{D_{ac}} \left(c \dfrac{T_{weak} - T^{w^f}}{\tau_{ac}} \right)^2$ is a weakening velocity above which flash heating is activated, T_{weak} is a weakening temperature, τ_{ac} is the (average) shear strength of asperity contacts and D_{ac} their (average) size.

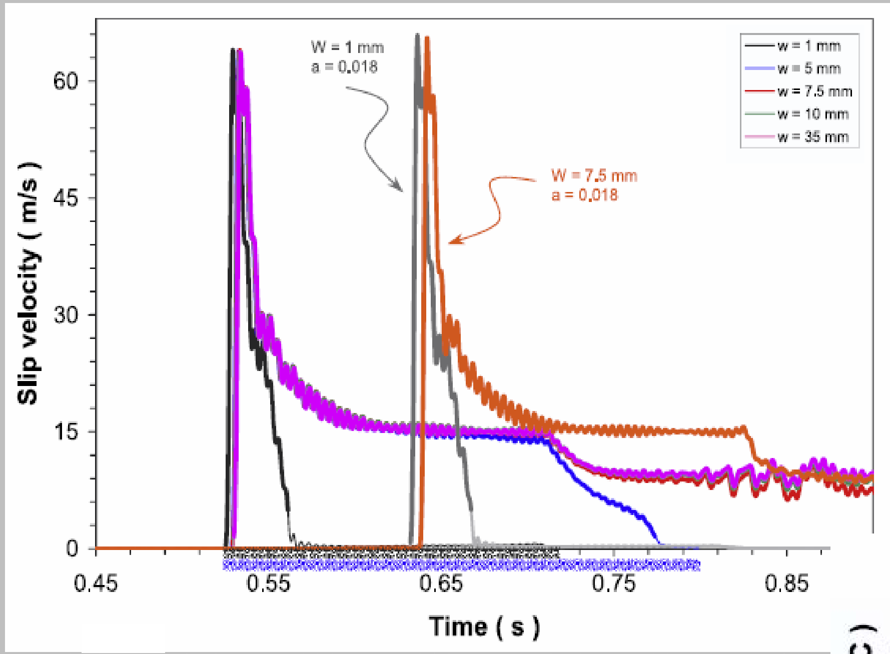
Bizzarri (2009, *GRL*)

Crack - like ruptures or slip pulses?

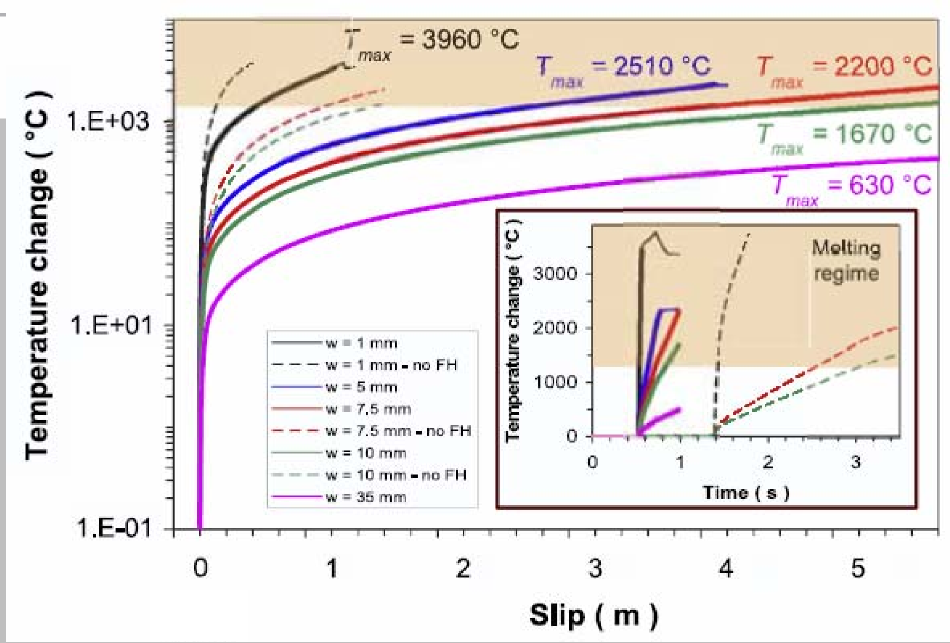




The prominent importance of 2*w*

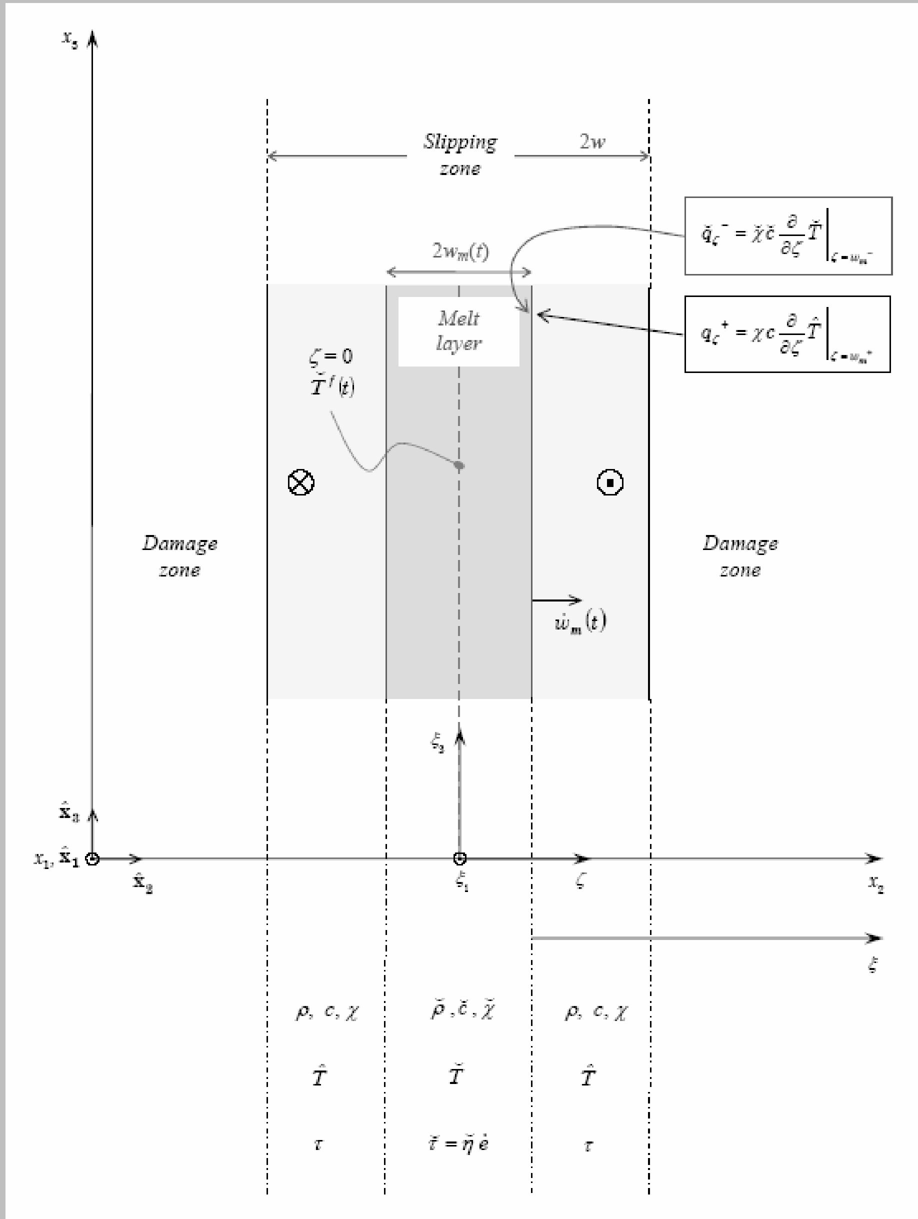


Localized shear (2*w* ≤ 10 mm): self–healing pulses



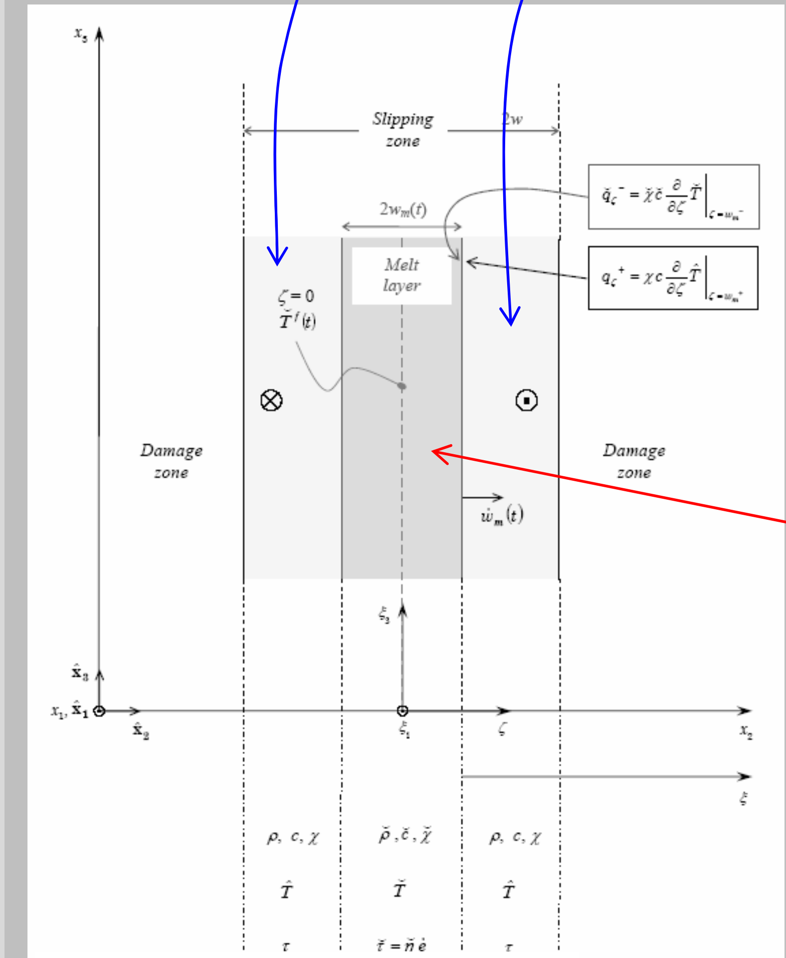
III. Melting of rocks and gouge

Mathematical background



Bizzarri (2010, *JGR*)

Mathematical background



Bizzarri (2010, *JGR*)

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

$$q(\zeta,t) = \begin{cases} \dfrac{\tau(t)v(t)}{2w} & , t > 0, |\zeta| \le w \\ 0 & , |\zeta| > w \end{cases}$$

$$T^f(t) \equiv T(0,t) = T_0^f + \frac{1}{2cw} \int_0^{t-\varepsilon} dt' \operatorname{erf}\left(\frac{w}{2\sqrt{\chi(t-t')}}\right) \tau(t')v(t'),$$

$$\frac{\partial}{\partial t} \breve{T}(\zeta,t) = \breve{\chi} \frac{\partial^2}{\partial \zeta^2} \breve{T}(\zeta,t) + \frac{d}{dt} w_m(t) \frac{\partial}{\partial \zeta} \breve{T}(\zeta,t) + \frac{1}{\breve{c}} \breve{q}(\zeta,t)$$

$$\breve{q}(\zeta,t) = \frac{\breve{\tau}(\zeta,t)\, v(t)\, e^{-\frac{\zeta^2}{2w_m^2(t)}}}{\sqrt{2\pi} w_m(t)} \Theta(t - t_m)$$

$$\breve{T}^f(t) \equiv \breve{T}(0,t) = T_m + \frac{\left(\sqrt{\frac{2\pi}{e}} + \pi \operatorname{erf}\left(\frac{1}{\sqrt{2}}\right) - \sqrt{2\pi}\right)}{2\pi\, \breve{c}\, \breve{\chi}} \cdot \Theta(t-t_m) w_m(t)\, \breve{\tau}(t) v(t).$$

Mathematical background

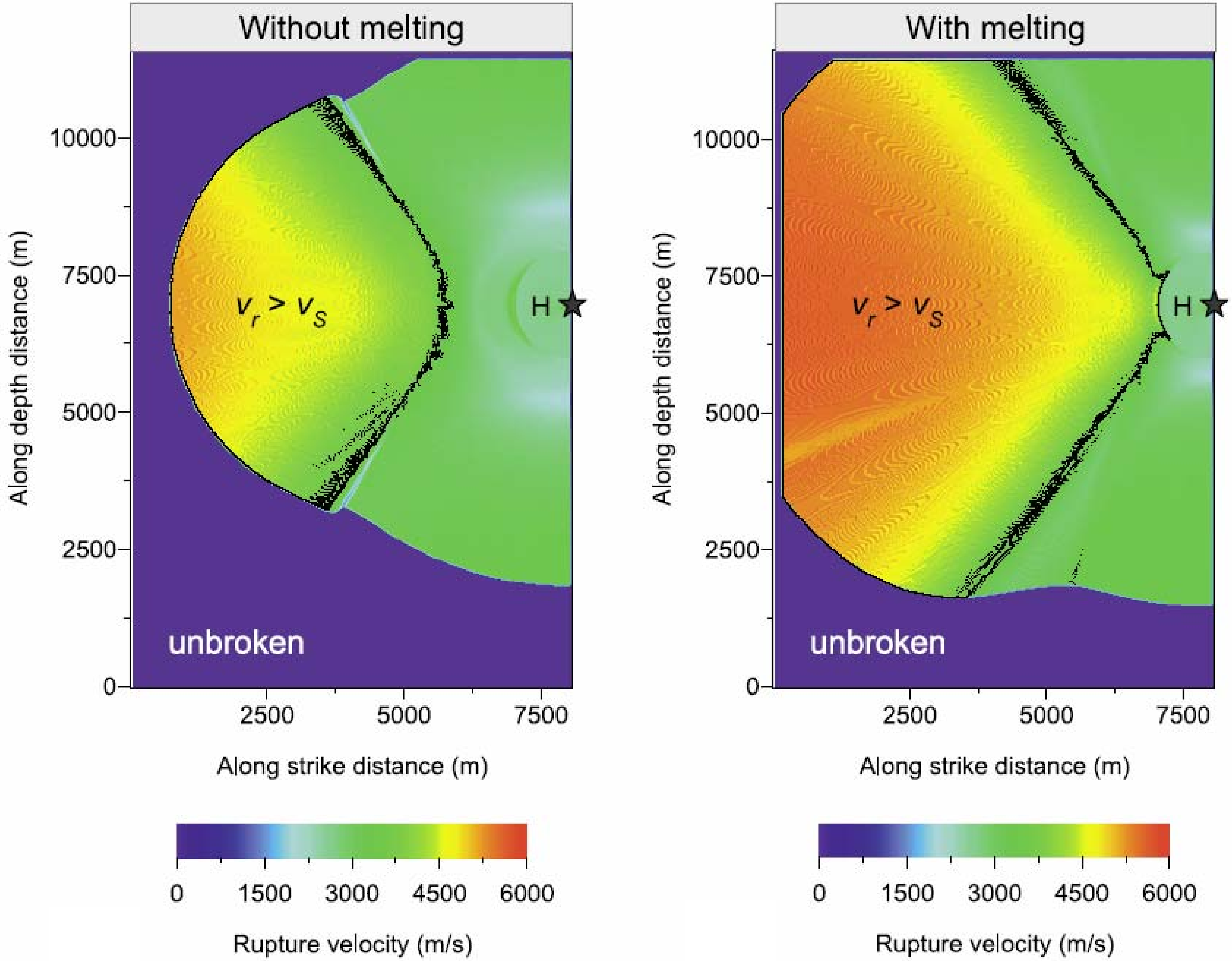
Coulomb friction is no longer valid and we then consider a Newtonian fluid (e.g., Fialko, 2004):

$$\tau^{(\mathrm{NF})} = \breve{\eta}\,\frac{v}{2\,w_m}$$

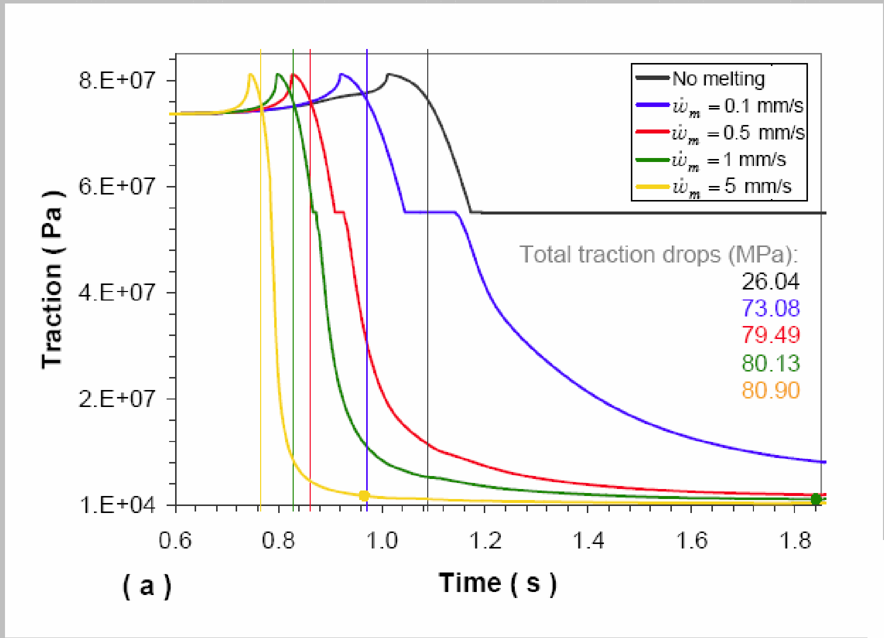
$$\breve{\eta}(\zeta,t) = \breve{K}\;\mathrm{e}^{\frac{\breve{T}_a}{\breve{T}(\zeta,t-\varepsilon)\,+\,273.15}}$$

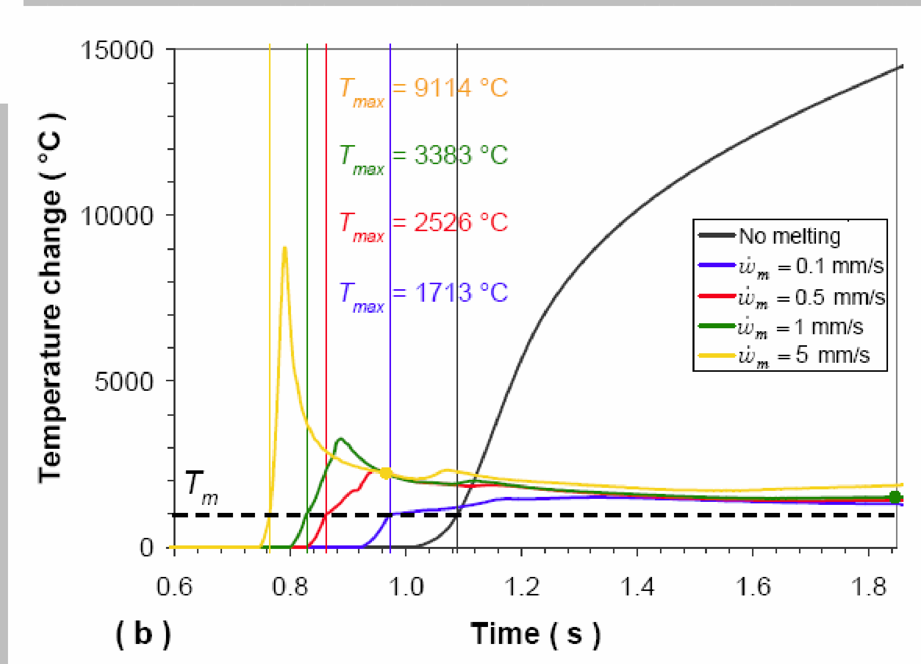
Bizzarri (2010, *JGR*)

Melting enhances supershear EQs



Transition to a viscous rheology

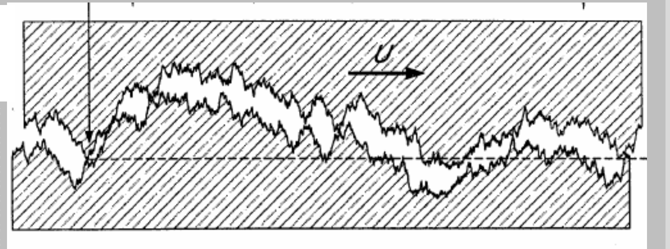




IV. Mechanical lubrication

Mathematical background

Brodsky and Kanamori (2001)



$$\tau = \begin{cases} \mu_u \sigma_n^{\text{eff}} + \dfrac{\langle 2w \rangle}{u} p_{\text{lub}} = \mu_u \sigma_{n_0} - \left(\mu_u - \dfrac{\langle 2w \rangle}{u} \right) p_{\text{lub}} & , So < 1 \\ \dfrac{\langle 2w \rangle}{u} p_{\text{lub}} & , So \geq 1 \end{cases}$$

Effective normal stress $\sigma_n^{eff} = \sigma_n - p_{res} - p_{lub}$

Sommerfeld number $So \equiv \dfrac{p_{\text{res}} + p_{\text{lub}}}{\sigma_n}$

$$\langle 2w \rangle^3 p_{\text{lub}} - 6\eta\, r\, u^2\, v = 0$$

In the special case of (temporally) constant gap height (<2w> = <2w_0>)

Lubrication pressure

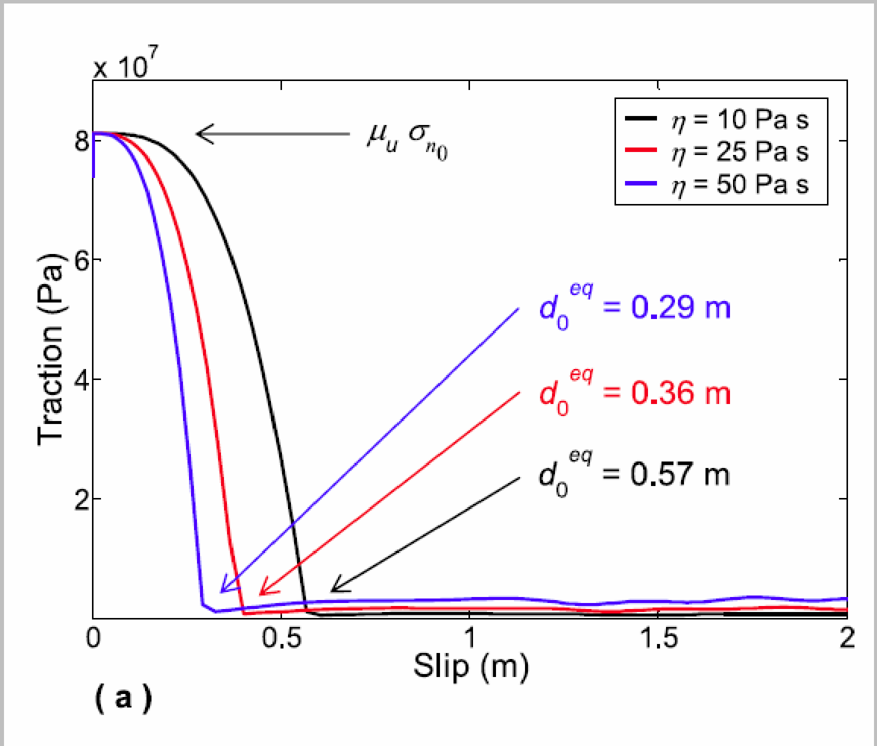
$$\frac{6\,\eta\, r}{\langle 2w_0 \rangle^3}\, u^2\, v$$

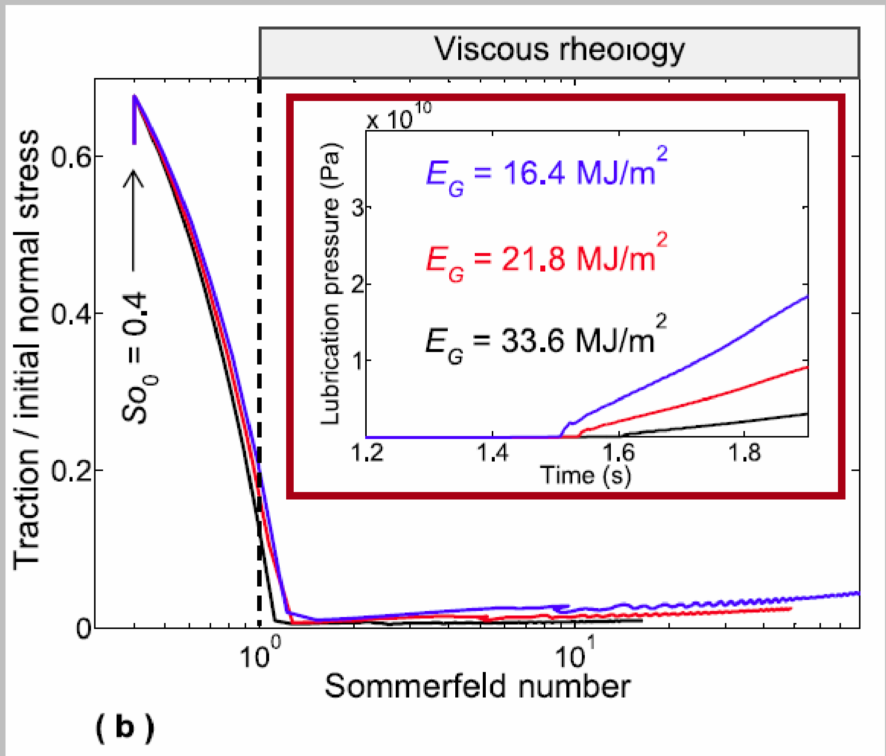
Frictional resistance

$$\begin{cases} \mu_u \sigma_{n_0} - \dfrac{6\,\eta\, r\, \mu_u}{\langle 2w_0 \rangle^3}\, u^2\, v + \dfrac{6\,\eta\, r}{\langle 2w_0 \rangle^2}\, u\, v & , So < 1 \\ \dfrac{6\,\eta\, r}{\langle 2w_0 \rangle^2}\, u\, v & , So \geq 1 \end{cases}$$

Bizzarri (2012, *JGR*, **117**, B05304)

Viscous rheology after *So* = 1





Conclusions

- ✓ Many different physical and chemical mechanisms may occur during faulting
- ✓ They strongly affect the overall dynamics of the fault, the radiated energy and the resulting ground motions
- ✓ Thermal pressurization of pore fluids, flash heating, melting and mechanical lubrication tend to enhance supershear ruptures…
- ✓ … produce a nearly complete stress drop (heat paradox)
- ✓ … increase the (equivalent) slip–weakening distance and thus the “fracture” energy
- ✓ In some cases the weakening behavior becomes exponential, as suggested by laboratory observations

- ✓ Different competing mechanisms can significantly affect the recurrence time of an eartquake sequence…
- ✓ … and they can make the concept itself of the seismic cycle meaningless

Open questions and future developments

1) Theoretical results will predict a nearly complete stress drop and therefore we should find a signature of these high stress drop values in the recorded seismograms. <u>Seismological estimates of stress drop do not support such an evidence</u>;

⇨ the estimation of stress drop from seismic waves is biased (for instance by the difficulties in analyzing high frequency radiation)

or

the effects of pressurization, melting and so on on the dynamic traction evolution are less pronounced

2) We need to test theoretical predictions against laboratory evidence; numerical results definitively represent an input for the development of next–generation machines

- Current high velocity lab. experiments only deal with <u>friction</u> (of pre–cut surfaces) and not with <u>fracture</u> (of intact rocks)

- We need to reproduce real–world conditions in terms of BOTH <u>high sliding velocity</u> and <u>confining stress</u>

3) Do real data (recorded during natural earthquakes) contain signatures of the specific friction law governing the sesimogenic fault?

We know from numerical models that, for ruptures having exactly the same energetics (namely, the same fracture energy density), the resulting ground motions are virtually indistinguishable

A multidisciplinary approach

Theoretical models

of the fault constitutive behavior based on rock physics

Numerical models

of the fault response, given some hypotheses on the fault geometry, governing eqts., initial conditions, …

Inferences from data

recorded during a real event and analysis of some specific signatures of the rupture dynamics (e.g., kinematic inversions, spectral analysis of ground motions, etc.)

Geological observations

conducted in the field (exhumed faults) and by analyzing samples in the laboratory

Laboratory experiments

conducted in “realistic” conditions on rock (or gouge) samples

Thank you!

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Why " *truly* " 3 – D ?

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

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

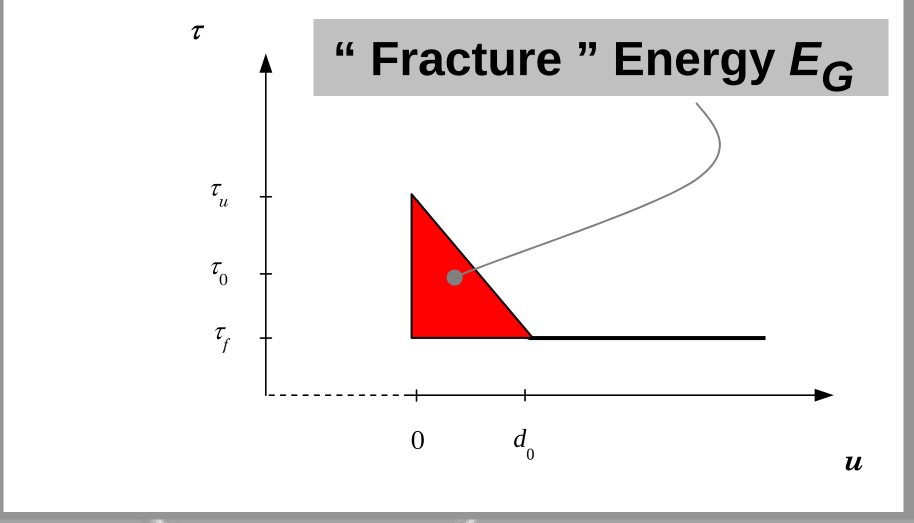
3 – D Mixed mode: $\mathbf{u} = (u_1(x_1,t), u_2(x_1,t), 0)$

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

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

Slip - Weakening Friction Laws

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



Barenblatt (1959a, 1959b), Ida (1972), Andrews (1976a, 1976b), and many authors thereinafter

d_0 is the characteristic slip – weakening distance

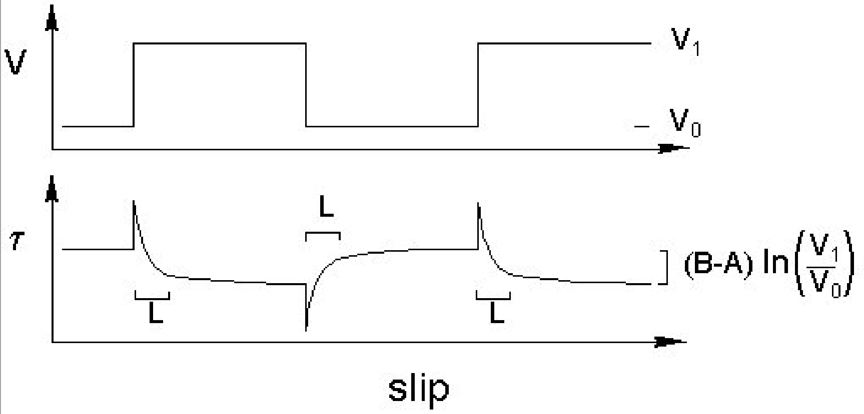
Rate - and State - Dependent

DIETERICH – RUINA WITH VARYING NORMAL STR.

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

Linker and Dieterich (1992), Dieterich and Linker (1992), Bizzarri and Cocco (2006a, 2006b)

Response to an abrupt jump in load



Crack vs. Pulse