Multiphysics couplings and strain localization in geomaterials

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WEAKENING MECHANISMS AND STRAIN LOCALIZATION
Deformation bands in the form of shear or compaction bands 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...)

Deformation bands in geomechanics
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).
Hydromechanical coupling and instability

Key mechanism of hydromechanical coupling in frictional geomaterials: dilation or contraction in due course of inelastic shear (e.g. dense/loose sands, tight/porous rocks)

- Inelastic volume changes in fluid-saturated geomaterials tend to cause a change in pore fluid pressure.

- Under drained boundary conditions and slow enough deformations, pore pressure remains constant as its alterations are equilibrated by pore fluid flow.

- Under undrained boundary conditions or if deformation occurs too rapidly for fluid flow to take place, pore pressure changes persist.

Hydromechanical coupling and instability

- Shear strength of geomaterials is affected by the effective compressive stress.
- Pore pressure drop in undrained shearing of dilatant material causes an increase of the undrained shear stress $\tau$ (dilatant hardening).
- Undrained shear stress “weakening” over the corresponding drained strength is observed in contracting geomaterials.
- Material strengthening, $h_u > h$, (or weakening), $h_u < h$, occurs for dilation ($\beta > 0$) (or contraction ($\beta < 0$).
Thermo-Hydro-Chemo-Mechanical (THMC) coupling and instability

- Instability can be triggered by pore pressure changes: inelastic volume changes, thermal pressurization of the pore fluid, chemical reactions with release of a fluid phase (e.g. thermal decomposition of minerals) (e.g. Vardoulakis, 1996, Rice, 2006, Sulem et al., 2011, Rice et al. 2014).

- Instability can be triggered by softening of the solid skeleton: inelastic deformations, thermal weakening, chemical weakening (e.g. dissolution, dehydration reactions) (e.g. Rice, 1975, Brantut & Sulem, 2012, Stefanou & Sulem, 2014, Sulem & Stefanou, 2016).
Fault structures at different scales

- **Regional scale** (1 à 100 km)
  Network of oriented fractures of the earth crust (stress reorientation)

- **Local scale** (1 à 100m)
  Individual faults in the network consist in an array of parallel deformation bands containing zones of intense fracturing (cataclasite) surrounded by damaged zones (breccia)

- **Small scale** (0.1 à 10 cm)
  Shear band characterized by intense fracturation (ultra-cataclasite) and strain localisation in very narrow slip zones (<1mm)

(Ben Zion & Sammis, 2003)
## Thickness of Principal Slip Zones
Examples from drilling in active faults

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

Slip is localized in extremely thin zones
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

\[ \log_{10} E \approx 4.5 + 1.5 M_w \] (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
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 crystalline clays
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.
SHEAR HEATING ANF PORE FLUID PRESSURISATION DURING RAPID SHEAR IN FLUID-SATURATED MATERIAL
Application to seismic slip
Thermal pressurization of pore fluids

• The permeability of the highly granulated fault gouge is very low.
• Fluids and heat are trapped inside the slip zone during an earthquake

Thermal pressurization of the fluid occurs because the thermal expansion coefficient of water is much greater than that of the rock particles.


Undrained adiabatic shearing of a saturated rock layer
Destabilizing effect of shear heating and pore fluid pressurization

Shear strain and volume strain

\[ \gamma = \frac{\partial u_x}{\partial z}, \quad \varepsilon = \frac{\partial u_z}{\partial z} \]

Uniform state of stress in the layer

\[ \frac{\partial \tau}{\partial z} = 0, \quad \frac{\partial \sigma}{\partial z} = 0 \]

It is assumed that the layer is at critical state (constant friction, no dilatancy)

\[ \tau = \mu(\sigma - p) \]
Fluid mass balance

Fluid mass per unit volume of porous medium

\[ m_f = \rho_f n \]

\( n \) is the pore volume fraction (Lagrangian porosity)

\( \rho_f \) and is the density of the saturating fluid.

\[
\frac{\partial m_f}{\partial t} = -\frac{\partial q_f}{\partial z}
\]

\( q_f \) is the flux of fluid

\[
\frac{\partial m_f}{\partial t} = n \frac{\partial \rho_f}{\partial t} + \rho_f \frac{\partial n}{\partial t}
\]

\[ q_f = -\frac{\rho_f}{\eta_f} k_f \frac{\partial p}{\partial z} \]

Darcy law for the fluid flow, with viscosity \( \eta_f \) through a material with permeability \( k_f \)
\[
\frac{\partial \rho_f}{\partial t} = \rho_f \beta_f \frac{\partial p}{\partial t} - \rho_f \lambda_f \frac{\partial T}{\partial t}
\]

\[
\frac{\partial n}{\partial t} = n \beta_n \frac{\partial p}{\partial t} + n \lambda_n \frac{\partial T}{\partial t} + \frac{\partial n^p}{\partial t}
\]

\(\frac{\partial n^p}{\partial t}\): rate of plastic porosity change

\[
\beta_f = \frac{1}{\rho_f} \left( \frac{\partial \rho_f}{\partial P_p} \right)_T \quad : \text{pore fluid compressibility}
\]

\[
\lambda_f = -\frac{1}{\rho_f} \left( \frac{\partial \rho_f}{\partial T} \right)_p \quad : \text{pore fluid thermal expansion coefficient}
\]

\[
\beta_n = \frac{1}{n} \left( \frac{\partial n}{\partial P_p} \right)_T \quad : \text{pore volume compressibility} \quad \beta_n = \frac{1}{n} \left( \beta_d - (1+n) \beta_s \right)
\]

\[
\lambda_n = \frac{1}{n} \left( \frac{\partial n}{\partial T} \right)_p \quad : \text{pore volume thermal expansion coefficient}
\]

\(\beta_d\): compressibility of the porous rock

\(\beta_s\): compressibility of the solid phase
Pore fluid production and diffusion equation:

\[
\frac{\partial p}{\partial t} = c_{hy} \frac{\partial^2 p}{\partial z^2} + \Lambda \frac{\partial T}{\partial t} - \frac{1}{\beta^*} \frac{\partial n^p}{\partial t}
\]

\[
\Lambda = \frac{\lambda_f - \lambda_n}{\beta_n + \beta_f}
\]

is the coefficient of thermal pressurization
(typical values: 0.1 to 1 MPa/°C)

\[
\beta^* = n(\beta_n + \beta_f)
\]

is the storage coefficient.

For incompressible fluid and solid phase \( \beta^* = 1/K \)

\[
c_{hy} = k_f / (\beta \eta_f)
\]

is the hydraulic diffusivity

For plastically incompressible solid matrix:

\[
\frac{\partial n^p}{\partial t} = \frac{\partial \varepsilon^p}{\partial t} = 0 \text{ for zero dilatancy}
\]
Energy balance equation

\[ \rho C \frac{\partial T}{\partial t} = E_F - \frac{\partial q_h}{\partial z} \]

- \( E_F \) is the rate of frictional heat produced during slip
- \( \rho C \) is the specific heat per unit volume of the fault material
- \( q_h \) is the heat flux and according to the Fourier law is proportional to the temperature gradient

\[ q_h = -k_T \frac{\partial T}{\partial z} \]

- \( k_T \) is the thermal conductivity of the saturated rock

It is assumed that all the plastic work is converted into heat

\[ E_F = \tau \dot{\gamma}^p \approx \tau \dot{\gamma} \]

\[ \frac{\partial T}{\partial t} = c_{th} \frac{\partial^2 T}{\partial z^2} + \frac{1}{\rho C} \tau \dot{\gamma} \]

- \( c_{th} = \frac{k_T}{\rho C} \) is the thermal diffusivity
Spatially uniform solution under undrained adiabatic conditions

The drainage and the heat flux are prohibited at the boundaries of the layer.

\[ q_f = 0 \text{ and } q_h = 0 \]

The normal stress \( \sigma_n \) acting on the sheared layer is constant.

\[ \dot{\sigma} = 0 \]

The undrained adiabatic limit is applicable as soon as the slip event is sufficiently rapid and the shear zone broad enough to effectively preclude heat or fluid transfer (e.g. earthquakes, landslides).

Summary of the governing equations

mass balance: \[ \frac{\partial p}{\partial t} = \Lambda \frac{\partial T}{\partial t} \]

energy balance: \[ \frac{\partial T}{\partial t} = \frac{1}{\rho C} \left( \sigma_n - p \right) \mu \dot{\gamma}_0 \]
Spatially uniform solution under undrained adiabatic conditions

Solution:

\[ p = p_0 + \left( \sigma_n - p_0 \right) \left( 1 - \exp\left( -\frac{\mu \Lambda}{\rho C} \dot{\gamma}_0 t \right) \right) \]

\[ T = T_0 + \frac{\left( \sigma_n - p_0 \right)}{\Lambda} \left( 1 - \exp\left( -\frac{\mu \Lambda}{\rho C} \dot{\gamma}_0 t \right) \right) \]

In undrained adiabatic conditions, the pore-pressure increases towards its geostatic limit \( \sigma_n \) which corresponds to full fluidization exponentially with the slip displacement.

In due course of the shear heating and fluid pressurization process, the shear strength \( \tau \) is reduced towards zero.
Example: Fault zone at 7 km depth

Initial conditions: \( T_0 = 210^\circ C, \ p_0 = 70\text{MPa}, \ \sigma_n = 180\text{MPa} \)

Slip velocity: 1m/s; Shear band thickness: \( L=5\text{mm} \)

Maximum temperature: \( T_{\text{max}} = T_0 + \frac{\sigma_n - p_0}{\Lambda} = 577^\circ C \)
Linear stability analysis of uniform shear

Rate-dependency of the friction coefficient is considered

\[ \mu = \mu_0 + H \log \frac{\dot{\gamma}}{\dot{\gamma}_0} \]

Stability condition:

\[ \lambda < \lambda_{cr}, \text{ with } \lambda_{cr} = 2\pi \sqrt{\frac{H \rho C (c_{th} + c_{hy})}{\mu_0 \Lambda (\mu_0 + 2H) \dot{\gamma}_0}} \]

Competing processes: Fluid and thermal diffusion and rate-dependent frictional strengthening tend to expand the localized zone, while thermal pressurization tends to narrow it.

Only shear zones with a thickness \( h < \frac{\lambda_{cr}}{2} \) will support stable homogeneous shear.

Typical values at seismogenic depth: few tens of microns

The localized zone thickness may be comparable with the gouge grain size.
Stability analysis of undrained adiabatic shearing of a rock layer with Cosserat microstructure

Sulem, Stefanou, Veveakis (2011), *Granular Matter*

Strain hardening elasto-plasticity for 2D Cosserat continuum
Material length $R$ related to the material grain size

Dominant instability mode with a selected finite wave length and a finite growth coefficient

With $R=1$ to $10\mu$m (grain size for highly finely granulated fault core) the obtained localized zone thickness is about 0.1 to 1 mm.
THCM COUPLINGS AND STABILITY OF FAULT ZONES
Deep earthquakes triggered by metamorphic reactions

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)

$$5 \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4 \rightarrow \text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2 + 6\text{Mg}_2\text{SiO}_4 + 9\text{H}_2\text{O}.$$  
Ultra-fine grained olivine weaker than the serpentinite aggregates
Chemically weakening and slip instability


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.\textsuperscript{44}

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction coefficient, $f_0$</td>
<td>0.6</td>
</tr>
<tr>
<td>Rate strengthening parameter, $\alpha$</td>
<td>0.002</td>
</tr>
<tr>
<td>Reaction weakening parameter $b$</td>
<td>0.5</td>
</tr>
<tr>
<td>Specific heat capacity, $\rho C$</td>
<td>2.7 MPa °C$^{-1}$</td>
</tr>
<tr>
<td>Thermal dependency of the chemical kinetics, $c_T$</td>
<td>$2.58 \times 10^{-7} , \text{°C}^{-1} , \text{s}^{-1}$</td>
</tr>
<tr>
<td>Depletion dependency of the chemical kinetics, $c_\mu$</td>
<td>$2.12 \times 10^{-6} , \text{s}^{-1}$</td>
</tr>
<tr>
<td>Initial shear stress, $\tau_0$</td>
<td>240 MPa</td>
</tr>
<tr>
<td>Nominal strain rate, $\dot{\gamma}_0$</td>
<td>$10^{-6} , \text{s}^{-1}$</td>
</tr>
<tr>
<td>Thermal pressurization coefficient, $\Lambda$</td>
<td>0.5 MPa °C$^{-1}$</td>
</tr>
<tr>
<td>Thermal diffusivity, $c_{th}$</td>
<td>$10^{-6} , \text{m}^2 , \text{s}^{-1}$</td>
</tr>
<tr>
<td>Hydraulic diffusivity, $c_{hy}$</td>
<td>$10^{-6} , \text{m}^2 , \text{s}^{-1}$</td>
</tr>
</tbody>
</table>

Linear stability analysis

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

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

$$D = 5 \, \text{m}$$

$$\lambda_{cr}^{ch} = 0.12 \, \text{m}$$
Short lived slip instability (depletion of the reactant)

Nucleation of transient slip events, ‘slow’ earthquakes

\[ \dot{\gamma}_0 = 10^{-6} \text{s} \]
CHEMICAL DISSOLUTION AND COMPACTION BANDS: AN EXAMPLE OF MULTI-SCALE ANALYSIS

Strong coupling between chemical weakening and dissolution kinetics

Creep due to CO₂ injection in Lavoux limestone


Fluid velocity $10^{-6}$ m s$^{-1}$
Is the deformation homogeneous?

Pure compaction bands?

What is the influence of a reactive fluid flow on deformation band formation?
Conditions for localization due to mechanical softening

Criterion for compaction bands:

\[ \beta + \mu \leq -\sqrt{3} \]

Perfect associate plasticity:

\[ \beta = \mu = -\frac{\sqrt{3}}{2} \]

Issen & Rudnicki (2000)
Rudinicki & Rice (1975)
Conceptual model & chemical softening

Increase of the effective specific area of grains

Acceleration of dissolution

Localization?

Grain crushing & damage

Chemical Softening
Distinction of scales

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

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

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

where:

- \( w_2 \) 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 \( D \)

E.g. dissolution of quartz: \( \text{SiO}_2(\text{solid}) + 2\text{H}_2\text{O(liquid)} \rightleftharpoons \text{H}_4\text{SiO}_4(\text{aqueous solution}) \)

or diss. of carbonates: \( \text{CaCO}_3(\text{solid}) + \text{H}_2\text{CO}_3(\text{aqueous solution}) \rightleftharpoons \text{Ca} \left( \text{HCO}_3 \right)_2(\text{aqueous solution}) \)
Upscaling of the dissolution process

micro > macro

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

\( \ell_c \): Characteristic length
Evolution of the effective grain size
Grain crushing (micro-scale)

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

or

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

\( a \) 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)

Plasticity criterion

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

\[ p'_c \equiv p'_R - (p'_R - p'_0) \zeta^\kappa \]

Evolution of chemical softening

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

\[ \frac{\partial w_2^M}{\partial t} = \frac{\partial w_2}{\partial t} + \ell_c^2 \frac{\partial}{\partial t} \frac{\partial^2 w_2}{\partial z^2} \]

Modified Cam-Clay plasticity model as an example

Equilibrium (macro-scale)

\[ \frac{d\sigma_1}{dz} \approx 0 \]

\[ p'(z) - \frac{2}{\sqrt{3}} q(z) = \sigma_1 = \text{const} \]

Oedometric conditions
Mass balance (macro-scale)

\[
\frac{\partial p_f}{\partial t} = c_{hy} \nabla^2 x p_f - \frac{1}{n \beta_f} \frac{\partial \varepsilon}{\partial t} - c_{p, ch} \frac{\partial w_2}{\partial t}
\]

- \(c_{hy}\) is the hydraulic diffusivity
- \(n\) is the porosity
- \(\beta_f\) is the fluid compressibility
- \(c_{p, ch}\) is the chemical pressurization coefficient
- \(p_f\) is pressure of the fluid
- \(\varepsilon\) is the volumetric strain
Bifurcation analysis -> Conditions for localization

\[ \mu = -\frac{\sqrt{3}}{2} \]

More crushable solid skeleton ( \( \alpha \rightarrow \uparrow \))

Instability / localization

Instability region
Compaction banding in a reservoir
Carbonate grainstone

Initial stress state at 1.8km (oedometric)

\[ \sigma_v \approx 45 \text{MPa} \]
\[ p_f \approx 18 \text{MPa} \]

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

\[ c_{hy} = 10^{-3} \, \text{m}^2 \, \text{s}^{-1} \]
\[ D_{50} = 0.2 \text{mm} \]
\[ n = 25\% \]

Chemical parameters

\[ k^* = 1.6 \times 10^{-10} \, \text{m} \, \text{s}^{-1} \]
\[ \kappa = 2 \]

Grain crushing parameter: \[ a = 1 \, \text{MPa} \]
Homogeneous deformation under open flow conditions
Localization – compaction banding

Sulem, J., & Stefanou I., 2016, Thermal and chemical effects in shear and compaction bands, Geomechanics for Energy and the Environment
Localization – compaction banding

5-10 times more compaction than the average inside the CB
Effect of chemical heterogeneity

$\ell_c = 4\text{mm (20 grains)}$

$\ell_c = 16\text{mm (80 grains)}$
CONCLUSIONS

✓ Strain localization is favored by strength softening. Softening can be due to mechanical/thermal degradation (softening of the yield surface) and/or softening due to THMC couplings (thermal/chemical pressurization of the pore fluid)

✓ Finite thickness of the localized zone can be obtain for rate dependent constitutive law, higher order continua or non local constitutive models

✓ Heat and fluid diffusion tend to stabilize the system and broaden the localized zone whereas fluid pressurization tends to destabilize it.

✓ Stronger weakening leads to narrower localized zone.

✓ The actual thickness of the localized zone plays a major role in the energy budget of the system: control of the feedback of the dissipative terms (e.g. frictional heating)

✓ Chemo-mechanical couplings can induce instabilities of various forms (shear localization, compaction banding...)

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