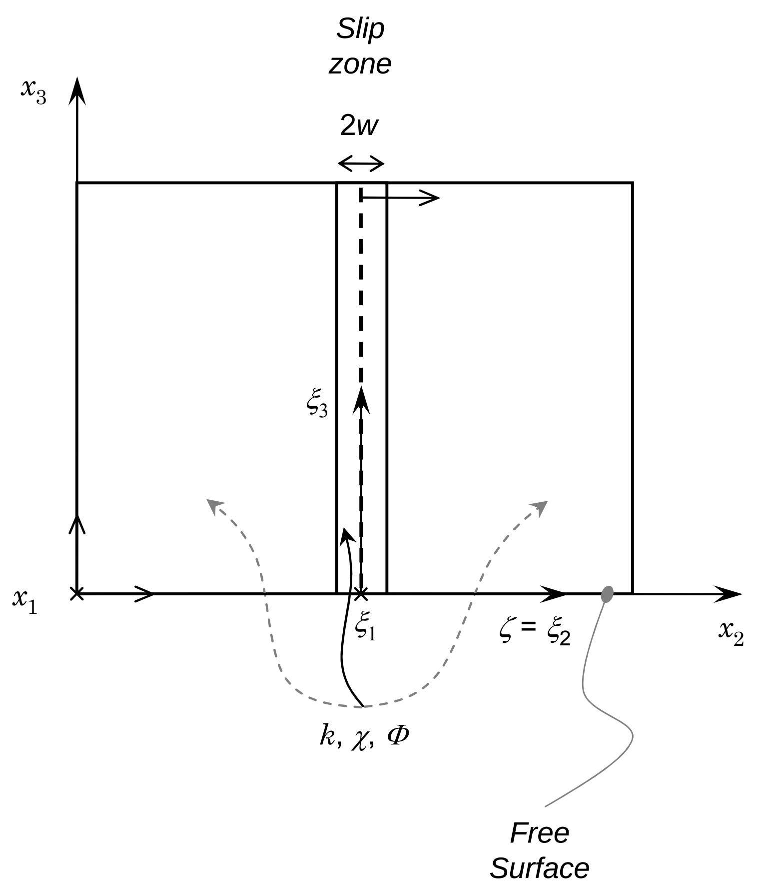
Application I. Thermal pressurization of pore fluids

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:

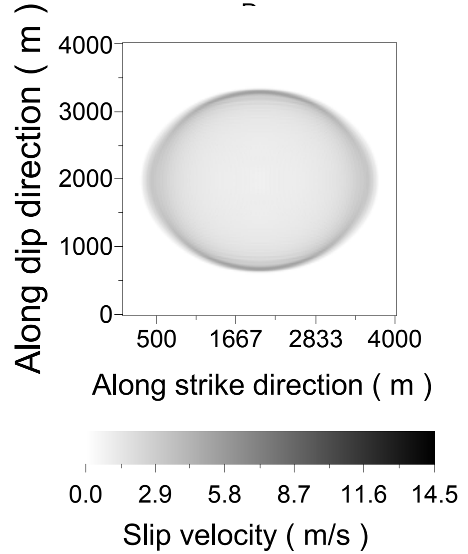
$$T^{w^f}(\xi_1,\xi_3,t) = T_0^{\ f} + \frac{1}{2\,cw(\xi_1,\xi_3)} \int_0^{t-\varepsilon} \mathrm{d}t' \ \mathrm{erf}\left(\frac{w(\xi_1,\xi_3)}{2\sqrt{\chi(t-t')}}\right) \tau(\xi_1,\xi_3,t') v(\xi_1,\xi_3,t')$$

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

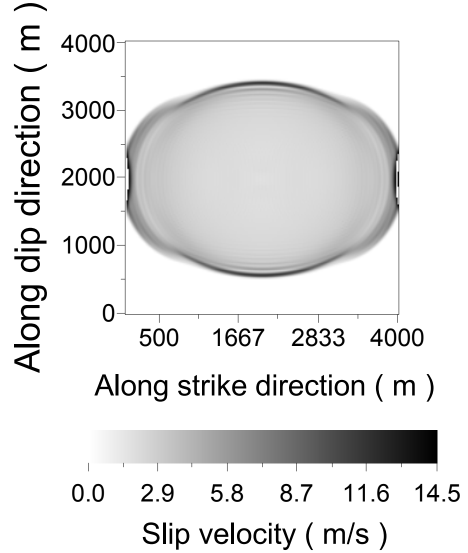
Bizzarri and Cocco (2006a, 2006b, *JGR*)

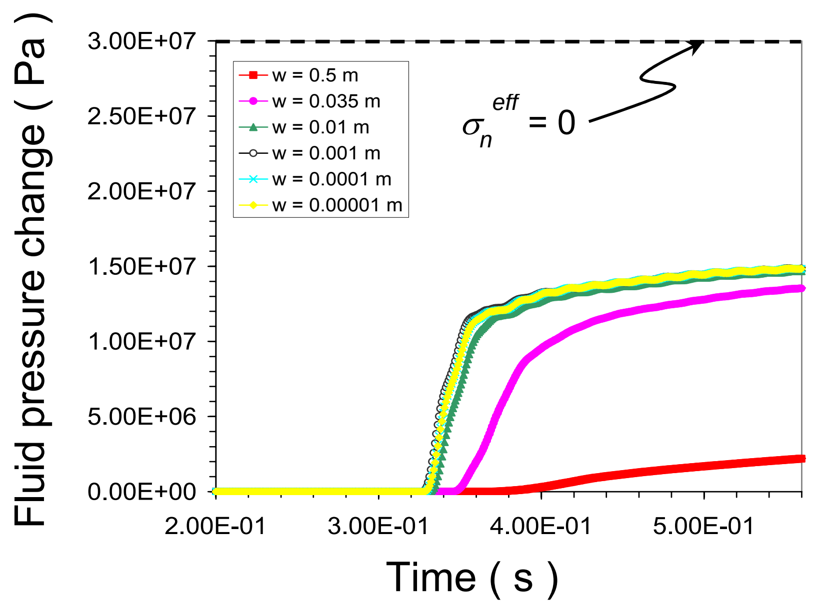
Results with SW law

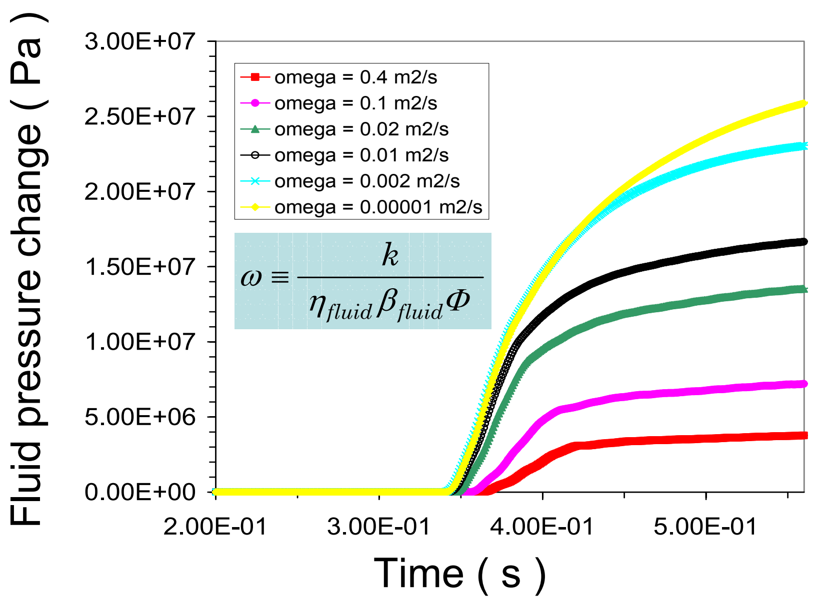
Dry fault (σ_n^{eff} = const)



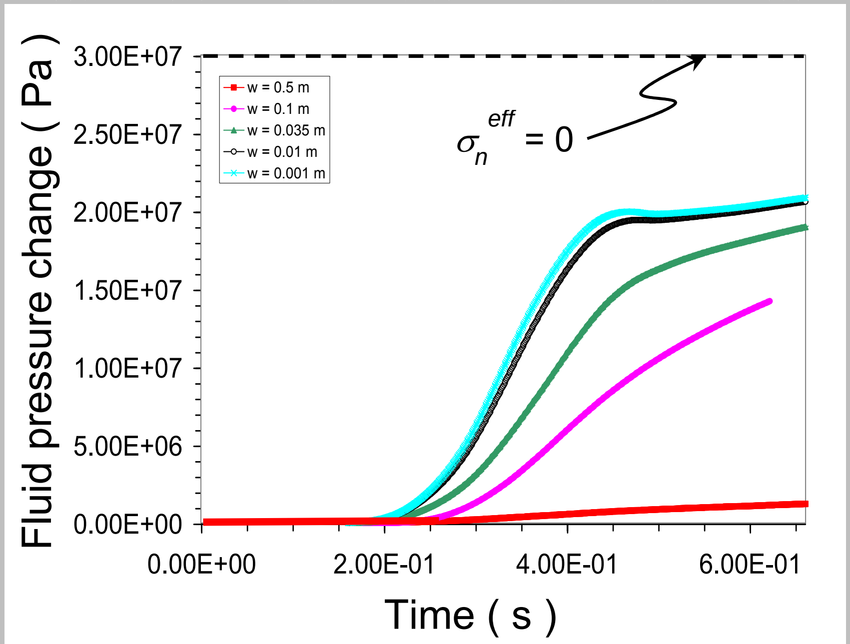
Wet fault (σ_n^{eff} varies)

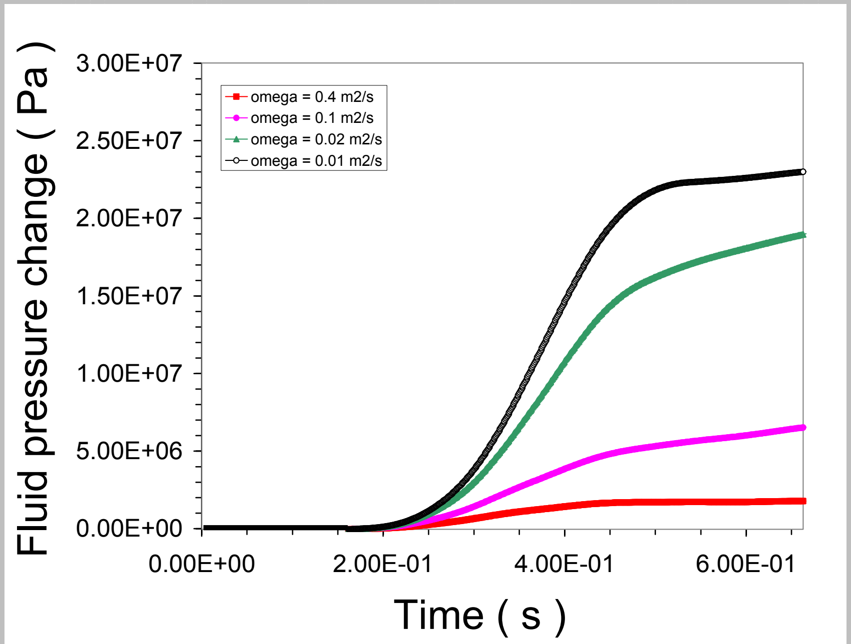




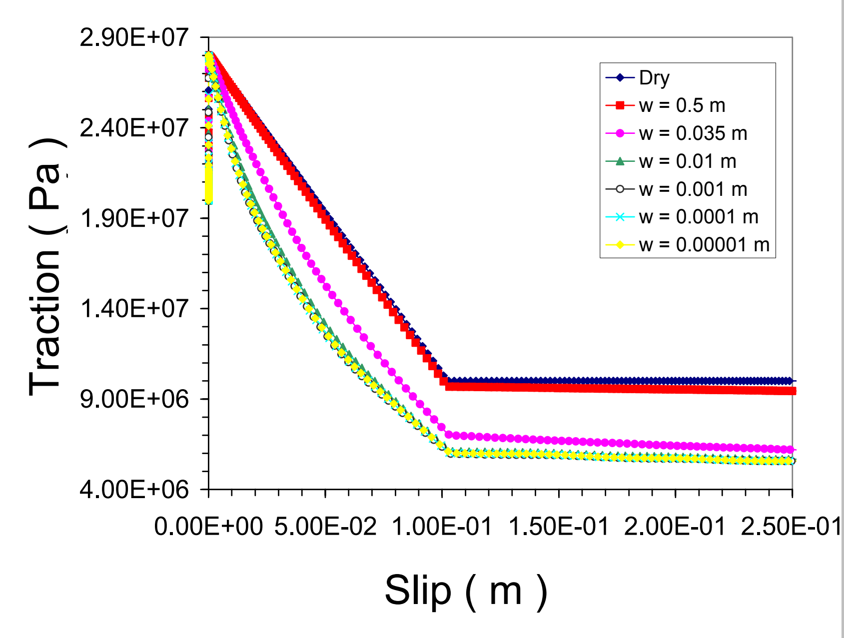


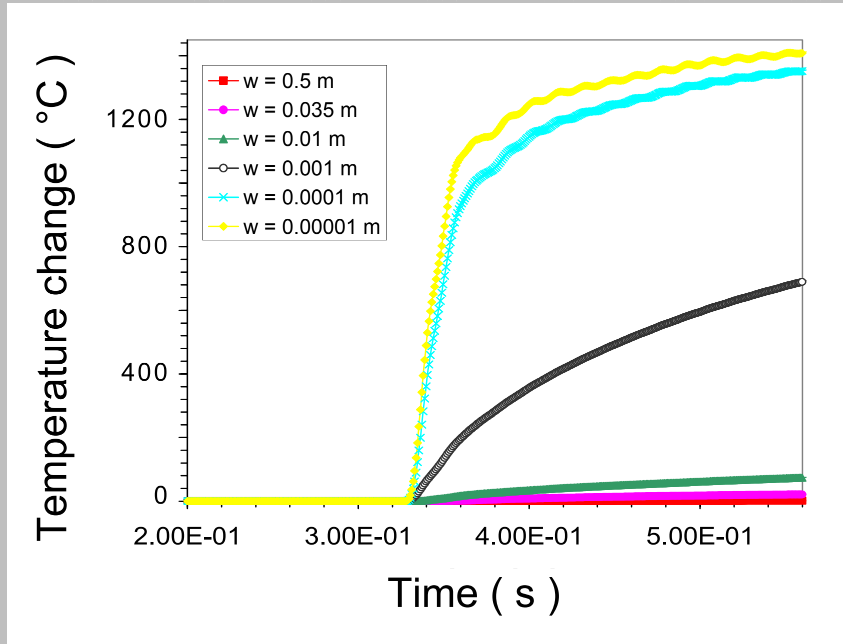
Results with DR law

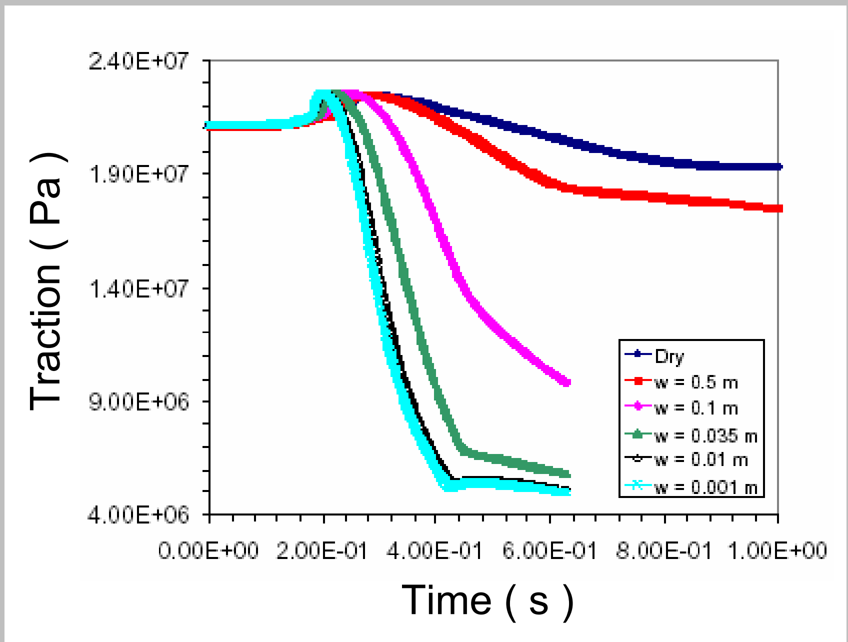


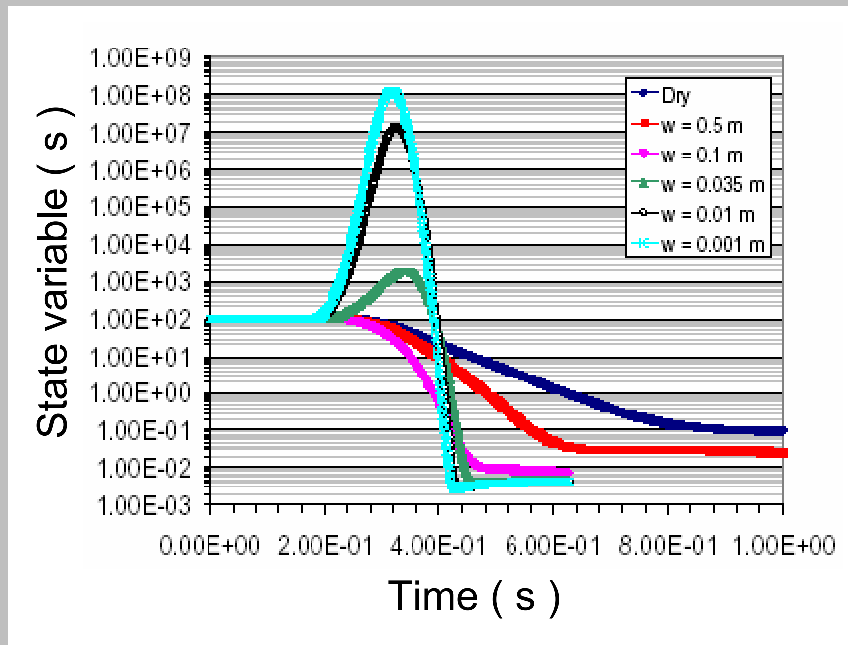


The breakdown zone









Application II. Flash heating of micro – asperity contacts

Mathematical background

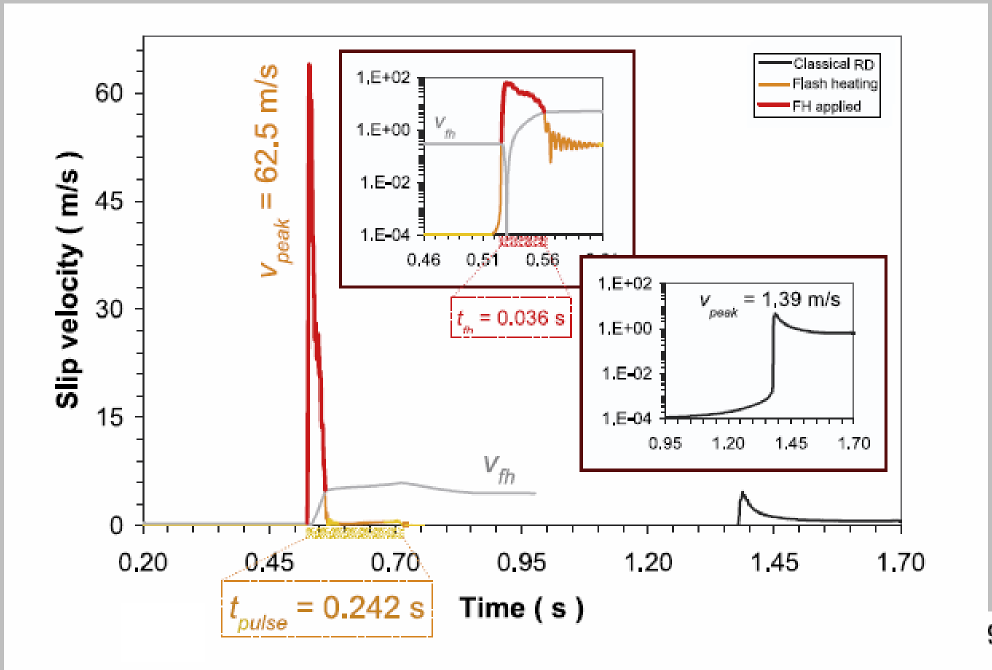
RUINA – DIETERICH WITH FLASH HEATING

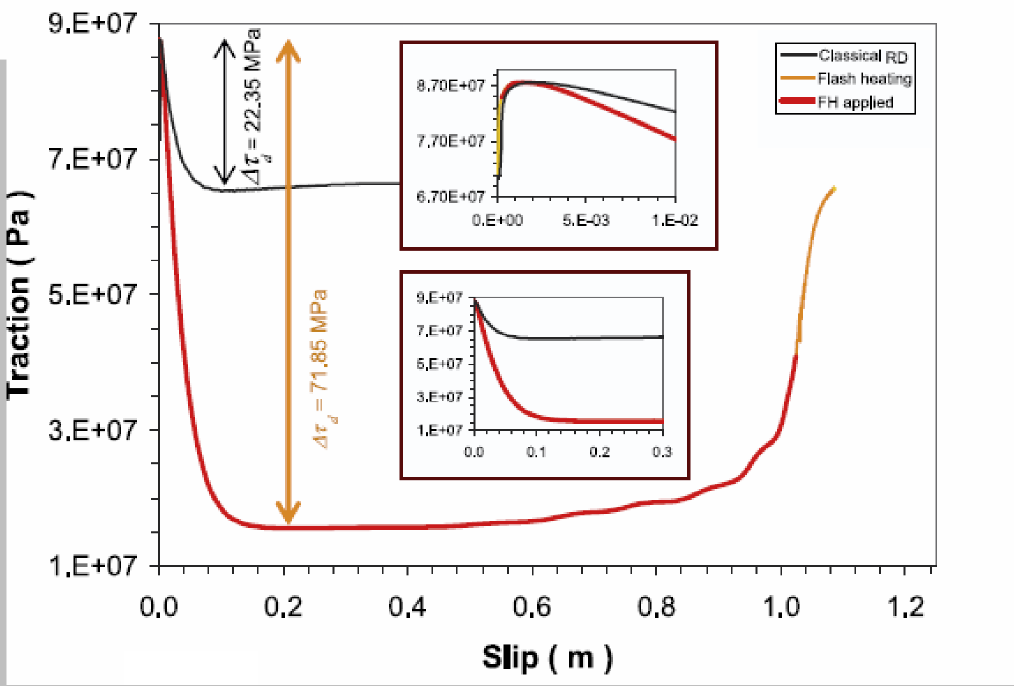
$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v} \right) + \theta \right] \sigma_n^{\ eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t}\theta = \begin{cases} -\dfrac{v}{L}\left[\theta + b \ln\left(\dfrac{v}{v_*} \right) \right] & , v \le v_{fh} \\ \boxed{-\dfrac{v}{L}\left[\theta + b \dfrac{v_{fh}}{v}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

where $v_{fh} = \dfrac{\pi\chi}{D_{ac}}\left(c\, \dfrac{T_{weak} - T^{wf}}{\tau_{ac}} \right)^2$ 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.

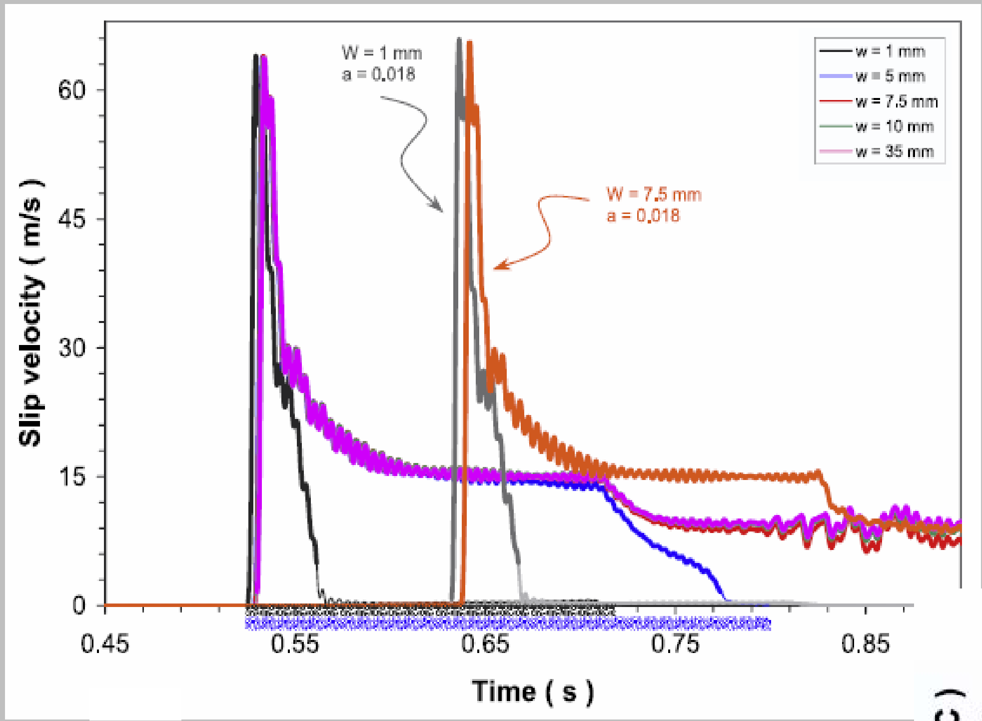
Bizzarri (2009, *GRL*)

Crack - like ruptures or slip pulses?

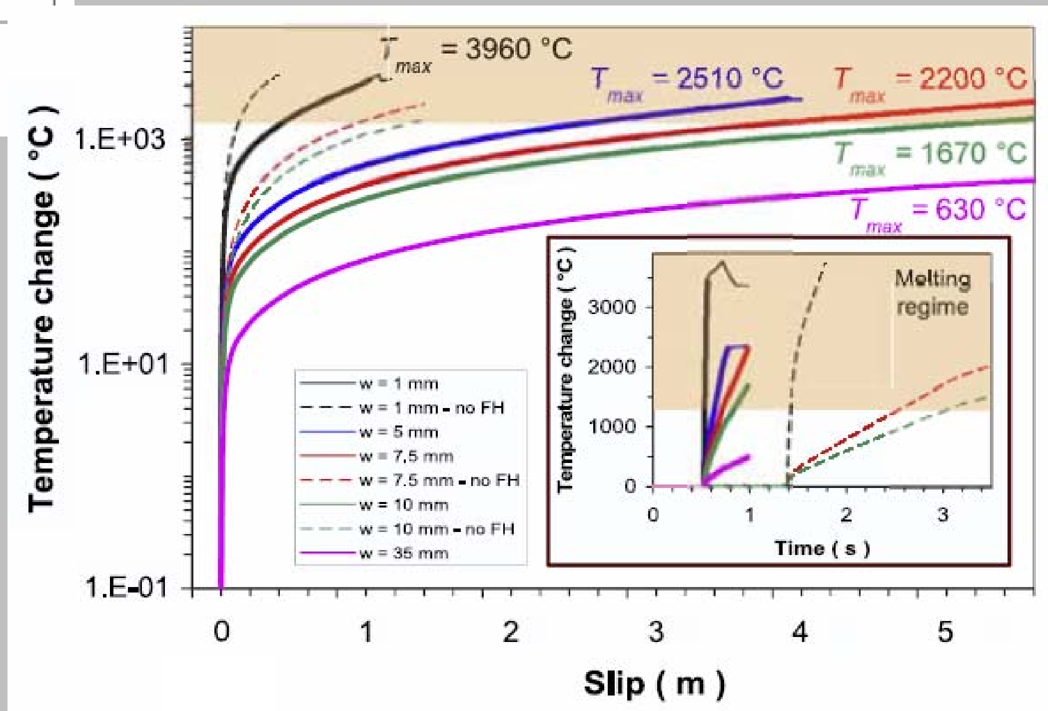




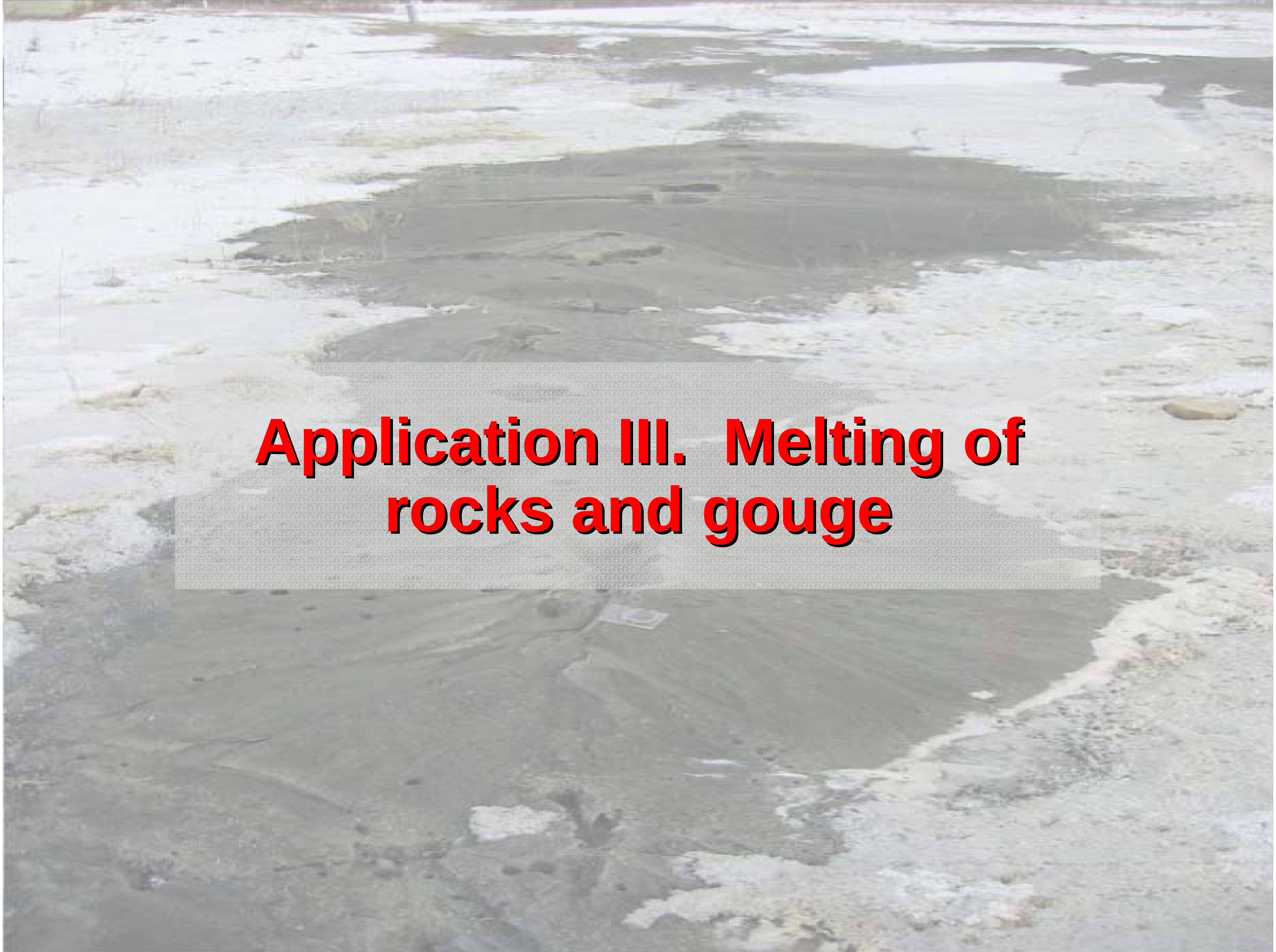
The prominent importance of 2*w*



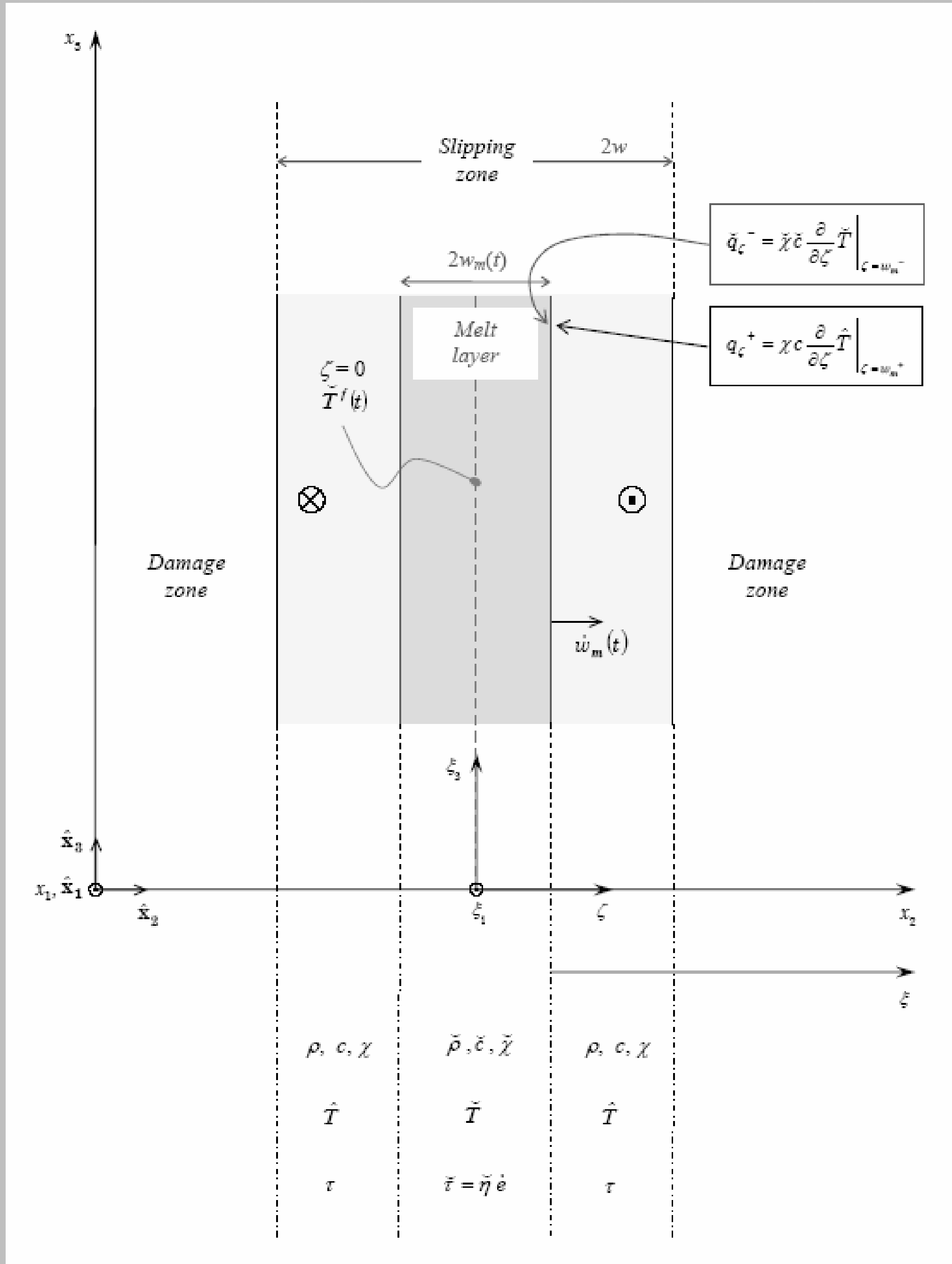
Localized shear (2$w \leq$ 10 mm):
self–healing pulses



Application III. Melting of rocks and gouge

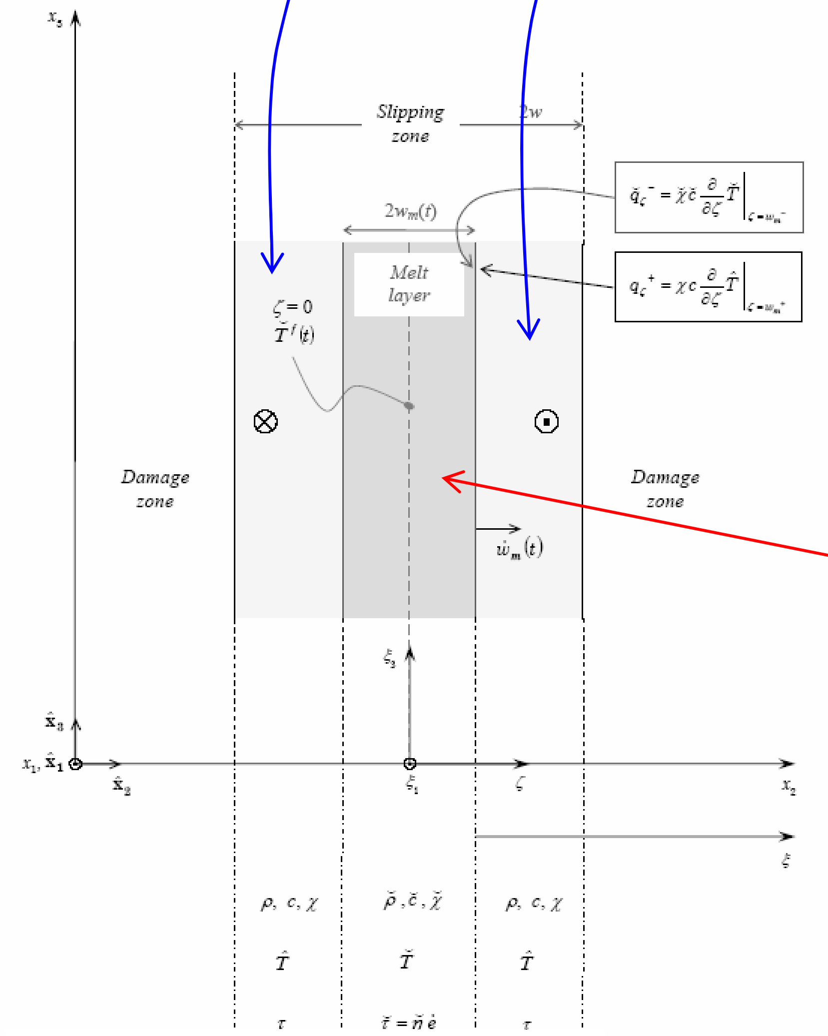


Mathematical background



Bizzarri (2010, *JGR*)

Mathematical background



Bizzarri (2010, *JGR*)

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

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

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

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

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

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

Mathematical background

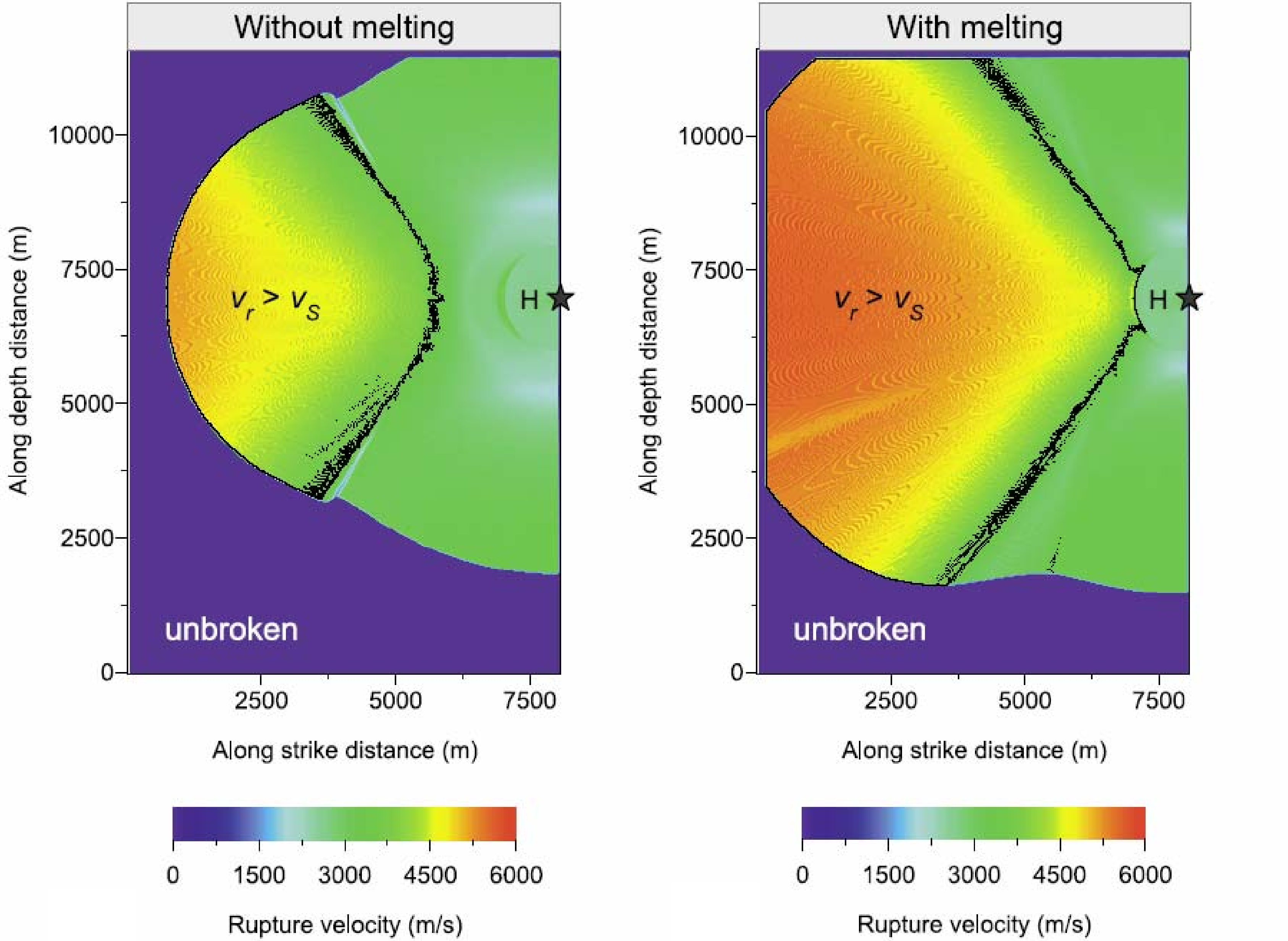
Coulomb friction is no longer valid and we then consider a Newtonian fluid (e.g., Fialko, 2004):

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

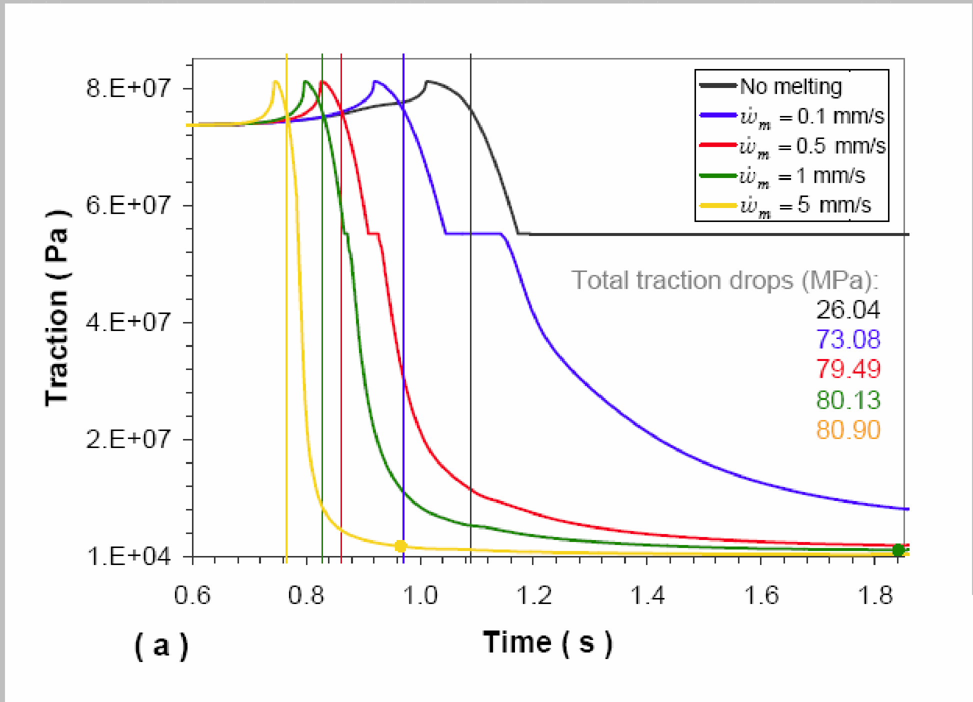
$$\breve{\eta}(\zeta, t) = \breve{K}\;\mathrm{e}^{\frac{\breve{T}_a}{\breve{T}(\zeta, t-\varepsilon)\,+\,273.15}}$$

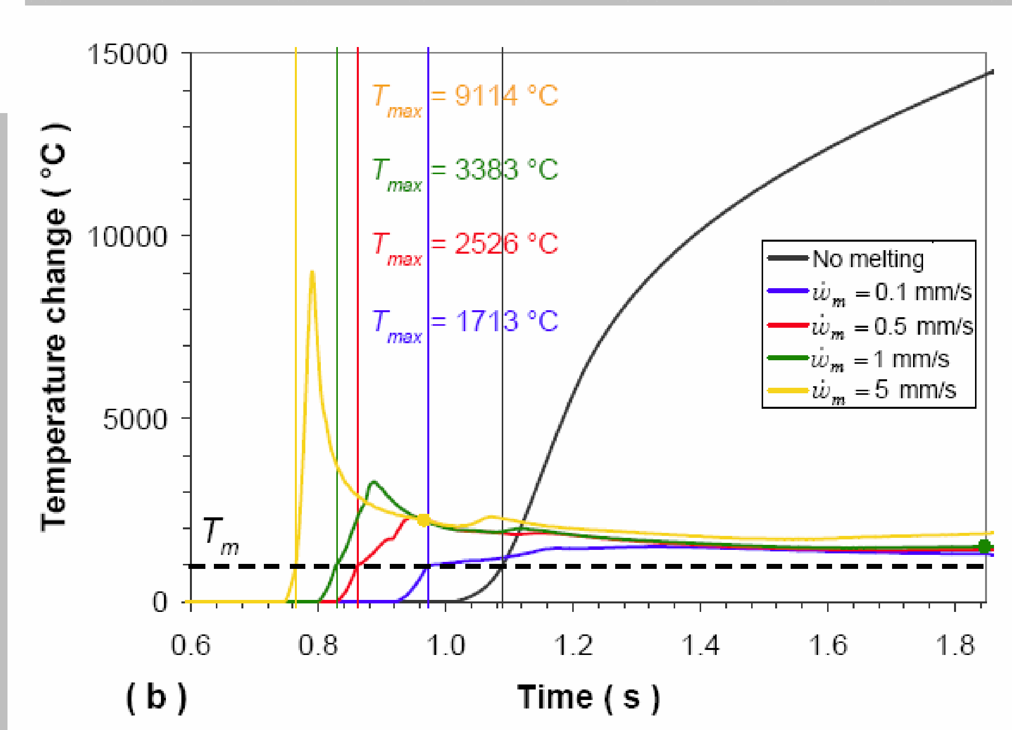
Bizzarri (2010, *JGR*)

Melting enhances supershear EQs



Transition to a viscous rheology

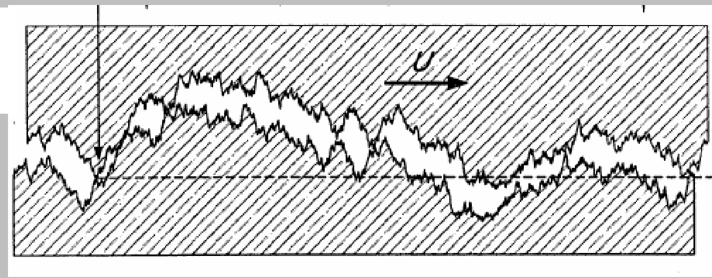




Application IV. Mechanical lubrication

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 (<2*w*> = <2w_0>)

Lubrication pressure

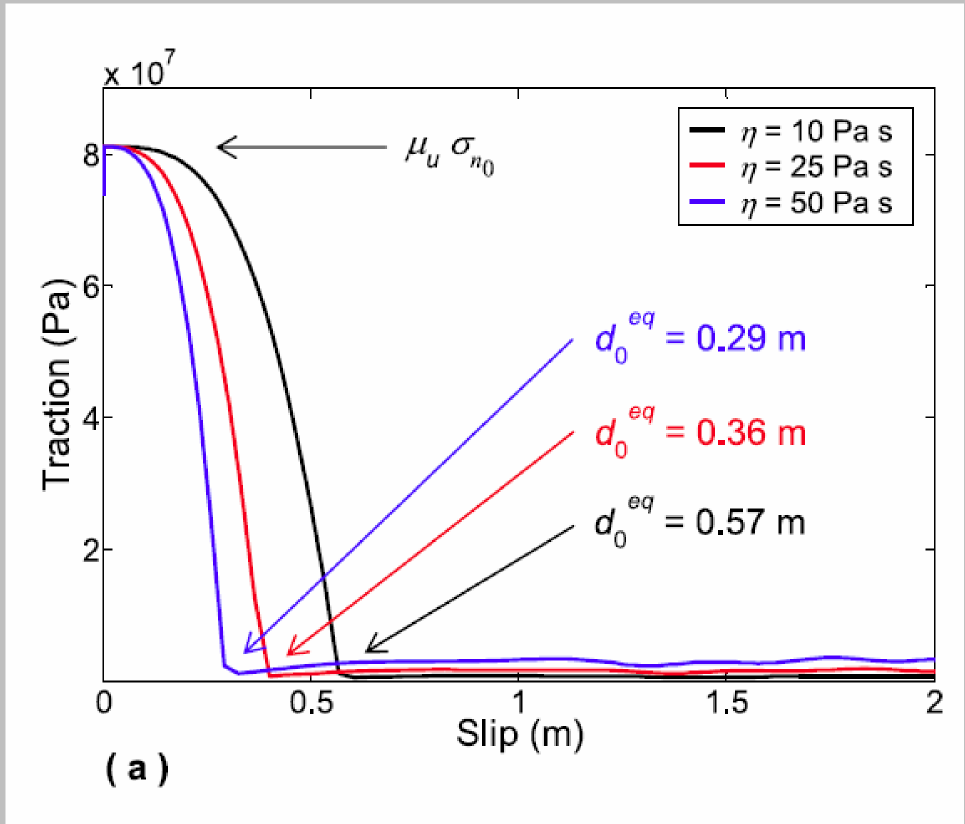
$$\frac{6\,\eta\, r}{\langle 2w_0 \rangle^3}\, u^2\, v$$

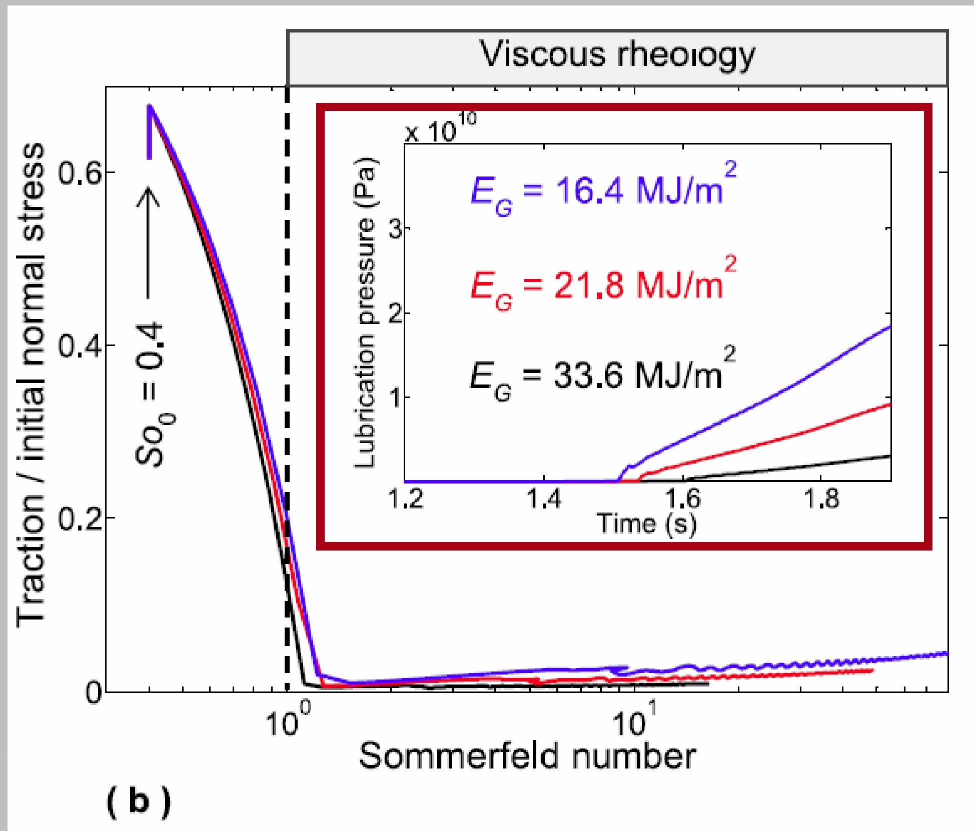
Frictional resistance

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

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 friction (of pre–cut surfaces) and not with fracture (of intact rocks)

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

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

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Support Slides: Parameters, Notes, etc.

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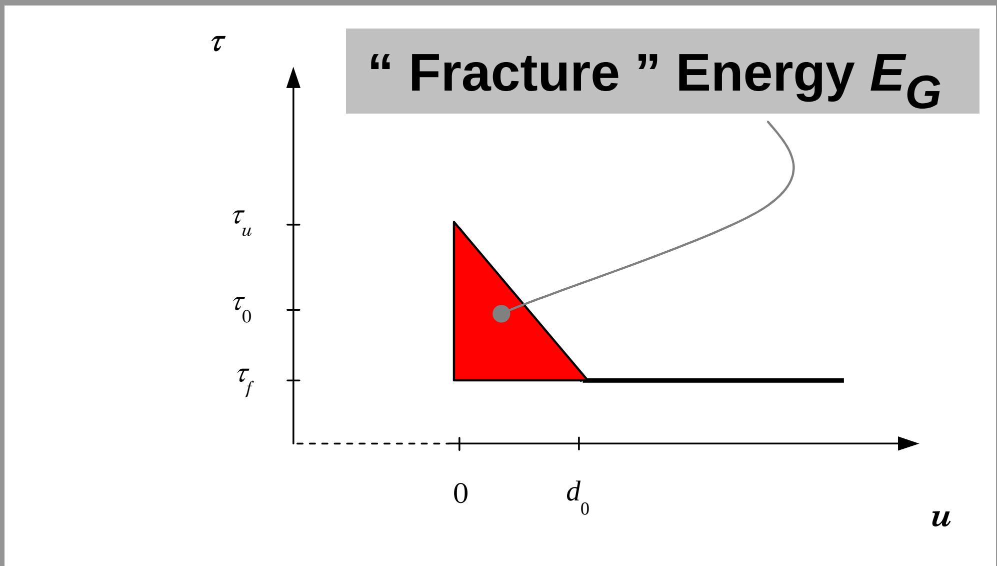
Slip - Weakening Friction Laws

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



Barenblatt (1959a, 1959b), *<u>Ida (1972)</u>, Andrews (1976a, 1976b),* and many authors thereinafter

d_0 is the characteristic slip – weakening distance

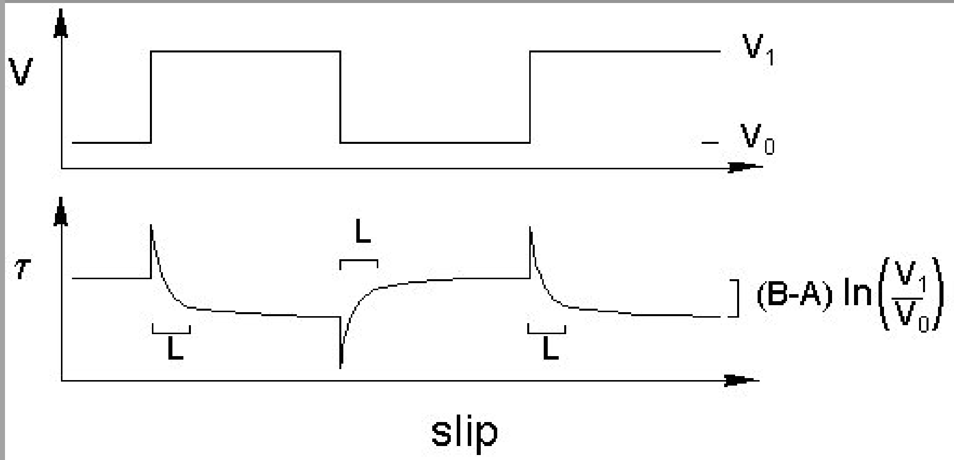
Rate - and State - Dependent

DIETERICH – RUINA WITH VARYING NORMAL STR.

$$
\begin{cases}
\tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v} \right) + b \ln\left(\dfrac{\Psi\, v_*}{L} \right) \right] \sigma_n^{\,eff} \\[2ex]
\dfrac{\mathrm{d}}{\mathrm{d}t}\Psi = 1 - \dfrac{\Psi\, v}{L} - \left(\dfrac{\alpha_{LD}\Psi}{b\,\sigma_n^{\,eff}} \right) \dfrac{\mathrm{d}}{\mathrm{d}t}\sigma_n^{\,eff}
\end{cases}
$$

<u>Linker and Dieterich (1992)</u>, Dieterich and Linker (1992), Bizzarri and Cocco (2006a, 2006b)

Response to an abrupt jump in load



Crack vs. Pulse