IV International workshop

Modern Trends in Geomechanics

Assisi, May 16 -18 2016

Multiphysics couplings and instability in geomechanics

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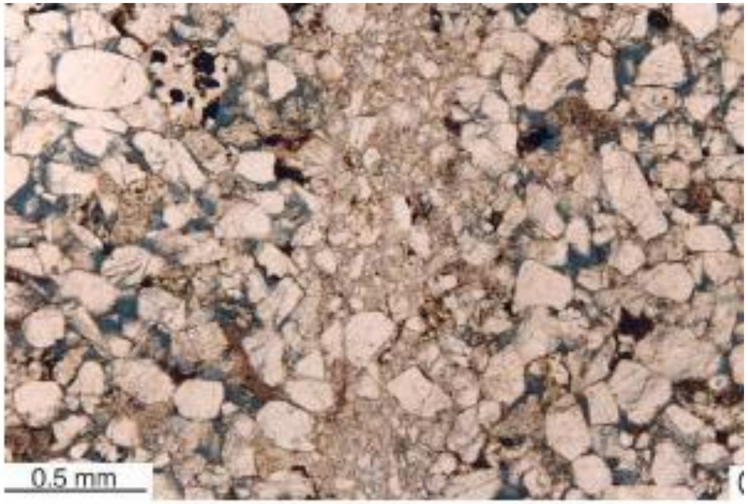
Deformation bands in geomechanics

- Deformation bands in the form of shear or compaction bands are observed are observed on a very large range of scales from sub-millimetric (grain size) to kilometric scale (geological structures).

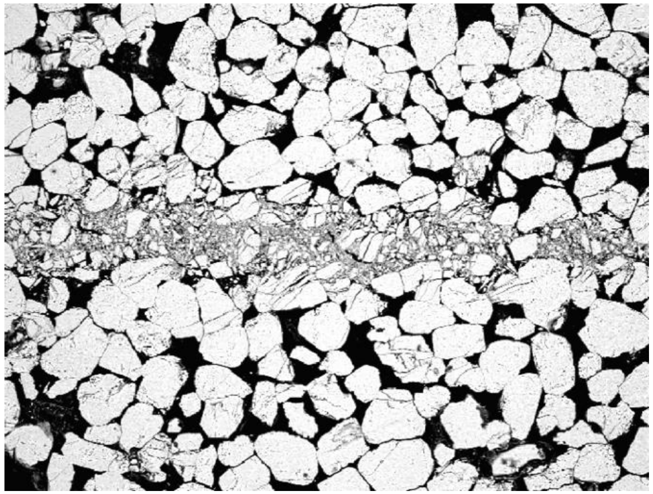
- Strong heterogeneity of mechanical (e.g. strength) and physical properties (e.g. porosity, permeability) induced by the deformation bands.

- Major role of localized deformation bands
  - ✓ in the failure of engineering structures (e.g. foundations, oil wells instability..),
  - ✓ in the nucleation of earthquakes and landslides
  - ✓ in the flow of fluids (hydrocarbon exploration and production, deep waste storage repositories, CO2 sequestration, geothermal systems…)

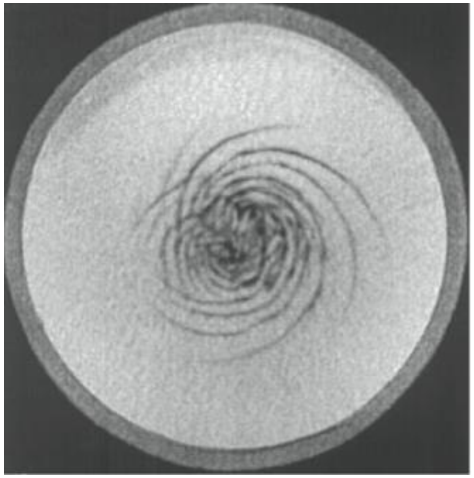


Labaume et al, 2001, *J. Struct. Geol.*

Valley of fire, Nevada, *Courtesy of I. Stefanou*



Sulem & Ouffroukh, 2006, *Int. J. Rock Mech. Min. Sci*



Papamichos et al. 2001, *Int. J. Num. An. Meth. Geom.*

Multiphysics weakening mechanisms

Softening behavior favors strain localization.

- Mechanical degradation of the rock properties (microcracking, grain crushing and grain size reduction…), (e.g. Das et al., 2011).

- Thermal pressurization of the pore fluid (e.g. Rice, 2006, Ghabezloo & Sulem, 2009)

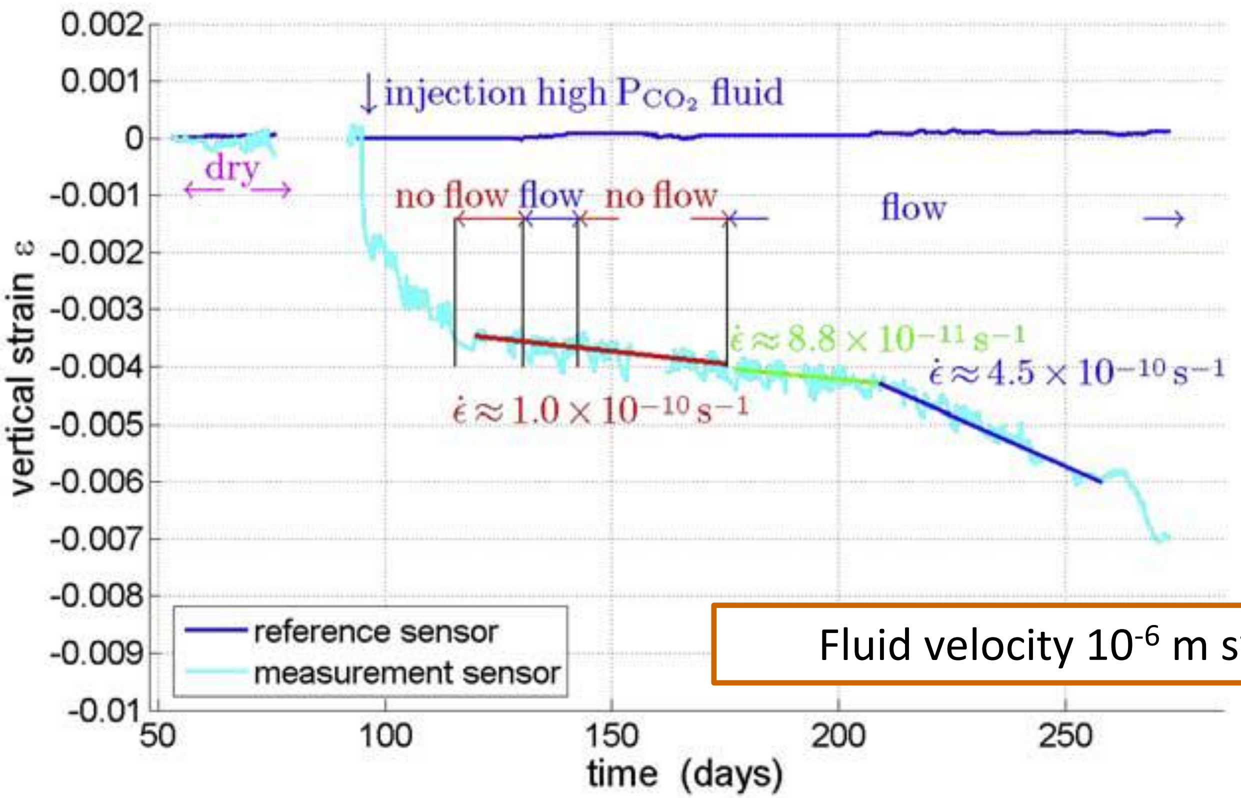
- Chemical reactions such as dissolution/ precipitation, mineral transformation at high temperature (dehydration of minerals, decomposition of carbonates, …) (e.g. Castellanza & Nova, 2004, Hu & Hueckel, 2007, Sulem & Famin, 2009, Sin & Santamarina, 2010, Brantut & Sulem 2012, Veveakis et al. 2014).

CHEMICAL DISSOLUTION AND COMPACTION BANDS

Strong coupling between chemical weakening and dissolution kinetics

Stefanou & Sulem, 2014, *J. Geoph. Res*.

Creep due to CO_2 injection in Lavoux limestone



Fluid velocity 10^{-6} m s^{-1}

Y. Le Guen, F. Renard, R. Hellmann, E. Brosse, M. Collombet, D. Tisserand, and J.-P. Gratier, “Enhanced deformation of limestone and sandstone in the presence of high P_{CO2} fluids,” *Journal of Geophysical Research*, 2007, 112.

R. H. Brzesowsky, S. J. T. Hangx, N. Brantut, and C. J. Spiers, “Compaction creep of sands due to time-dependent grain failure: Effects of chemical environment, applied stress and grain size,” *Journal of Geophysical Research*, 2014, 119.

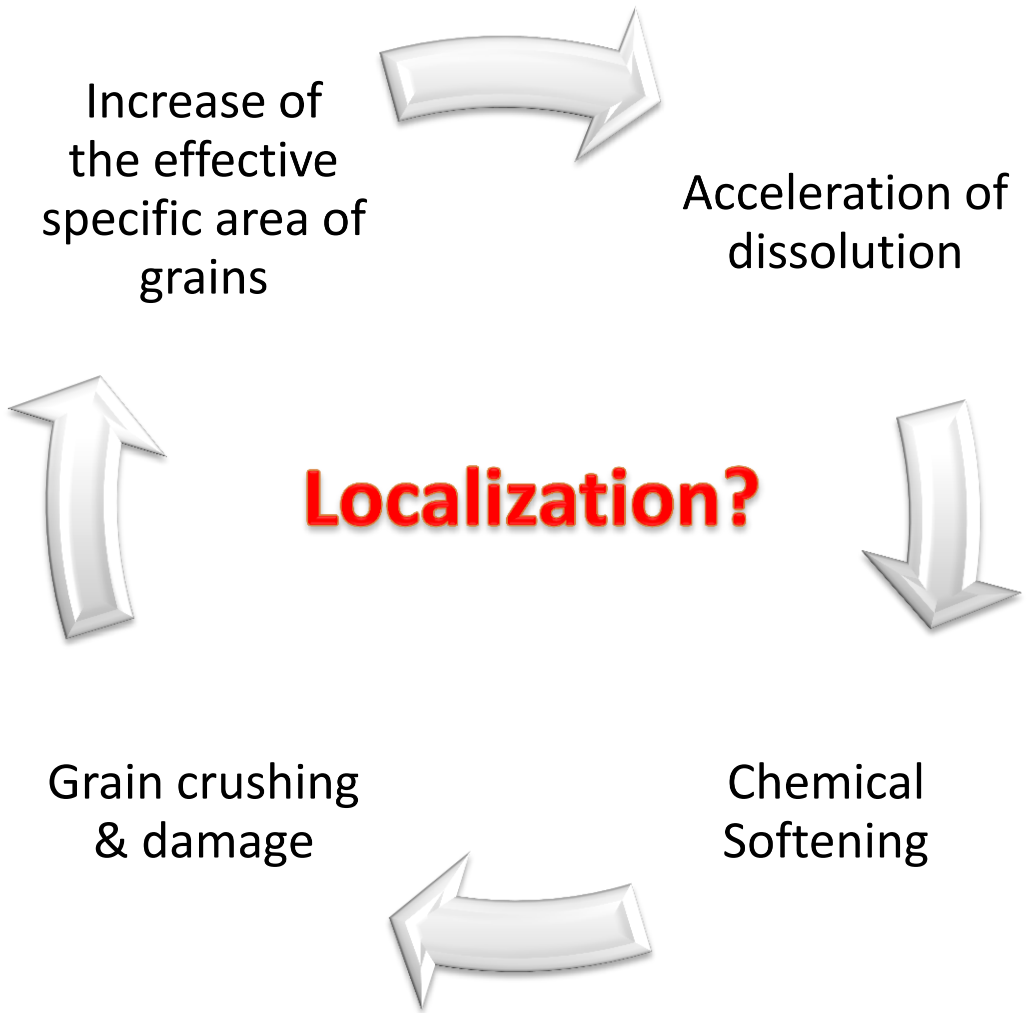
Is the deformation homogeneous?

Pure compaction bands?

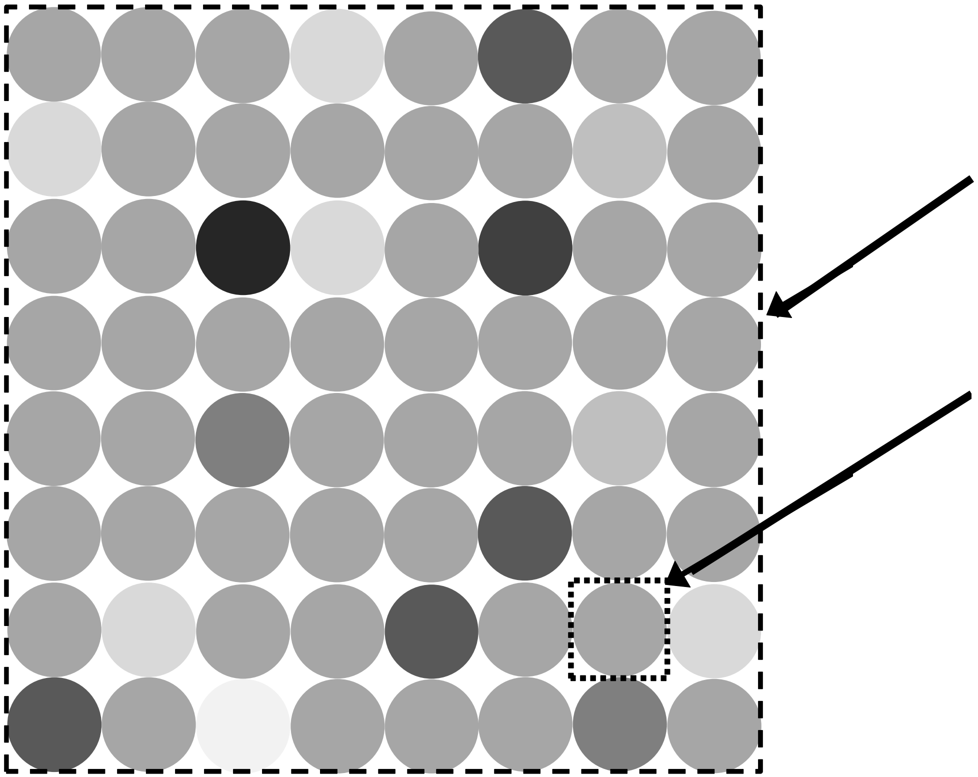
What is the influence of a reactive fluid flow on

deformation band formation?

Conceptual model & chemical softening



Distinction of scales



Macro-scale / Elementary volume (REV)
- Constitutive equations
- Momentum balance
- Mass balance

Micro-scale / Single grain
- Reaction kinetics of dissolution
- Grain crushing, solid skeleton damage, microcracking …

Reaction kinetics (micro-scale)

$$\underset{(3)}{\text{solid}} + \underset{(1)}{\text{solvent}} \rightleftharpoons \underset{(2)}{\text{solution}}$$

e.g. dissolution of quartz $SiO_2\text{(solid)}+2H_2O\text{(liquid)} \rightleftharpoons H_4SiO_4\text{(aqueous solution)}$

or carbonate $CaCO_3\text{(solid)}+H_2CO_3\text{(aqueous solution)} \rightleftharpoons Ca\left(HCO_3\right)_2\text{(aqueous solution)}$

$$\frac{\partial w_2}{\partial t} = k^* \frac{S}{e}\left(1 - \frac{w_2}{w_2^{eq}}\right)$$

Hu & Hueckel, 2007

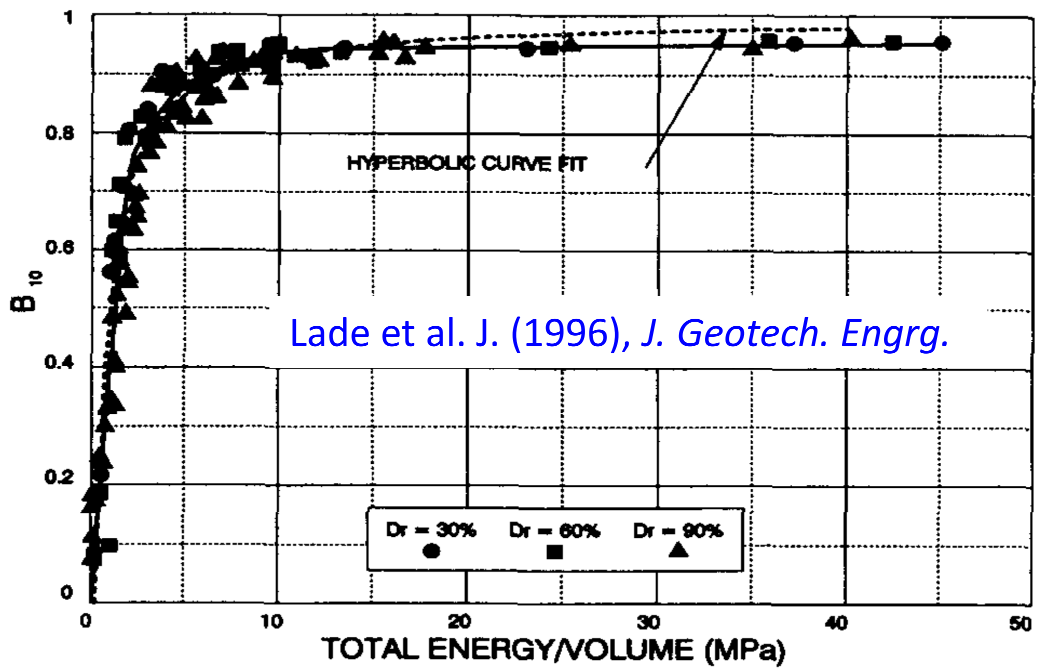
w_2 is the mass fraction of the dissolution product in the fluid

k^* is a reaction rate coefficient

e is the void ratio

$S \propto \frac{1}{D}$ is the specific area of a single grain of diameter *D*

Evolution of the effective grain size
Grain crushing (micro-scale)

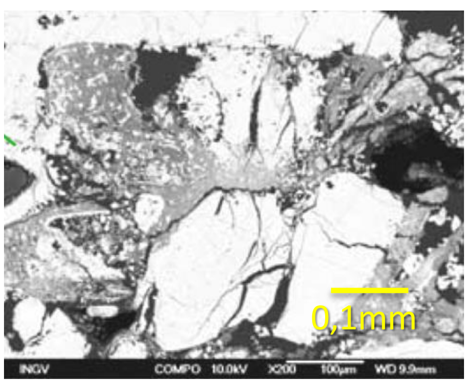


Lade et al. J. (1996), *J. Geotech. Engrg.*

$$D = D_0\left(\frac{a}{a+E_T}\right)$$

or

$$S = S_0\left(1+\frac{E_T}{a}\right)$$



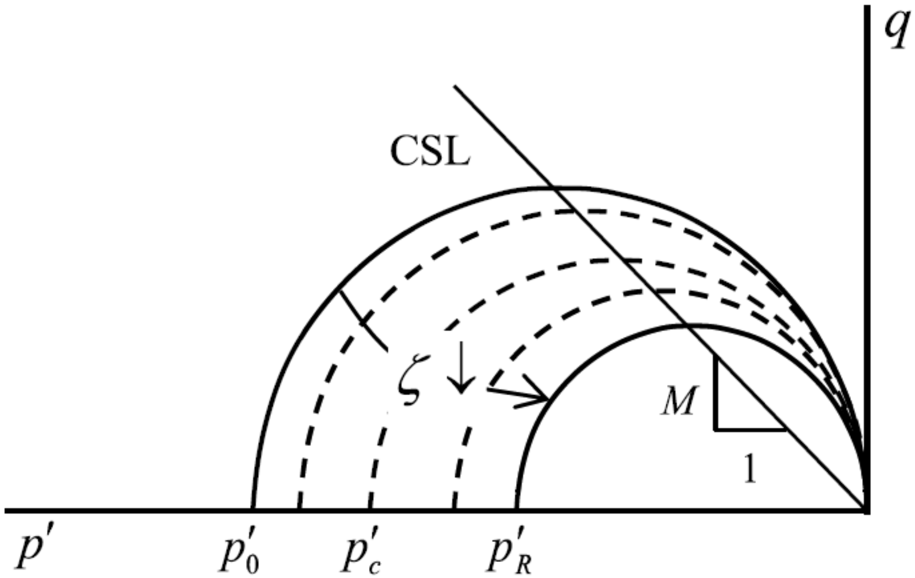
Baud et al. (2009)

a is a material constant which expresses the influence of grain crushing

E_T is the total energy density given to the system

Grain breakage: Einav (2007), *JMPS*

Constitutive behavior (macro-scale)



Modified Cam-Clay plasticity model

$$f \equiv q^2 + M^2 p'(p' - p'_c) = 0$$

$$p'_c \equiv p'_R - \left(p'_R - p'_0\right)\varsigma^{\kappa}$$

The chemical softening parameter is the ratio of the current solid mass over its initial value

$$\varsigma = \frac{M_s}{M_0}, 0 \le \varsigma \le 1$$

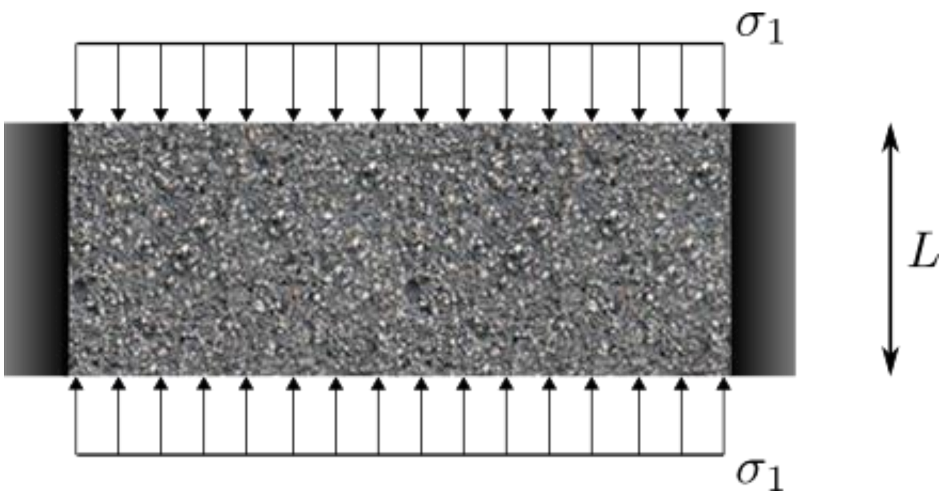
Non local chemical softening

$$\frac{\partial \zeta}{\partial t} = -\frac{\mu_3}{\mu_2}\frac{\rho_f}{\rho_s} e \zeta \frac{\partial w_2^M}{\partial t}$$

$$w_2^M = \frac{1}{V_T}\int_{V_T} w_2 dV \approx w_2 + \ell_c^2 \frac{\partial^2 w_2}{\partial z^2}$$

ℓ_c characteristic length

Linear stability analysis of oedometric compaction



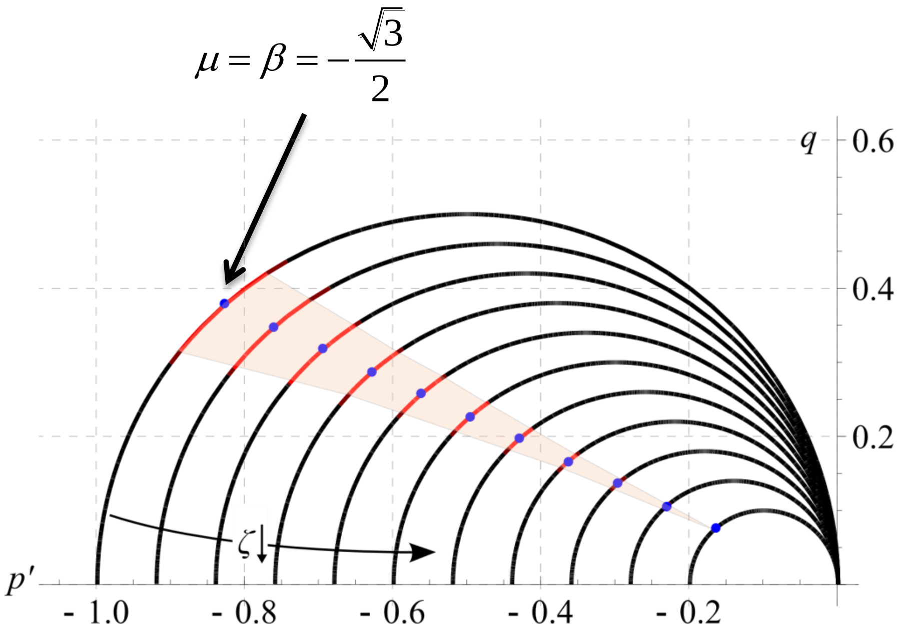
$$u_z(z,t) = u_z^h + \tilde{u}_z(z,t) \qquad \tilde{u}_z(z,t) = Ue^{st}\cos\left(\frac{z}{\lambda}\right)$$

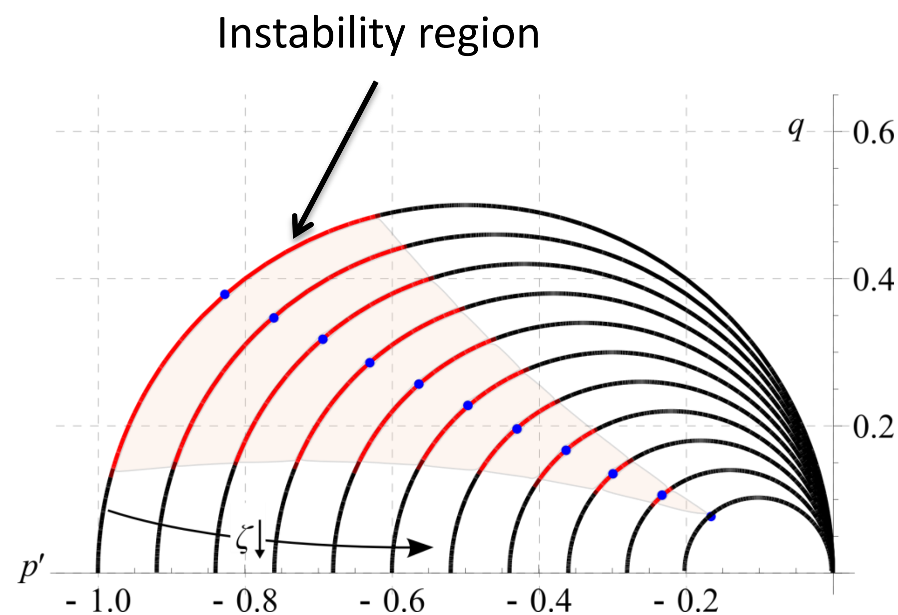
$$p_f(z,t) = p_f^h + \tilde{p}_f(z,t) \qquad \tilde{p}_f(z,t) = Pe^{st}\sin\left(\frac{z}{\lambda}\right)$$

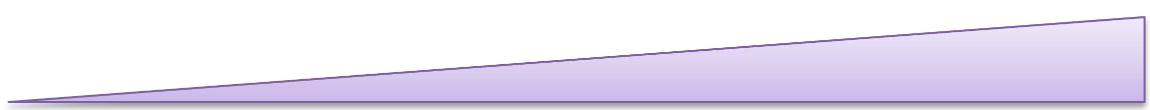
$$w_2(z,t) = w_2^h + \tilde{w}_2(z,t) \qquad \tilde{w}_2(z,t) = We^{st}\sin\left(\frac{z}{\lambda}\right)$$

s is the growth coefficient of the perturbation (Lyapunov exponent)

Linear Stability Analysis & zones of instability







Instability region becomes larger

Tendency for grain crushing $\frac{1}{a}\uparrow$

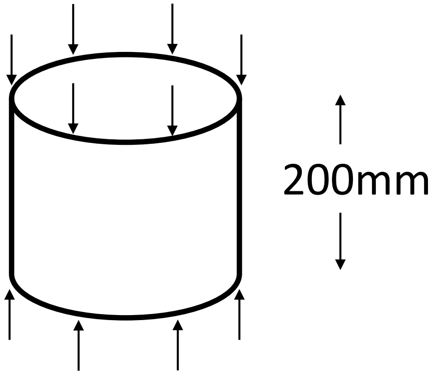
Compaction banding in a reservoir

Carbonate grainstone

Initial stress state at 1,8km (oedometric)

$$\sigma_V \simeq 45\text{MPa}$$

$$p_f \simeq 18\text{MPa}$$



Elastic constants

$$K = 5\text{GPa}$$

$$G = 5\text{GPa}$$

Cam clay yield surface

$$p'_R = 30\%\, p'_0$$

$$p'_0 = 35\text{MPa}$$

$$M = 0,9$$

Physical properties

$$c_{hy} = 10^{-3}\,\text{m}^2\,\text{s}^{-1}$$

$$D_0^{50} = 0,2\text{mm}$$

$$n = 25\%$$

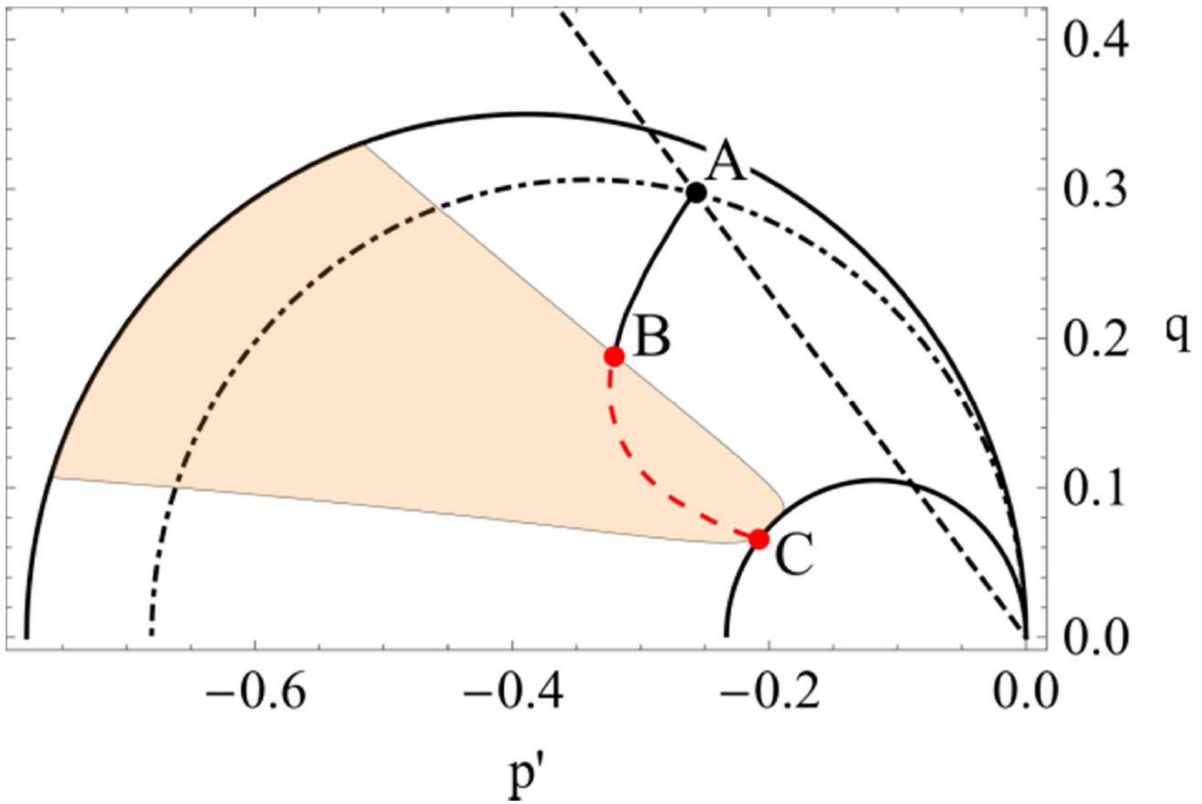
Chemical parameters

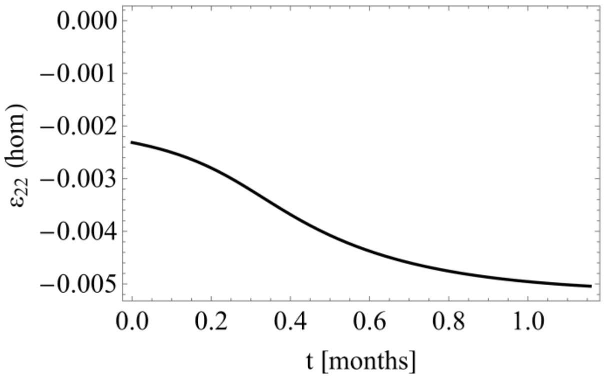
$$k^* = 1,6\,10^{-10}\,\text{m}\,\text{s}^{-1}$$

$$\kappa = 2$$

Grain crushing parameter: $a = 1\,\text{MPa}$

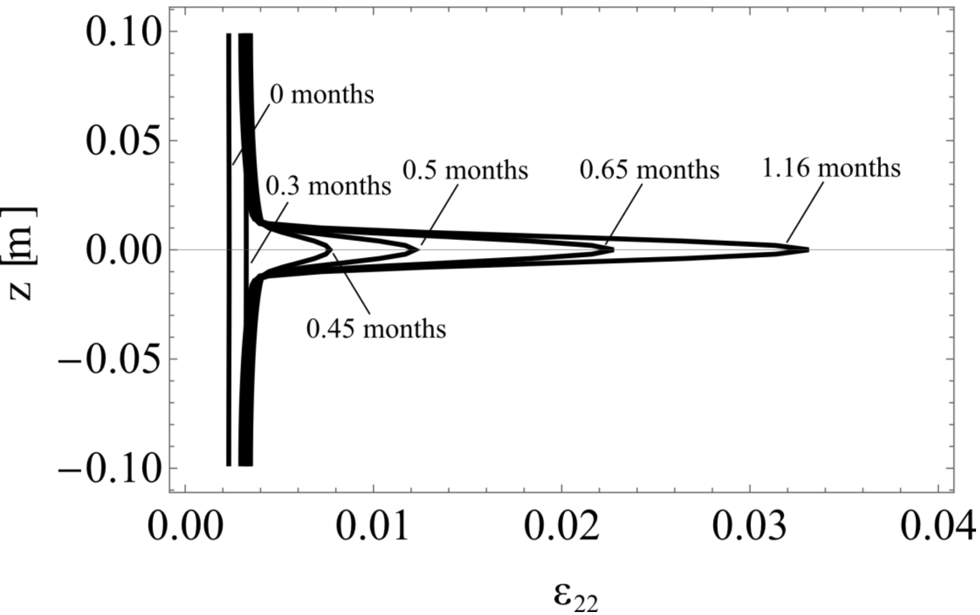
Homogeneous deformation under open flow conditions



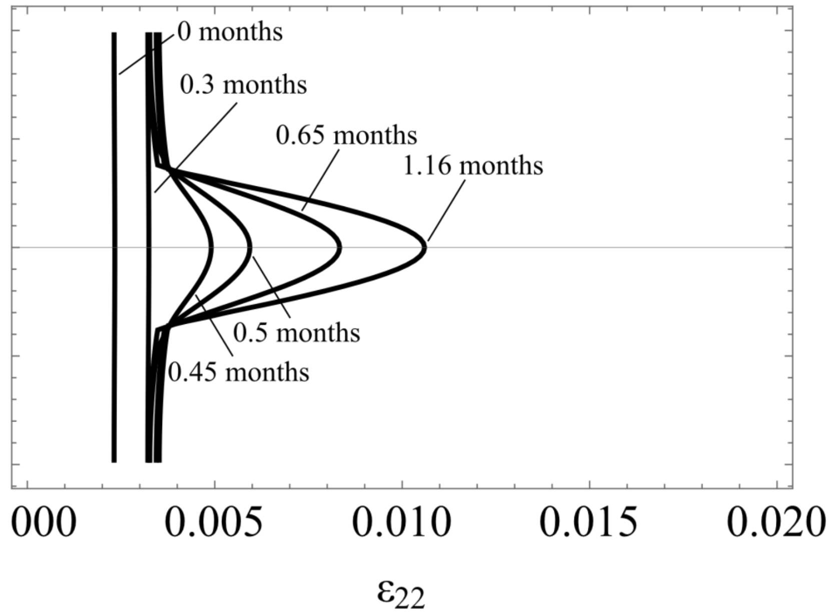


Effect of chemical heterogeneity

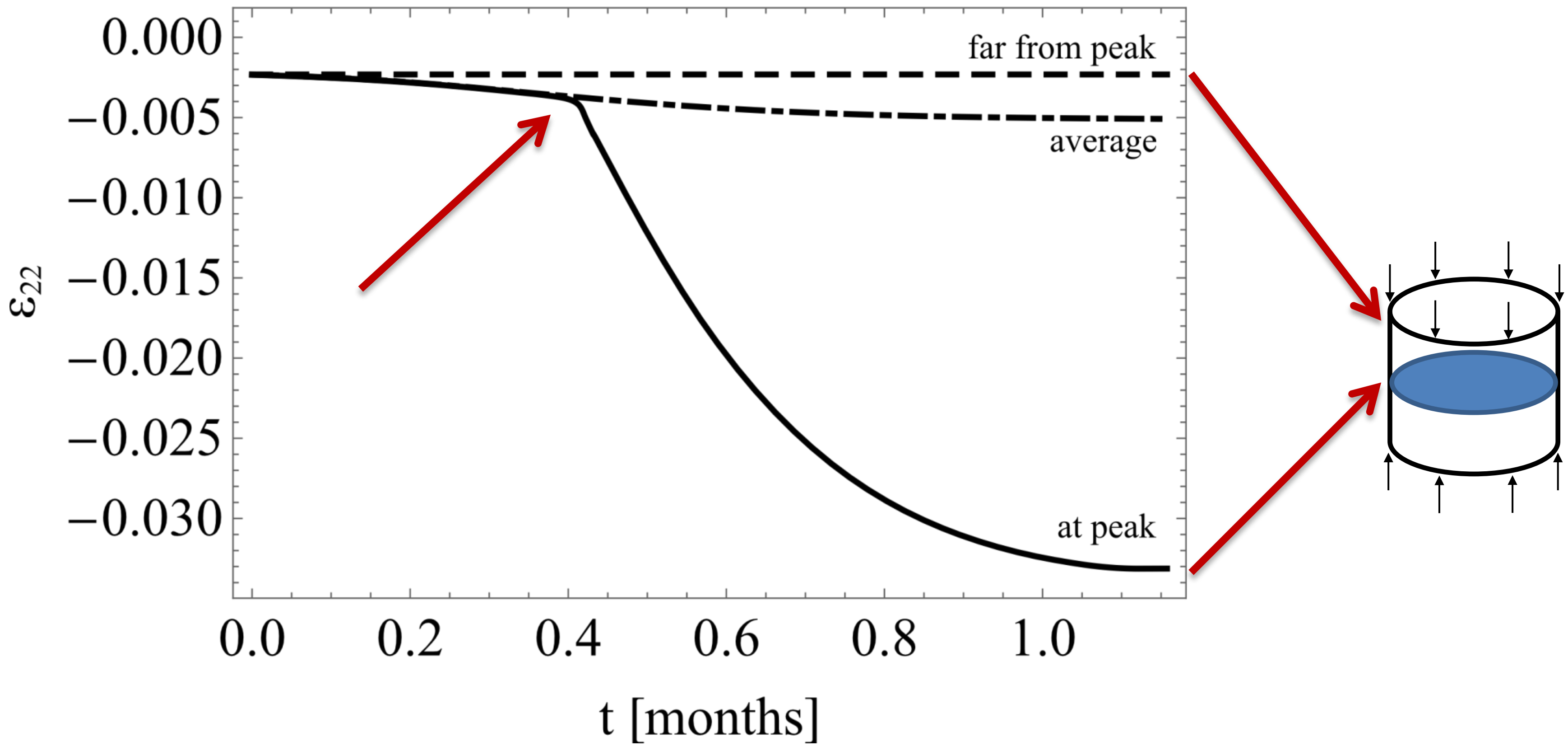
ℓ_c =4mm (20 grains)



ℓ_c =16mm (80 grains)



Localization – compaction banding



5-10 times more compaction than the average inside the CB

THCM COUPLINGS AND STABILITY OF FAULT ZONES

Sulem & Famin, 2009, *J. Geoph. Res.*
Brantut & Sulem, 2012, *J. Appl. Mech.*
Sulem & Stefanou, 2016, *GETE*.

Energy partitioning during an earthquake

During an earthquake, the potential energy (mainly elastic strain energy and gravitational energy) stored in earth is released as:

• Radiated energy : Energy radiated by seismic waves

$\log_{10}E \sim 4.5 + 1.5\, M_w$ (E in joules, M_w is the magnitude of the earthquake)

For example for $M_w = 7$, $E = 10^{15}$ Joules, for $M_w = 9$, $E = 10^{18}$ Joules

• Fracture energy: Energy associated with expanding the rupture area over the fault zone

• Thermal energy: Part of the frictional work (energy required to overcome fault friction) converted into heat

More than 90% of the mechanical work is dissipated into heat

Thermally induced weakening mechanisms are of major importance

Thickness of Principal Slip Zones
Examples from drilling in active faults

Fault system	**Earthquake**	**Magnitude**	**Thickness of the PSZ**	**Reference**
Nojima fault	Kobe, Japan (1995)	7.2	**1 mm**	Otsuki, 2003
Chelungpu fault	Chi Chi, Taiwan (1999)	7.6	**few mm**	Kuo et al., 2013
Longmenshan fault	Wenchuan, China (2008)	8	**1cm**	Li et al. , 2013

Slip is localized in extremely thin zones

A key parameter: Width of the deformation band

Very narrow localized shear zone (typically ~ 100 µm) nested within the fault core where frictional heat is concentrated

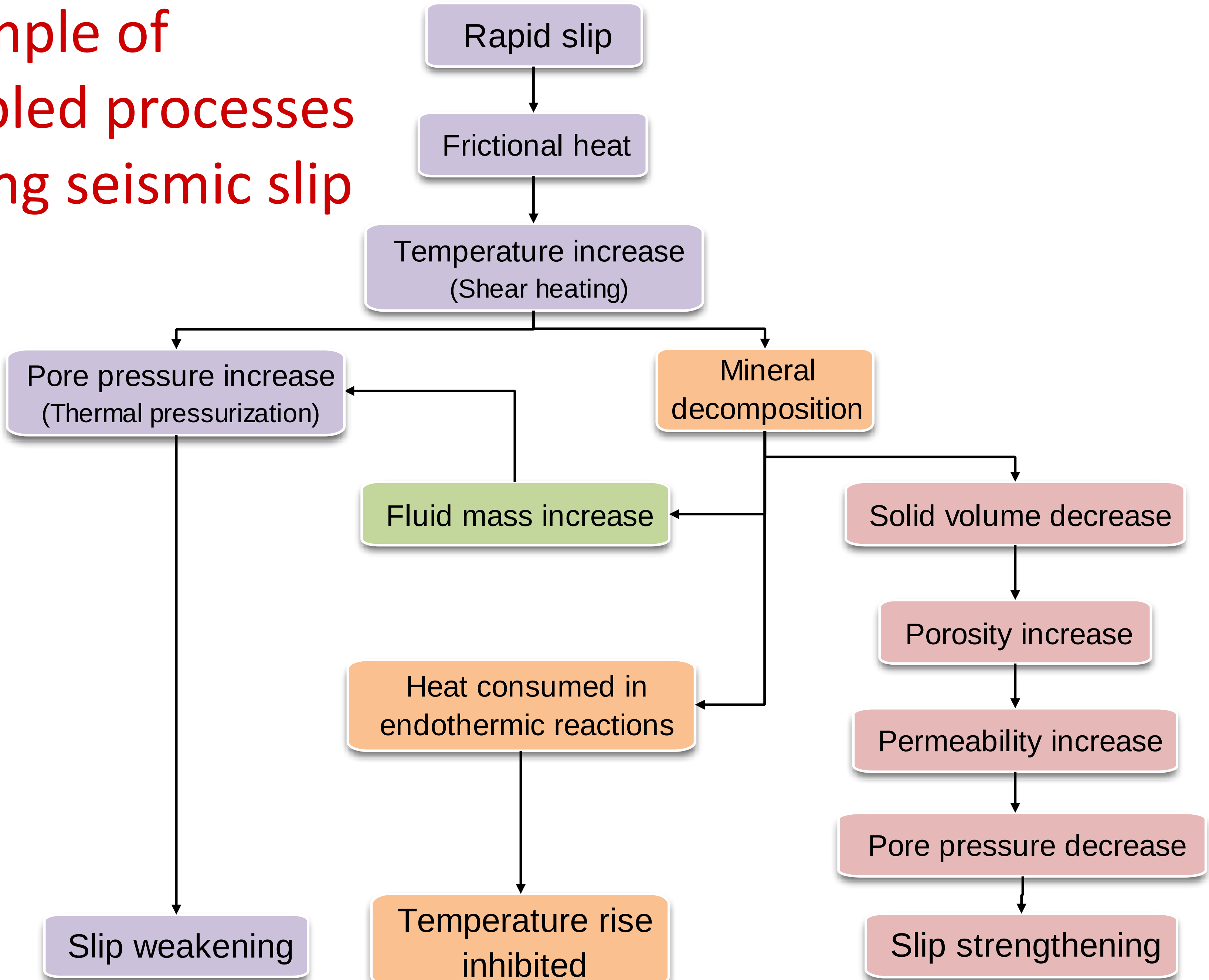
Major role of the width of the slip zone:

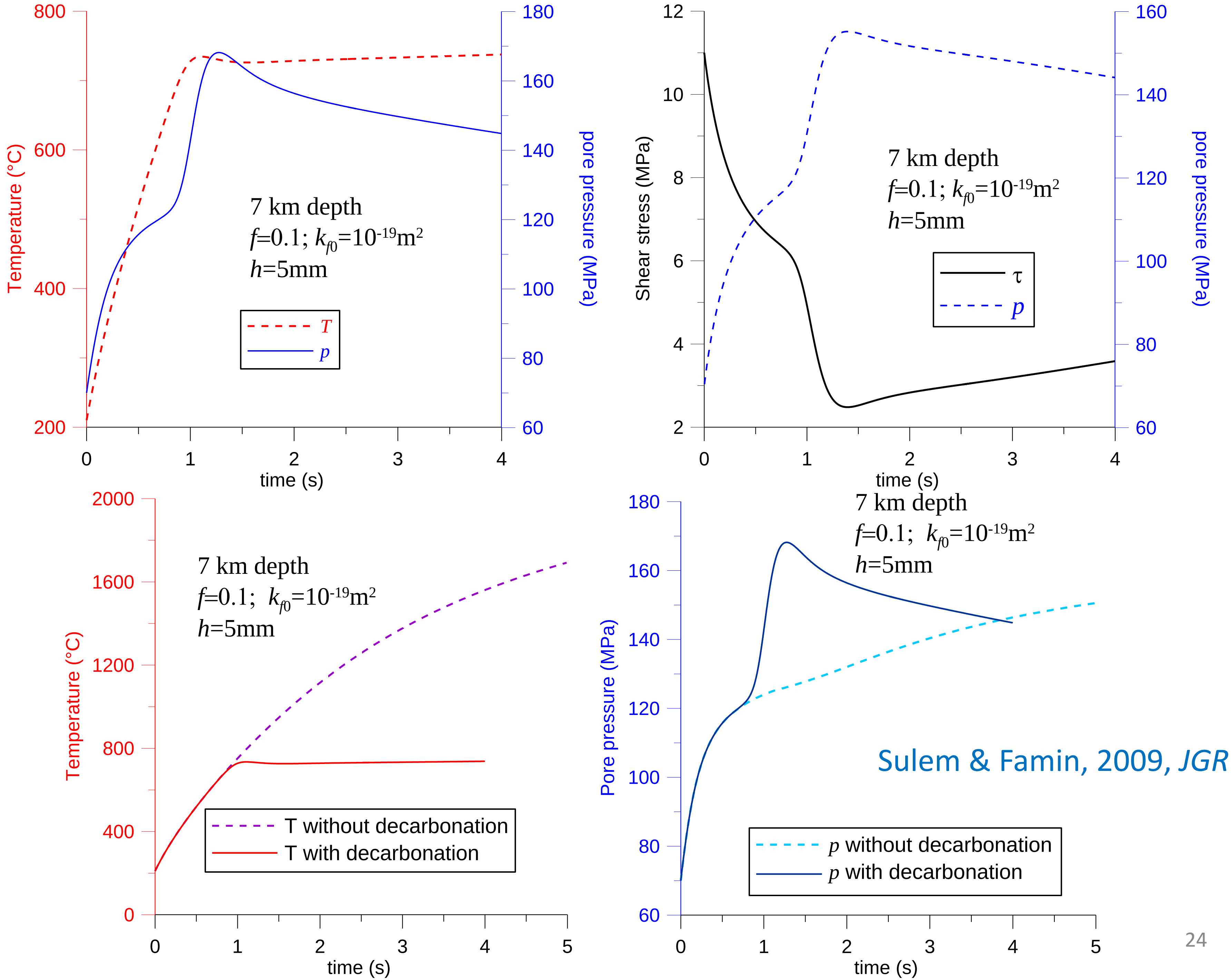
- in the energy budget of the system: control of the feedback of the dissipative terms (e.g. frictional heating)
- in the rupture propagation mode (stronger weakening for thinner shear zones)

Evolution of the width of the slip zone in time:

Stronger weakening favors a decrease of the localized zone thickness, heat and fluid diffusion tend to broaden it.

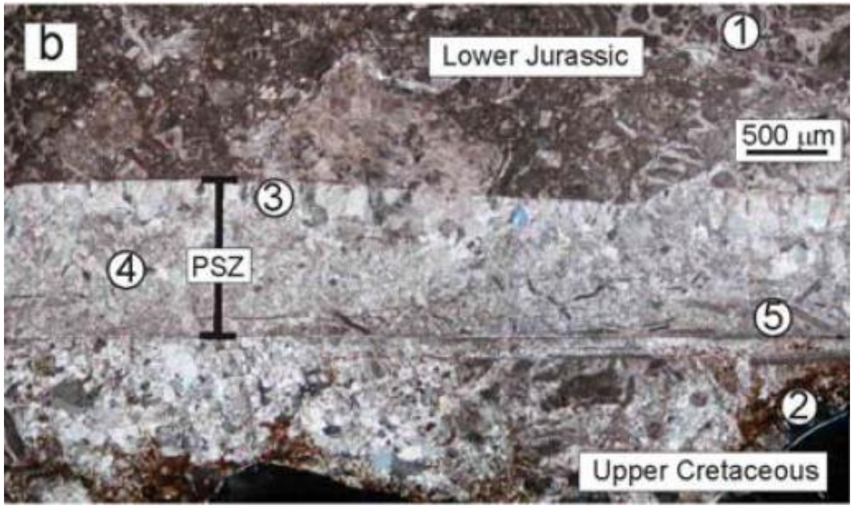
Example of coupled processes during seismic slip





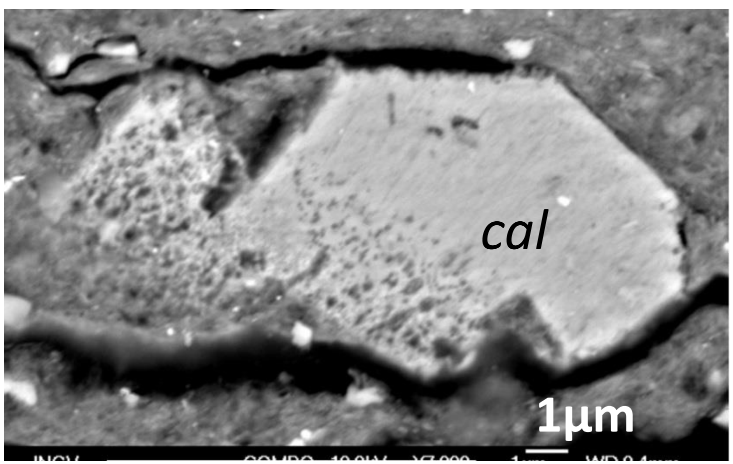
Sulem & Famin, 2009, *JGR*

Observations of thermal decomposition of minerals in exhumed faults

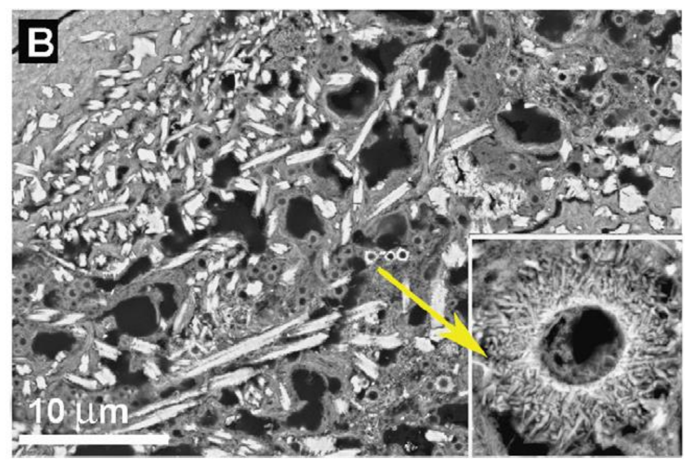


Spoleto thrust fault in Central Italy.
Principal slip zone (0.3 to 1mm)
5-10km of accumulated displacement

(from Collettini et al., 2012, *Geology*)

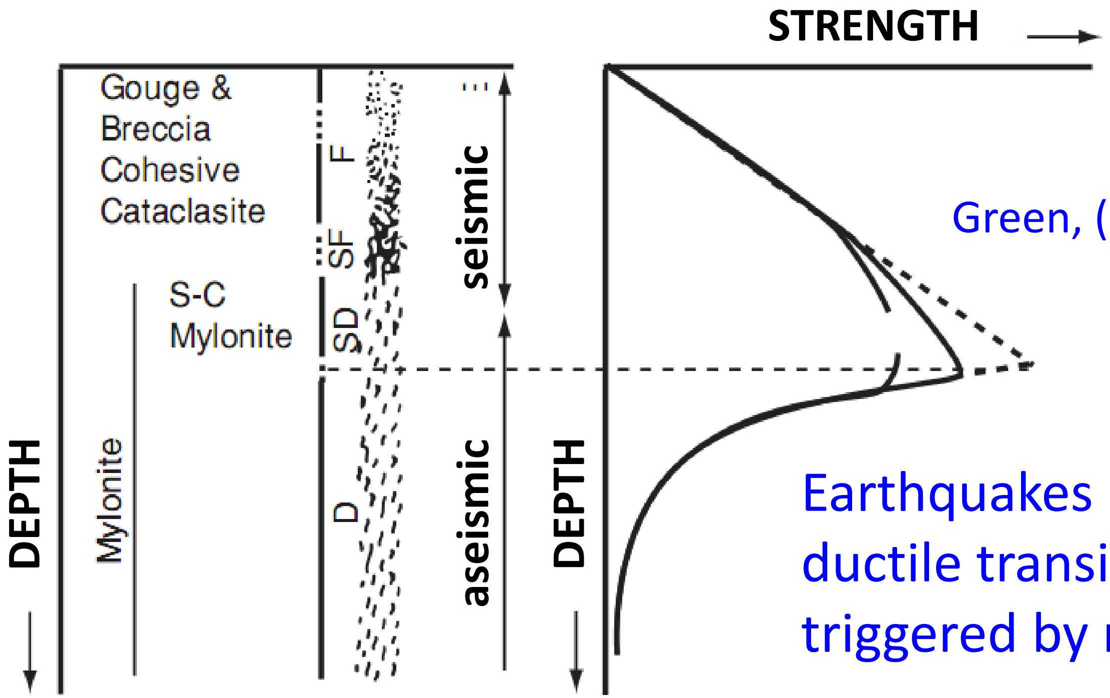


Calcite crystal showing decarbonation



Amorphous silicate phase: dehydration and amorphization of poorly cristalline clays

Deep earthquakes in subduction zone triggered by metamorphic reactions



Green, (2007), *P.N.A.S.*

Earthquakes below the brittle-ductile transition of the crust may be triggered by metamorphic reactions

Metamorphic dehydration reactions may produce weaker products
example: dehydration of lizardite (serpentinite)

$$\underbrace{5\,Mg_3Si_2O_5(OH)_4}_{\text{lizardite}} \longrightarrow \underbrace{Mg_3Si_4O_{10}(OH)_2}_{\text{talc}} + 6\,\underbrace{Mg_2SiO_4}_{\text{olivine}} + 9\,H_2O.$$

Ultra-fine grained olivine weaker than the serpentinite agregates

Chemically weakening and slip instability

Brantut & Sulem, (2012), *J. Appl. Mech.*

Reaction rate:

$$\frac{\partial \xi}{\partial t} = A(1-\xi)\exp\left(-\frac{E_a}{RT}\right)$$

Constitutive model:
(rate hardening/reaction weakening)

$$\tau = f(\dot{\gamma},\xi)\sigma', \quad f(\dot{\gamma},\xi) = f_0 + a\ln(\dot{\gamma}/\dot{\gamma}_0) - b\xi$$

Mass balance:

$$\frac{\partial p}{\partial t} = c_{hy}\frac{\partial^2 p}{\partial z^2} + \Lambda\frac{\partial T}{\partial t} + \frac{1}{\rho_f \beta^*}\frac{\partial m_d}{\partial t} - \frac{1}{\beta^*}\frac{\partial n_d}{\partial t}$$

Fluid diffusion | Thermal pressurization | Fluid production | Inelastic porosity change

Energy balance:

$$\frac{\partial T}{\partial t} = c_{th}\frac{\partial T^2}{\partial z^2} + \frac{\tau\dot{\gamma}}{\rho C} - m_0\frac{\Delta H}{\rho C}\frac{\partial \xi}{\partial t}$$

Heat diffusion | Frictional heat | Heat consumed in the chemical reaction

Effect of lizardite dehydration @ 30km depth along subduction zones

Table 1

Parameter values for lizardite dehydration at a depth of around 30 km.[44]

Quantity	Value
Friction coefficient, f_0	0.6
Rate strengthening parameter, a	0.002
Reaction weakening parameter b	0.5
Specific heat capacity, ρC	2.7 MPa $°C^{-1}$
Thermal dependency of the chemical kinetics, c_T	2.58×10^{-7} $°C^{-1}$ s^{-1}
Depletion dependency of the chemical kinetics, c_μ	2.12×10^{-6} s^{-1}
Initial shear stress, τ_0	240 MPa
Nominal strain rate, $\dot{\gamma}_0$	10^{-6} s^{-1}
Thermal pressurization coefficient, Λ	0.5 MPa $°C^{-1}$
Thermal diffusivity, c_{th}	10^{-6} m^2 s^{-1}
Hydraulic diffusivity, c_{hy}	10^{-6} m^2 s^{-1}

Linear stability analysis

$$\lambda_{cr}^{ch} = 2\pi \sqrt{\frac{ac_{th}}{\gamma_0} \frac{\rho C}{b\tau_0} \frac{c_\mu}{c_T}}$$

$$\dot{\gamma}_0 = 10^{-6} \text{ s}$$

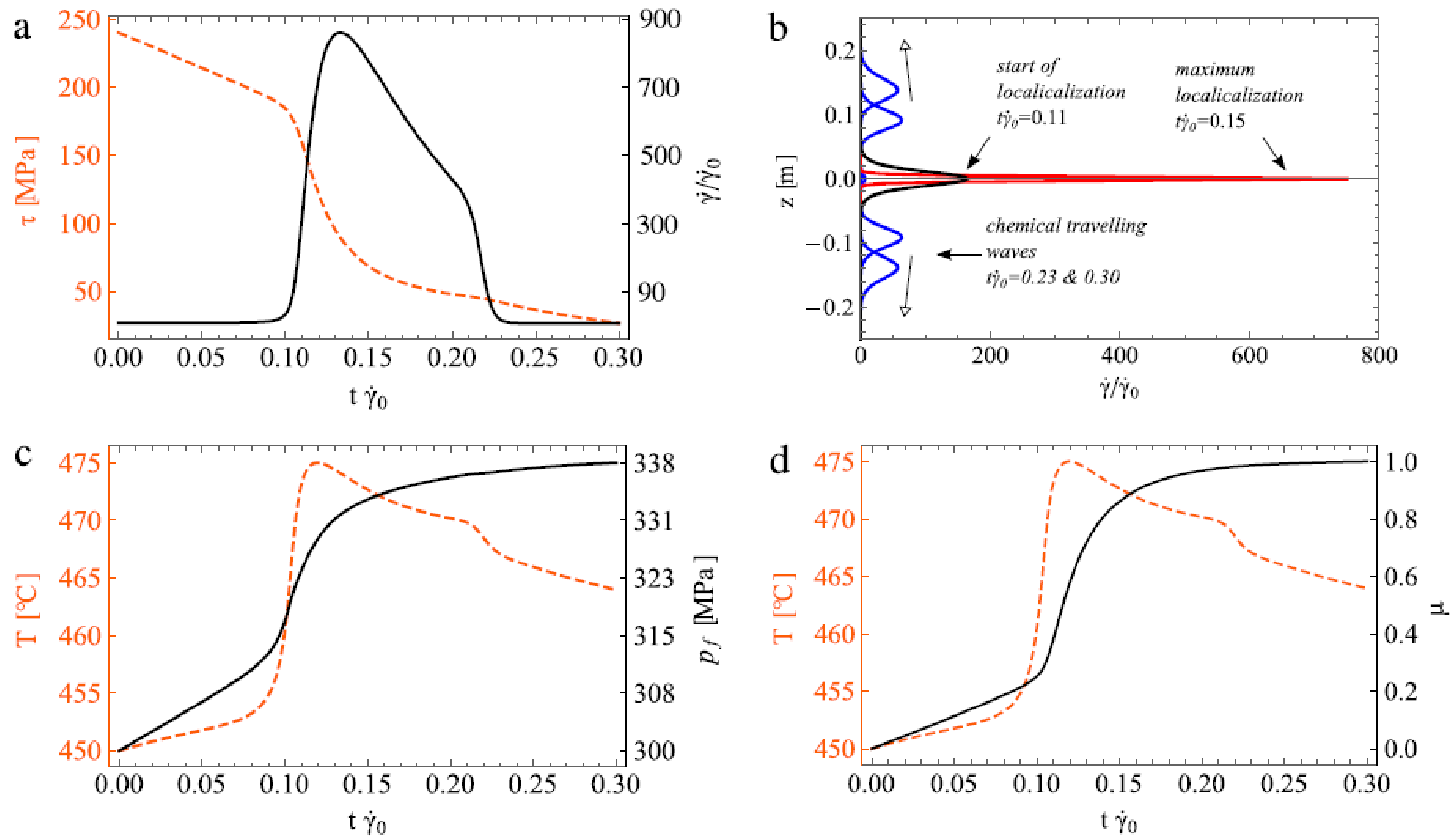
$$\lambda_{cr}^{ch} = 0.12 \text{ m}$$

Only shear zones with a thickness $h < \lambda_{cr}/2$ will support stable homogeneous shear

Short lived slip instability (depletion of the reactant)

Nucleation of transcient slip events, ‘slow’ earthquakes

$$\dot{\gamma}_0 = 10^{-6}\,\mathrm{s}$$



Challenging questions

Major role of the width of the localized zone on the dissipative processes

Modeling of coupled thermo-chemo-hydro-mechanical phenomena with evolution of the microstructure of the material through various mechanical and chemical processes

The effect of evolving micro-structural length scale on the macroscopic constitutive behaviour of granular media