# How fluid-rock interactions and fabric development affect friction: towards a microphysical basis for Rate-and-State Friction

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# Outline

1. History and background of rate-and-state friction (RSF)

2. Fault-scale modeling using RSF

3. Physical interpretations of RSF

4. Variation of friction with active foliation development

   and fluid-rock interactions – analogue experiments and models
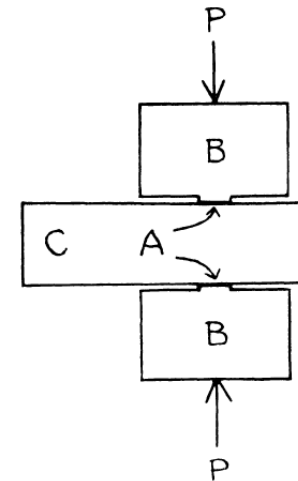
5. Experiments on real fault gouge materials & model

# Some history

These rupture phenomena may or may not be superposed on the ordinary phenomena of plastic flow. Thus there are substances, of which graphite is a conspicuous example, which show no trace of plastic flow; rupture occurs, there is a jump in angular displacement and a jump down in the force, the force then builds up again with practically no further increase in angular displacement until the critical force for rupture is reached, and the process repeats.

First description of rupture in the laboratory !

Experiments on a wide variety of materials using a rotary shear device

# Some history

Abstract. *Stick-slip often accompanies frictional sliding in laboratory experiments with geologic materials. Shallow-focus earthquakes may represent stick-slip during sliding along old or newly formed faults in the earth. In such a situation, observed stress drops represent release of a small fraction of the stress supported by the rock surrounding the earthquake focus.*

- Brace & Byerlee (Science, 1966) propose that "stick-slips" are the laboratory equivalent of earthquakes.
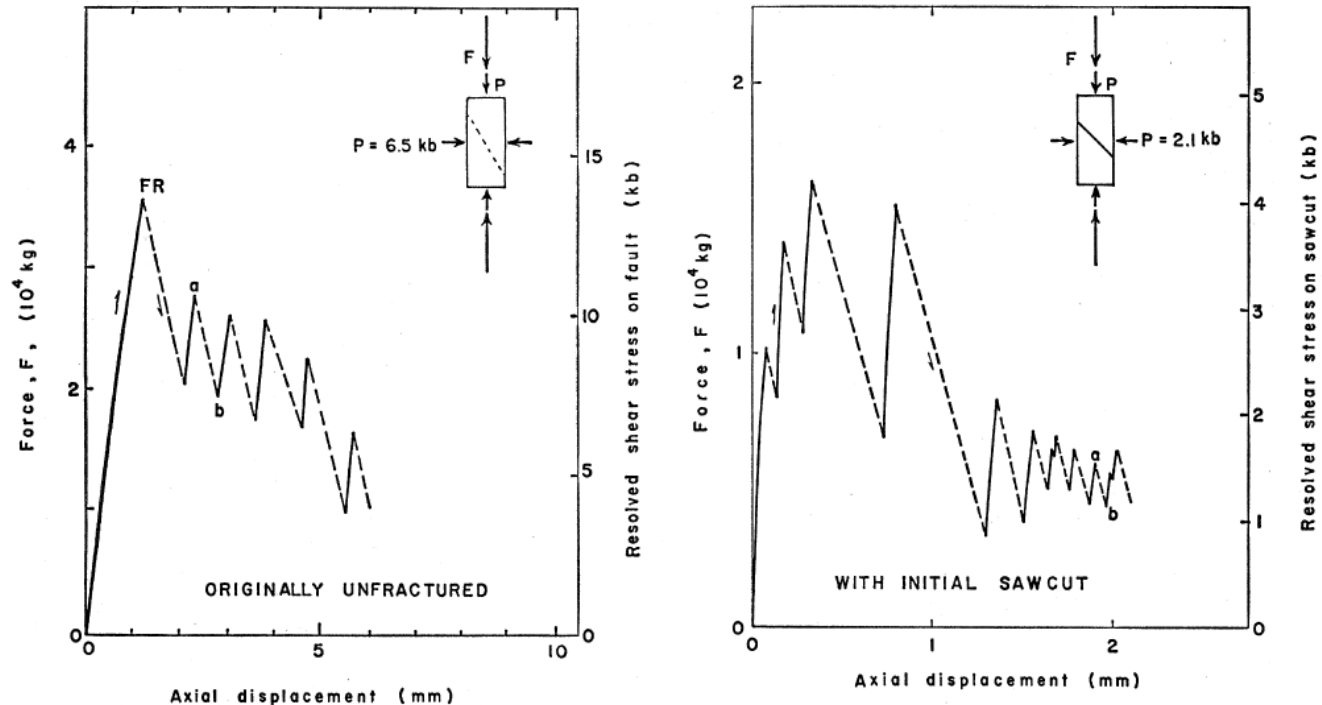- Friction as opposed to fracture



Fig. 1 (left). Force-displacement curve for the axial direction in a cylindrical sample of Westerly granite. Small diagram above the curve shows schematically how stress was applied to the sample. The sample fractured at point *FR* forming the fault which is shown as a dotted line in the small diagram. The exact shape of the curves during a stress drop (such as *ab*) is not known and is shown dotted. *P* is confining pressure. Fig. 2 (right). Same as Fig. 1 except that the sample contained a sawcut with finely ground surfaces as shown schematically (small figure) by a heavy line.

26 AUGUST 1966

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# Some history

## MODEL AND THEORETICAL SEISMICITY

### By R. Burridge and L. Knopoff
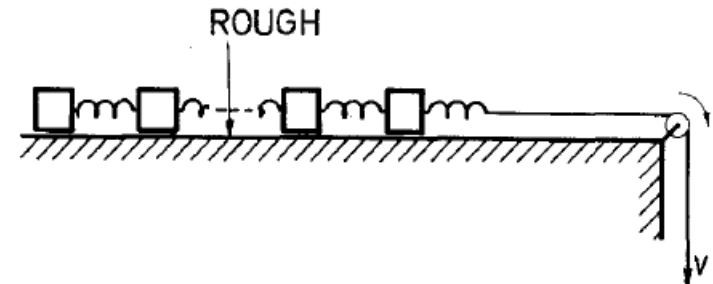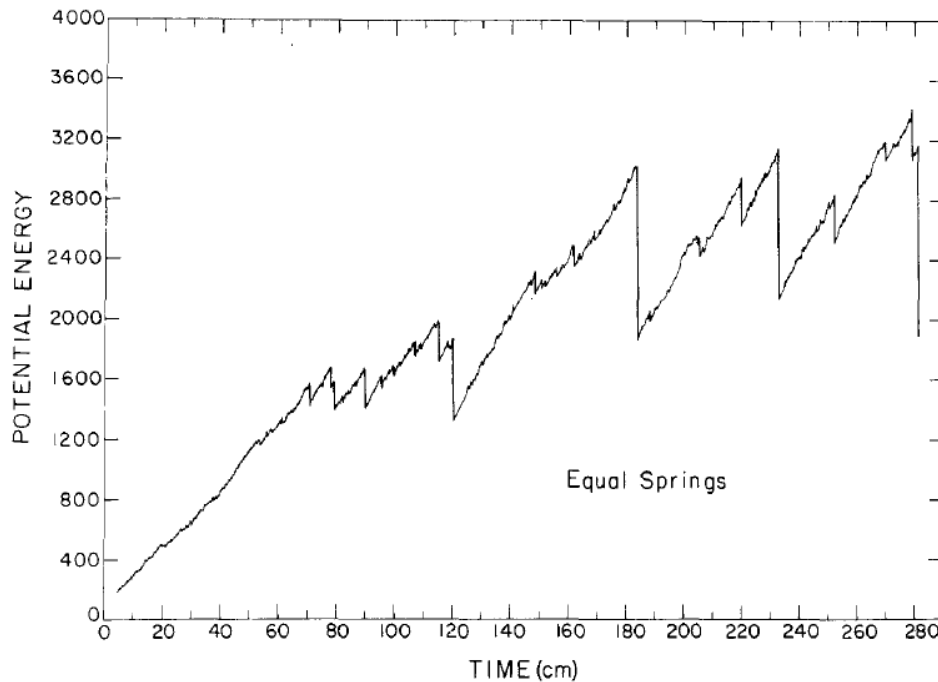


FIG. 3. Schematic diagram of the laboratory model.



FIG. 4. Potential energy as a function of time for the mass-spring system with all springs equal.

- Spring-slider model generating quasi-periodic slip events
- EQ cycle controlled by friction

# Some history

## Modeling of Rock Friction
## 1. Experimental Results and Constitutive Equations

JAMES H. DIETERICH



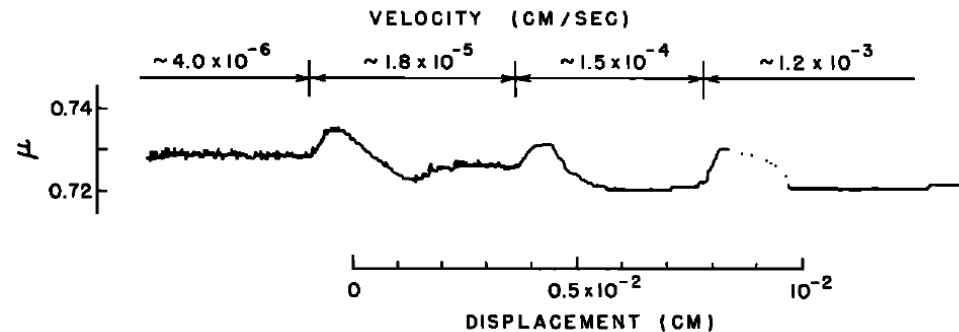Fig. 1. Coefficient of friction $\mu$ versus displacement. Slip velocities are shown by the arrows above the experimental curves.

- Results from sliding experiments on granodiorite at 6.07 MPa and room $T$
- Velocity-dependence of friction result of time-dependence of contact area
- Formulation of time and displacement-dependent friction, initial form of rate-and-state-friction equations (RSF)

# Some history

## Slip Instability and State Variable Friction Laws

ANDY RUINA

$$\tau = F(\sigma, V, \theta_1, \theta_2, \cdots) \tag{3a}$$

$$d\theta_i/dt = G_i(\sigma, V, \theta_1, \theta_2, \cdots) \qquad i = 1, 2, \cdots \tag{3b}$$

One hopes that for practical purposes the numbers of state variables $\theta_i$ required is small. The variables $\theta_i$ then represent some kind of average of an undoubtedly complicated surface state.

- Concept of state variables
- Formulation of RSF equations

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# Some history

## Slip Instability and State Variable Friction Laws

ANDY RUINA

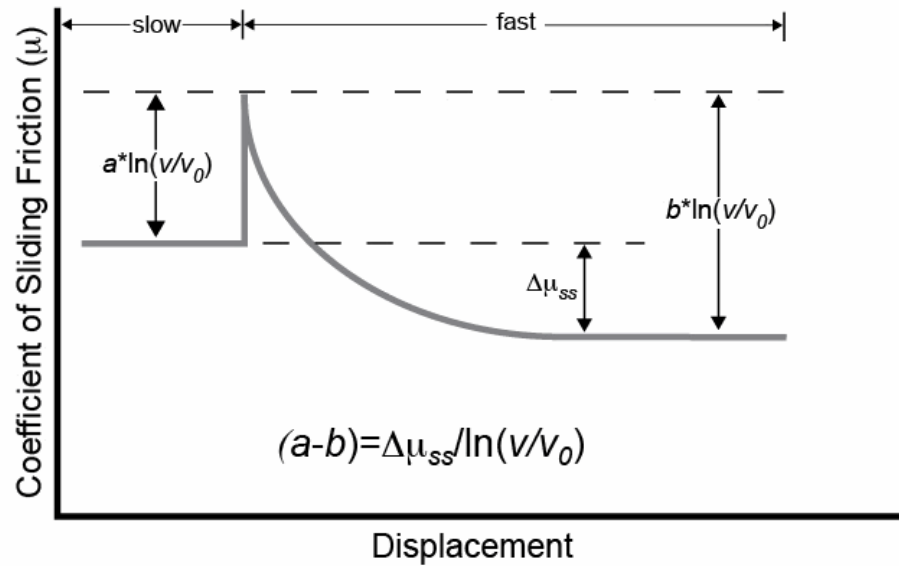$$\tau = F(\sigma, V, \theta_1, \theta_2, \cdots) \tag{3a}$$

$$d\theta_i/dt = G_i(\sigma, V, \theta_1, \theta_2, \cdots) \qquad i = 1, 2, \cdots \tag{3b}$$

One hopes that for practical purposes the numbers of state variables $\theta_i$ required is small. The variables $\theta_i$ then represent some kind of average of an undoubtedly complicated surface state.

- Concept of state variables
- Formulation of RSF equations

The usefulness of the state variable concept does not depend on physical interpretation of the state variables (like temperature or entropy in thermodynamics) though discovery of such interpretation would add tremendously to the credence and usefulness of the theory.

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# Rate and State friction equations



$$\mu = \mu_0 + a \cdot ln\left(\frac{v}{v_0}\right) + b \cdot ln\left(\frac{v_0\theta}{d_c}\right)$$

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{d_c}$$ "Slowness law" or "Dieterich-Ruina law"

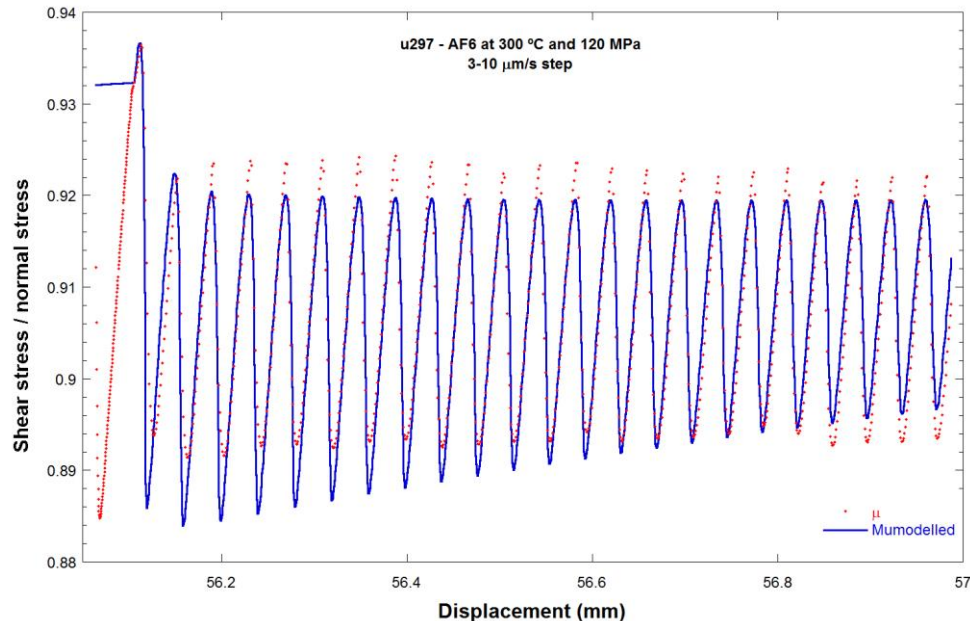$$\frac{d\theta}{dt} = -\frac{v\theta}{d_c}\ln\left(\frac{v\theta}{d_c}\right)$$ "Slip law" or "Ruina law"

# RSF - experiments

Coupling of RSF equations with an equation describing the interaction with the elastic loading frame
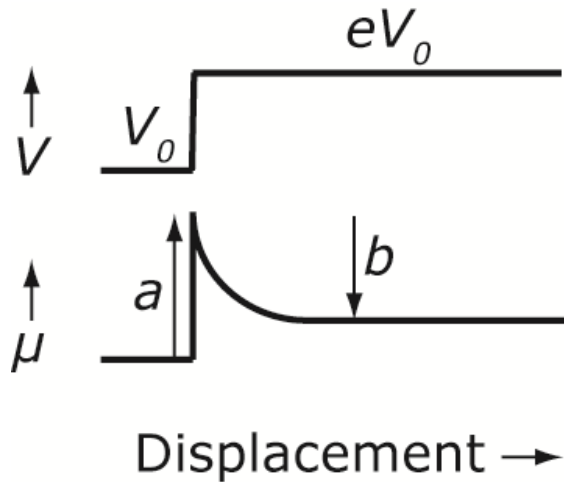
$$\frac{d\mu}{dt} = k\left(v_{lp} - v\right)$$

1. Solve for *v* gives the evolution of friction with time (displacement)
2. Invert for experimental data to obtain *a, b* and $d_c$



**Stick-slip behaviour**

# RSF − (*a-b*)

At steady state: **(*a-b*) =** $\dfrac{\Delta\mu_{ss}}{\ln(V/Vo)}$



$(a-b) \geq 0$
Velocity strengthening
**Stable slip**
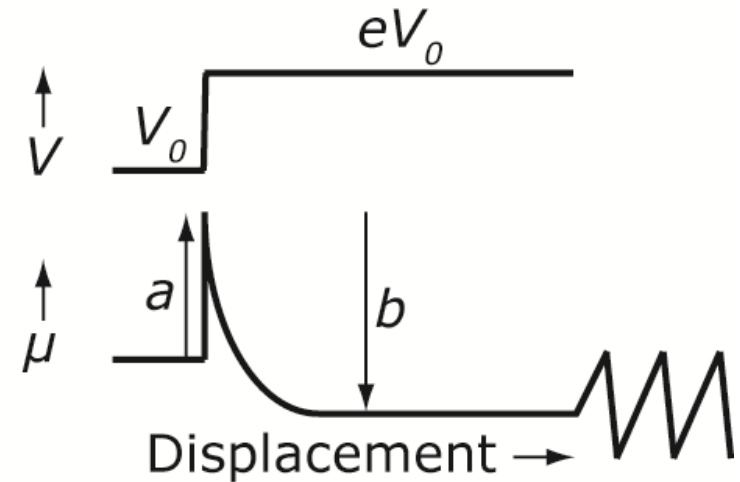
$(a-b) < 0$
Velocity weakening
**Potentially unstable slip**

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# RSF – seismic cycle

Spring-slider analogue
RSF equations coupled with the equation of motion
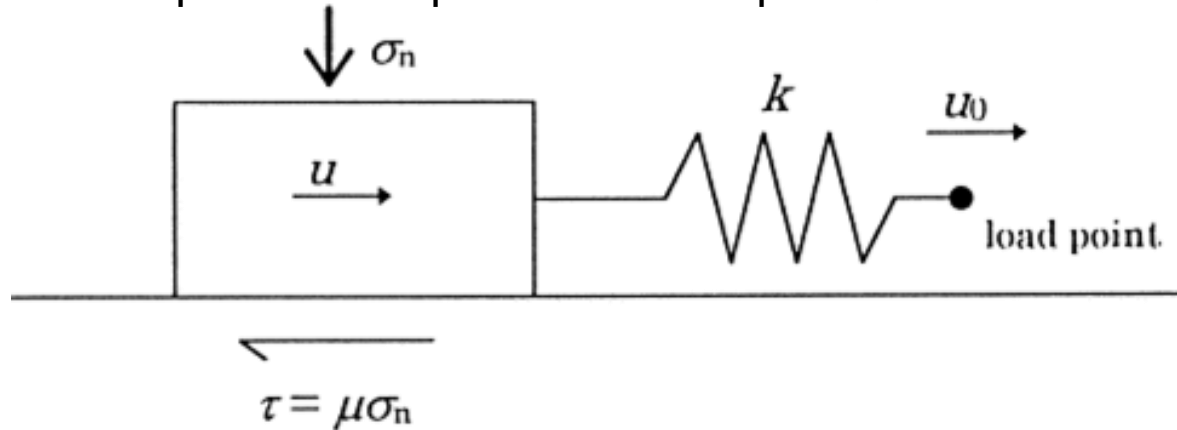


If (a-b) > 0, stable sliding
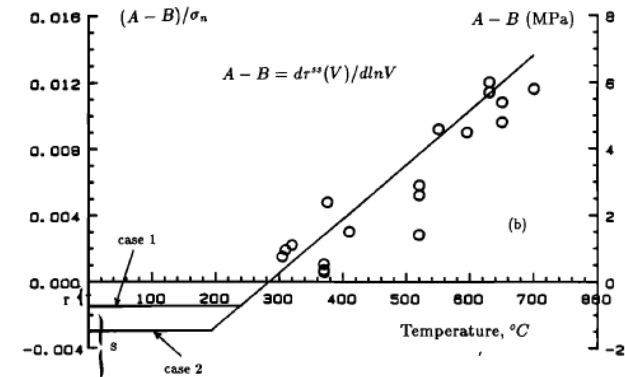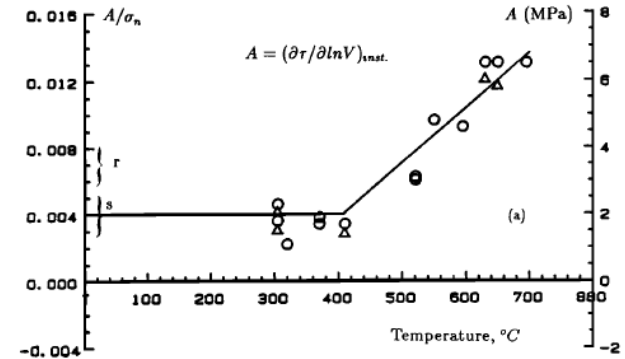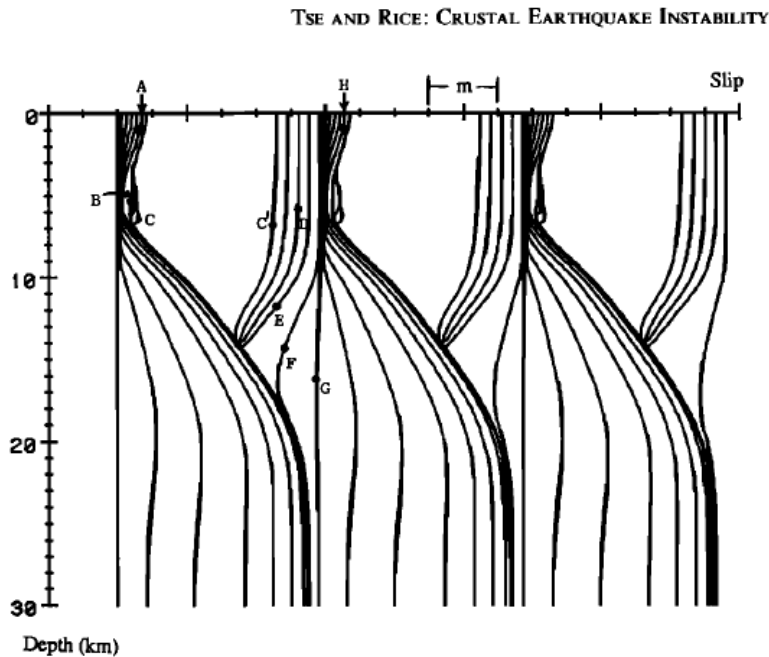→ $V_{block}=V_{spring}$

If (a-b) < 0, unstable sliding possible
→ $V_{block}=0$ until $F > \mu_{static}F_n$ → sudden drop in force and $V_{block} >> V_{spring}$

Stability criterion: unstable slip when $\sigma > \sigma_c = \dfrac{Kd_c}{-(a-b)}$

# RSF – seismic cycle simulation

*Tse & Rice, JGR, 1986*

*(a-b)* varies with temperature (depth)

TSE AND RICE: CRUSTAL EARTHQUAKE INSTABILITY

| Time Interval | |
| --- | --- |
| A to B | 2.4 yrs. |
| B to C | 4.6 hrs. |
| C to C' | instantaneous |
| C' to D | 4 secs. |
| D to E | 3.5 mins. |
| E to F | 77.8 days |
| F to G | 3.6 yrs. |
| G to H | 77.2 yrs. |

$T_{cy}$ = 83.8 yrs.

C2L40L00

$A = (\partial\tau/\partial lnV)_{inst.}$

$A - B = d\tau^{ss}(V)/dlnV$

1. Simulations explain depth extent of seismicity
2. Nucleation occurs at depths of 3-7 km, which depends on only mild variations in the constitutive parameters

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# RSF – seismic cycle simulation

*Tse & Rice, JGR, 1986*

*(a-b)* varies with temperature (depth)



*Scholz (2002)*
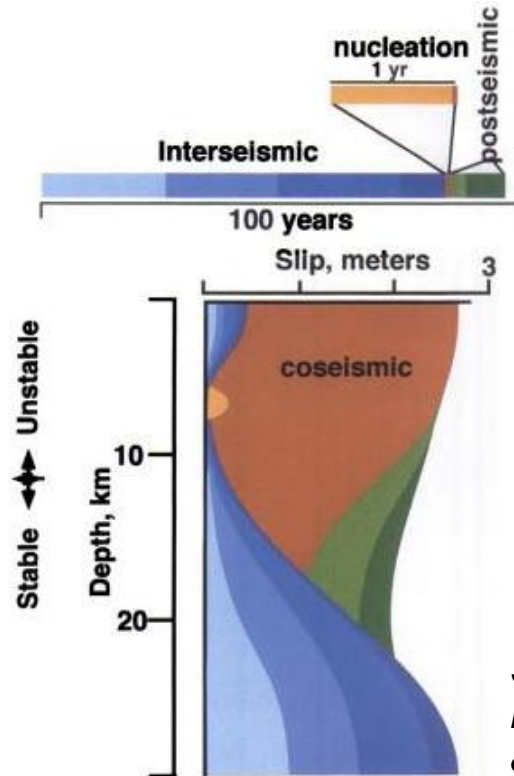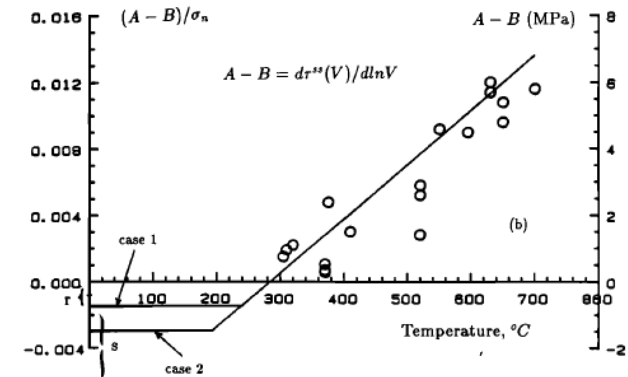*Modified from Tse*
*& Rice (1986)*

1. Simulations explain depth extent of seismicity
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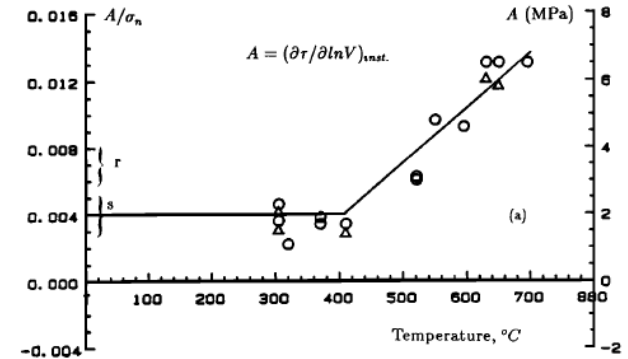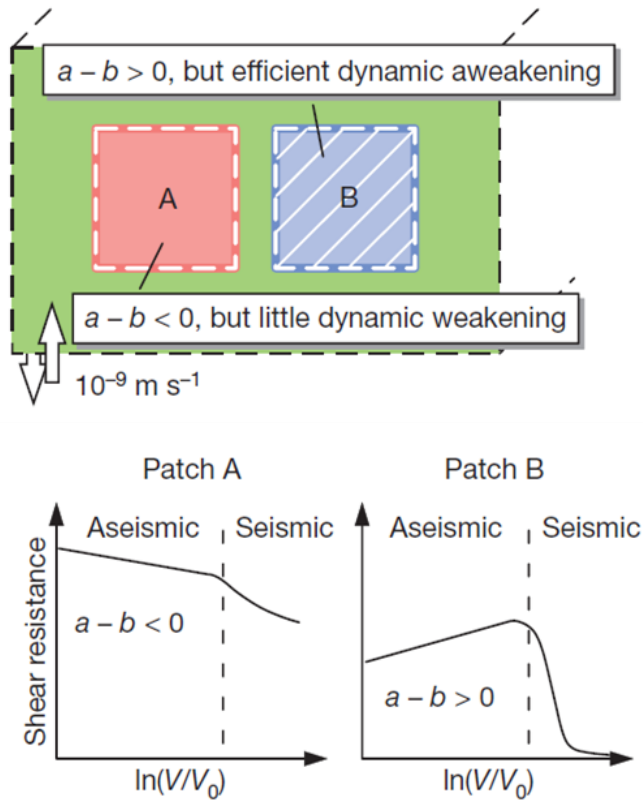
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# RSF – seismic cycle simulation

*Noda and Lapusta, Nature, 2013*



Variation in (a-b) with sliding velocity

Enhanced weakening at seismic velocities allows propagation of seismic slip in velocity-strengthening material.

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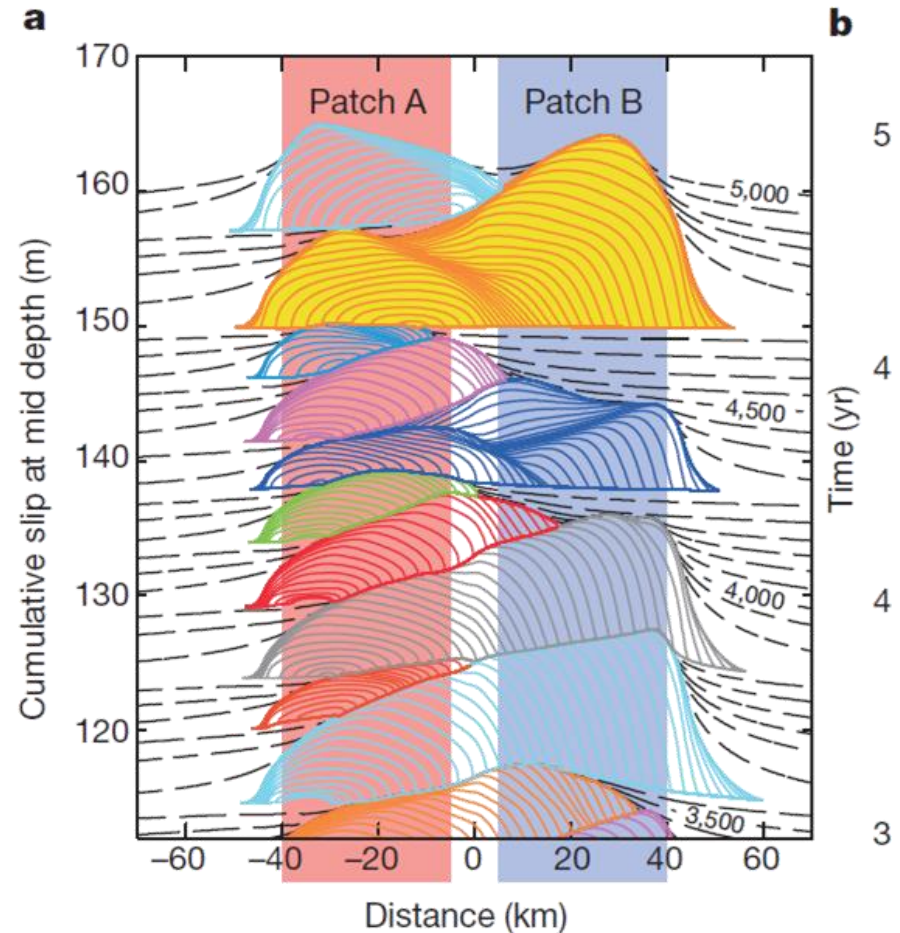
# RSF – seismic cycle simulation

Many more examples, e.g.
- Weeks, JGR, 1993, effect of positive (a-b) at high velocities on earthquake stress drop
- Dieterich, JGR, 1994, earthquake clustering (aftershocks)
- Boatwright and Cocco, JGR, 1996, effect of spatial distribution of (a-b) on earthquake size
- Kaneko et al, Nature Geoscience, 2010, effect of the presence of stable (positive (a-b) patch on earthquake size

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# Interpretation of Rate-and State

Baumberger et al. (1999) rewrote RSF as:

$$F = s(V)A_r(\theta)$$

with

$$A_r(\theta) = A_0\left[1 + \beta \ln\left(\frac{\theta V_0}{D_c}\right)\right] \qquad (1)$$
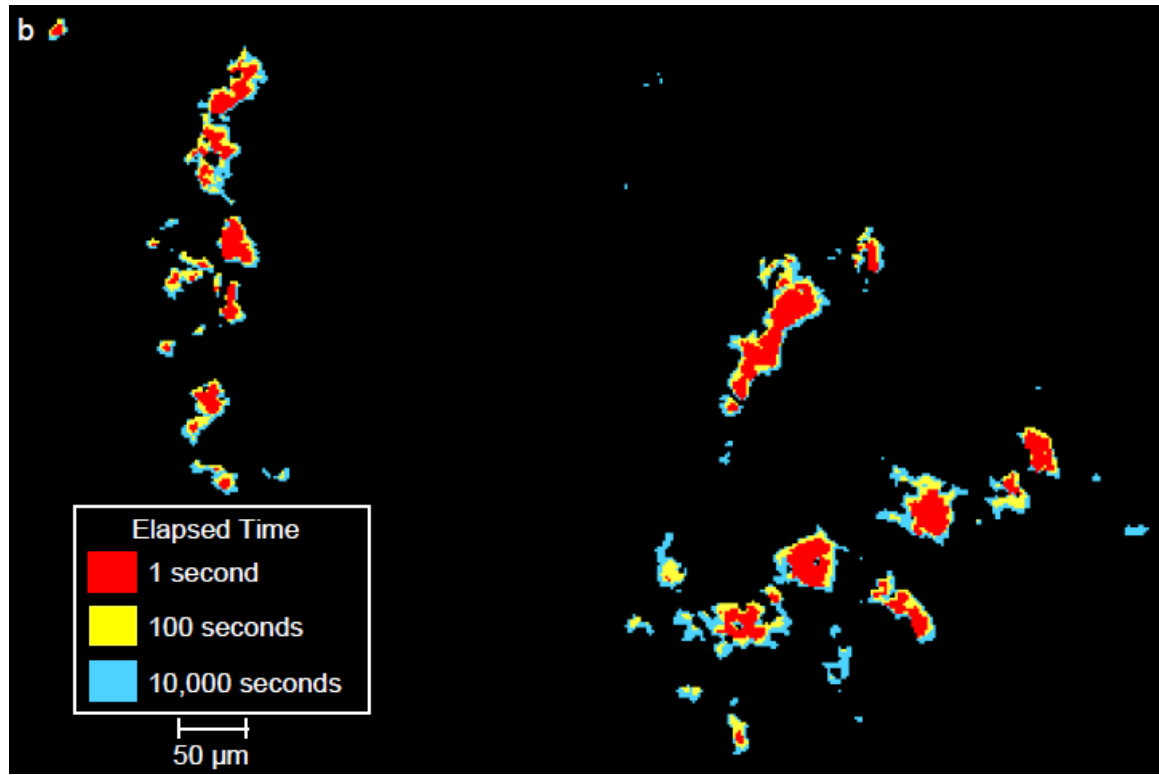
"b"

and

$$s(V) = s_0\left[1 + \alpha \ln\left(\frac{V}{V_0}\right)\right] \qquad (2)$$

"a"

Equation (1) represents the increase of real area of contact with (log) contact time
Equation (2) represents the velocity dependence of contact shear strength

# Interpretation of Rate-and State



*Dieterich & Kilgore, Pageoph,1994*

Growth of real area of contact under stationary load
- Attributed to "asperity creep"
- Occurs only in the presence of water (vapor)
- Underlying mechanism(s) unclear
- Mechanism probably varies with P,T, $H_2O$-content/composition

# Interpretation of Rate-and State

Velocity dependence of contact shear strength has been argued to be due to a form of thermally activated anelastic shear creep at contact junctions (Baumberger et al. 1999, Nakatani, 2001, Scholz, 2002):

$$s(V, T) = \frac{kT}{\Omega} \left[ \ln \left( \frac{V}{V_0} \right) + \frac{Q}{kT} \right]$$

with $\Omega$ and Q the activation volume and energy, respectively

→ Actual deformation mechanism still not defined – how to extrapolate ?

- Beeler et al. (JGR, 2007) showed that for weak phyllosilicates (serpentinite and talc), *a* can be directly (and quantitatively) related to the strain dependence of **dislocation glide.**
- However, a similar approach could not quantitatively link the direct effect to the rate dependence of subcritical crack growth in granitic or quartz-rich rocks.

**Importance of a 3D-volume vs. slip on an interface → contribution of volume changes to friction (shear stress)**

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# Interpretation of Rate-and State

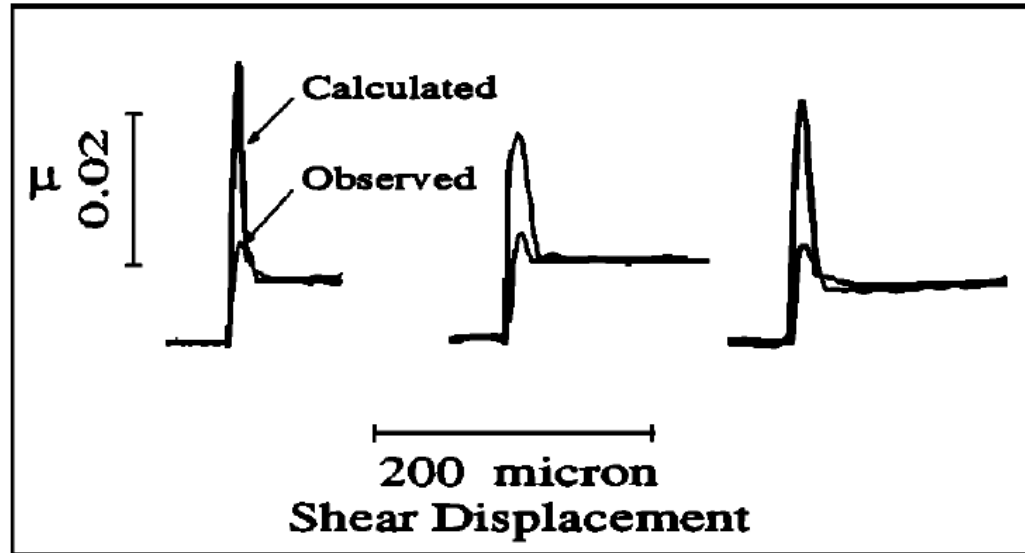**Importance of a 3D-volume vs. slip on an interface → contribution of volume changes to friction (shear stress)**



Fig. 22. Calculated and observed friction over three velocity steps assuming (1) an intrinsic steady state velocity weakening term of −0.002 (a−b) for $\mu_f$ and (2) that transient slip occurs at 15° to the gouge layer. The calculated curve was derived using equation (7) with normal stress increasing linearly from (0.65 σ') to σ' over the
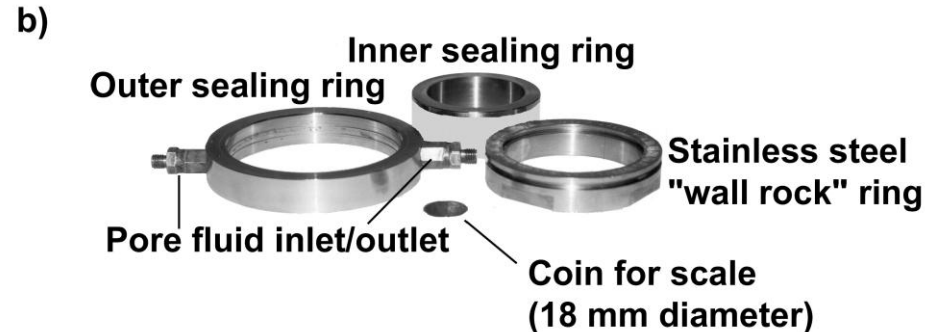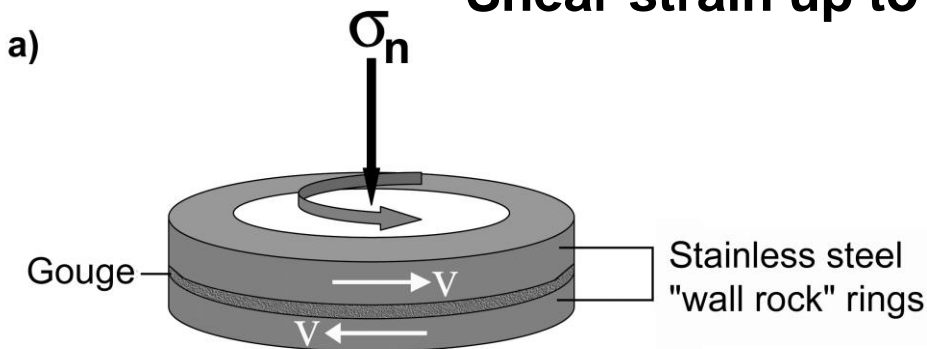
- Marone et al, JGR, 1990 showed that dilatancy significantly affects observed *a*
- Depends on sliding history (displacement), grain size, localization, etc.

*See also Sammis and Steacy, Pageoph, 1994 and other work by Sammis and co-workers*

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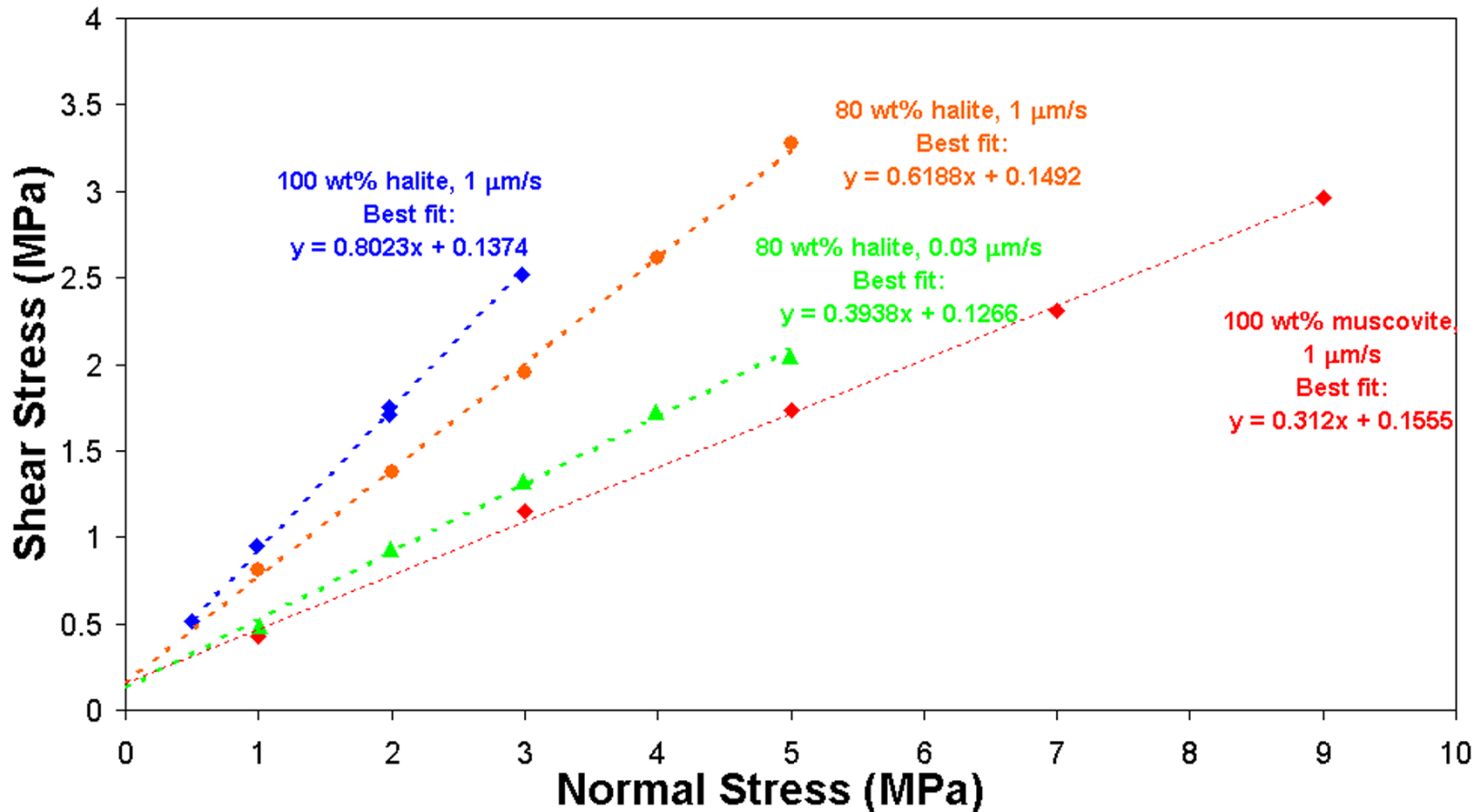
# Interpretation of Rate-and State

- **Despite > 30 years of work, no microphysical, mechanistic model for friction of fault gouge and its velocity dependence**

- **Extrapolation to natural spatial and temporal scales difficult**

- **Natural fault zones often contain phyllosilicates which typically form some type of foliation**

- **Fluids are ubiquitous in the Earth's crust →**
  **fluid-rock interactions must be considered in friction**

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# Experiments on simulated fault gouges
## (*cf.* Bos and coworkers, 2000)

- **Granular Halite (grain size ~105 $\mu$m)**

- **Muscovite (grain size ~13 $\mu$m)**

- **Initial gouge thickness of ~ 2 mm.**

- **Saturated brine as pore fluid (drained)**

- **Room temperature**

- **Normal stress: 1 - 5 MPa**

- **Sliding velocity: 0.001 – 13 $\mu$m/s**

- **Slide-hold-slide tests**

- **Shear strain up to 150**

a)

$\sigma_n$

Gouge

V

V

Stainless steel
"wall rock" rings

b)

Inner sealing ring

Outer sealing ring

Stainless steel
"wall rock" ring
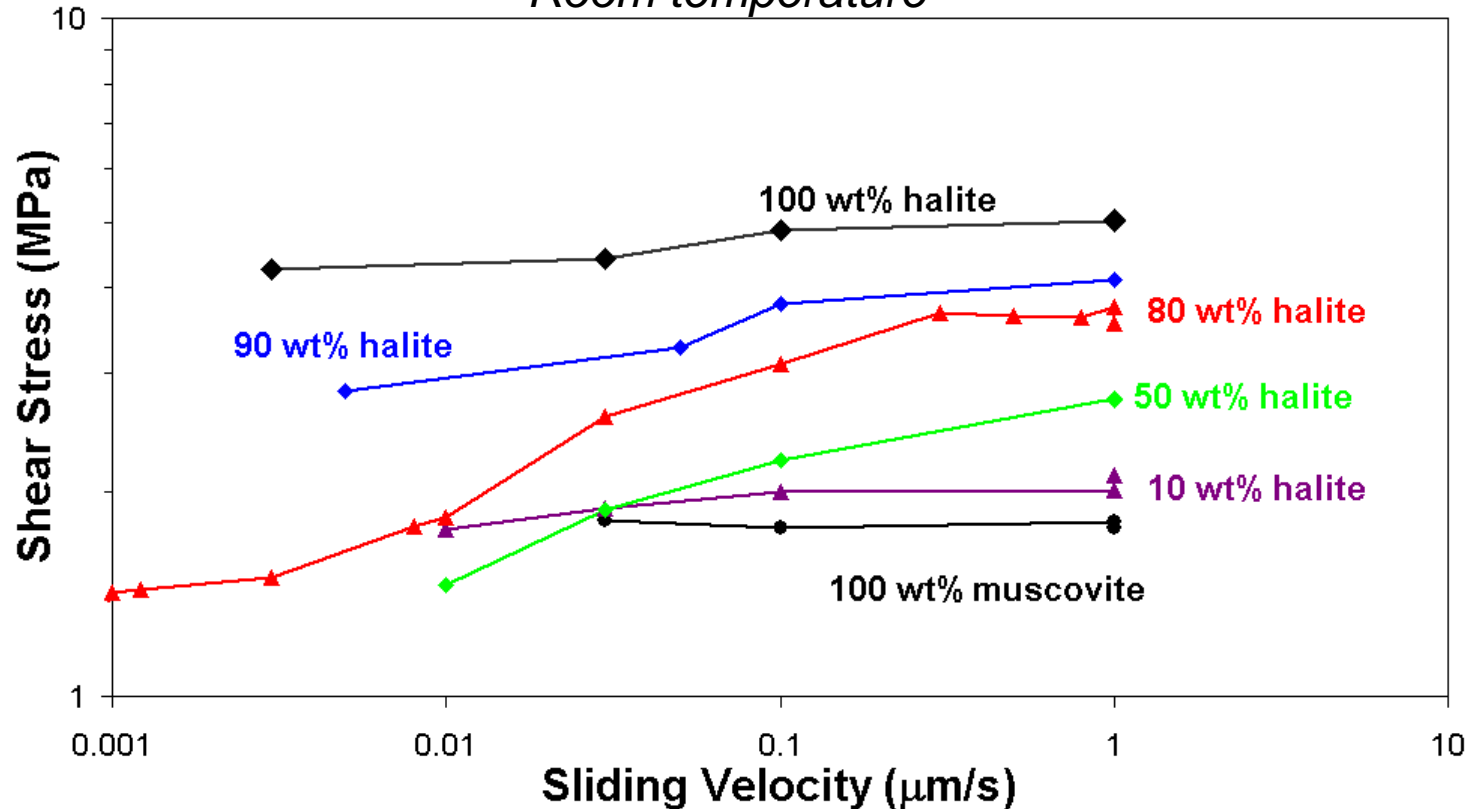
Pore fluid inlet/outlet

Coin for scale
(18 mm diameter)

# Normal stress-stepping



- Linear normal stress dependence – frictional
- Strong dependence of slope on sliding velocity for mixtures

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# Velocity summary
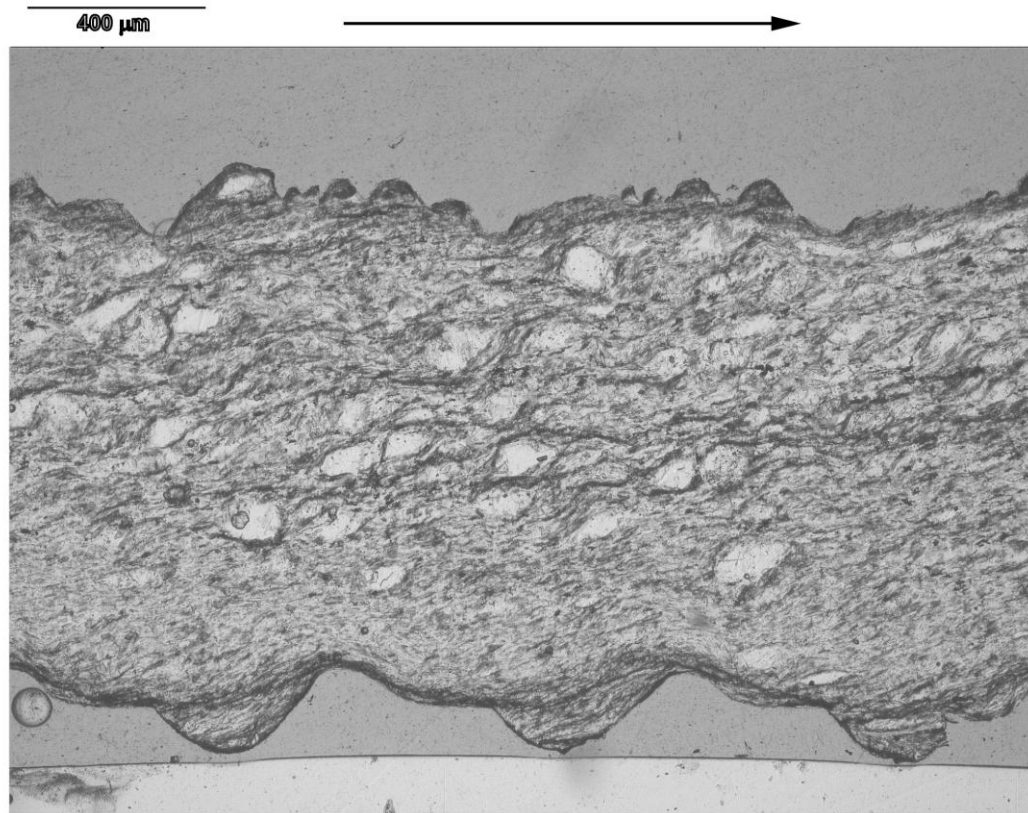
*Normal stress is 5 MPa*
*Room temperature*



- Friction increases from ~0.25 to ~0.85 with 3 orders of magnitude change in *v* for the 80/20 wt% halite/muscovite mixtures
- Average *(a-b)* of almost 0.1
- An order of magnitude larger than "typical" experiments (without fluid-rock interactions)

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# Microstructures

*80 wt% Halite, 20 wt% muscovite 0.03 μm/s, 30 mm displacement Normal stress is 5 MPa*



*Niemeijer & Spiers, Geol. Soc, 2005*

- Wavy foliation
- Evidence for operation of solution-transfer
- NOTE: no dislocation creep active !!

# Detail of microstructure
Taken with crossed polarizers

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# Comparison with natural microstructure

Microstructure from a mica-rich band from a natural shear zone of the Barthelémy massif, French Pyrenees.
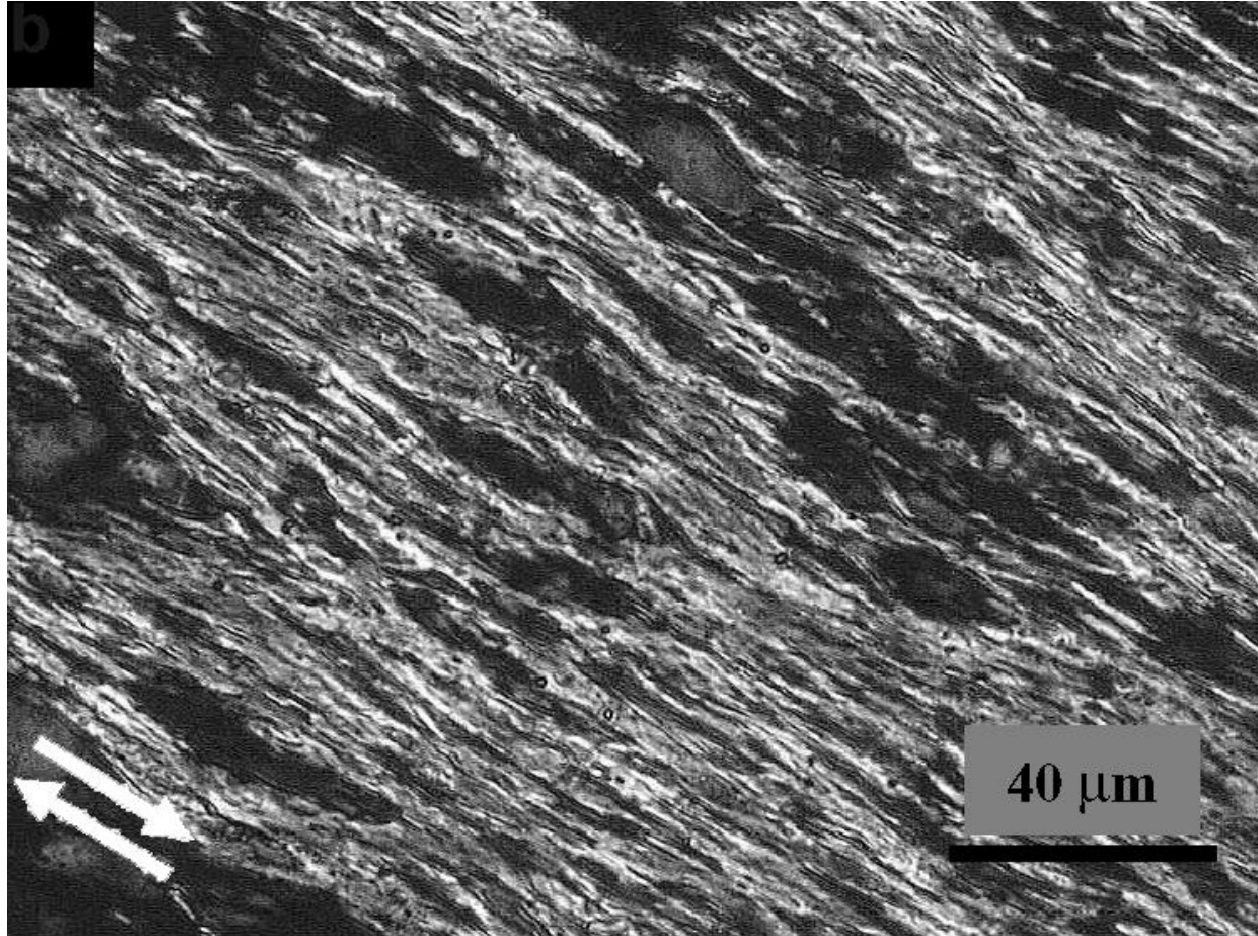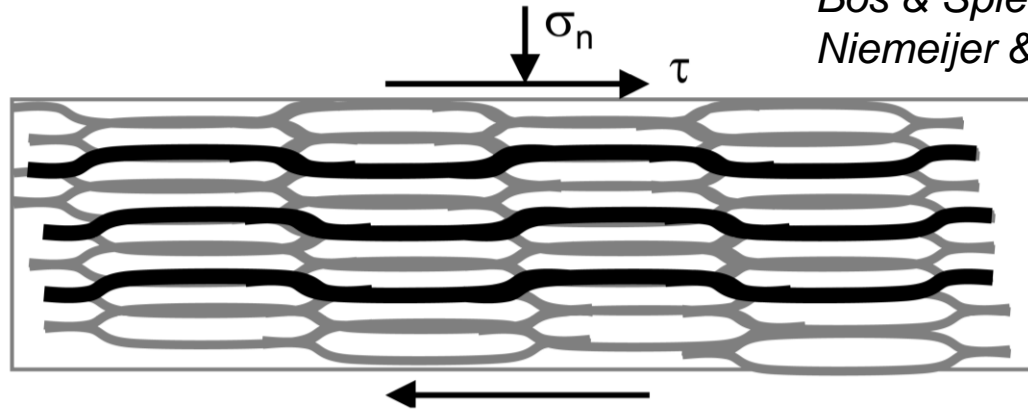


Fine-grained mixture of mica grains (light) and quartz elongated grains (dark).
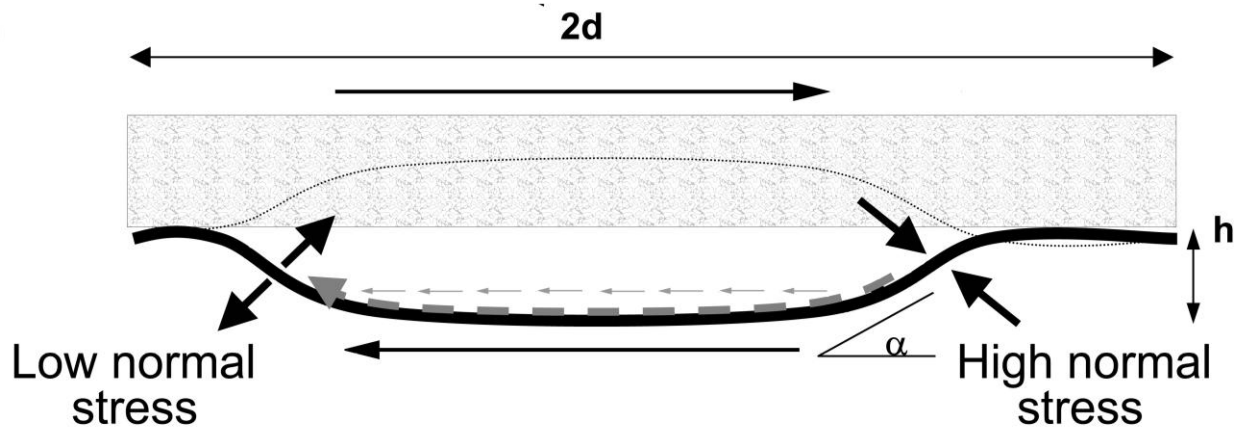
# Deformation mechanism for low velocity regime

Foliation development followed by frictional sliding on the foliation accommodated by dissolution-diffusion-precipitation of intervening halite grains.
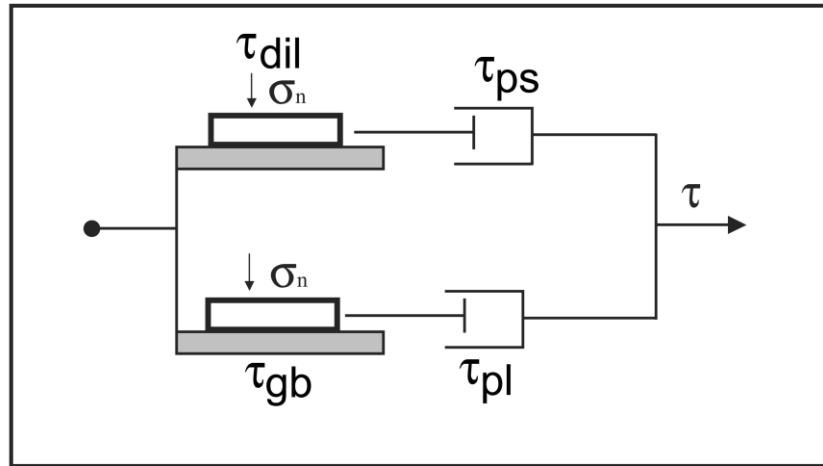
*Bos & Spiers, JGR, 2002*
*Niemeijer & Spiers, Geol. Soc, 2005*

a)

b)

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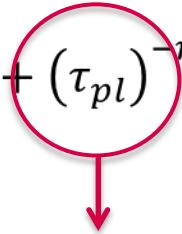
# Microphysical model



$$\tau = \left\{ (\tau_{gb})^{-m} + (\tau_{pl})^{-m} \right\}^{-\frac{1}{m}} + \left\{ (\tau_{dil})^{-n} + (\tau_{ps})^{-n} \right\}^{-\frac{1}{n}}$$

Shear stress due to sliding over the horizontal part of the wavy foliation

$$\tau_{gb} = P \cdot \mu_{gb} \cdot \sigma_n{}^{eff}$$

P=factor expressing the proportion of the foliation undergoing  active sliding (3/4)

# Microphysical model

$$\tau = \left\{ (\tau_{gb})^{-m} + (\tau_{pl})^{-m} \right\}^{-\frac{1}{m}} + \left\{ (\tau_{dil})^{-n} + (\tau_{ps})^{-n} \right\}^{-\frac{1}{n}}$$

Shear stress contribution due to plastic flow of the phyllosilicate foliae

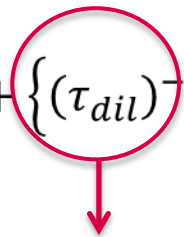From compressive experiments on e.g. biotite (Kronenberg, et al 1990)

$$\dot{\varepsilon} = C \cdot \exp(\alpha \cdot \sigma_d) \exp\left( \frac{-Q}{RT} \right)$$

$\dot{\varepsilon}$ axial strain rate, $\sigma_d$ differential stress, $C$, $\alpha$ empirical constants, $Q$ apparent activation energy

Rearranging and converting for simple shear due to dislocation slip on (001) gives:

$$\tau_{pl} = \frac{1}{\alpha} Log \left\{ \frac{3^{\frac{1}{2}} \dot{\gamma}_{pl}}{C \cdot \exp(-Q/RT)} \right\}$$
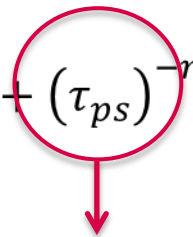
# Microphysical model

$$\tau = \left\{ (\tau_{gb})^{-m} + (\tau_{pl})^{-m} \right\}^{-\frac{1}{m}} + \left\{ (\tau_{dil})^{-n} + (\tau_{ps})^{-n} \right\}^{-\frac{1}{n}}$$

Shear stress contribution due to work against normal stress to cause dilatation

$$\tau_{dil} = \sigma_n{}^{eff} \cdot tan\alpha$$

With $\alpha$ being a geometrical parameter describing the angle of dilatation

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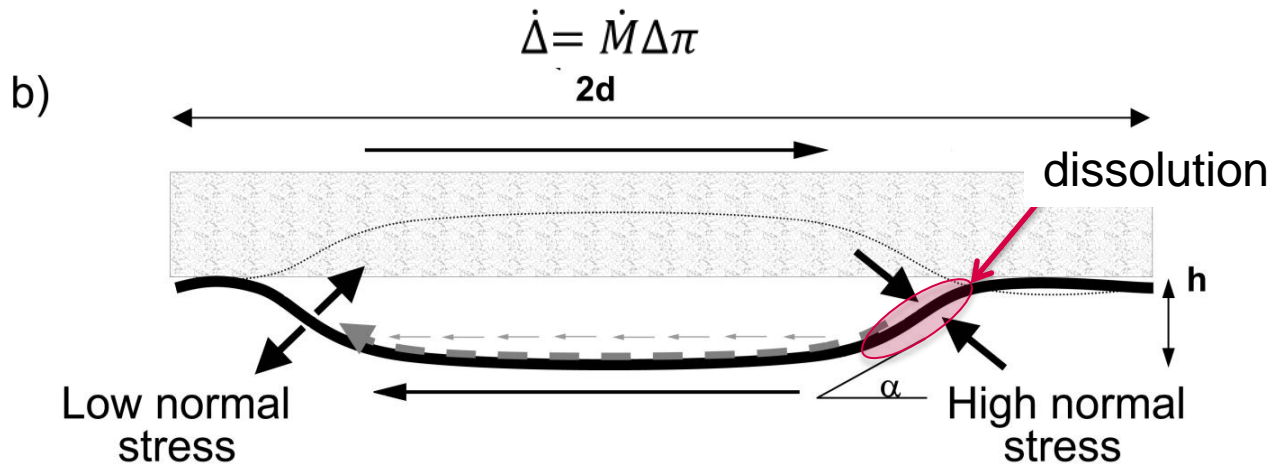
# Microphysical model

$$\tau = \left\{ (\tau_{gb})^{-m} + (\tau_{pl})^{-m} \right\}^{-\frac{1}{m}} + \left\{ (\tau_{dil})^{-n} + (\tau_{ps})^{-n} \right\}^{-\frac{1}{n}}$$

Shear stress contribution due to pressure solution

- No increase in internal energy/entropy → rate of external work equals rate of dissipation (1st law of thermodynamics; isovolumetric deformation)

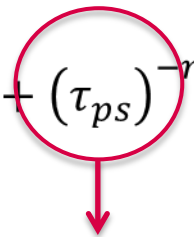$$\tau \dot{\gamma} = \dot{\Delta}$$

- Rate of dissipation equals mass rate (per unit volume) times the driving force

$$\dot{\Delta} = \dot{M} \Delta \pi$$


b)

Rate of pressure solution controlled by the slowest of three serial processes, dissolution, diffusion or precipitation
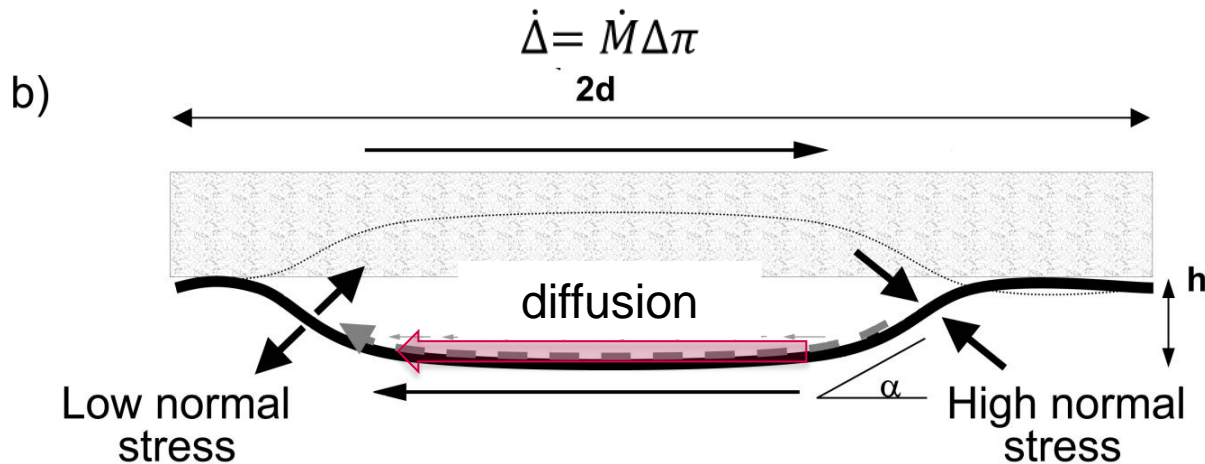
# Microphysical model

$$\tau = \left\{ (\tau_{gb})^{-m} + (\tau_{pl})^{-m} \right\}^{-\frac{1}{m}} + \left\{ (\tau_{dil})^{-n} + (\tau_{ps})^{-n} \right\}^{-\frac{1}{n}}$$

Shear stress contribution due to pressure solution

- No increase in internal energy/entropy → rate of external work equals rate of dissipation (1st law of thermodynamics; isovolumetric deformation)

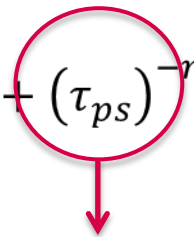$$\tau\dot{\gamma} = \dot{\Delta}$$

- Rate of dissipation equals mass rate (per unit volume) times the driving force

$$\dot{\Delta} = \dot{M}\Delta\pi$$

**2d**

diffusion

Low normal stress          $\alpha$          High normal stress

h

Rate of pressure solution controlled by the slowest of three serial processes, dissolution, diffusion or precipitation

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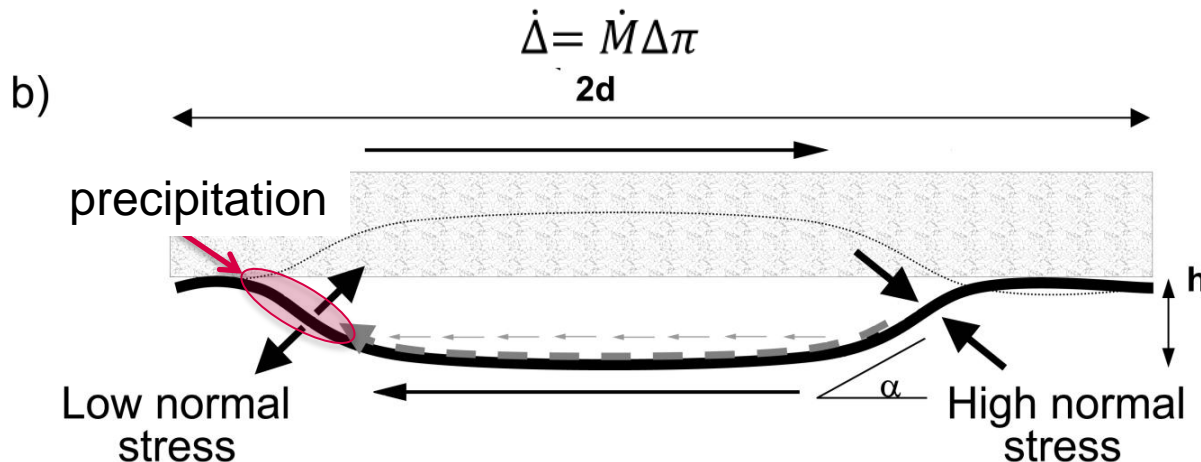
# Microphysical model

$$\tau = \left\{ (\tau_{gb})^{-m} + (\tau_{pl})^{-m} \right\}^{-\frac{1}{m}} + \left\{ (\tau_{dil})^{-n} + (\tau_{ps})^{-n} \right\}^{-\frac{1}{n}}$$

Shear stress contribution due to pressure solution

- No increase in internal energy/entropy → rate of external work equals rate of dissipation (1st law of thermodynamics; isovolumetric deformation)

$$\tau \dot{\gamma} = \dot{\Delta}$$

- Rate of dissipation equals mass rate (per unit volume) times the driving force

$$\dot{\Delta} = \dot{M} \Delta \pi$$

b)

precipitation

Low normal stress      2d      High normal stress

h

α

Rate of pressure solution controlled by the slowest of three serial processes, dissolution, diffusion or precipitation

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# Microphysical model

For halite (salt) at these conditions diffusion is the slowest process
- Start with Fick's law for diffusion along the foliation

$$J = P_f D\, grad C$$

- For each grain, diffusion works through a window w$\delta$, so flux per grain is
  (*w* grain length out of plane, $\delta$ is fluid film thickness)

$$J^* = p_f w \delta D\, grad C$$

- Concentration gradient can be expressed as a function of the driving force:

$$grad C = \frac{C_s M_s}{RT}\, grad\pi$$

- Assume the gradient occurs over an average diffusion distance *d* gives the mass flux

$$\dot{m} = \frac{p_f w \delta D C_s M_s}{RT d}\Delta\pi$$

- Multiply with the number of foliation leading edges actively undergoing pressure solution, N=A/*hwd* per unit volume gives the macroscopic mass transfer rate:

$$\dot{M} = \frac{A p_f w \delta D C_s M_s}{RT h d^2}\Delta\pi$$

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# Microphysical model

- Combine equations to get energy dissipation

$$\dot{\Delta} = \dot{M}\Delta\pi \quad and \quad \dot{M} = \frac{Ap_f w\delta DC_s M_s}{RThd^2}\Delta\pi \quad \Longrightarrow \quad \dot{\Delta} = \frac{RThd^2}{Ap_f w\delta DC_s M_s}\dot{M}^2$$

- Derive mass transfer rate geometrically:

$$\dot{\gamma} = \frac{Av_{diss}}{h}$$

- Assuming the dissolving contact has area hw/sinα, gives the mass transfer rate per grain

$$\dot{m} = hw\rho_s v_{diss}$$

- Using these two equations and the number of actively sliding foliation planes, N=A/*hwd* per unit volume gives the macroscopic mass transfer rate:

$$\dot{M} = \frac{hp_s}{d}\dot{\gamma}$$

- And the dissipation rate:

$$\dot{\Delta} = \frac{RTh^3\rho_s{}^2}{Ap_f w\delta DC_s M_s}\dot{\gamma}^2$$

# Microphysical model

- Simplify using $\dfrac{\rho_s}{M_s} = \dfrac{1}{\Omega_s}$ and $d = B\,h$, where $B$ is the aspect ratio of the grain
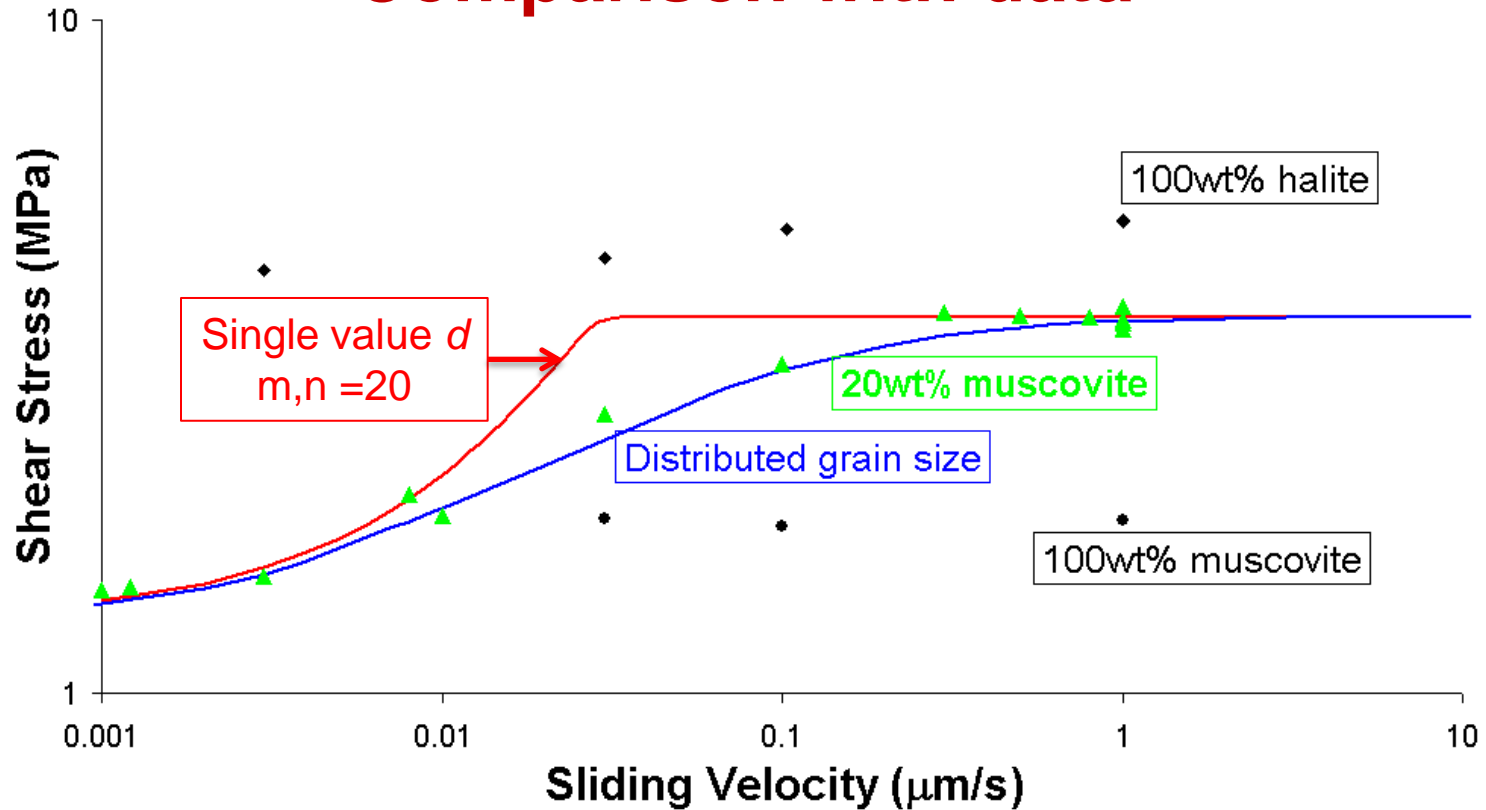
$$\dot{\Delta} = \frac{\alpha \rho_s R T h^3}{\rho_f D \delta C_s \Omega_s} \dot{\gamma}^2$$

- As we have $\tau\dot{\gamma} = \dot{\Delta}$ we get for the shear stress contribution due to diffusion-controlled pressure solution :

$$\tau_{ps} = \frac{R T d^3 \rho_s}{B^3 p_f w \delta D C_s \Omega_s} \dot{\gamma}$$

A similar derivation can be done for dissolution and precipitation-controlled pressure solution, see Bos and Spiers, JGR, 2002

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# Microphysical model Comparison with data



Model reproduces data well, but only if a distributed grain size is used
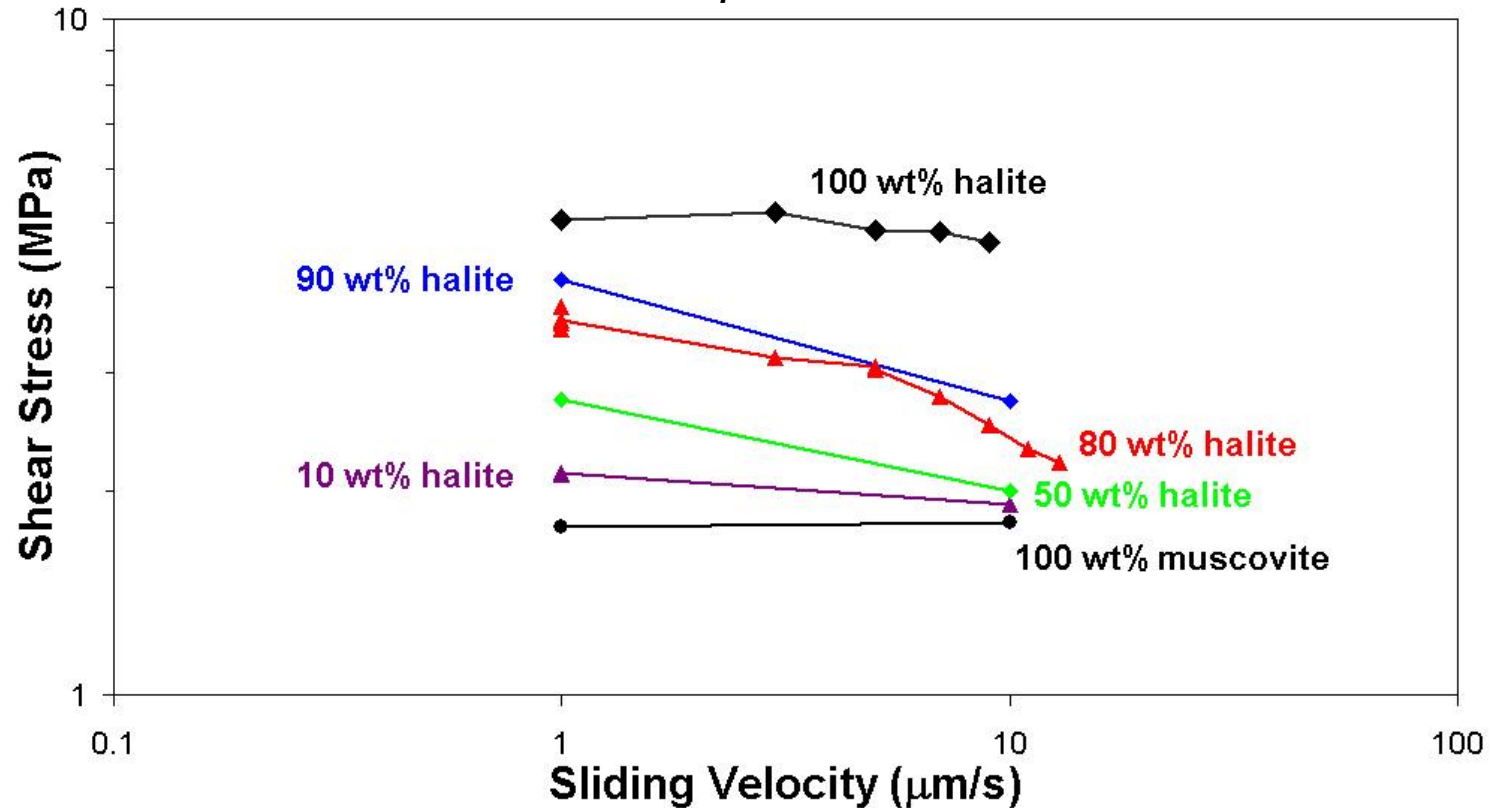
# Normal stress-stepping – high(er) velocity
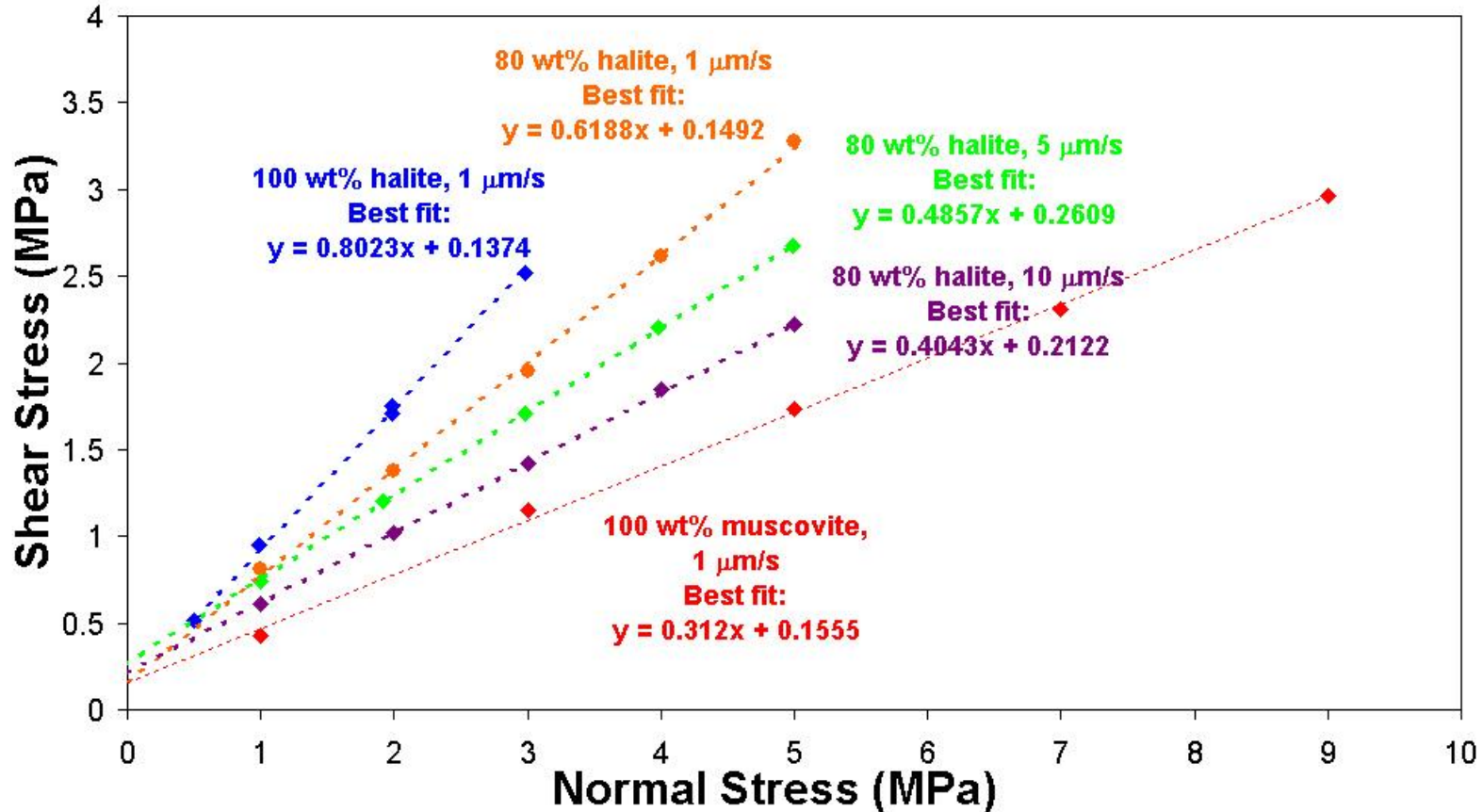


- Linear normal stress dependence – frictional
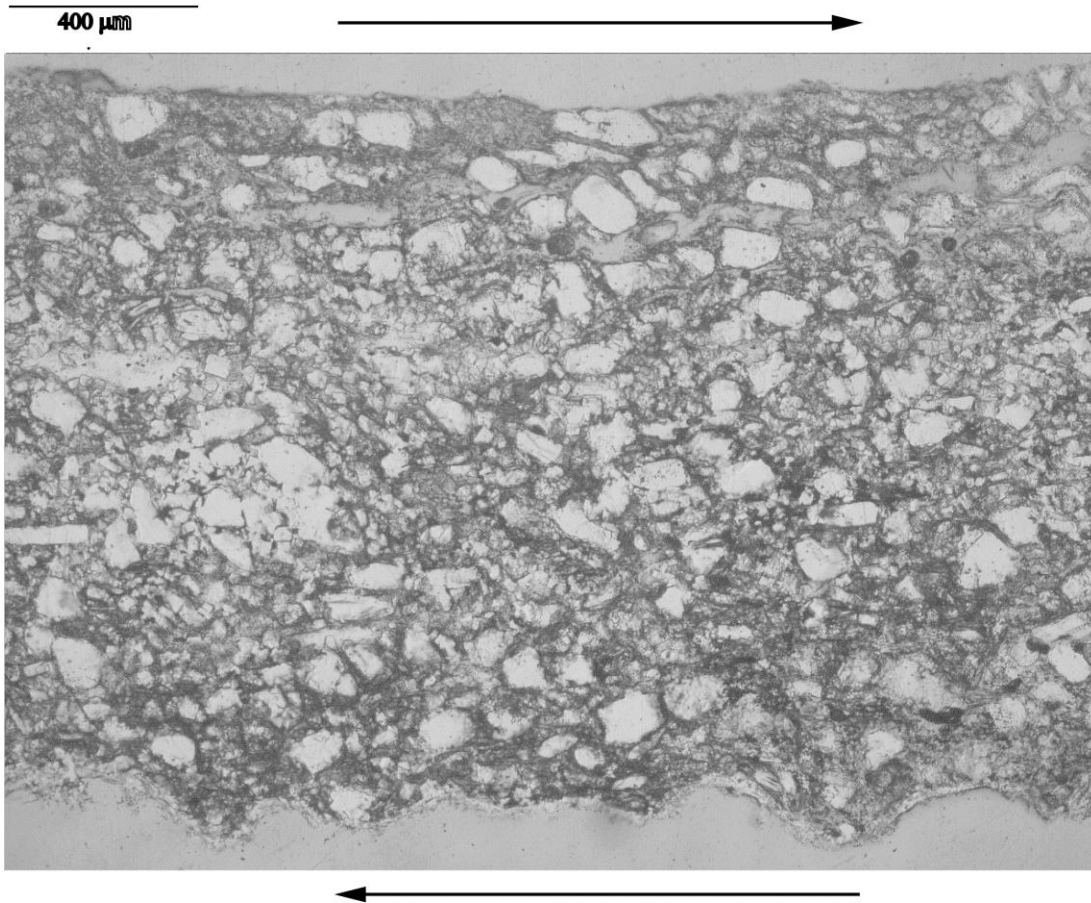- Strong dependence of slope on sliding velocity for mixtures

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# Velocity summary

*Normal stress is 5 MPa*
*Room temperature*



- Friction decreases from ~0.85 to ~0.4 within 1.5 orders of magnitude change in *v* for a 80/20 salt/muscovite mixture
- Average *(a-b)* of  ~ -0.1
- An order of magnitude larger than "typical" experiments (without fluid-rock interactions)

# Microstructures

80 wt% halite, 20 wt% muscovite 13 $\mu$m/s, 30 mm displacement
Normal stress is 5 MPa

400 µm



- No foliation
- Chaotic, structureless
- Dilatation vs. compaction
- Cataclastic flow

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# Inferred deformation mechanism at high sliding velocity

Granular flow at a critical porosity, controlled by a competition between slip-dependent dilatation and time-dependent compaction
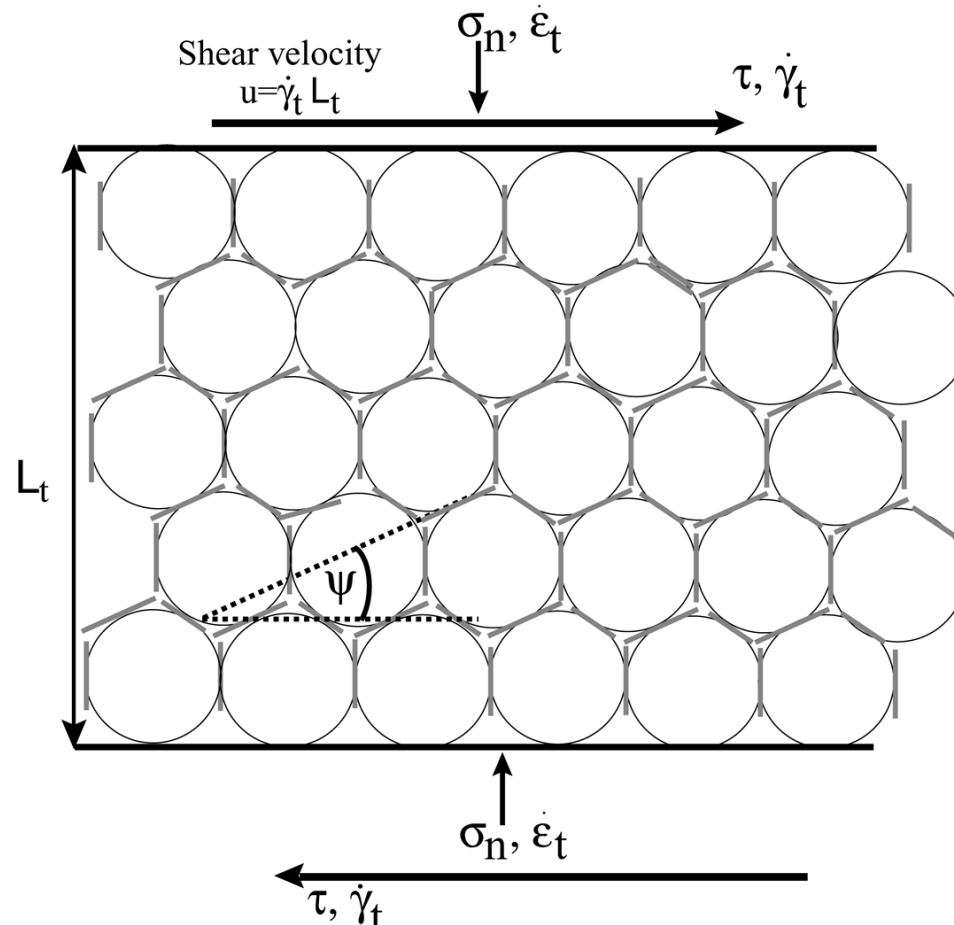


*Niemeijer & Spiers, JGR, 2007*

# Microphysical model

Time-dependent compaction occurs through IPS
*See e.g. Niemeijer et al., EPSL, 2002, Pluymakers & Spiers, JGR 2014*

dissolution-controlled:

$$\dot{\varepsilon}_s = A_s \frac{I_s}{d} \frac{\sigma_e \Omega_s}{RT} f_s(\phi)$$

diffusion-controlled:

$$\dot{\varepsilon}_d = A_d \frac{(DCS)}{d^3} \frac{\sigma_e \Omega_s}{RT} f_d(\phi)$$

precipitation-controlled:

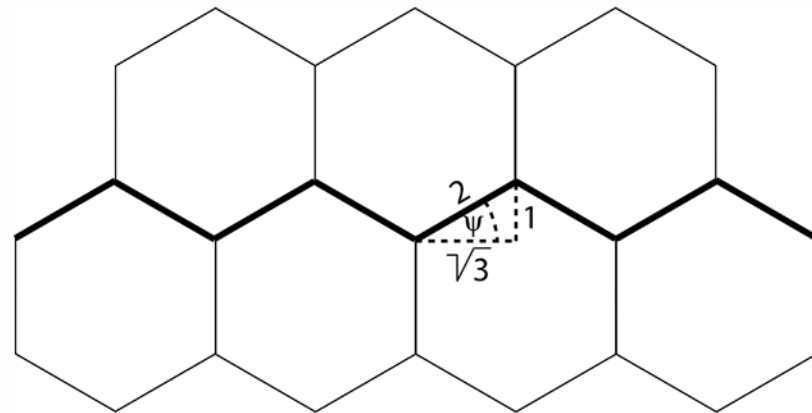$$\dot{\varepsilon}_p = A_p \frac{I_p}{d} \frac{\sigma_e \Omega_s}{RT} f_p(\phi)$$

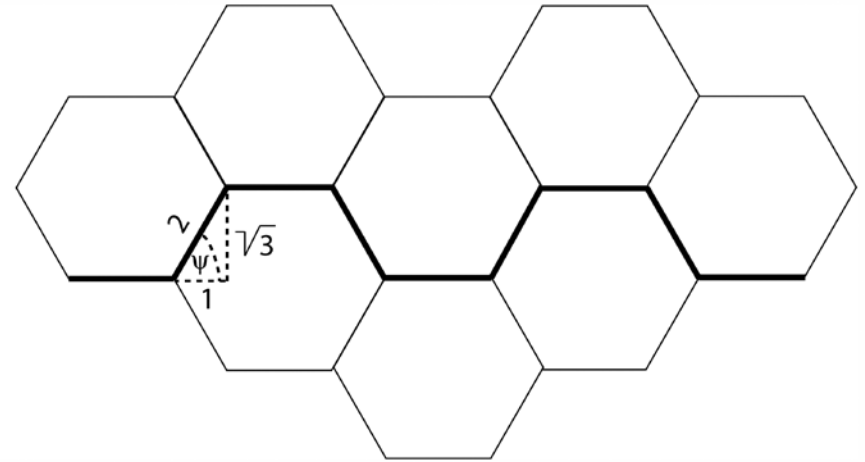# Microphysical model

Dilatancy angle through granular flow

$$tan\Psi = H(q - 2\phi)^n$$

q takes values of 0.8-1.0

Two possible end members for zero porosity



$$H = \frac{1}{\sqrt{3}}$$

$$H = \sqrt{3}$$

Gives volumetric strain rate due to dilational flow:

$$\dot{\varepsilon}_{gr} = -tan\Psi\dot{\gamma}_t$$

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# Microphysical model

At steady state, zero volume change:

$$\dot{\varepsilon}_{ps} = \dot{\varepsilon}_{gr}$$

$$A_s \frac{I_s}{d} \frac{\sigma_e \Omega_s}{RT} \frac{1}{(1-2\phi)} = -H(q-2\phi)^n \cdot \dot{\gamma}_t \qquad \text{dissolution-control}$$

$$\phi_{ss} \approx \frac{1}{2}\left\{ q - \left( A_s \cdot \frac{I_s}{d} \cdot \frac{\sigma_e \Omega_s}{R \cdot T} \cdot \frac{1}{\dot{\gamma}_t \cdot H} \right)^{\frac{1}{2}} \right\} \qquad \text{dissolution-control}$$
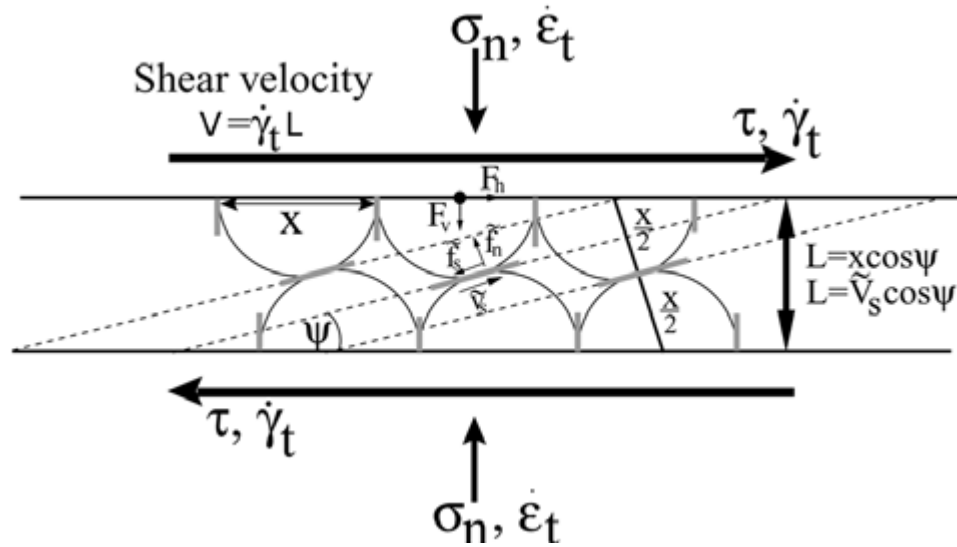
Or

$$tan\Psi_{ss} \approx H \left( A_s \cdot \frac{I_s}{d} \cdot \frac{\sigma_e \Omega_s}{R \cdot T} \cdot \frac{1}{\dot{\gamma}_t \cdot H} \right)^{\frac{1}{2}} \qquad \text{dissolution-control}$$

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# Microphysical model



Consider macroscopic forces

*horizontal*

$$F_h = \tau x^2$$

*vertical*

$$F_v = \sigma_n x^2$$

Consider contact forces

*normal*

$$\tilde{f}_n = F_v \cos\Psi + F_h \sin\Psi$$

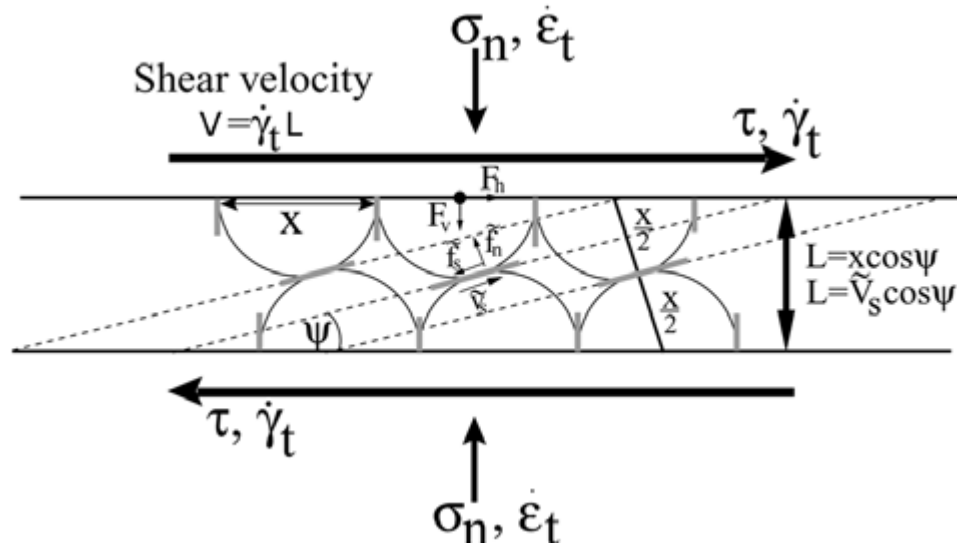*shear*

$$\tilde{f}_s = F_h \cos\Psi - F_v \sin\Psi$$

$$\tilde{f}_n = \sigma_n x^2 \cos\Psi + \tau x^2 \sin\Psi$$

$$\tilde{f}_s = \tau x^2 \cos\Psi - \sigma_n x^2 \sin\Psi$$

# Microphysical model



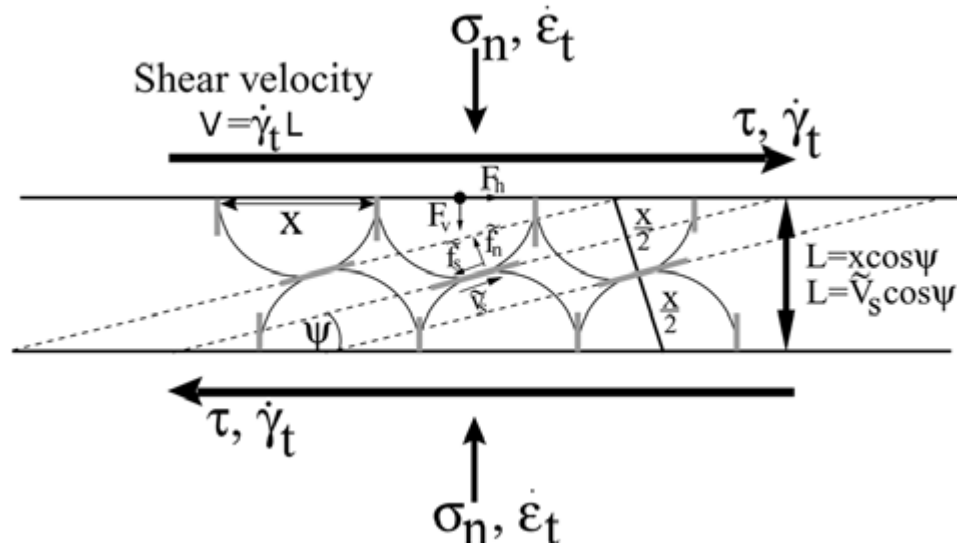Contact area in a compacting aggregate can be approximated by:

$$A_c = k\pi d^2 (q - 2\phi)$$

*where k = 1/6 (1/grain coordination nr.) and q ≈ 0.8-1.0*

$$\tilde{\sigma}_n = \frac{\tilde{f}_n}{A_c} = \frac{\tilde{f}_n}{k\pi d^2 (q - 2\phi)} \quad \text{with } x \approx d \implies \tilde{\sigma}_n = \frac{1}{k\pi (q - 2\phi)} (\sigma_n cos\Psi + \tau sin\Psi)$$

$$\tilde{\tau} = \frac{\tilde{f}_s}{A_c} = \frac{\tilde{f}_s}{k\pi d^2 (q - 2\phi)} \quad \text{with } x \approx d \implies \tilde{\tau} = \frac{1}{k\pi (q - 2\phi)} (\tau cos\Psi - \sigma_n sin\Psi)$$

# Microphysical model



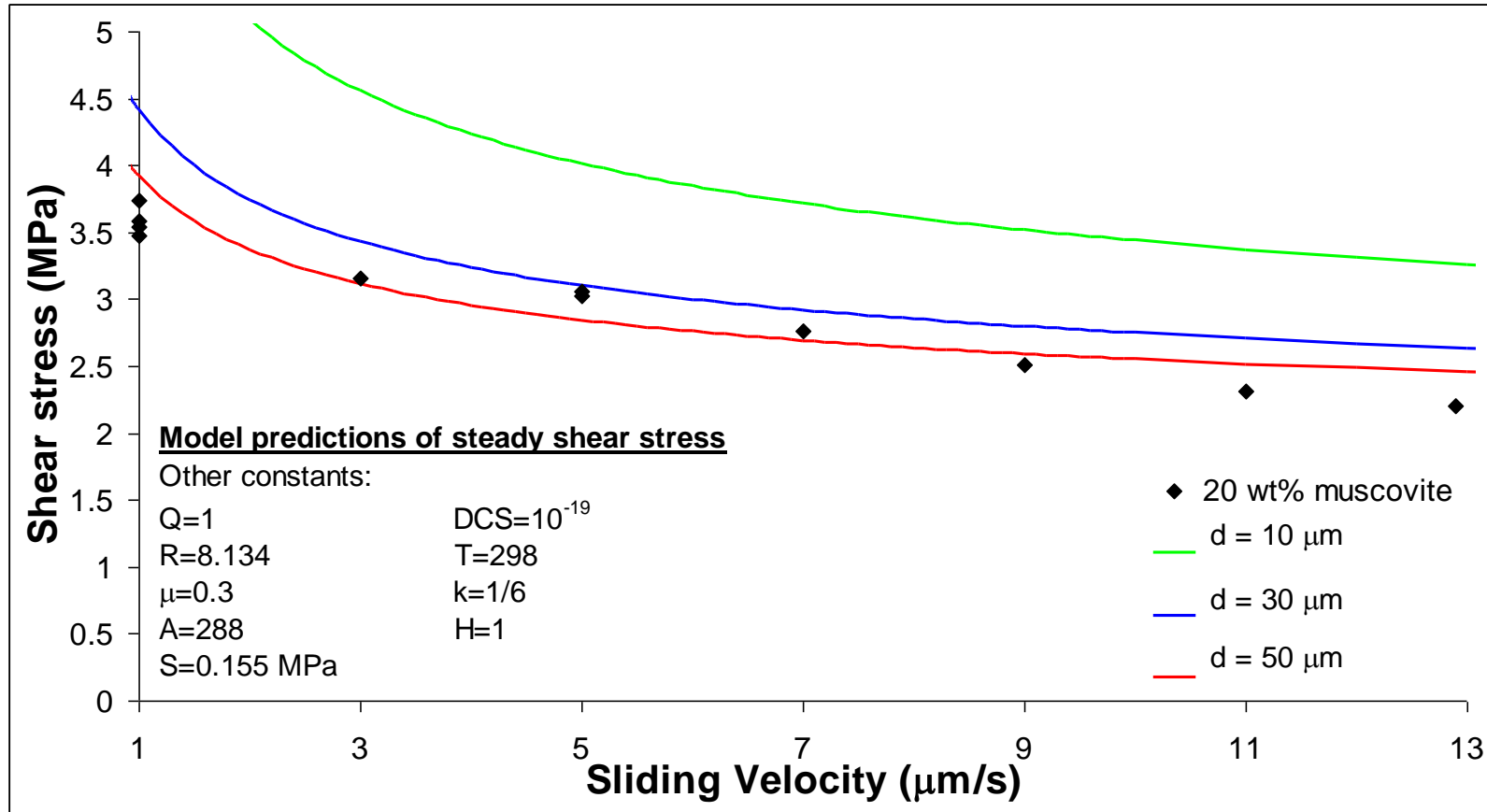Contacts obey Coulomb-type slip criterion:

$$\tilde{\tau} = \tilde{S}_0 + \tilde{\mu}\tilde{\sigma}_n$$

*where $\tilde{S}_0$ is the cohesion of the contact*

$$\frac{\tau cos\Psi - \sigma_n sin\Psi}{k\pi\,(q - 2\phi)} = \tilde{S}_0 + \tilde{\mu}\frac{\sigma_n cos\Psi + \tau sin\Psi}{k\pi\,(q - 2\phi)}$$

Recall $\quad tan\Psi = H(q - 2\phi) \implies \qquad \tau = \frac{k\pi}{H}\left(\frac{tan\Psi}{cos\Psi - \tilde{\mu}sin\Psi}\right)\tilde{S}_0 + \frac{(sin\Psi + \tilde{\mu}cos\Psi)}{(cos\Psi - \tilde{\mu}sin\Psi)}\sigma_n$

# Comparison with experiments



- Effect of grain size on model predictions quite large !
- Likely that grain size varies as a function of sliding velocity

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# Activation of same mechanisms in real materials:
## Recent results from quartz/muscovite experiments
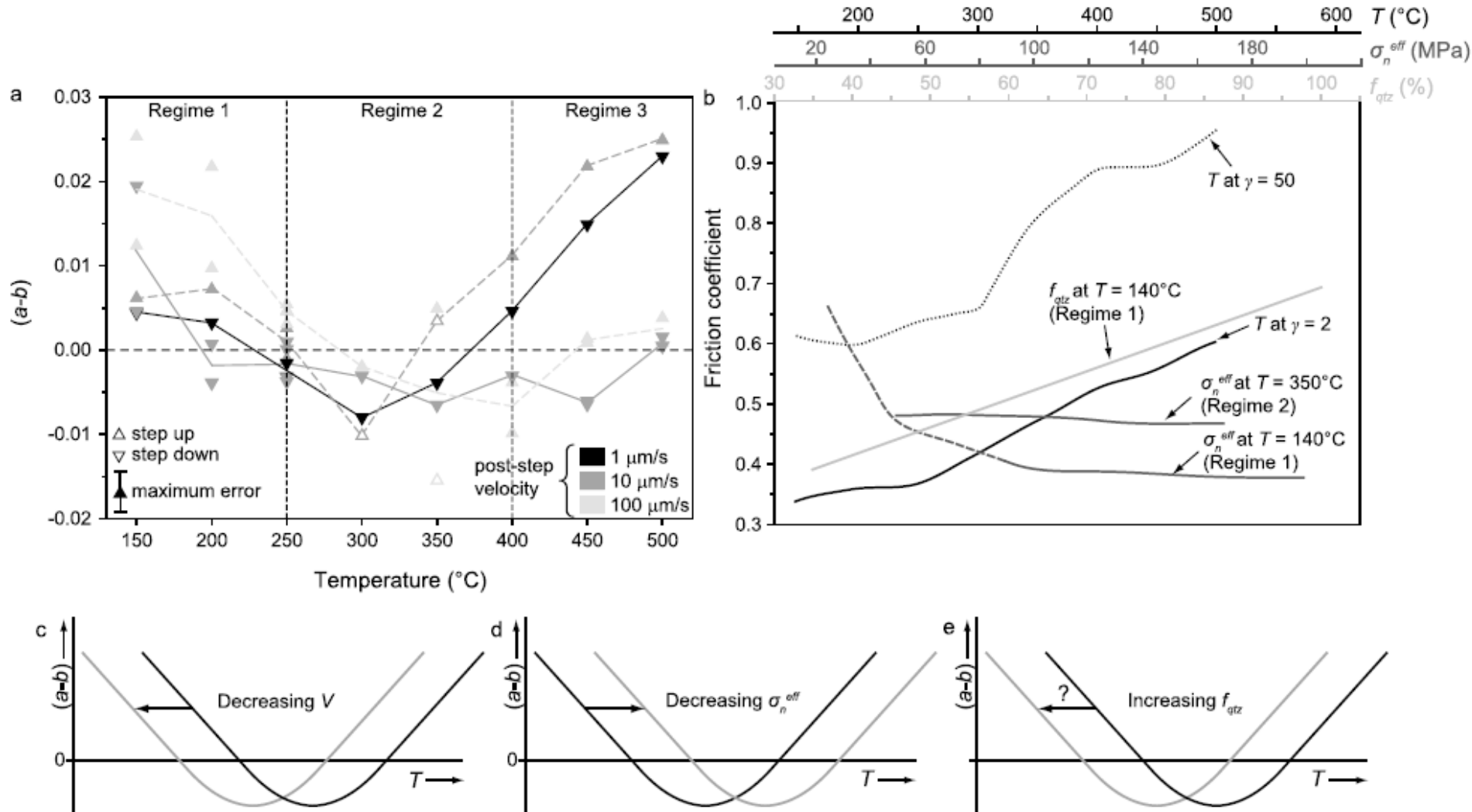## at 500 ˚C, $\sigma_n^{eff}$ 120 MPa, Pf 80 MPa, 30 mm displacement
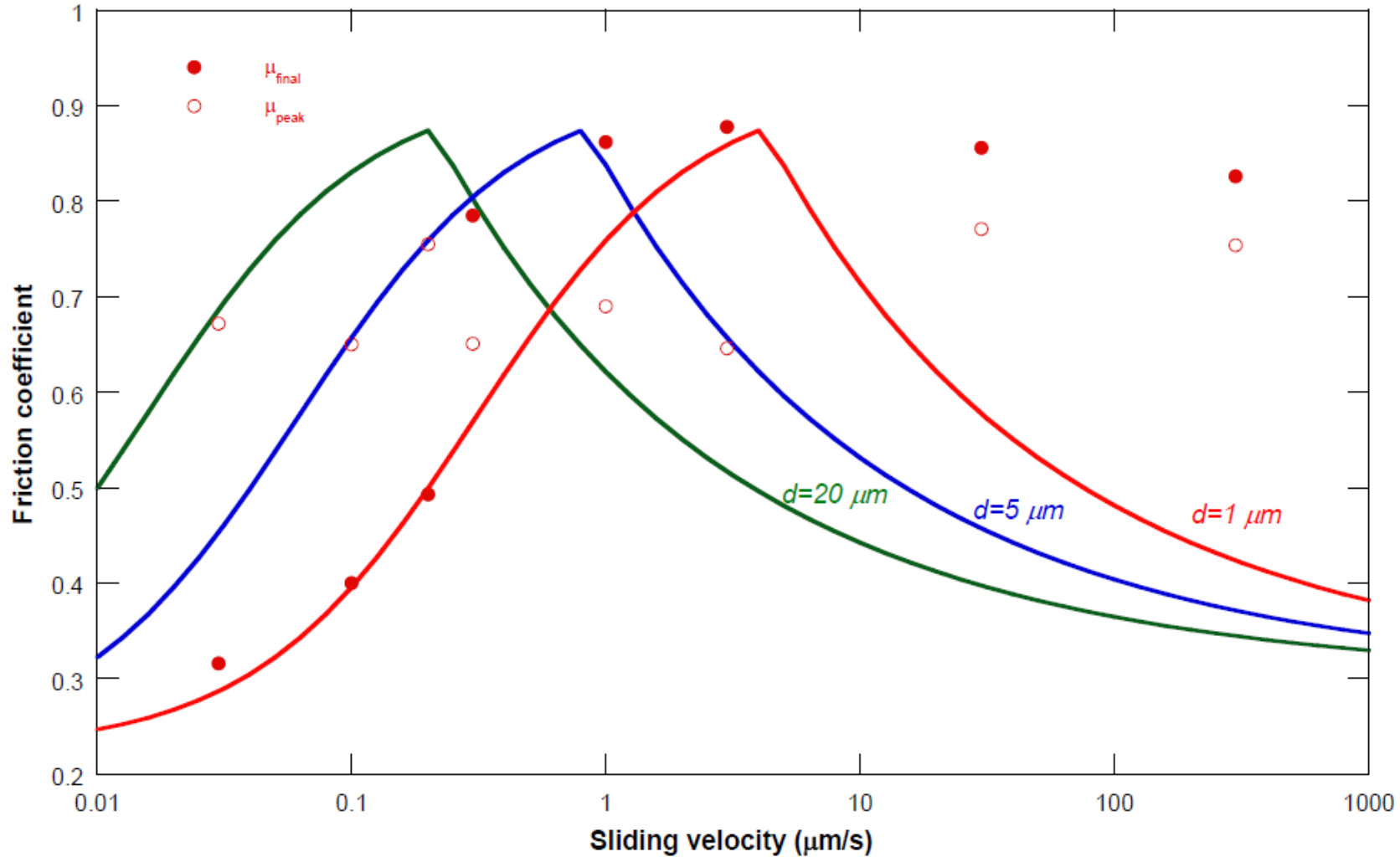
# Experiments on simulated megathrust fault gouges
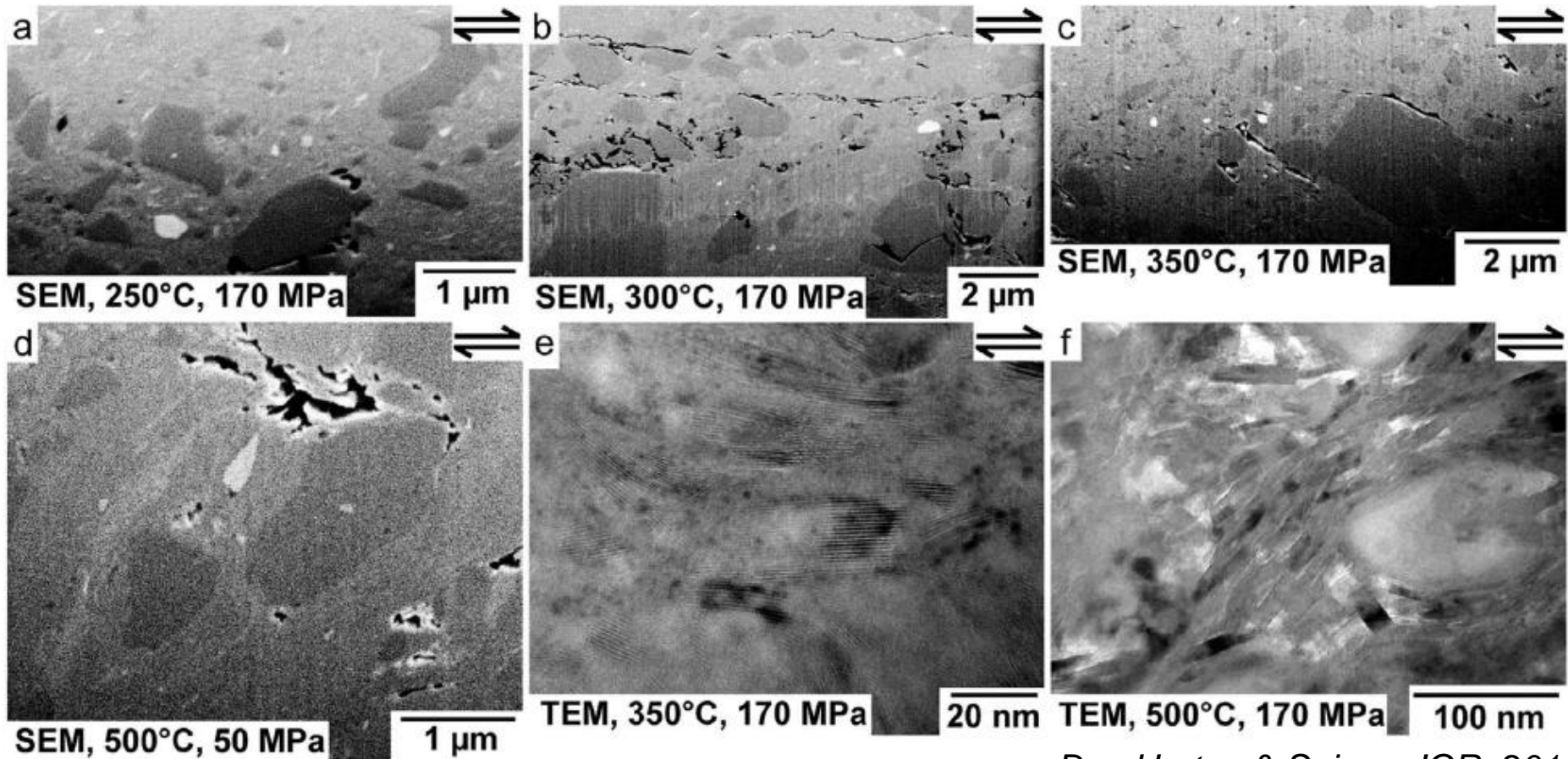## at in-situ subduction zone *PT* conditions
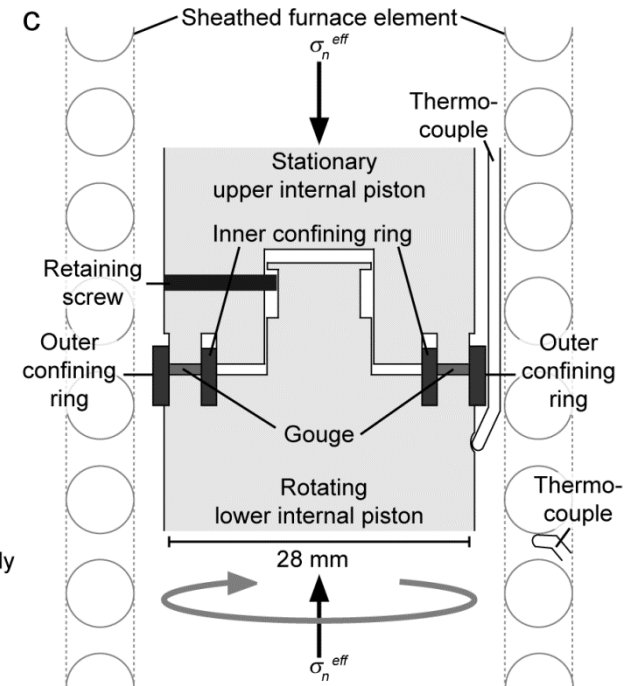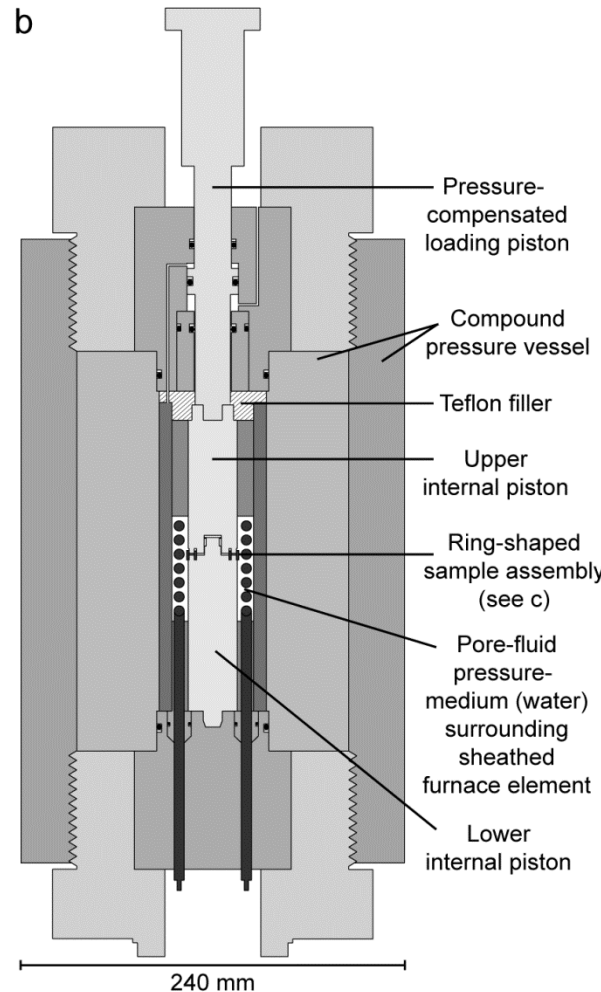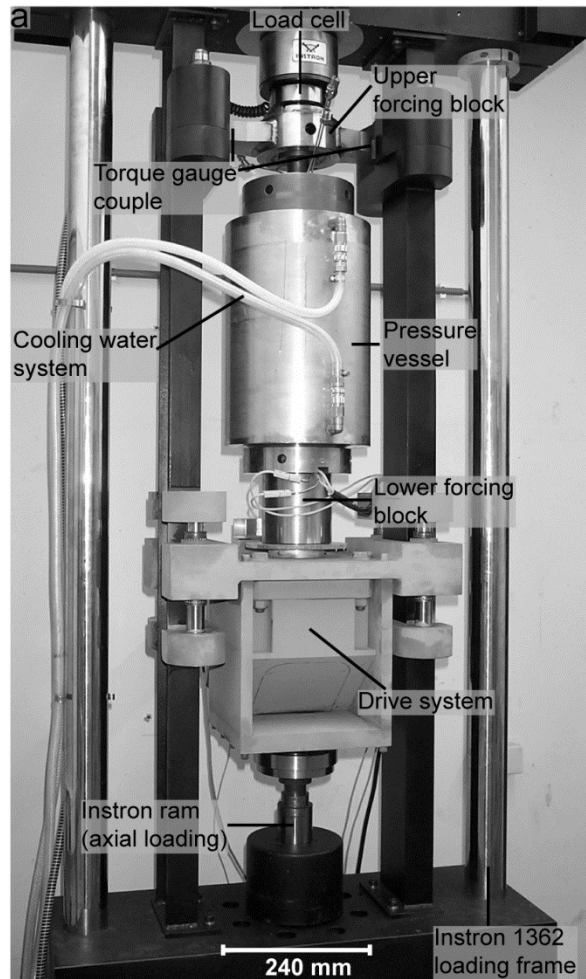


- Illite/qtz gouges (65/35 wt%)
- $T$ = 150-500°C
- $\sigma_n^{eff}$ = 170 MPa
- $P_f$ = 100 MPa $H_2O$
- $V$ = 1-100 $\mu$m/s
- $\gamma \leq$ ~170

# Main experimental trends



*Den Hartog & Spiers, JGR, 2014*

# Microstructural observations



a — SEM, 250°C, 170 MPa — 1 μm
b — SEM, 300°C, 170 MPa — 2 μm
c — SEM, 350°C, 170 MPa — 2 μm
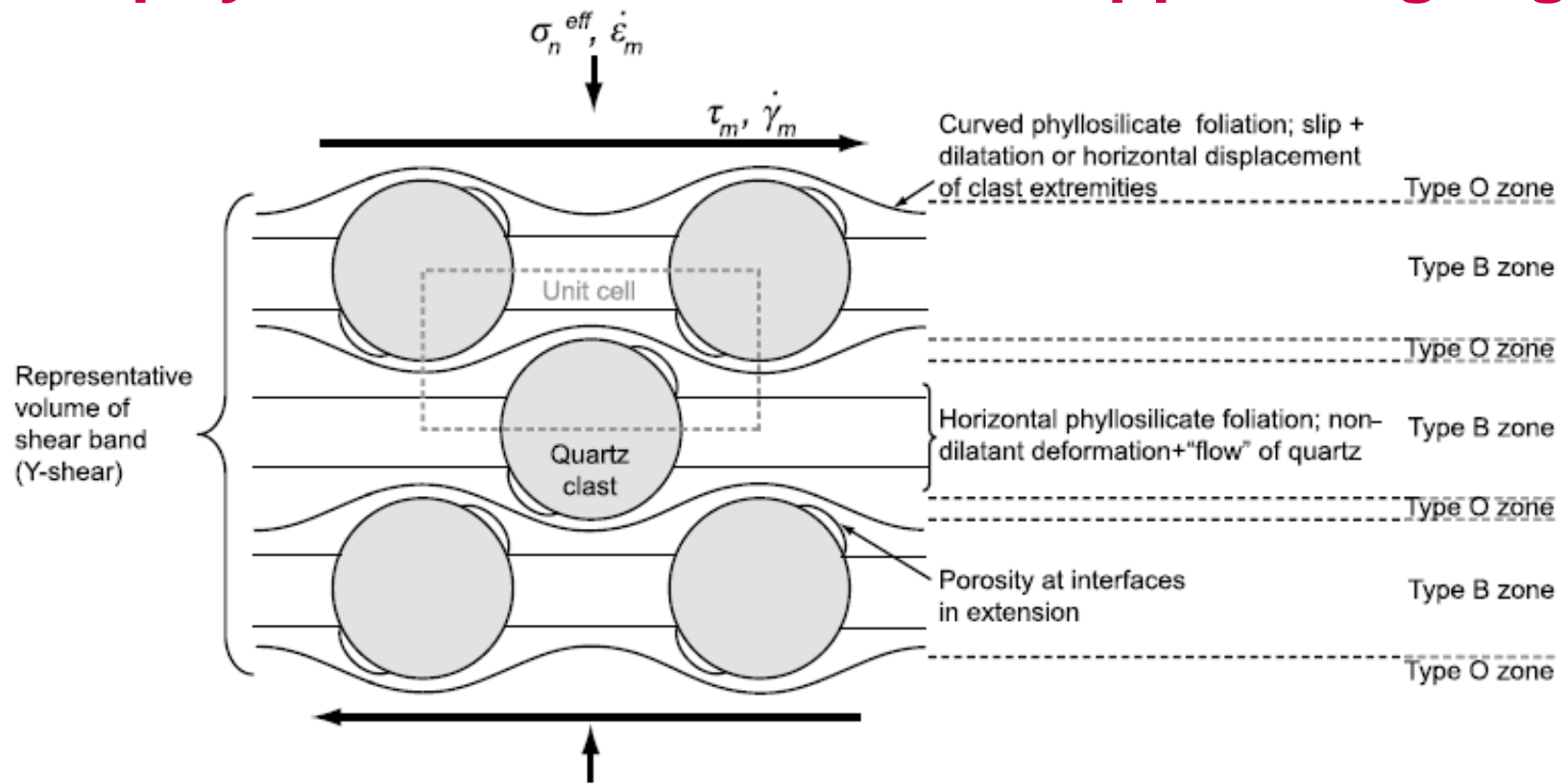d — SEM, 500°C, 50 MPa — 1 μm
e — TEM, 350°C, 170 MPa — 20 nm
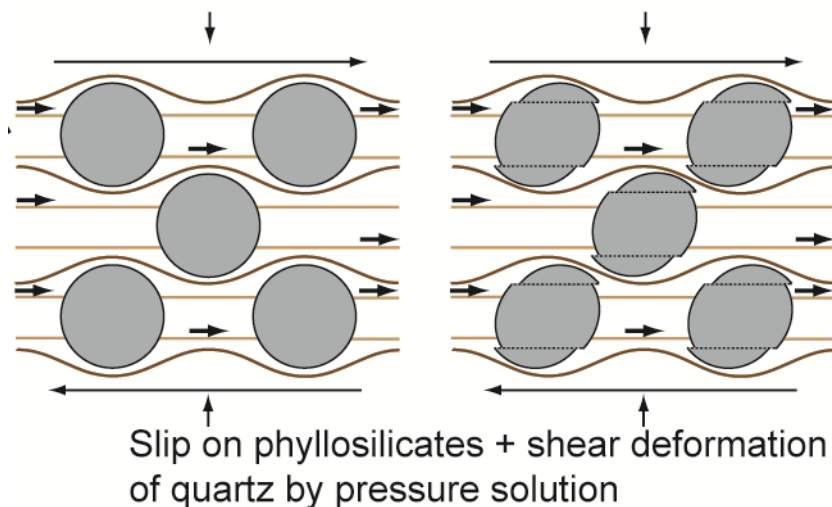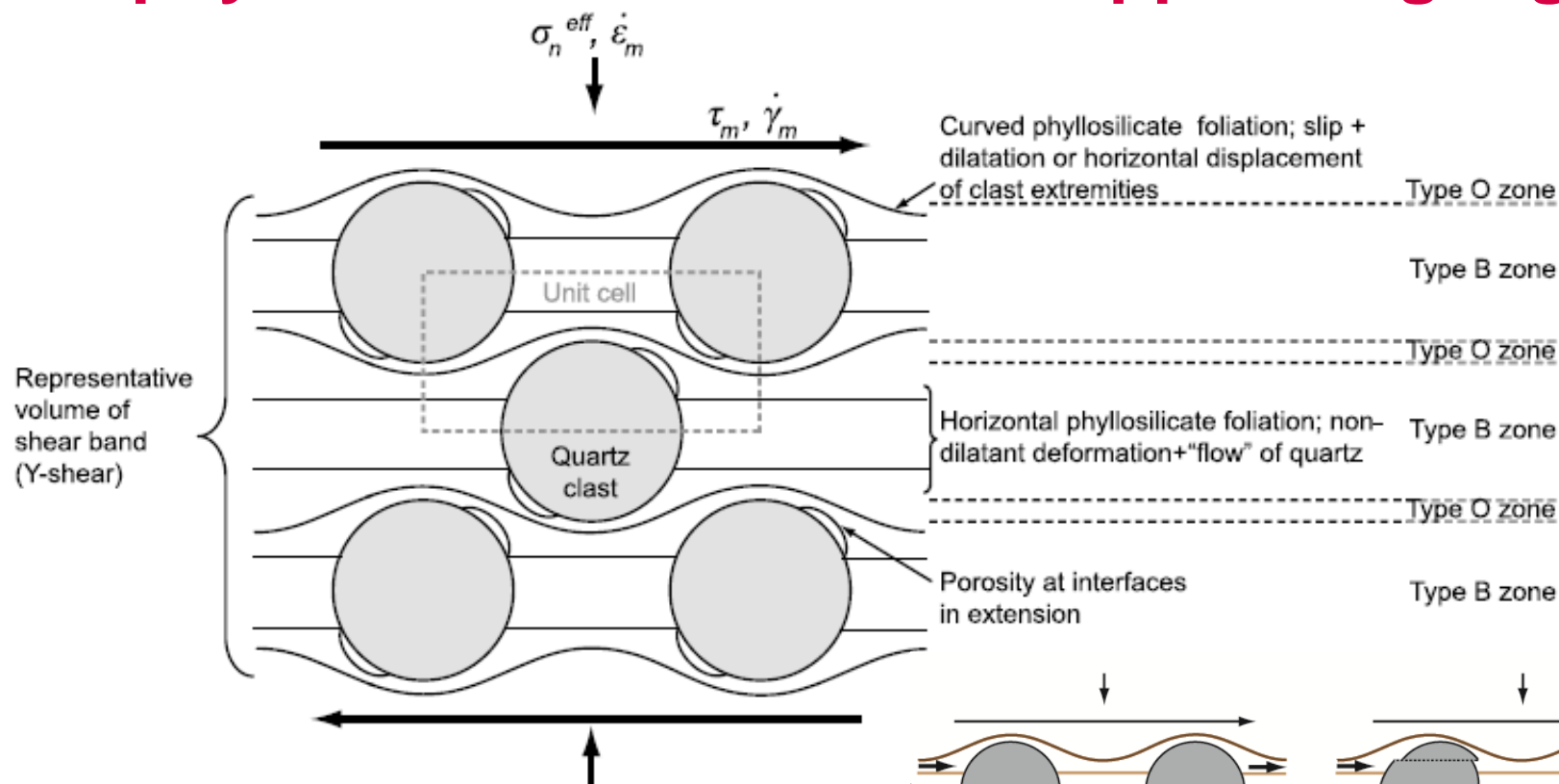f — TEM, 500°C, 170 MPa — 100 nm

*Den Hartog & Spiers, JGR, 2014*

- Phyllosilicate foliation wrapping around quartz clasts.
- Porosity at the clast-phyllosilicate interface under extension.
- Oval quartz shapes → pressure solution?
- Matrix supported → **cannot be modelled with preceding microphysical models!!**

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# Microphysical model for matrix-supported gouges



*Den Hartog & Spiers, JGR, 2014*

# Microphysical model for matrix-supported gouges



$\sigma_n^{eff}, \dot{\varepsilon}_m$

$\tau_m, \dot{\gamma}_m$

Curved phyllosilicate foliation; slip + dilatation or horizontal displacement of clast extremities — Type O zone

Type B zone

Type O zone

Horizontal phyllosilicate foliation; non–dilatant deformation+"flow" of quartz — Type B zone

Type O zone

Porosity at interfaces in extension — Type B zone

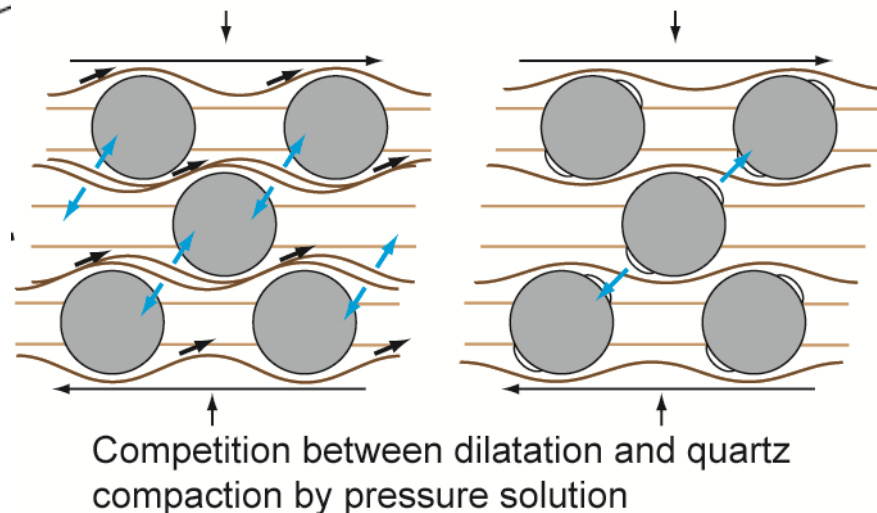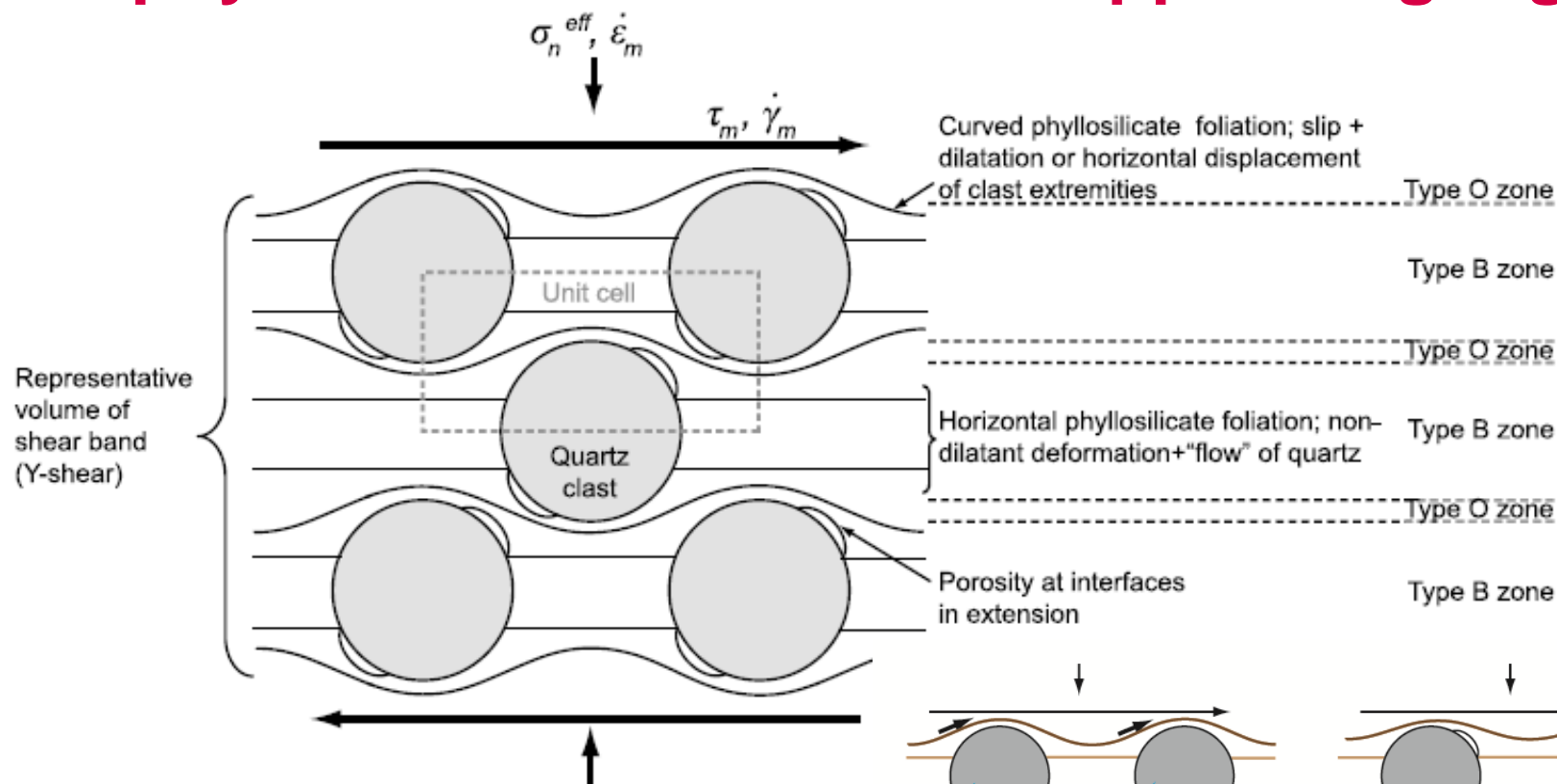Representative volume of shear band (Y-shear)

Unit cell

Quartz clast

Low *V* / high *T*:
- Easy shear deformation of quartz by pressure solution
- Slip on horizontal phyllosilicates with serial shear of quartz "bodies" or "overlaps"
→ **Non-dilatant deformation, (*a*-*b*)>0**

Slip on phyllosilicates + shear deformation of quartz by pressure solution

# Microphysical model for matrix-supported gouges



$\sigma_n^{eff}, \dot{\varepsilon}_m$

$\tau_m, \dot{\gamma}_m$

Curved phyllosilicate foliation; slip + dilatation or horizontal displacement of clast extremities — Type O zone

Type B zone

Type O zone

Unit cell

Representative volume of shear band (Y-shear)

Quartz clast

Horizontal phyllosilicate foliation; non–dilatant deformation+"flow" of quartz — Type B zone

Type O zone

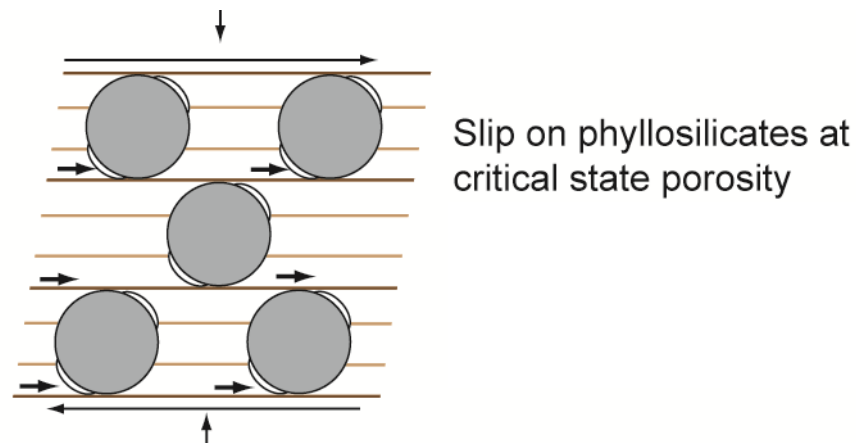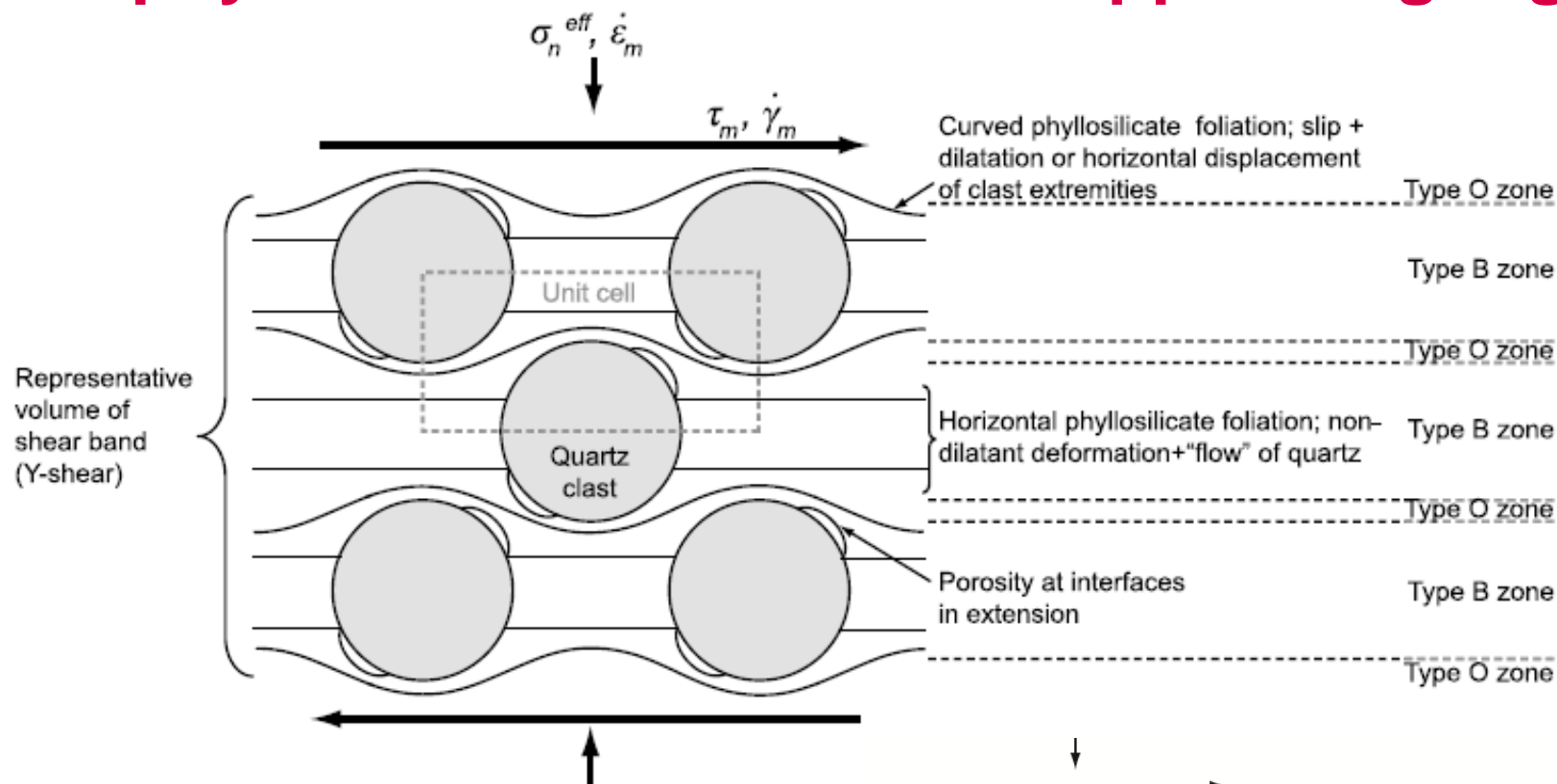Porosity at interfaces in extension

Type B zone

High *V* / low *T*:

- Too slow shear deformation of quartz by pressure solution
- Dilatant slip on curved phyllosilicates balanced by compaction of qtz by p.soln.

→ **Dilatant deformation, (*a-b*)<0**

Competition between dilatation and quartz compaction by pressure solution

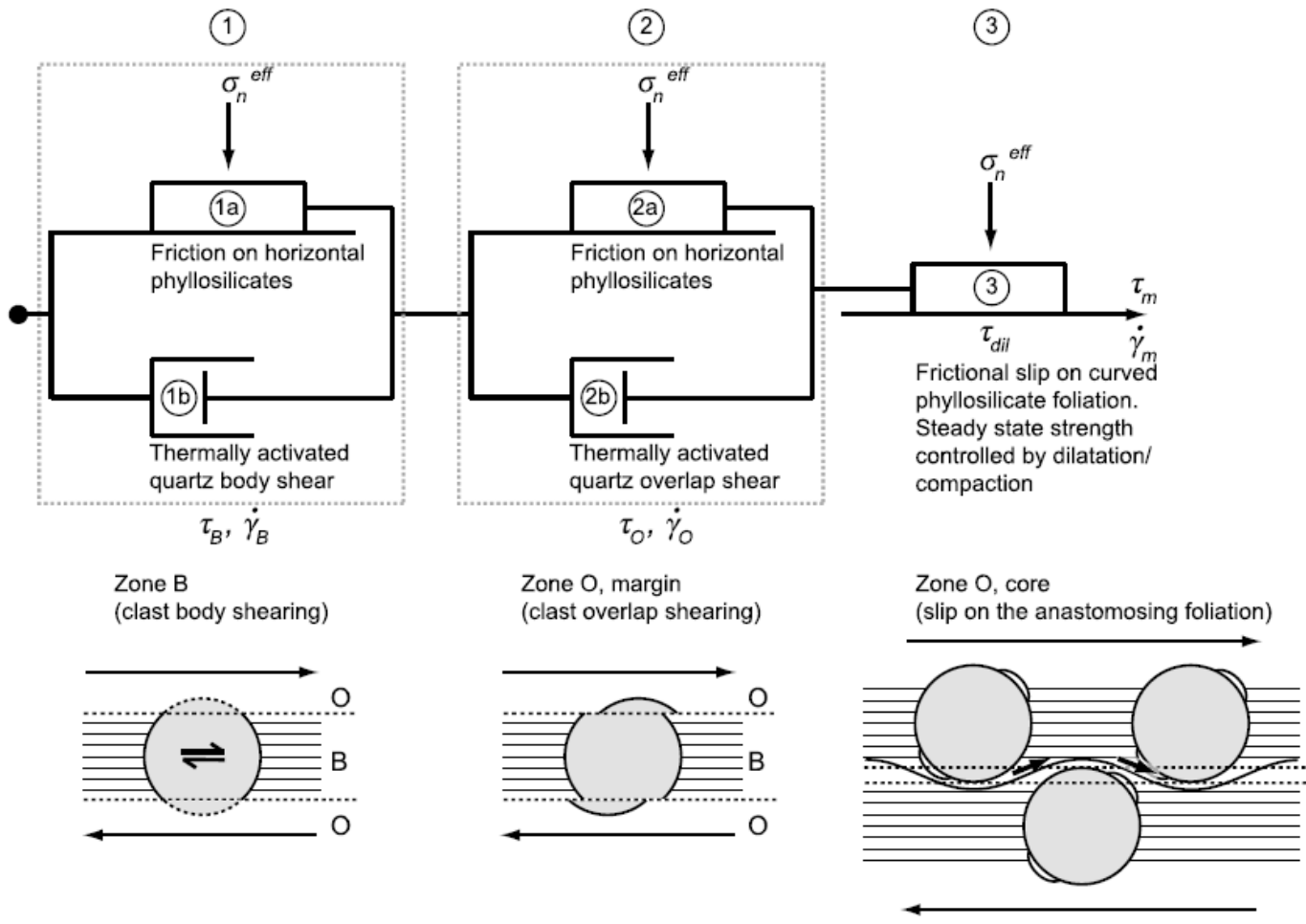# Microphysical model for matrix-supported gouges



High *V* / low *T*:
- Too slow shear deformation of quartz by pressure solution
- Dilatant slip on curved phyllosilicates balanced by compaction of qtz by p.soln.
→ **Dilatant deformation, (*a-b*)<0**

# Microphysical model for matrix-supported gouges



Non-dilatant deformation:
(1) and (2) active

$$\tau_m = \tau_B = \tau_O$$

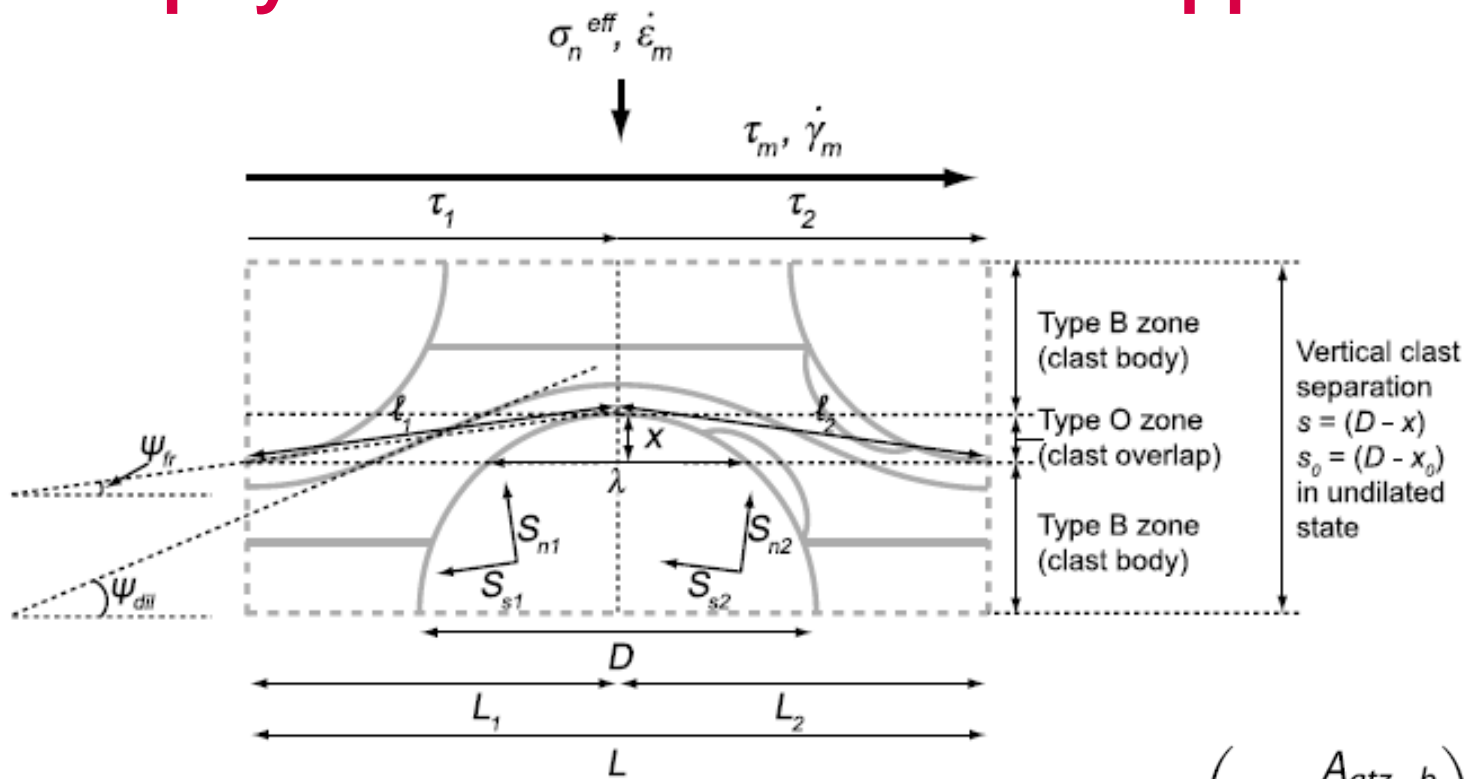$$\dot{\gamma}_m = \dot{\gamma}_B + \dot{\gamma}_O$$

Dilatant deformation:
(1), (2), (3) active

$$\tau_m = \tau_{dil} = \tau_B = \tau_O$$

$$\dot{\gamma}_m = \dot{\gamma}_B + \dot{\gamma}_O + \dot{\gamma}_{dil}$$

*Den Hartog & Spiers, JGR, 2014*

# Microphysical model for matrix-supported gouges



$$\tan \Psi_{fr} = \frac{2(D - x_0)f_{qtz}}{k_f \pi D^2}x$$

$$S_{n1}\ell_1 D = \sigma_n^{eff}L_1 D\cos\Psi_{fr} + \tau_1 L_1 D\sin\Psi_{fr}$$

$$S_{s1}\ell_1 D = \tau_1 L_1 D\cos\Psi_{fr} - \sigma_n^{eff}L_1 D\sin\Psi_{fr}$$

$$\tau_B = \tau_{ph}\left(1 - \frac{A_{qtz-b}}{LD}\right) + \tau_{qtz-b}\frac{A_{qtz-b}}{LD}$$

$$\tau_O = \tau_{ph}\left(1 - \frac{A_{qtz-o}}{LD}\right) + \tau_{qtz-o}\frac{A_{qtz-o}}{LD}$$

$$\tau_{dil} = \left\{\frac{\tilde{\mu}(1 + \tan^2\Psi_{fr})}{1 - \tilde{\mu}^2\tan^2\Psi_{fr}}\right\}\sigma_n^{eff}$$

# Microphysical model for matrix-supported gouges

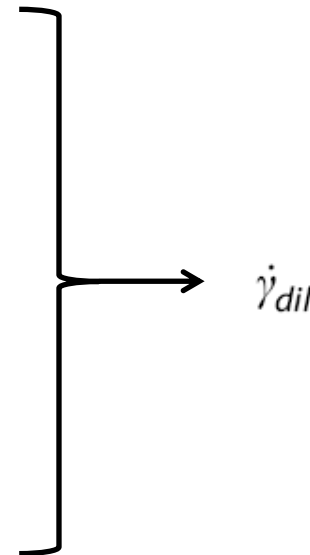$$\dot{\gamma}_B = \dot{\gamma}_{qtz-b} = \frac{Al\tau_{qtz-b}\Omega}{RT} \frac{D - 2x}{D(D - x)}$$

$$\dot{\gamma}_O = \dot{\gamma}_{qtz-o} = \frac{2l\tau_{qtz-o}\Omega}{RT} \frac{1}{\sqrt{Dx - x^2}}$$

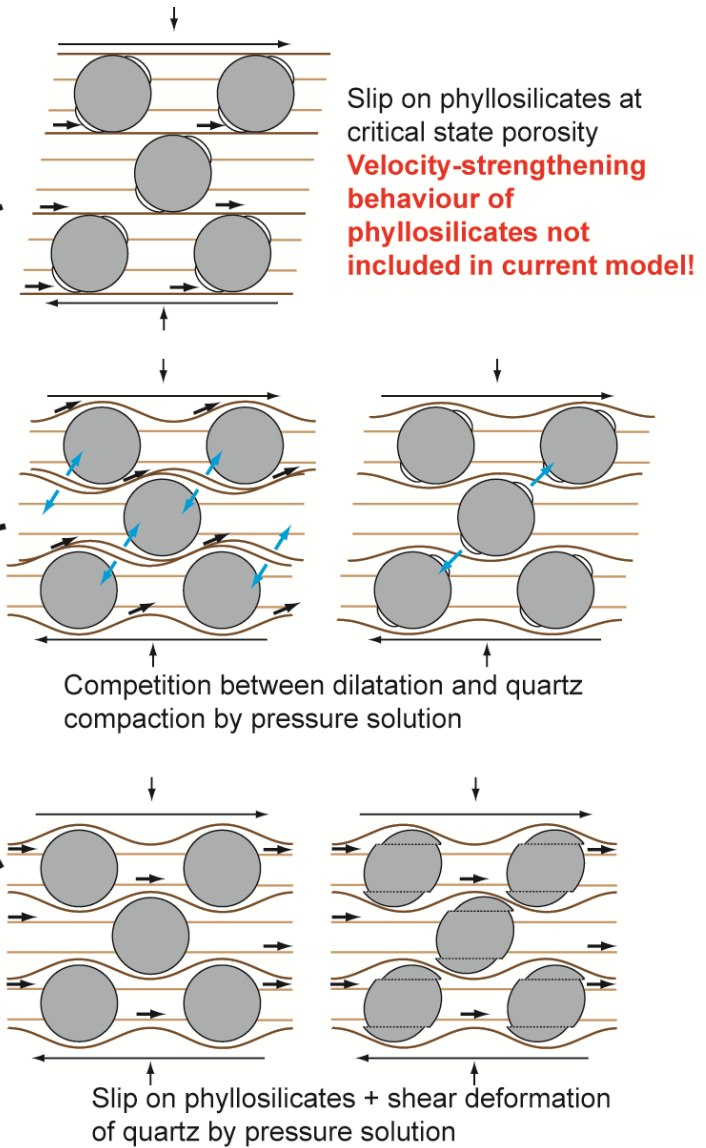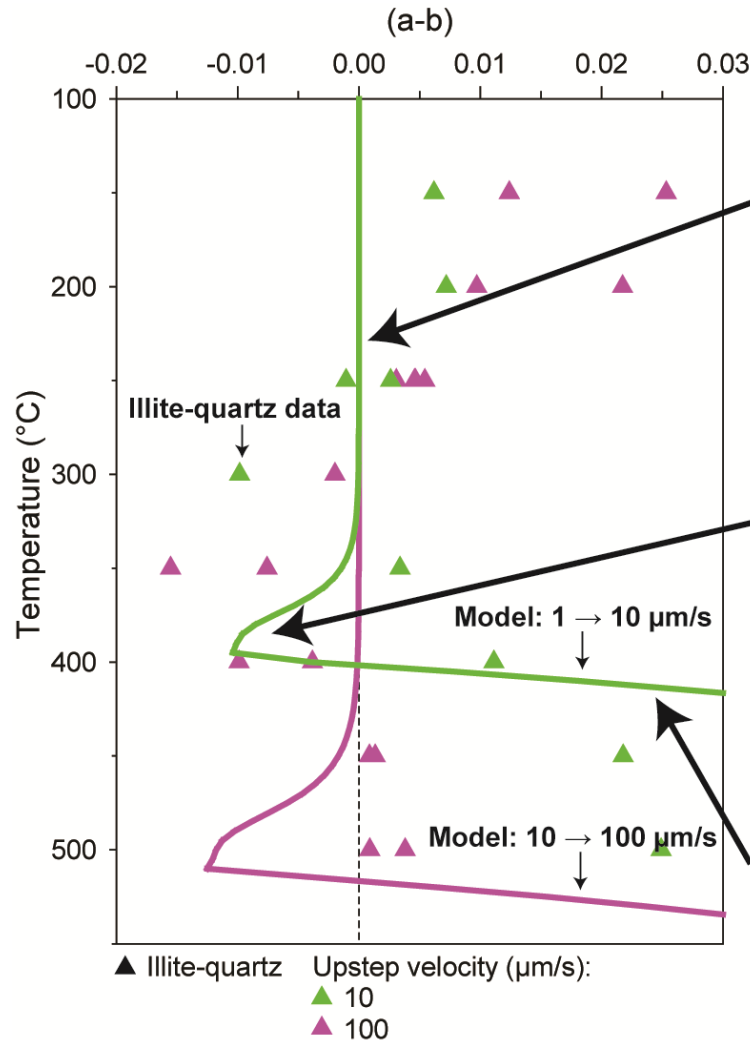$$\dot{\varepsilon}_{comp} = \dot{\varepsilon}_{dil}$$

$$\dot{\varepsilon}_{comp} = \frac{2l\sigma_n^{eff}\Omega}{RT} \frac{A_{pore}}{(D - x)DL}$$

$$\dot{\varepsilon}_{dil} = \left(\frac{d\varepsilon_{dil}}{d\gamma_{dil}}\right)\frac{d\gamma_{dil}}{dt} = (\tan\Psi_{dil})\dot{\gamma}_{dil}$$

$$\tan\Psi_{dil} = \left.\frac{\partial[(x/2)\sin(2\pi A_x/L)]}{\partial A_x}\right|_{A_x = 0}$$

$$\longrightarrow \dot{\gamma}_{dil}$$

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# Model predictions

# Take home messages

1. RSF equations are very useful to describe experimental data and model the seismic cycle.

2. But: RSF equations are empirical equations without a microphysical basis → extrapolation from lab to nature not possible.

3. A microphysical model for friction should account for fluid-rock interactions and the possibility of the presence of a foliation.

4. Microphysical models for the shear deformation of simulated/natural gouges predict a key role of dilatancy + compaction for velocity weakening behaviour (earthquake potential).