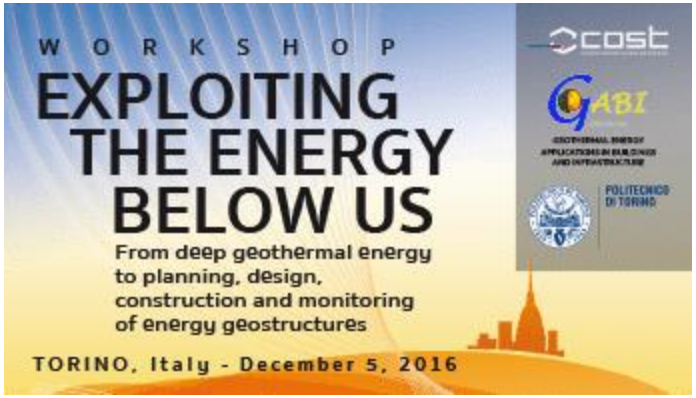

Thermal effects on the behavior of soils and rocks

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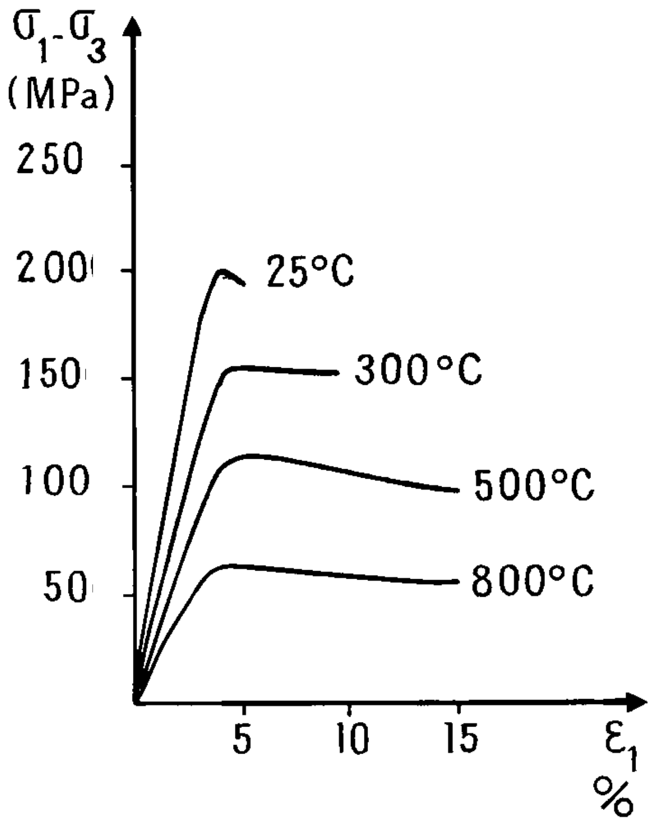
OUTLINE

- Effect of temperature on the mechanical properties of soils and rocks
- Experimental evidence of thermal activation of a failure plane by thermal pressurization of the pore fluid
- Thermal effects during seismic slip
- Conclusions

Effect of temperature on rocks physical properties

- The anisotropy of rock minerals thermal expansion may lead to internal stresses and to microcracking
- The heterogeneity of the mineral composition of the rocks induces heterogeneous thermal deformation at the grain scale leading to intergranular and intragranular cracking
- Thermal decomposition of minerals: e.g. dehydration of clay minerals, decomposition of carbonates

Effect of temperature on the mechanical behaviour of rocks



Triaxial tests on Solenhfen limestone (after Heard, 1960)

- Decrease of the elastic modulus
- Decrease of the uniaxial strength
- Transition from brittle to ductile behaviour
- Effect of thermal cycling (thermal fatigue) on rock failure
- Temperature dependent creep

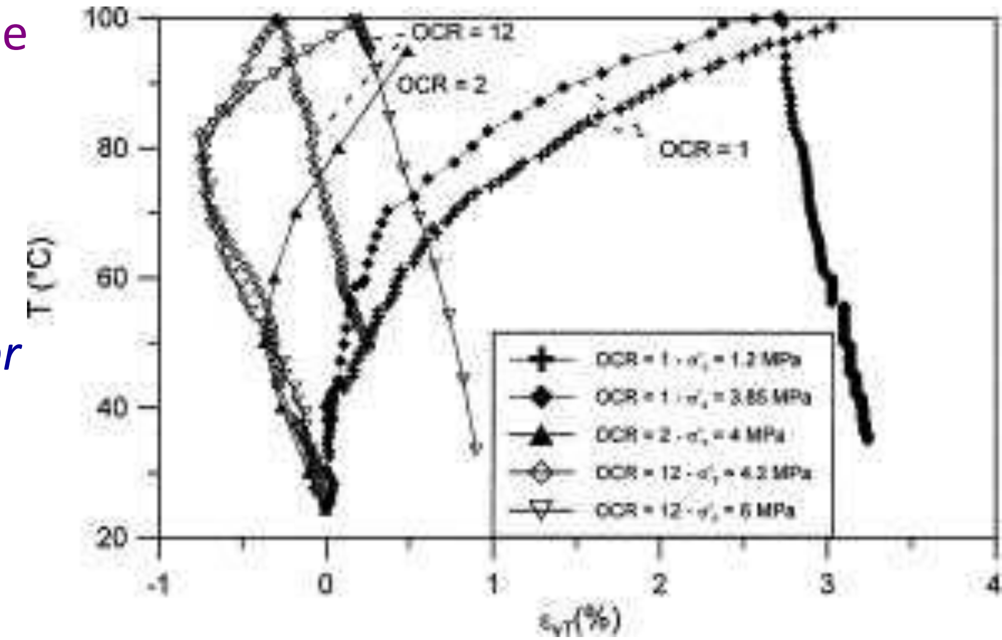
Thermal behaviour of clayey materials

Augmentation of temperature can induce dilatancy or contractancy of the soil depending on the state of stress, the thermal and mechanical history.

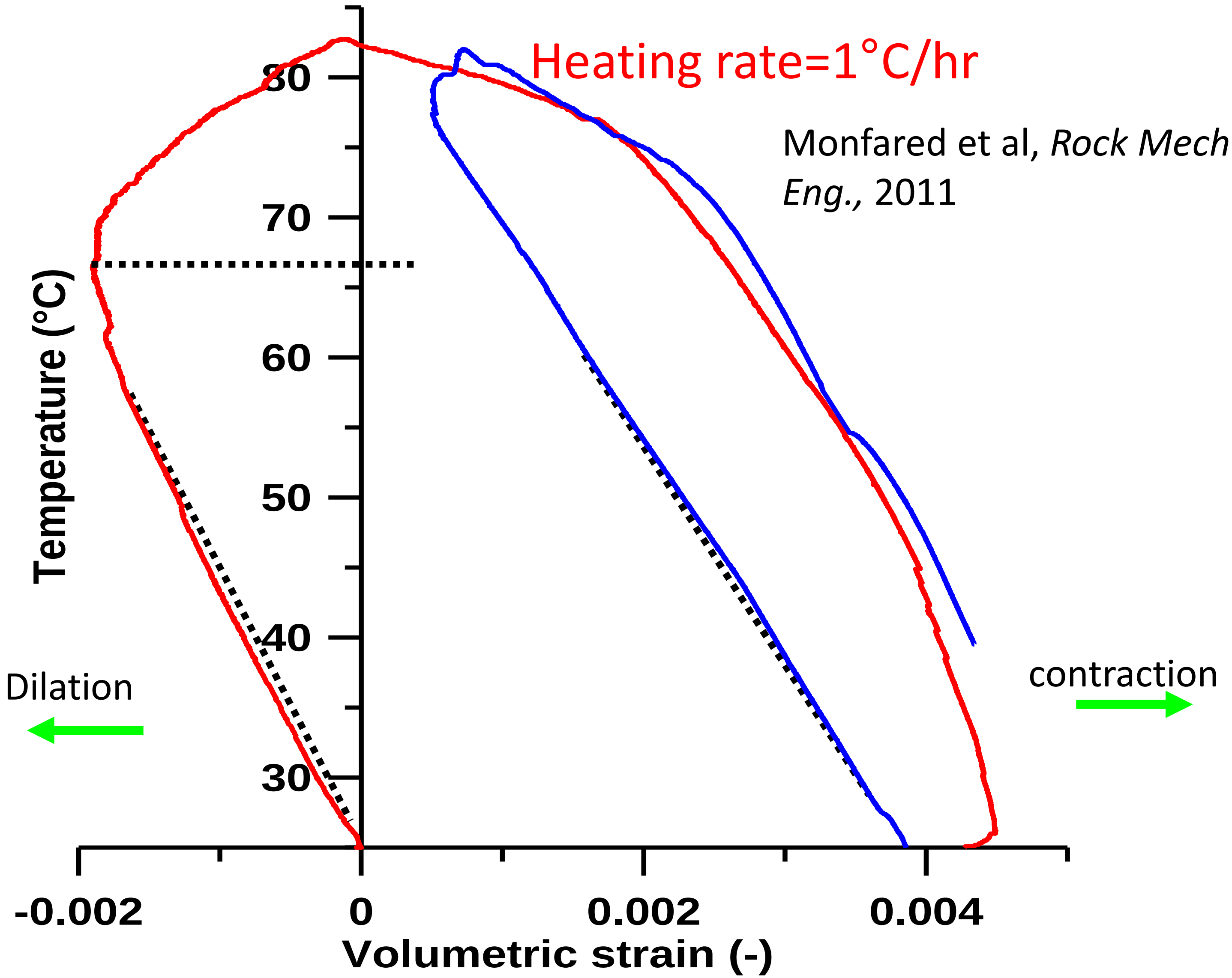
Thermal volumetric strain

- *increases with plasticity index*
- *is independent of the applied stress for normally consolidated state*
- *depends upon the over-consolidation ratio (OCR) of the soil: at low OCR it is contractant, at high OCR it is dilatant and then contractant*
- *is reversible (elastic) and contractant in cooling*

Volumetric deformation of Boom clay under thermal loading (after Sultan et al 2002)



Drained heating test on Opalinus clay



Monfared et al, *Rock Mech & Rock Eng.*, 2011

Confining pressure=4.1 MPa,

Pore pressure=2.2 MPa

$$\alpha_d = 6.4 \times 10^{-5} / °C$$

Elasto-plastic undrained thermal pressurization coefficient

$$\Lambda = \frac{\lambda_f - \lambda_n^e}{\beta_n + \beta_f} - \frac{\lambda_n^{ep} - \lambda_n^e}{n\left(\beta_n + \beta_f\right)}$$

Typical values of the thermal pressurization coefficient

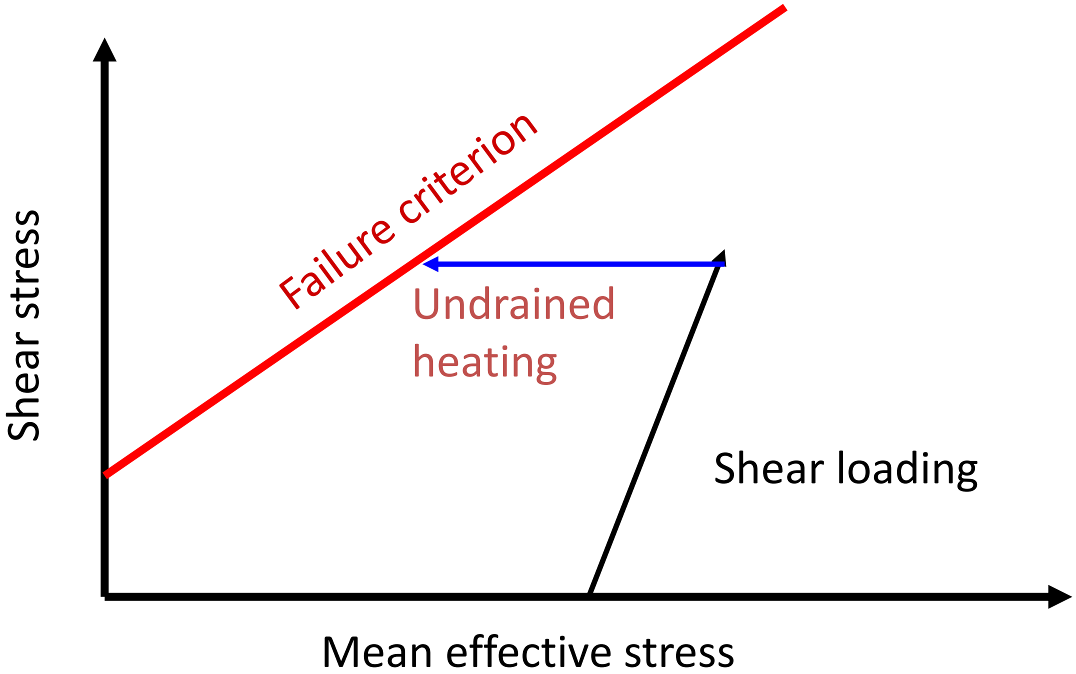
Clay: 0.01 to 0.1 MPa/°C

Rock: 0.05 to 1 MPa/°C

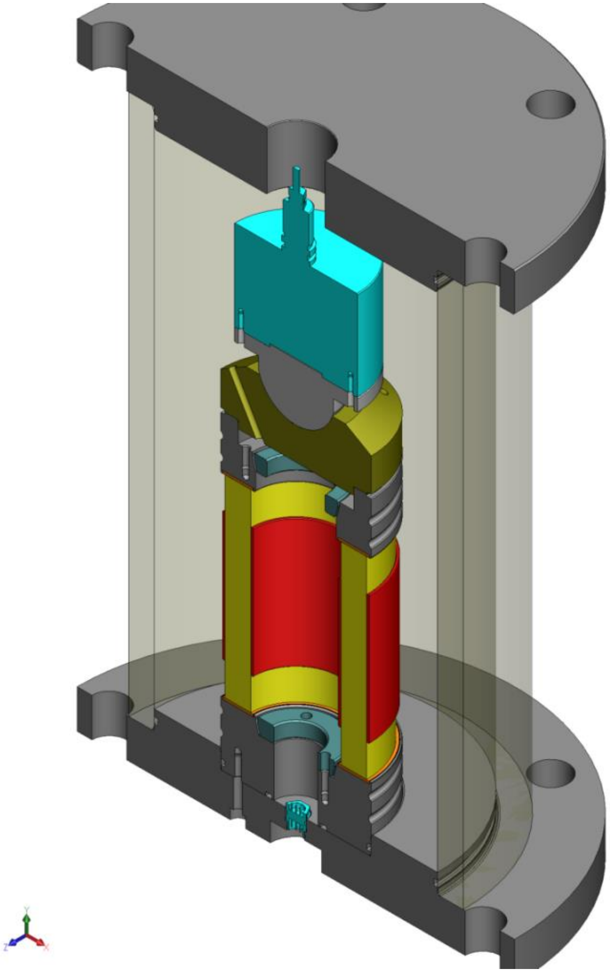
Experimental evidence of thermal activation of shear failure

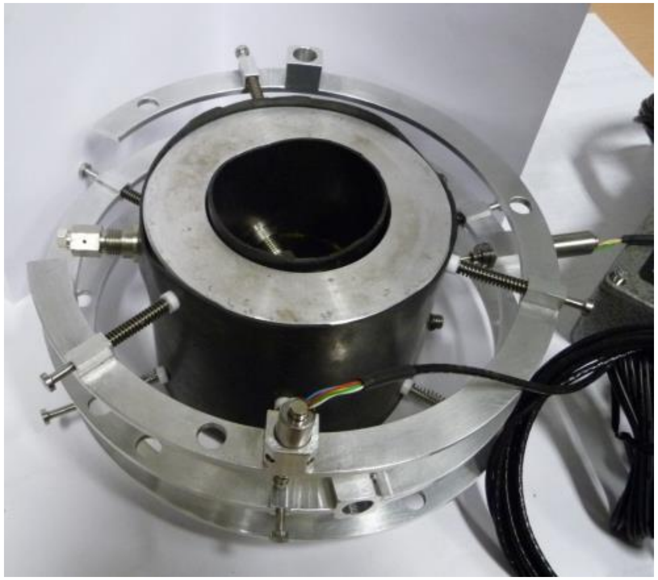
Thermal activation of shear failure on Boom Clay hollow cylinder sample

Thermal pressurization of the fluid during undrained heating is a mechanism of shear strength weakening in relation with the reduction of the effective stress.



Hollow cylinder apparatus for testing geomaterials with low permeability

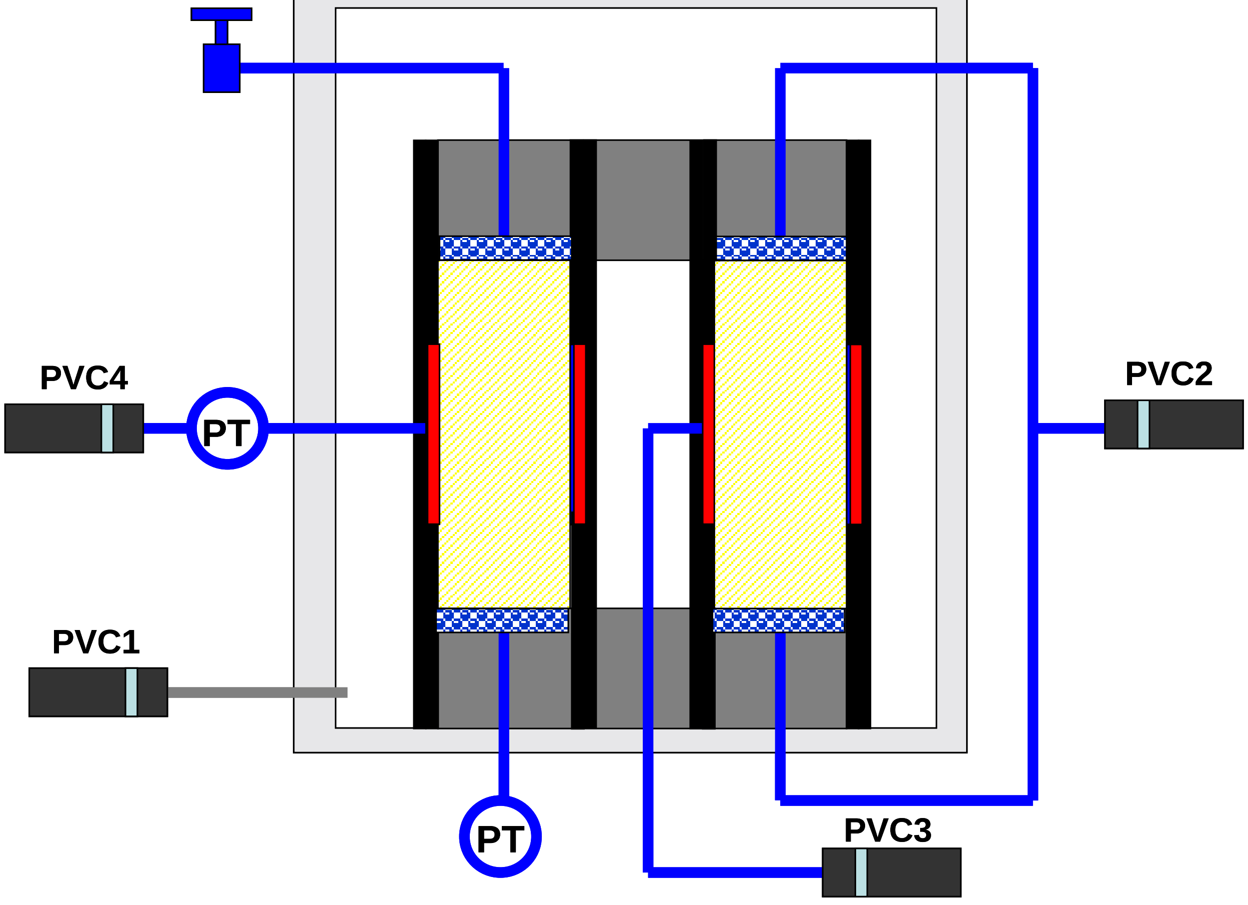




Hollow cylindrical samples:
internal diameter: 60 mm
external diameter: 100 mm
height 75 mm:

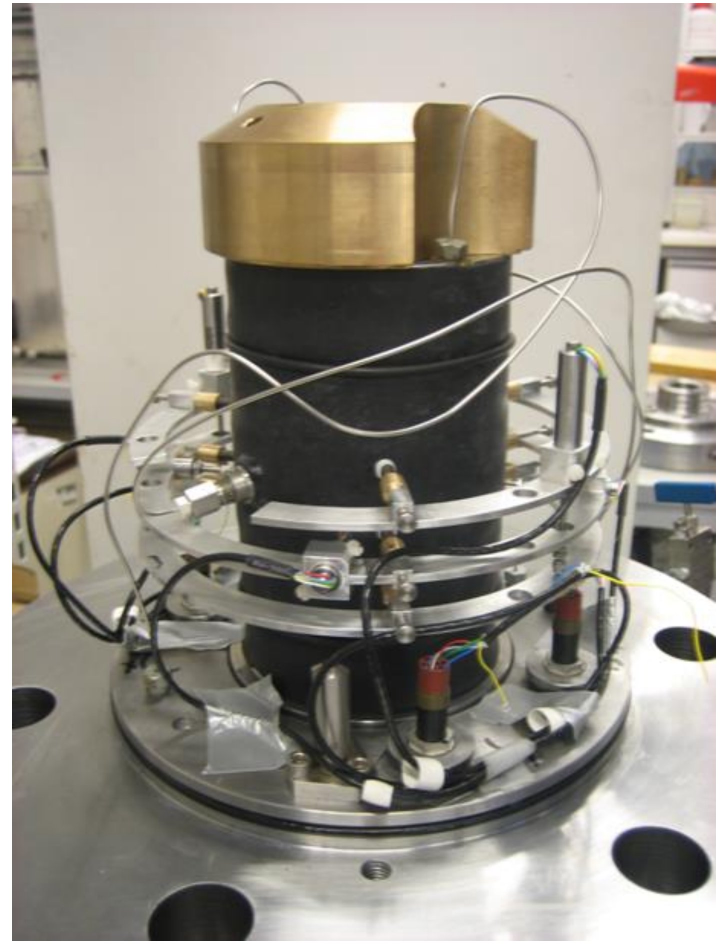
Drainage path: 10mm
(half-thickness of the hollow cylinder)

General Setting

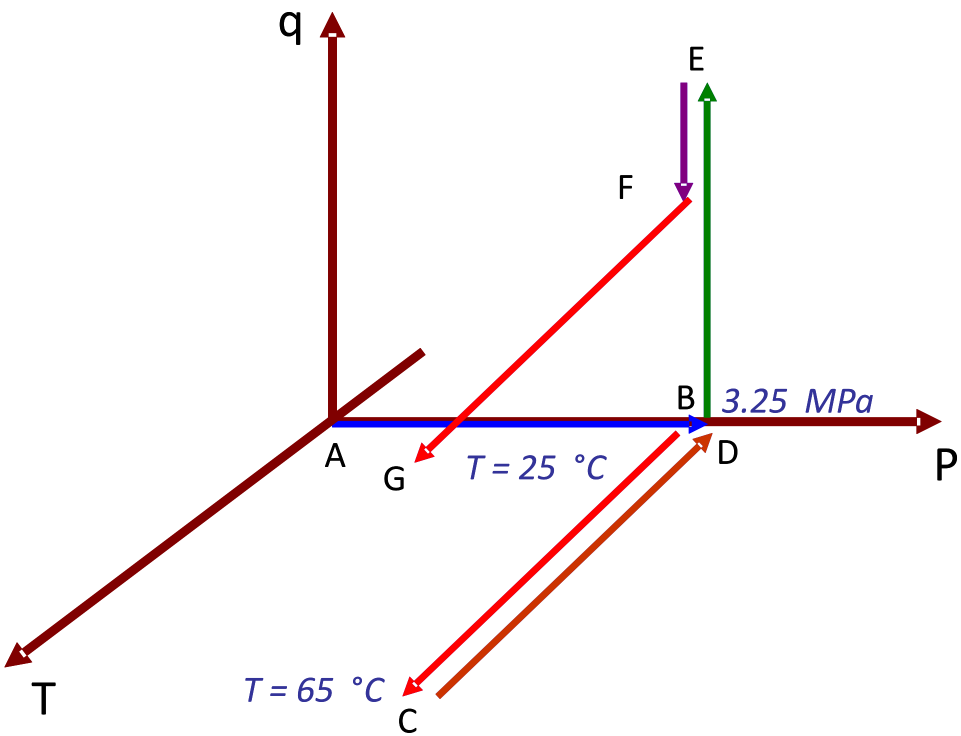


PT: Pressure transducer

PVC: Pressure Volume controller



Thermo-mechanical test on Boom clay



AB: Isotropic loading at constant temperature (25°C) up to 3.25MPa of confining pressure

BC: undrained heating under constant stress from 25°C to 65°C

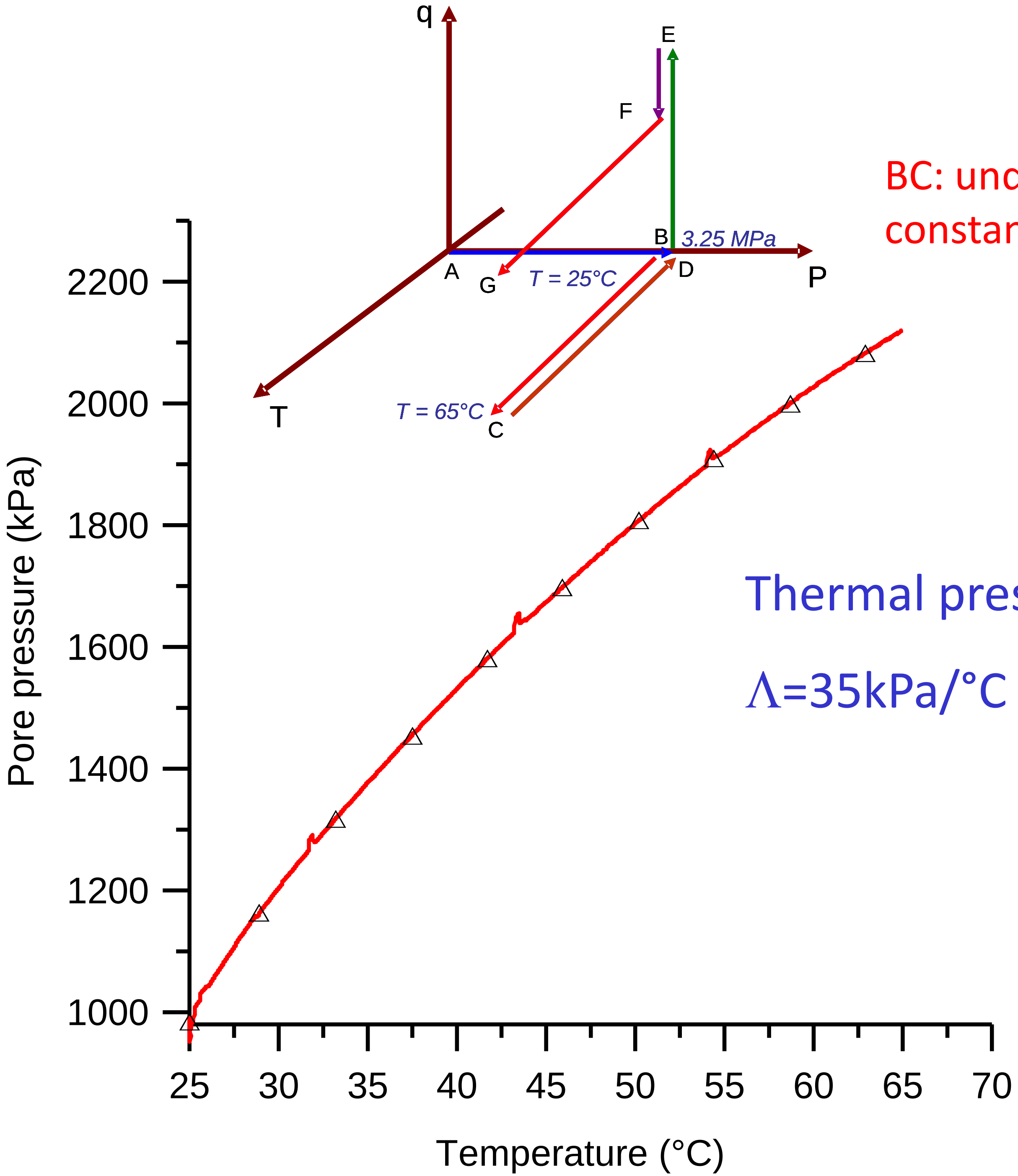
CD: Drained cooling

DE: Undrained shearing test at constant total mean stress up to maximum deviator

EF: Axial stress relaxation

FG: undrained heating under shear

Monfared et al, *Eng. Geol.*2011

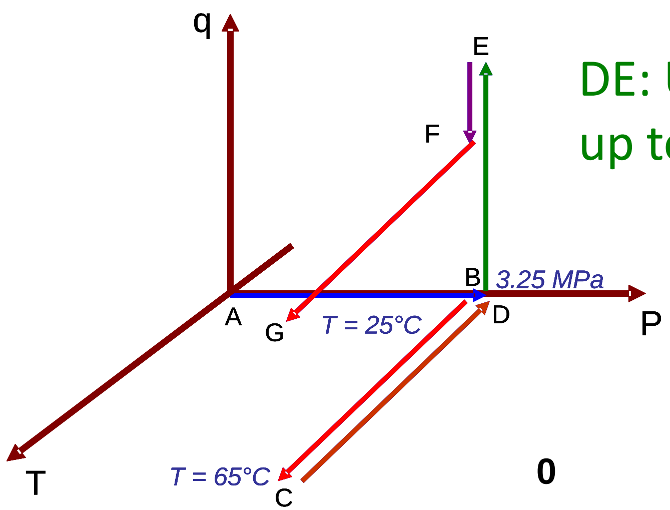


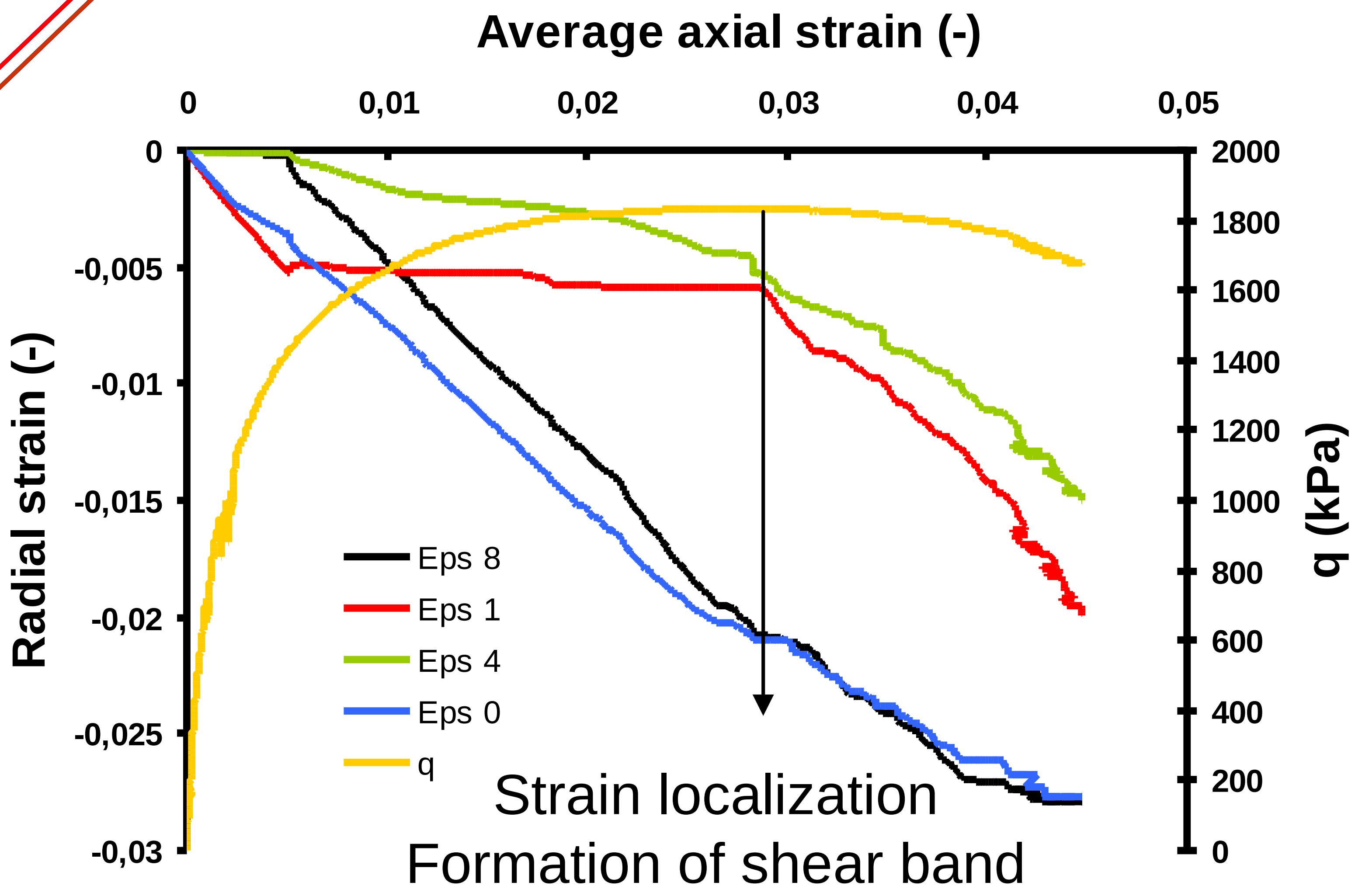
BC: undrained heating under constant stress from 25°C to 65°C

Thermal pressurization coefficient

Λ=35kPa/°C

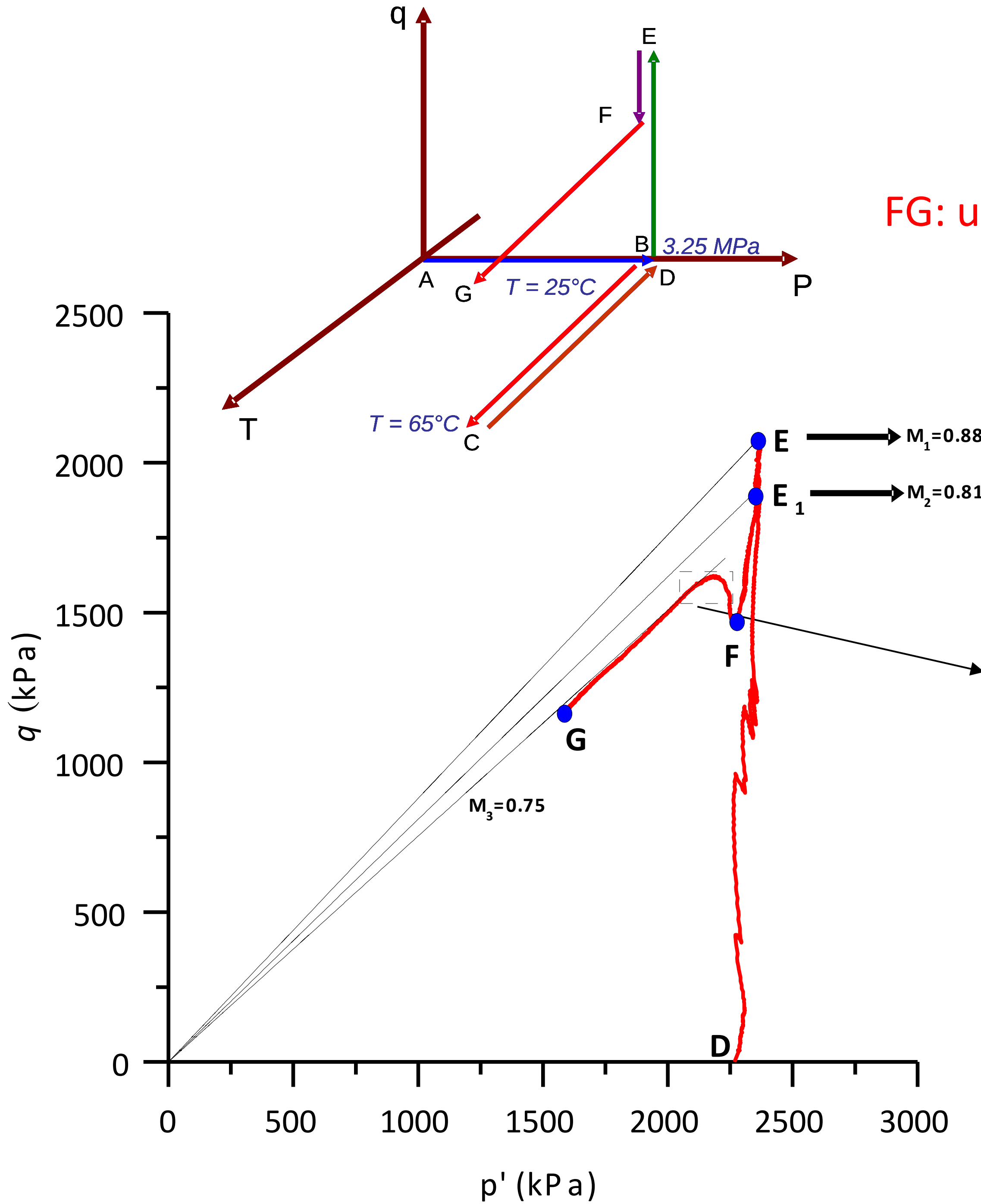
DE: Undrained shearing test at constant total mean stress up to maximum deviator

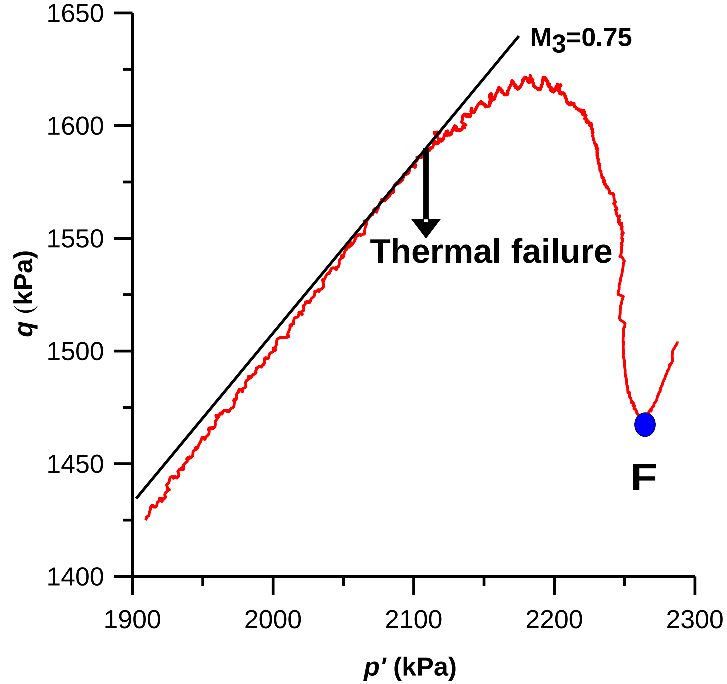




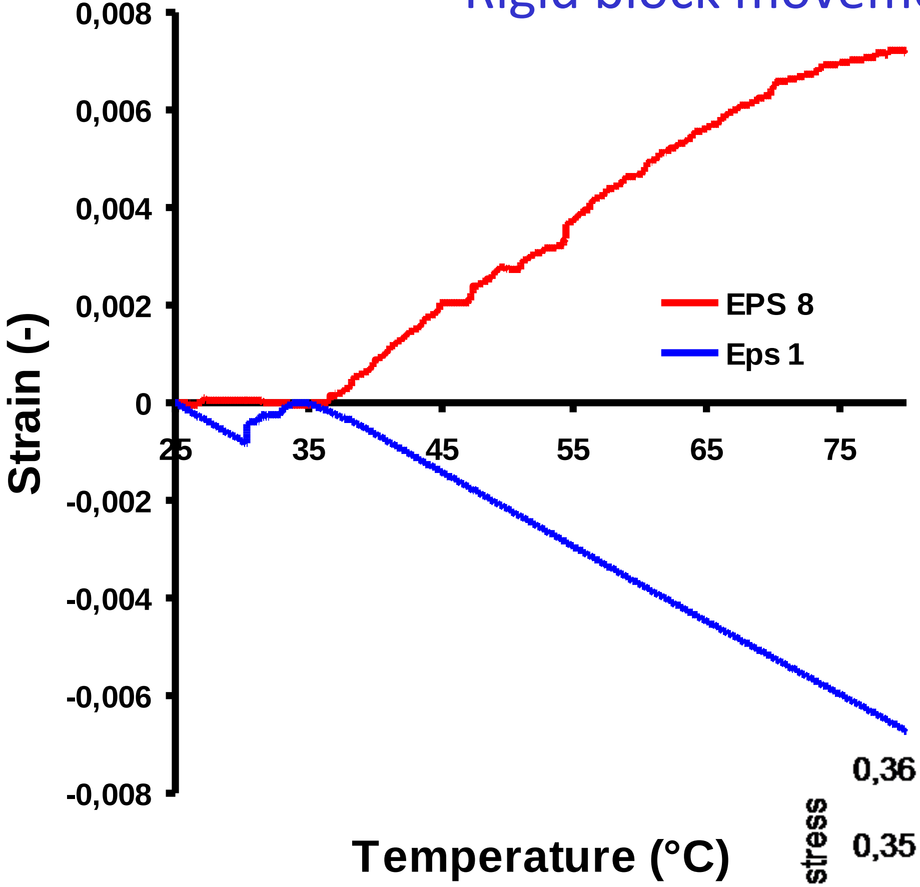

40°

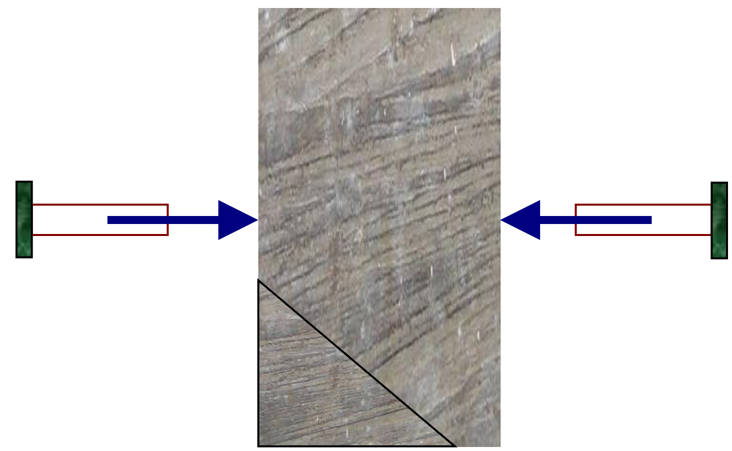
FG: undrained heating under shear



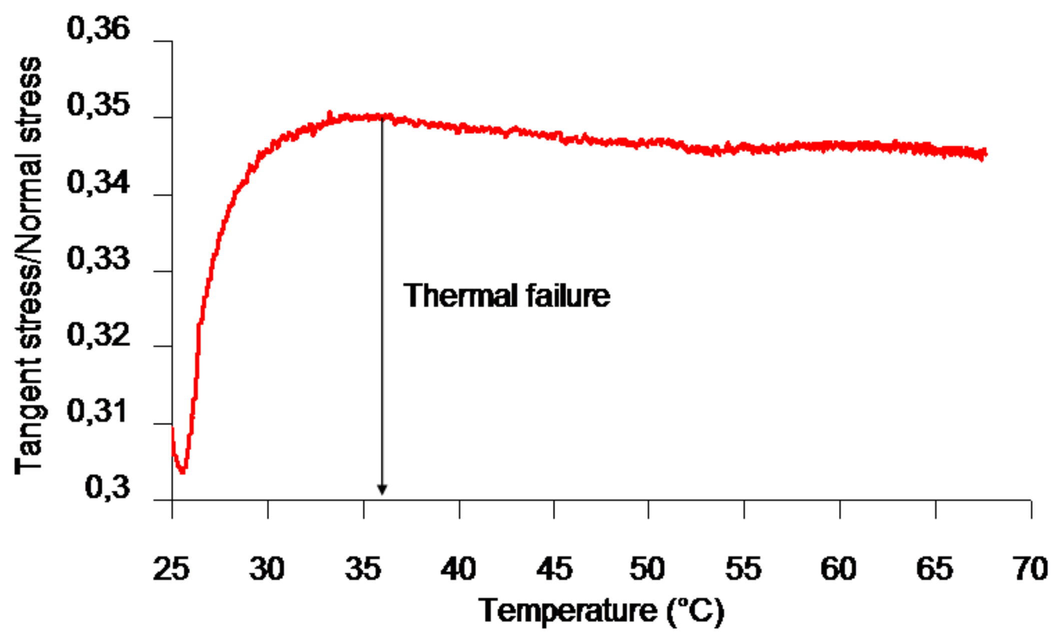


Rigid block movement above 35°C





227µm sliding along the shear band



Thermal effects during seismic slip

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

Thermally induced weakening mechanisms (1/3)

Frictional heating and 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.

Frictional heating is a mechanism of shear strength weakening because thermal pressurization of pore fluid reduces the effective stress

(*Lachenbruch, 1980, Vardoulakis, 2002, Sulem et al. 2005, Rice 2006, Ghabezloo & Sulem, 2009*).

Thermal pore fluid pressurization also occurs in large landslides (Habib, 1967, 1975, Vardoulakis, 2002, Veveakis et al, 2007)

Thermally induced weakening mechanisms (2/3)

- Flash heating and shear weakening at micro-asperity contacts: stress concentration and intense localized heat generation at contacting asperities (*Rice, JGR, 2006, Beeler et al. JGR, 2008)*

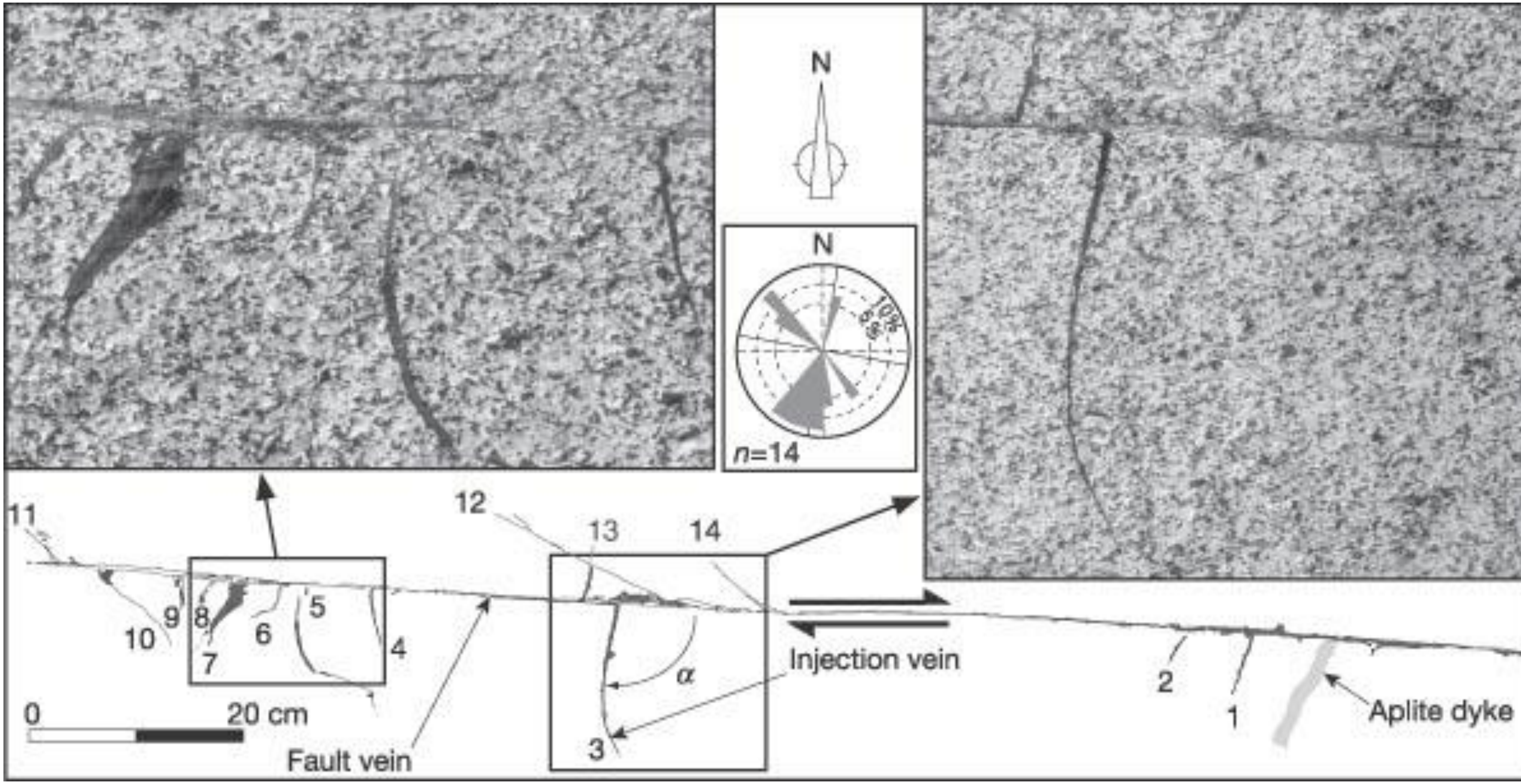
- Lubrication of the fault plane:

    Formation of a macroscopic melt layer

    Gelification in wet silica rich fault zones

    Production of nano-particles during slip

    (*Di Toro et al., Nature, 2004, 2011*).



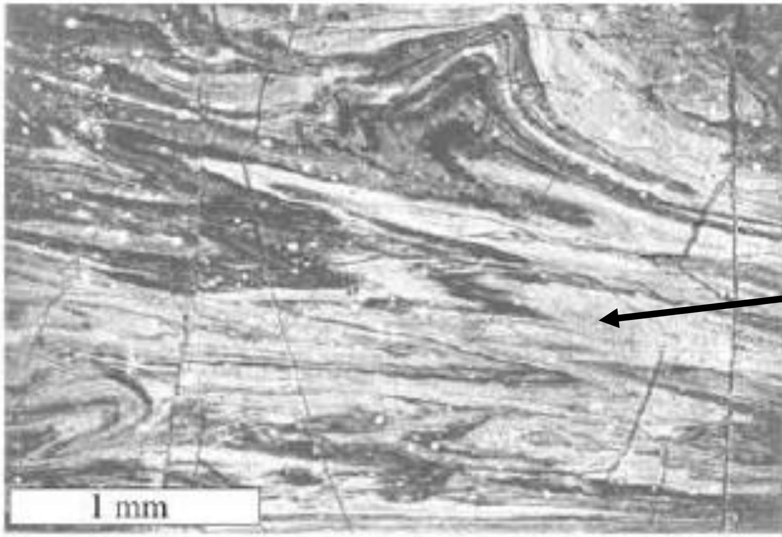
Pseudotachylite injection veins on the Alpine Fault of Gole Larghe, Italy

(Di Toro et al., 2005, *Nature*)

Microstructure pseudotachylytes in Nojima fault, Japan

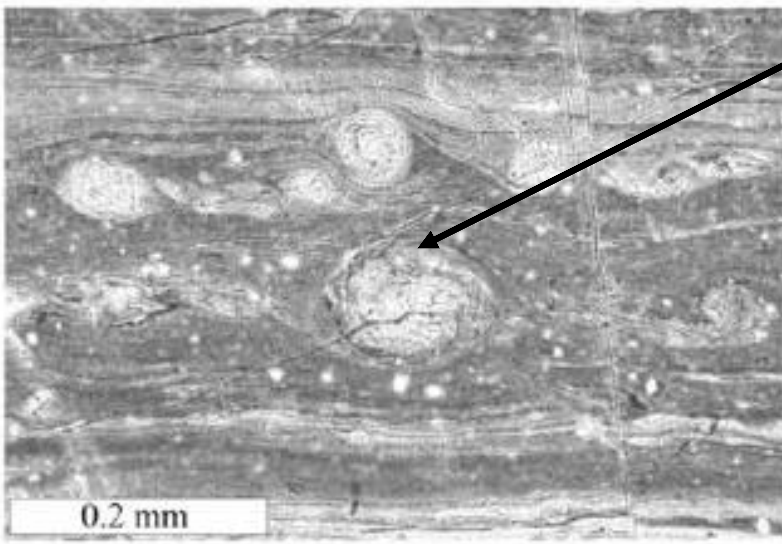
(Otsuki et al, *JGR, 2003)*

a



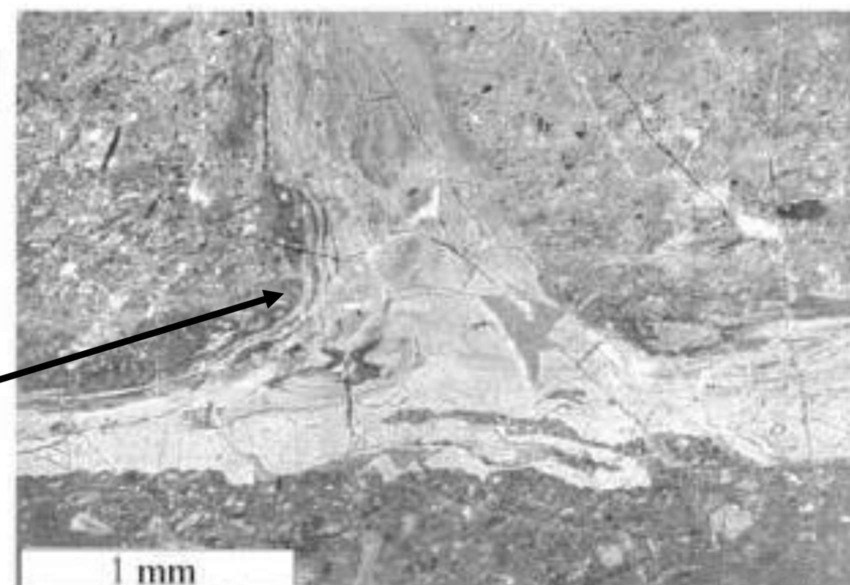
folds in the pseudotachylyte

c



rotational structures in a pseudotachylyte layer

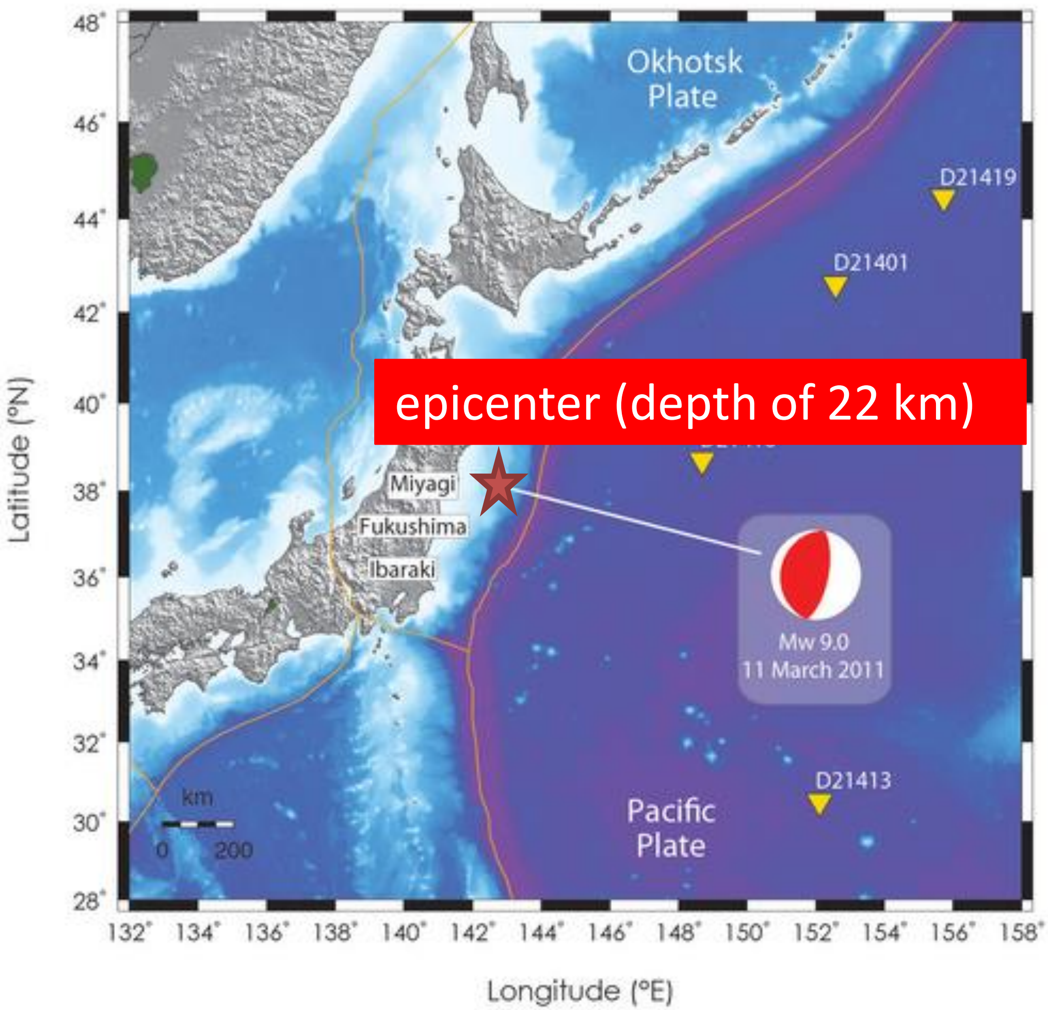
j



pseudotachylyte intruding into a gouge layer

Tohoku earthquake (Mw9.1, March 2011)

Shallow rupture propagation up to the surface (coseismic slip > 50 m) in a clay rich fault zone (5 m thick)



Dynamic weakening mechanism:

Shear heating and thermal pressurization of the pore fluid

Japan Trench Drilling Program

Fulton et al. (2013), *Science*

Estimated apparent friction coefficient: 0.08

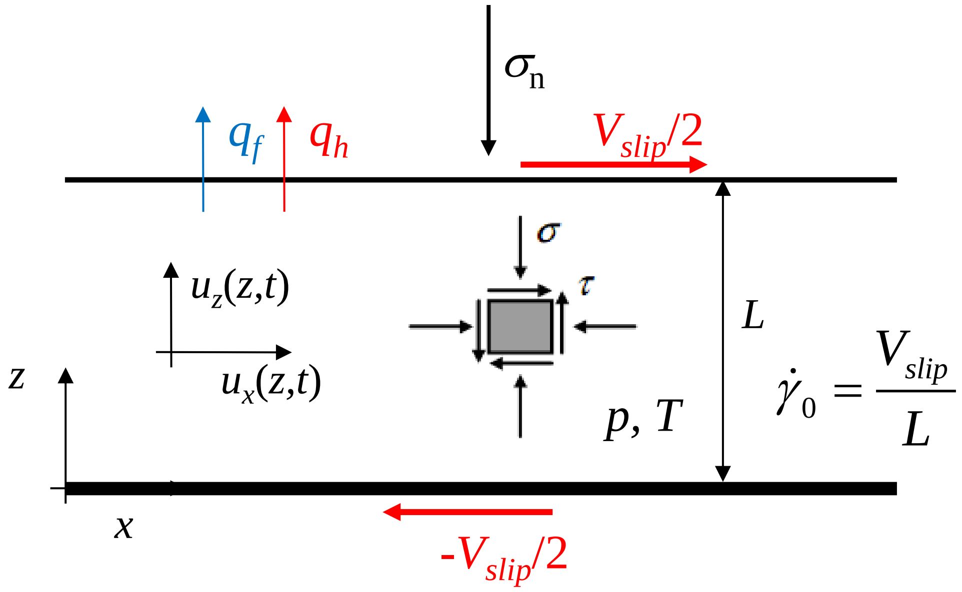
Romano et al. (2014, *Nature*

Ujiie, et al. (2013). *Science*

Chester et al. (2013), *Science*

Undrained adiabatic shearing of a saturated rock layer

Destabilizing effect of shear heating and pore fluid pressurization



Shear strain and volume strain

$$\gamma = \frac{\partial u_x}{\partial z} \qquad \varepsilon = \frac{\partial u_z}{\partial z}$$

Uniform state of stress in the layer

$$\frac{\partial \tau}{\partial z} = 0 \qquad \frac{\partial \sigma}{\partial z} = 0$$

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

$$\tau = \mu(\sigma - p)$$

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)

$\beta^* = n\left(\beta_n + \beta_f\right)$ is the storage coefficient.

$c_{hy} = k_f / (\beta \eta_f)$ is the hydraulic diffusivity

Energy balance equation

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

$c_{th} = k_T / \rho C$ 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 σ_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

$$\text{mass balance: } \frac{\partial p}{\partial t} = \Lambda \frac{\partial T}{\partial t}$$

$$\text{energy balance: } \frac{\partial T}{\partial t} = \frac{1}{\rho C}\left(\sigma_n - p\right)\mu\dot{\gamma}$$

Spatially uniform solution under undrained adiabatic conditions

Solution:

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

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

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

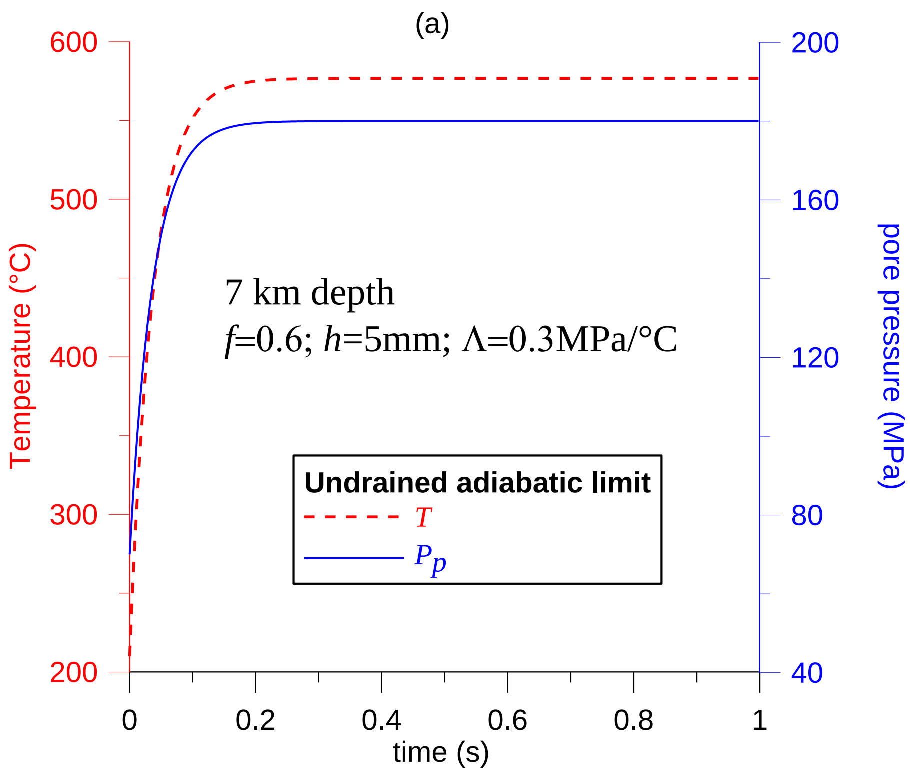
In due course of the shear heating and fluid pressurization process, the shear strength τ is reduced towards zero.

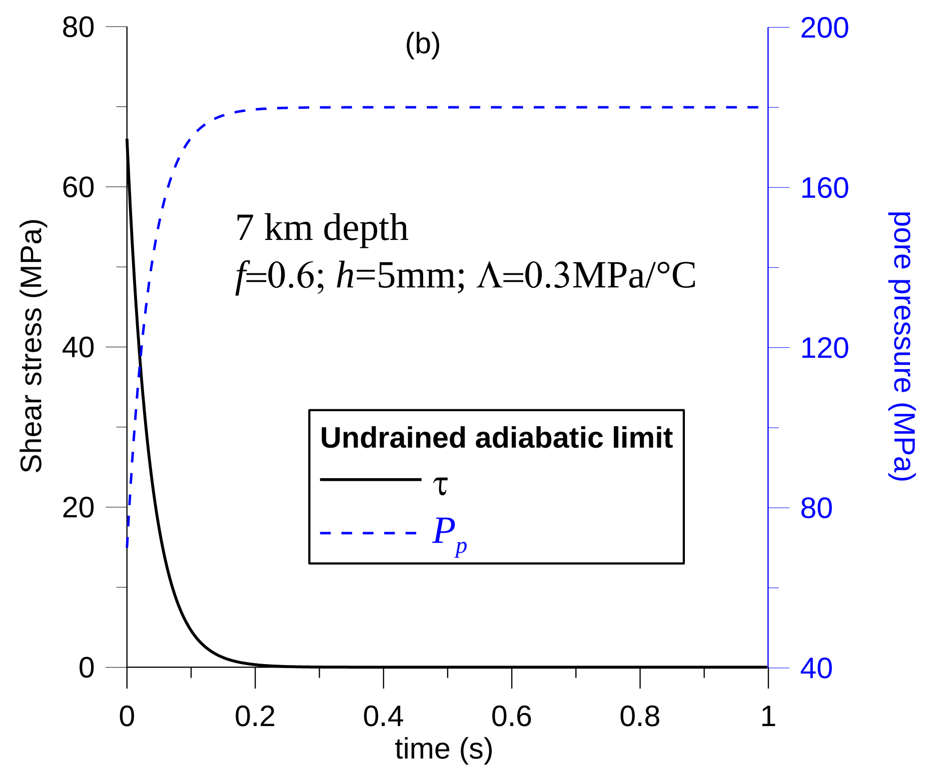
Example: Fault zone at 7 km depth

Initial conditions: $T_0 = 210°\text{C},\ p_0 = 70\text{MPa},\ \sigma_n = 180\text{MPa}$

Slip velocity: 1m/s; Shear band thickness: L=5mm

Maximum temperature: $T_{max} = T_0 + \dfrac{\sigma_n - p_0}{\Lambda} = 577°\text{C}$





Example of a fault at shallow depth

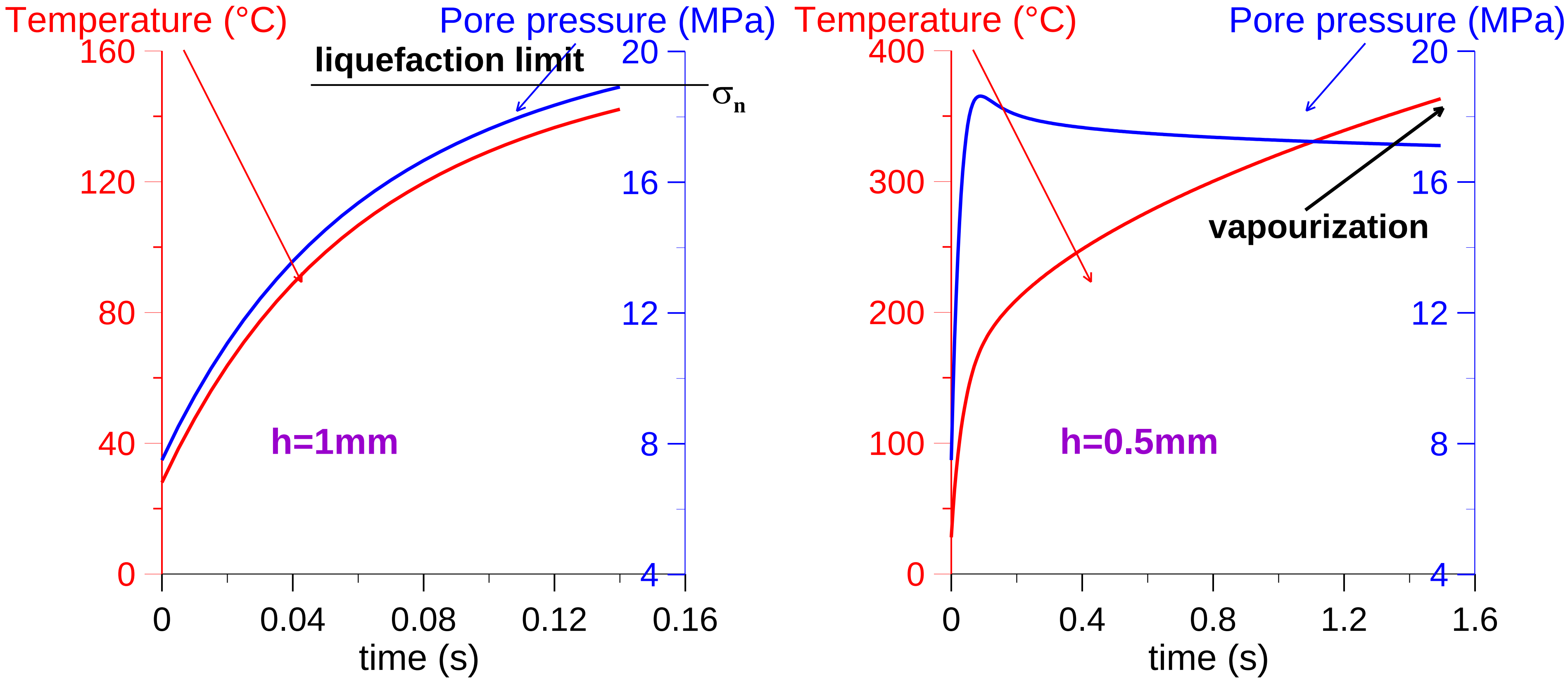
Aigion fault at 760m depth (σ_n = 19 MPa, P_{p0}=7.6 MPa, T_0= 28°C)

Sulem et al., Int. J. Num. Anal. Meth. Geomech. 2005

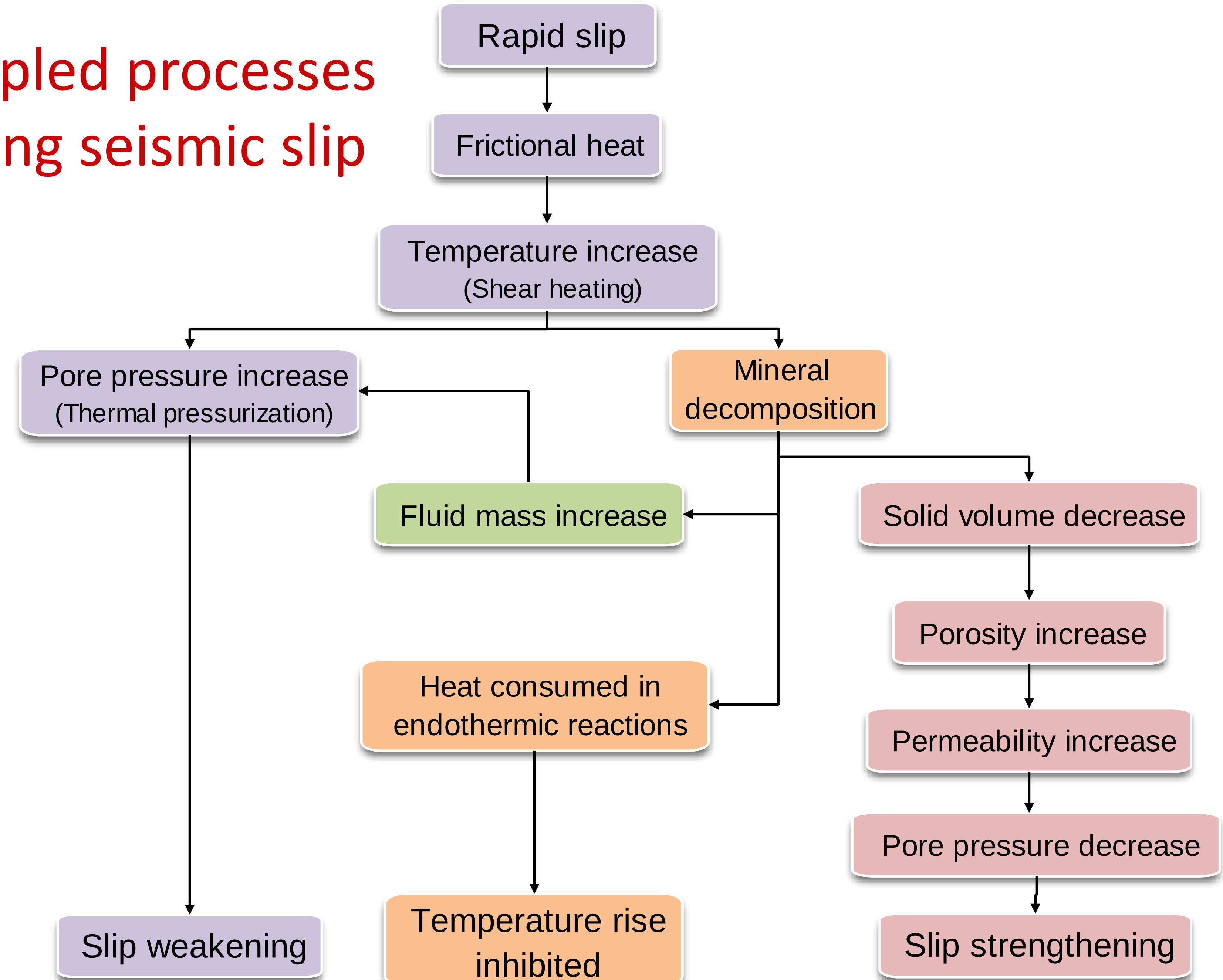
Numerical data

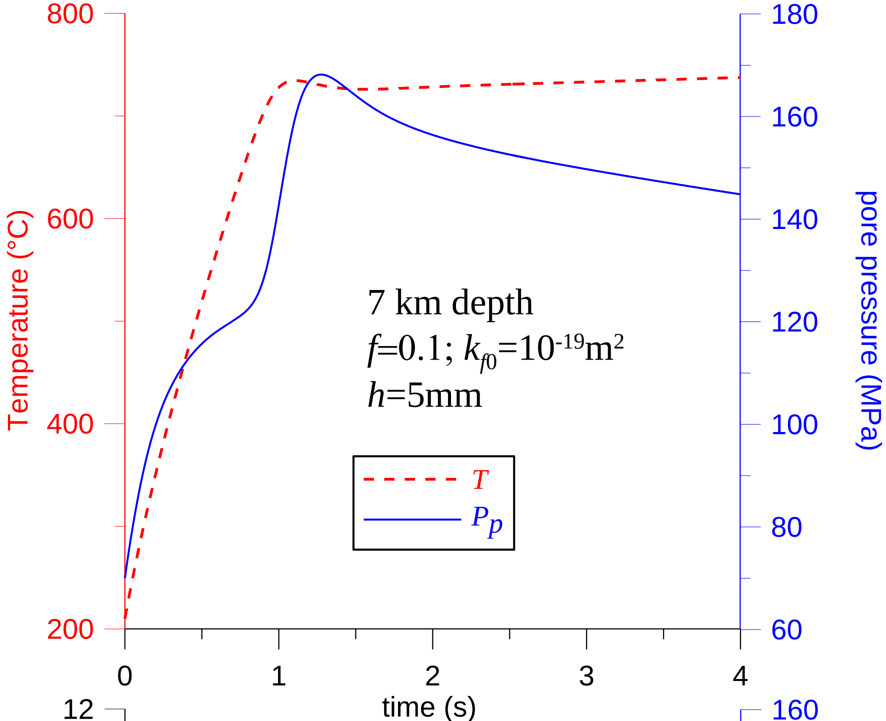
c_{hy}=0.32 mm2/s; Λ= 0.1 MPa/°C; f=0.5 , c_{hy}= 0.024 mm2 /s (permeability: $10^{-19}m^2$)

imposed shear velocity: 1 m/s

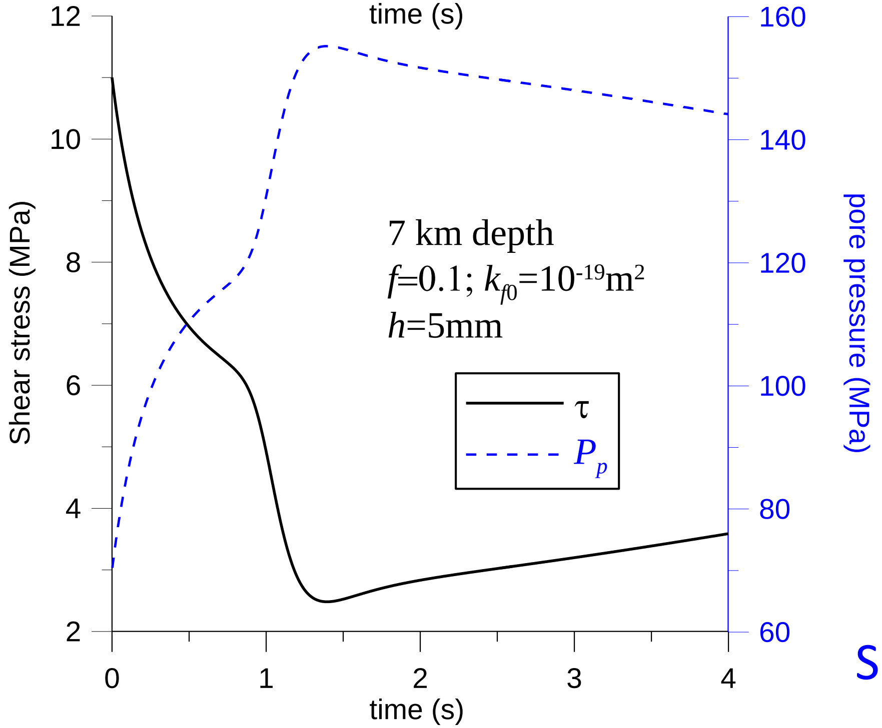


Coupled processes during seismic slip





Thermal decomposition of carbonates in fault zones: Slip-weakening and temperature-limiting effects



-The endothermic chemical reaction limits the co-seismic temperature increase

- Pore pressure exhibits a maximum and then decreases due to the reduction of solid volume (pore pressure pulse)

- Weakening/restrengthening of the shear stress

Sulem & Famin, (2009), *J. Geoph. Res.*

CONCLUSIONS

- ✓ Major role of the temperature on the physical and mechanical properties of rocks
- ✓ Coupled thermo-hydro-mechanical processes can induce weakening mechanisms
- ✓ Thermal weakening processes induced by shear heating are central in the understanding of the nucleation and the development of gravitational and seismic slip.