The effect of fluid injection on an experimental fault and its role on frictional stability and earthquake triggering

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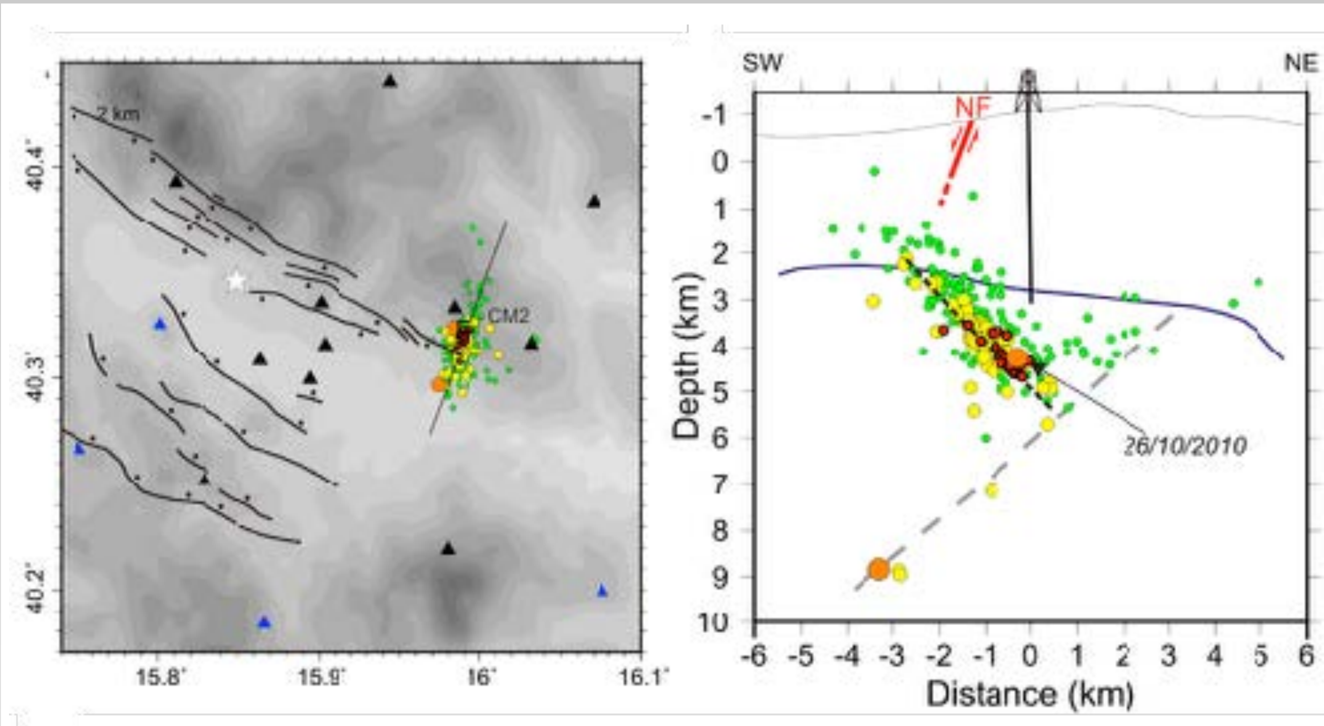
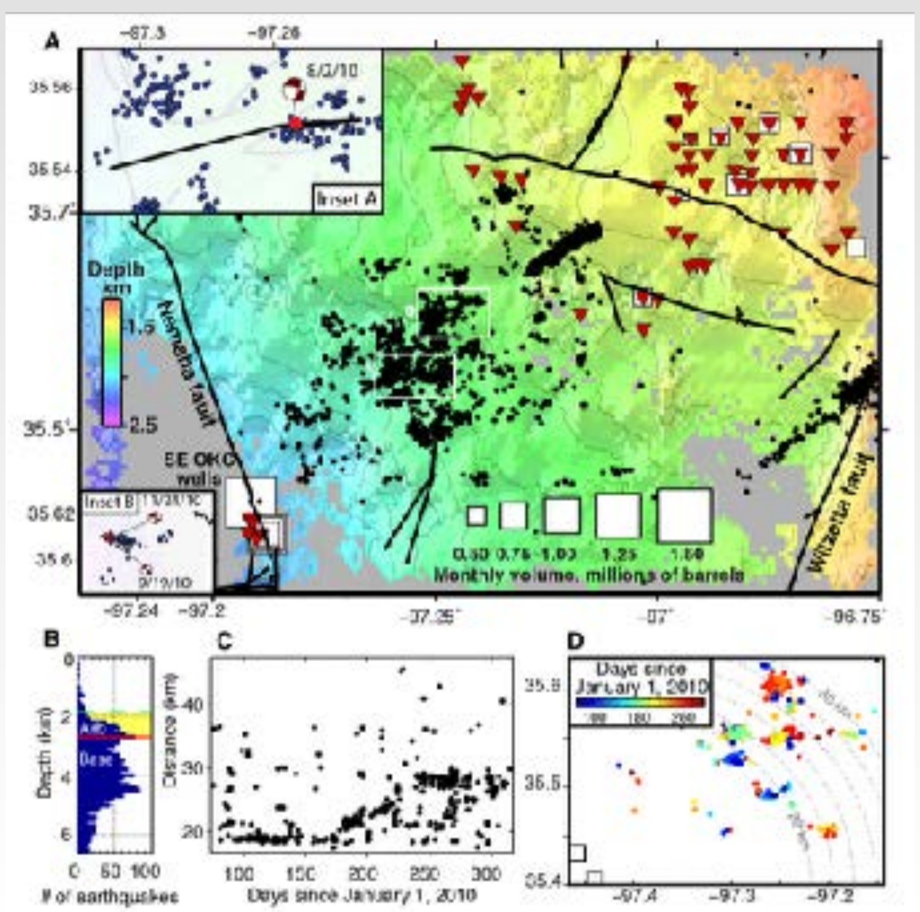
Important to understand the interaction between fluids and faulting



Val D`Agri oil field, Italy
Wastewater-induced seismicity ($M_L > 2$)

Seismicity relates to main peaks in the well-head injection pressure and shows a migration on a pre-existing fault confined within the Apulian carbonates.

Improta et al., 2015 *GRL*



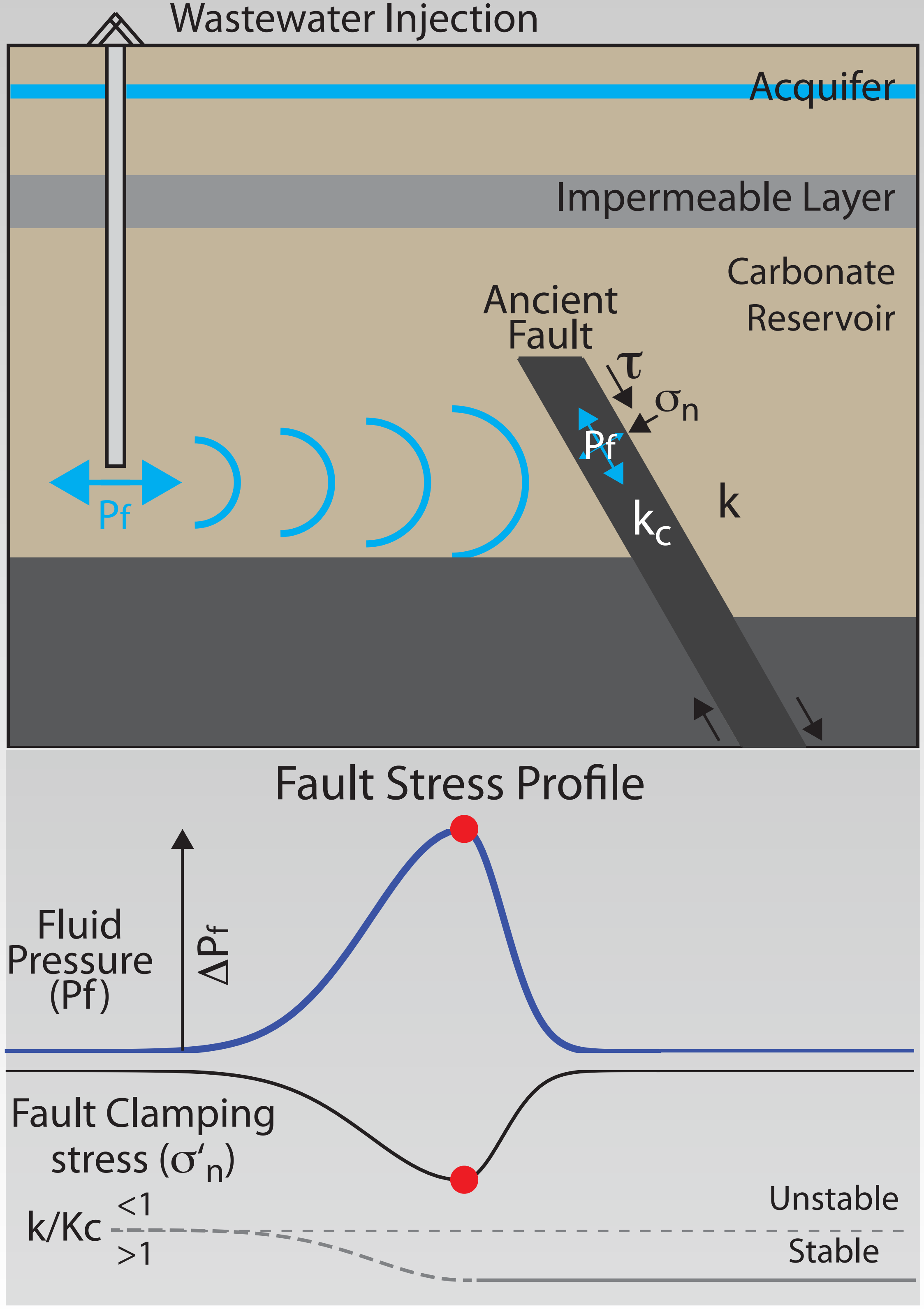
Oklahoma, USA
Wastewater-induced seismicity (many events $M_w > 5$)

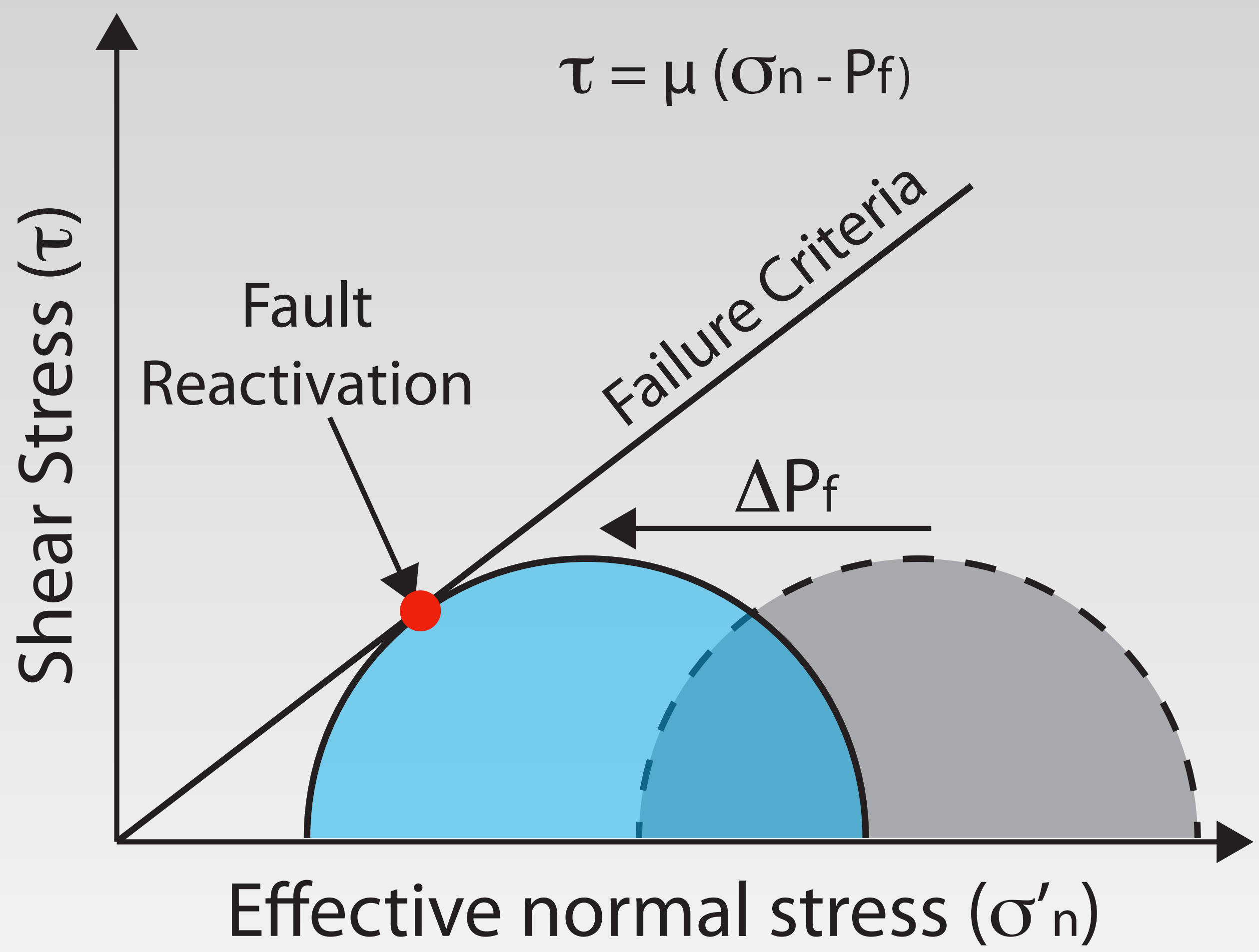
Wastewater injection increased seismicity rate dramatically

Keranen et al., 2014 *Science*

Fault Reactivation vs. Frictional Slip Stability

The increase in fluid pressure along a fault will decrease the effective normal stress that clamps the fault in place favoring fault reactivation





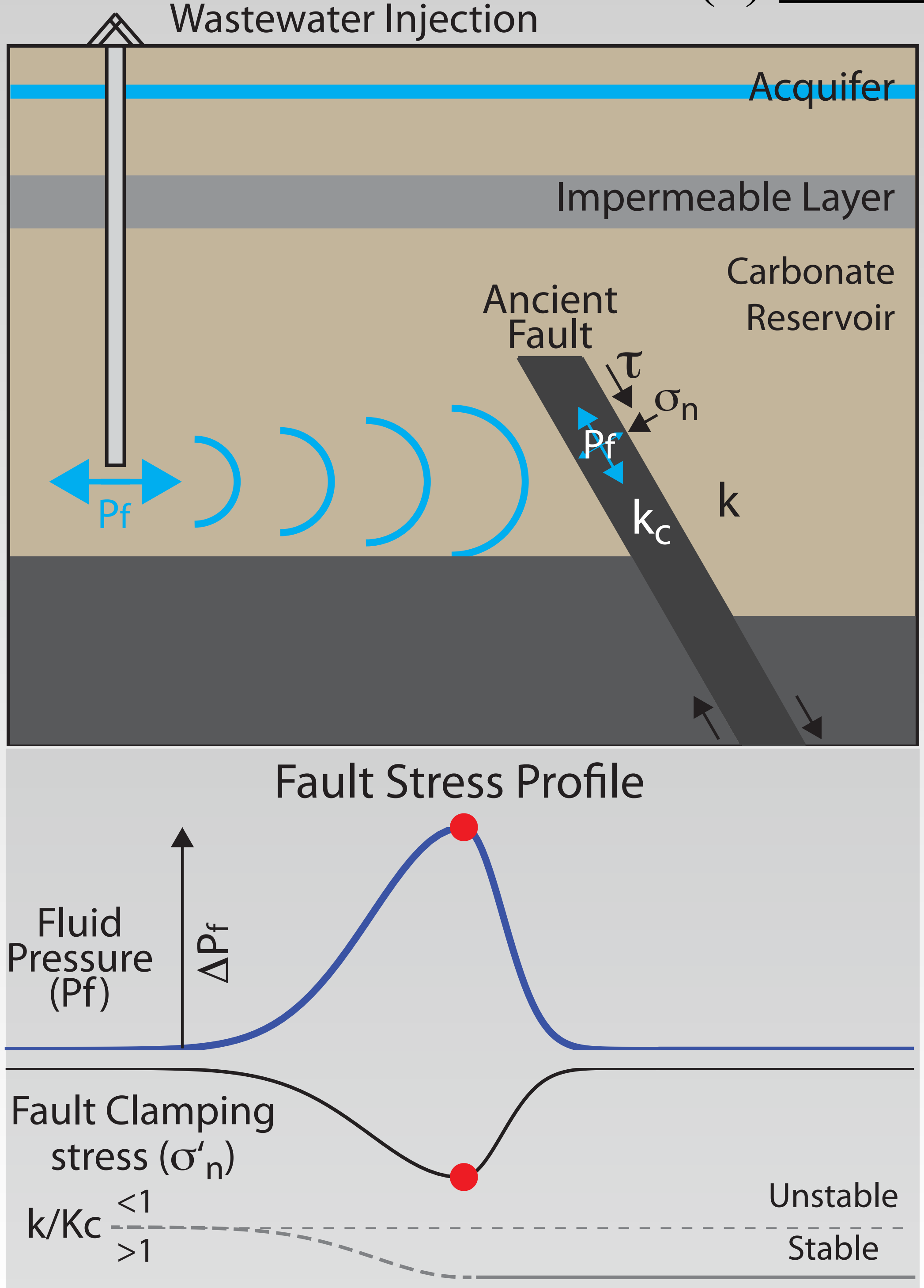
Hubbert and Rubey, 1959 *Bull. Geol.Soc. Am*

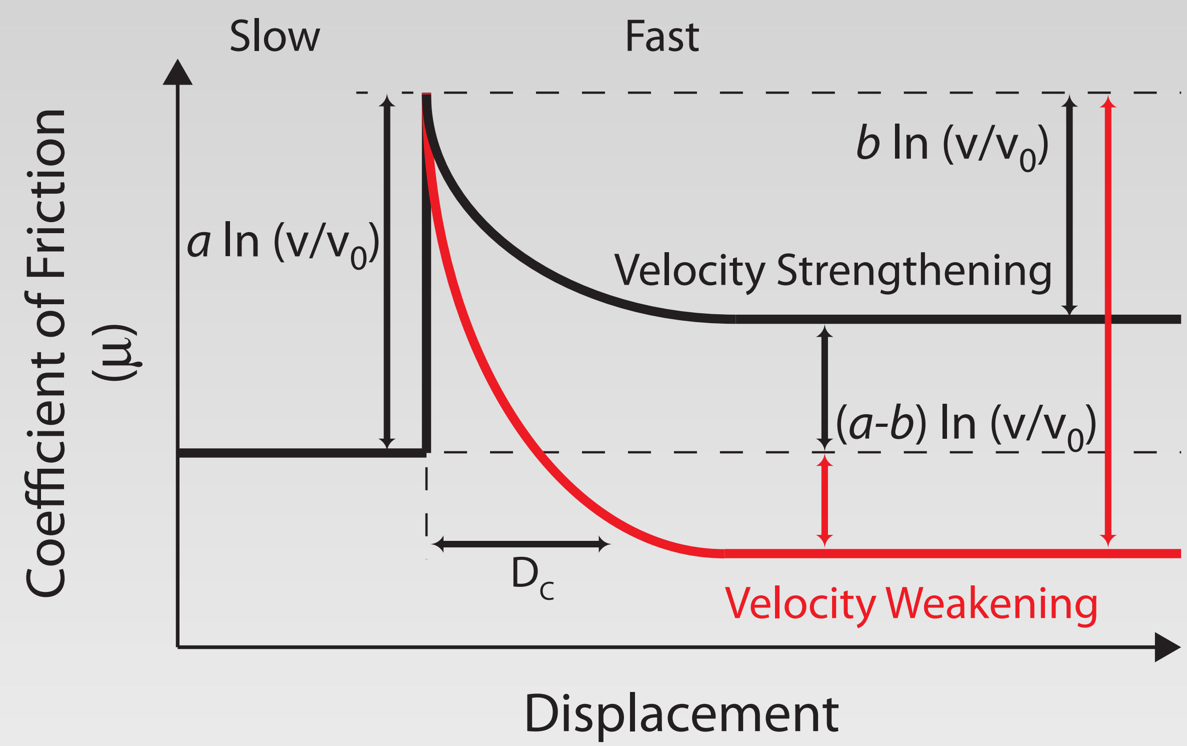
Fault Reactivation vs. Frictional Slip Stability

Upon reactivation fault slip behavior can be described via the **Rate- and State- Frictional Properties**:

(1) potentially seismic (Velocity Weakening)

(2) aseismic (Velocity Strengthening)





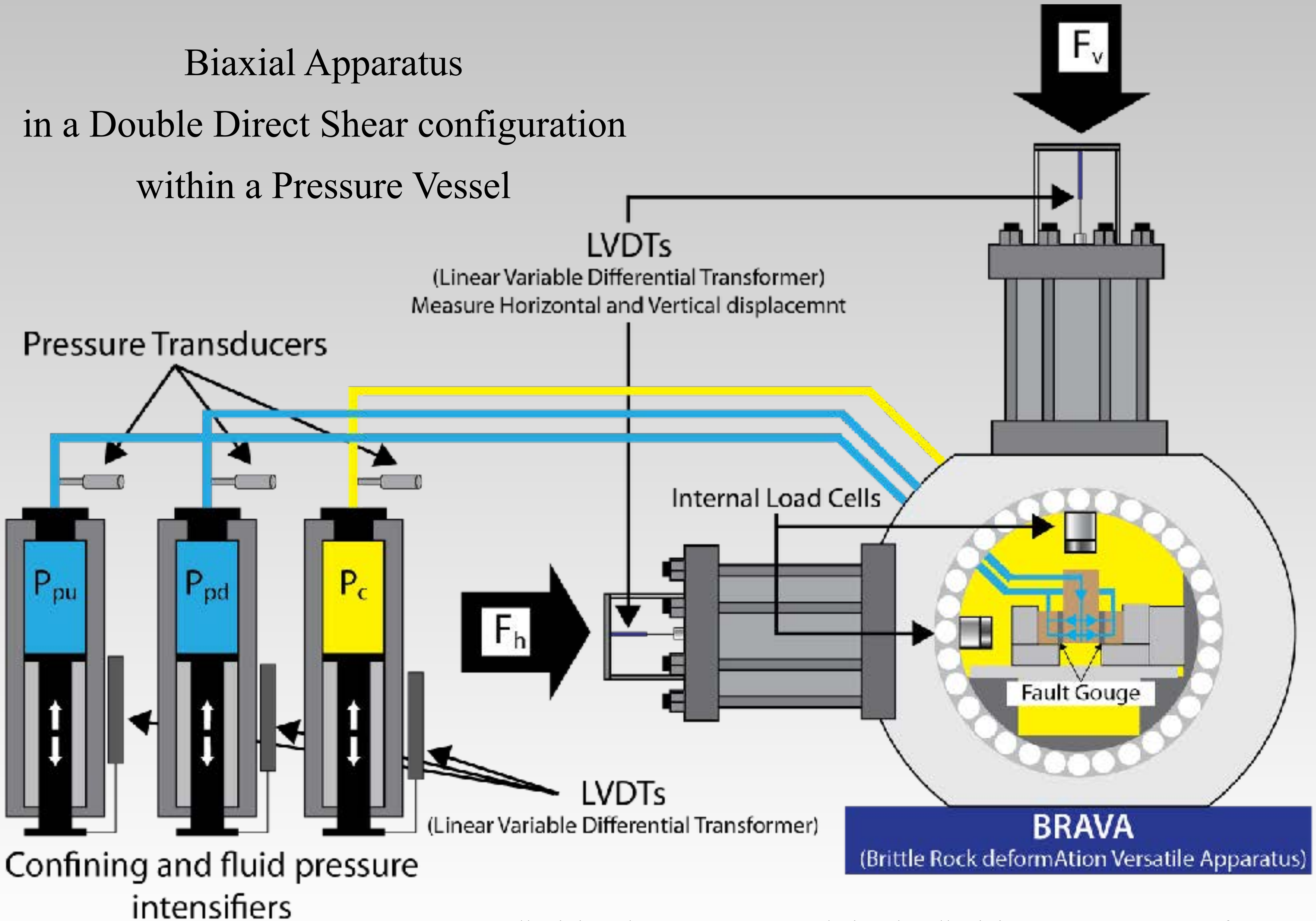
Criterion for fault Stability

defined by the critical stiffness (kc)

$$k_c = (\sigma_n - P_f)(b-a) / D_c$$

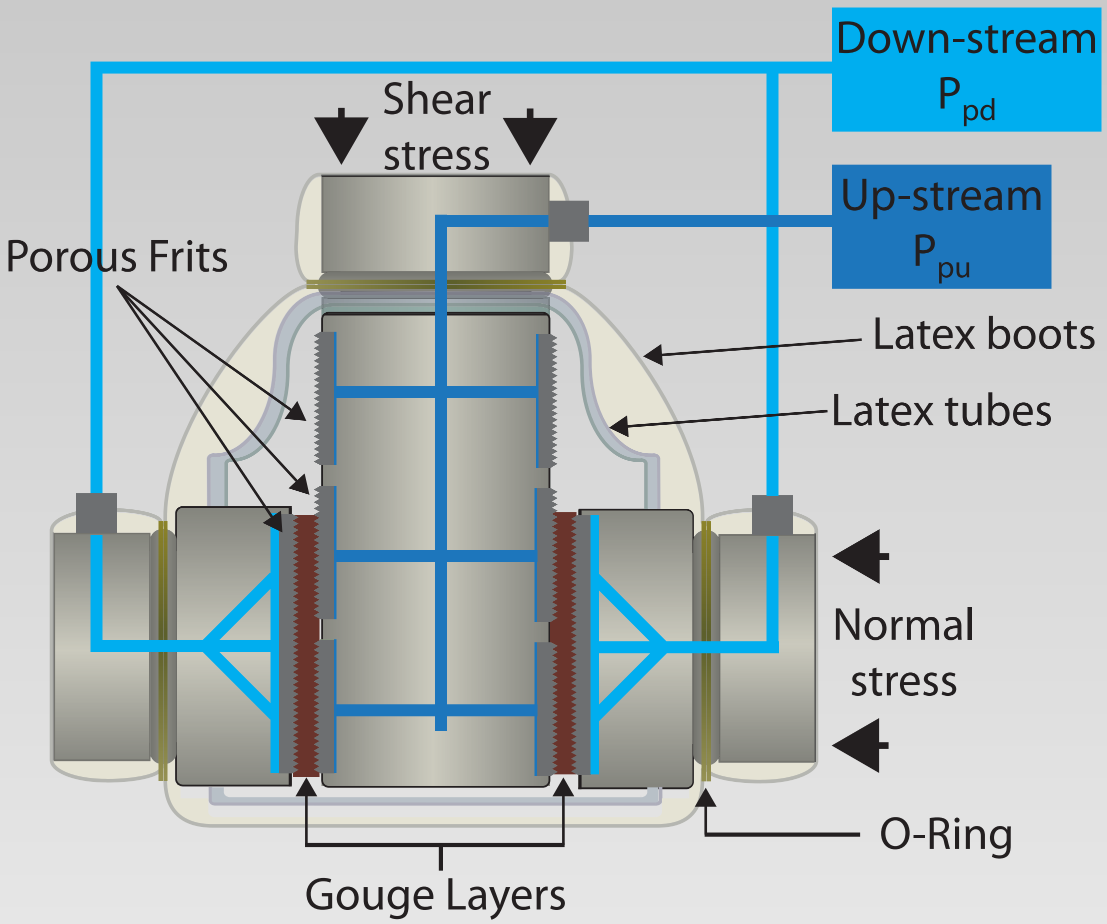
$k < k_c$	$k \sim k_c$	$k > k_c$
Unstable	*Conditionally Stable*	*Stable*

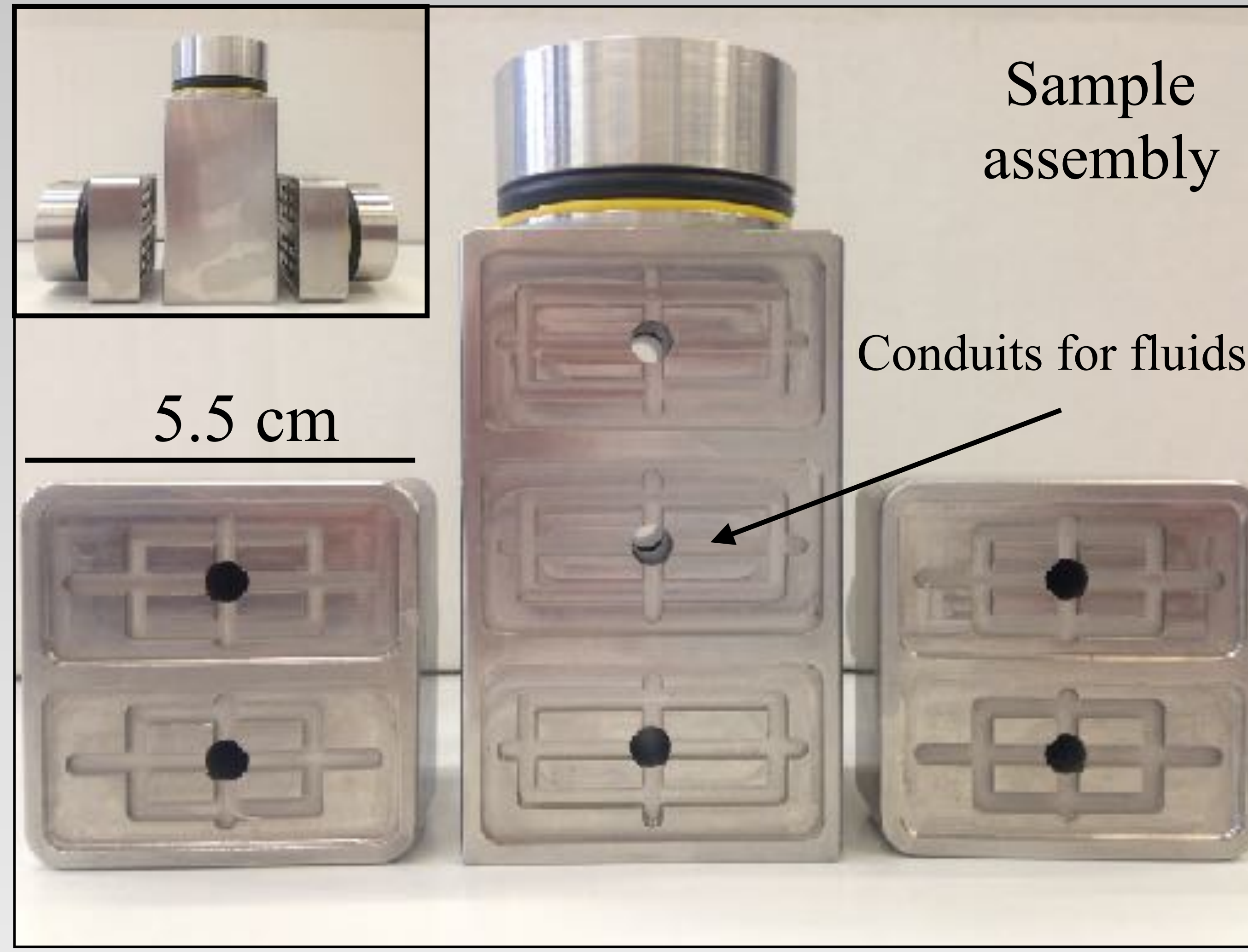
Biaxial Apparatus in a Double Direct Shear configuration within a Pressure Vessel



Collettini et al., 2014 *IJRM;* Scuderi and Collettini, 2016 *Nature Scientific Report*

Double Direct Shear configuration within a pressure vessel

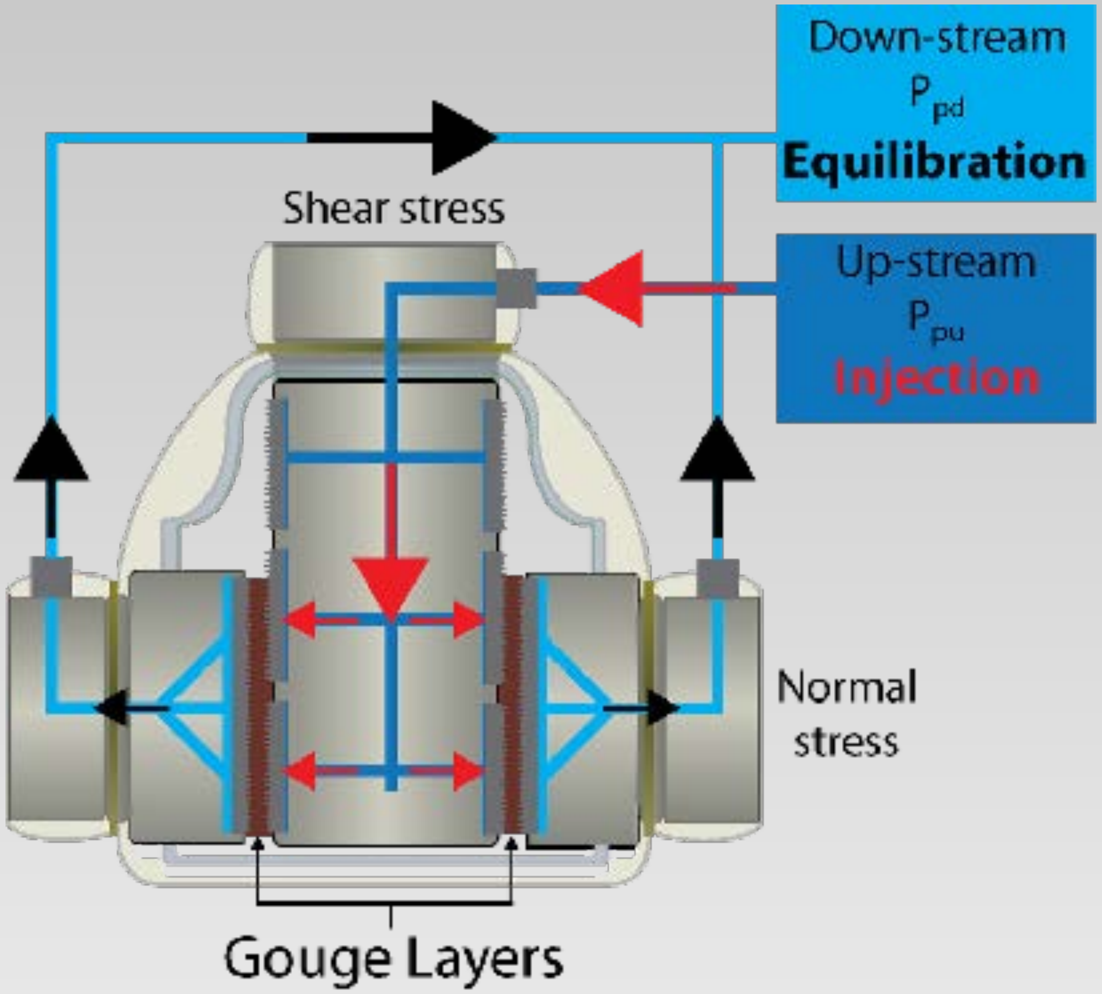


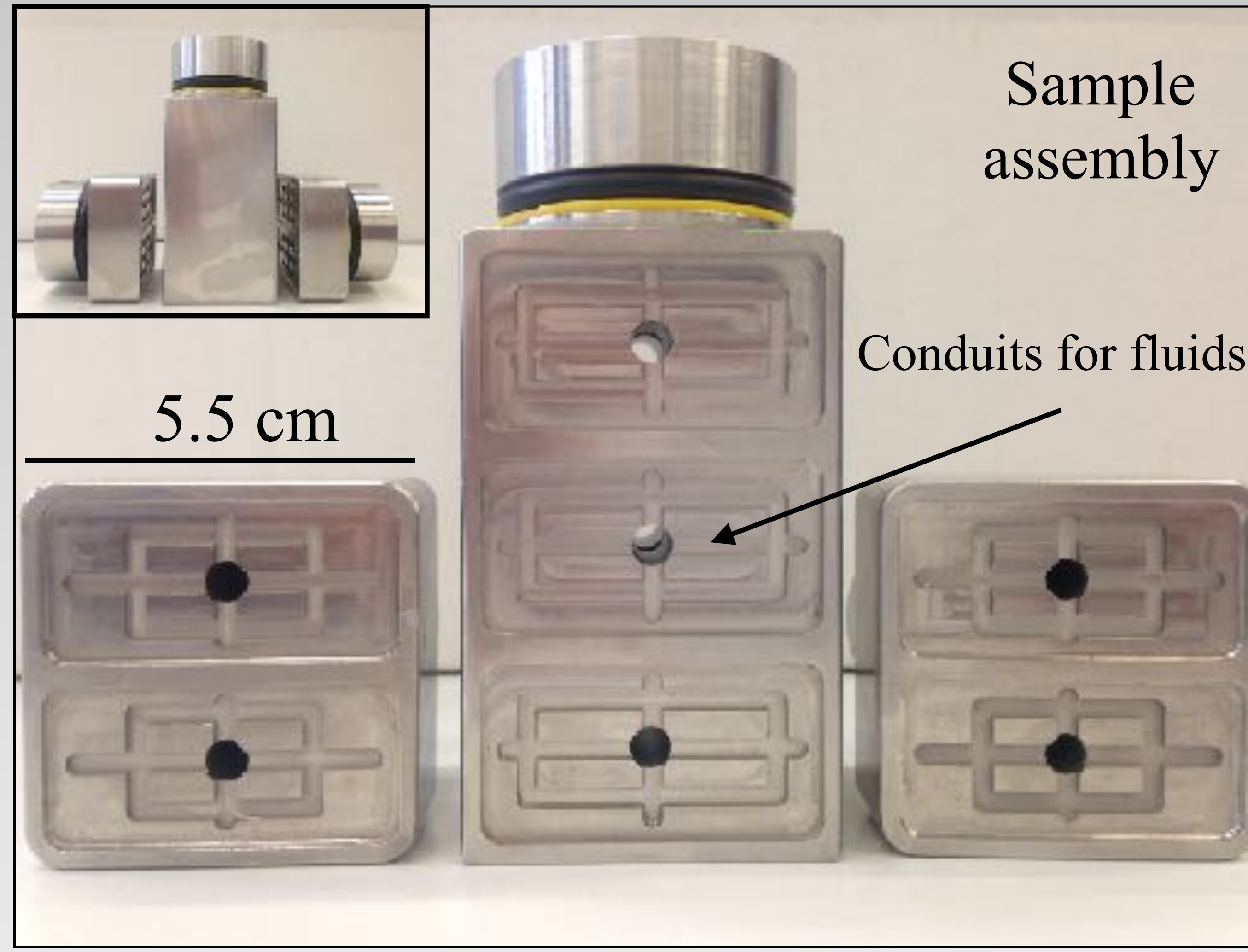


Latex jacket

Porous Frits

Double Direct Shear configuration within a pressure vessel

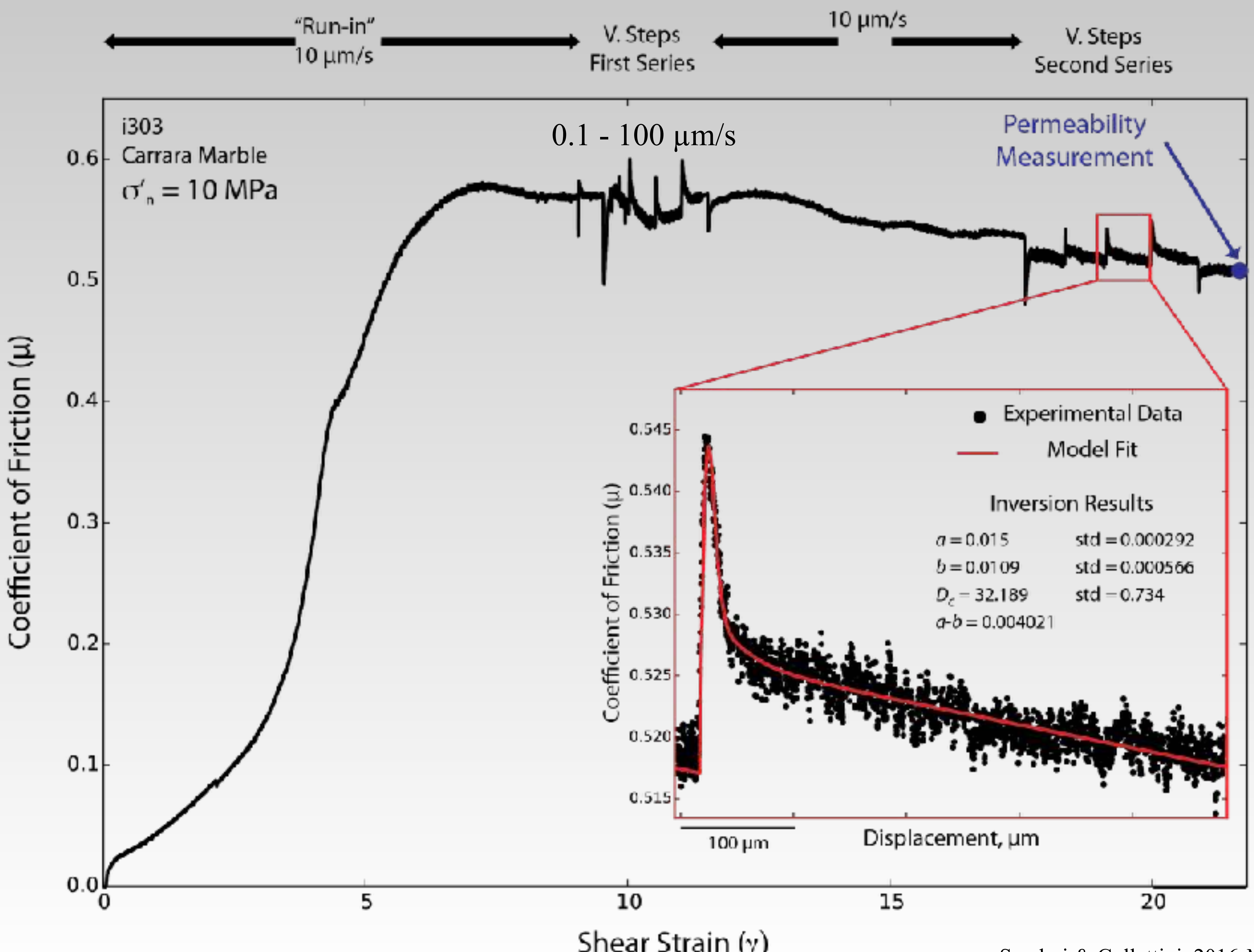




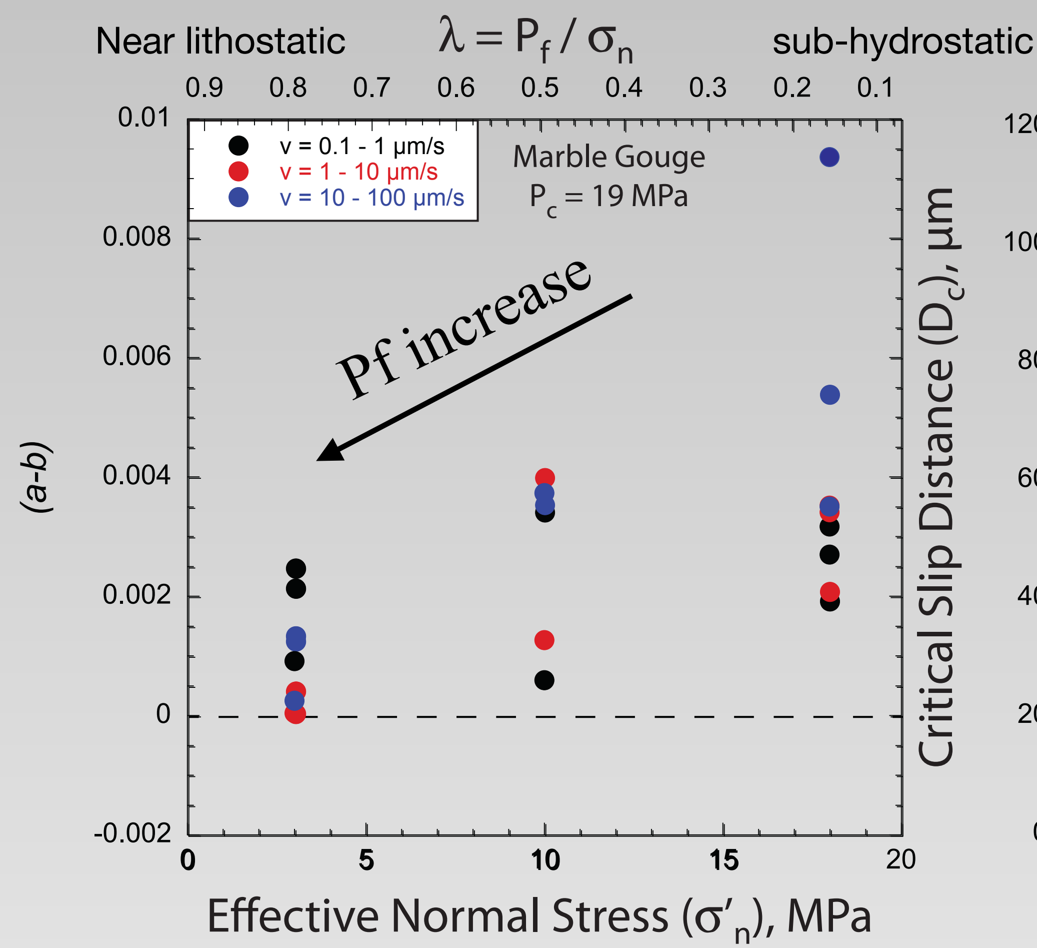
Latex jacket

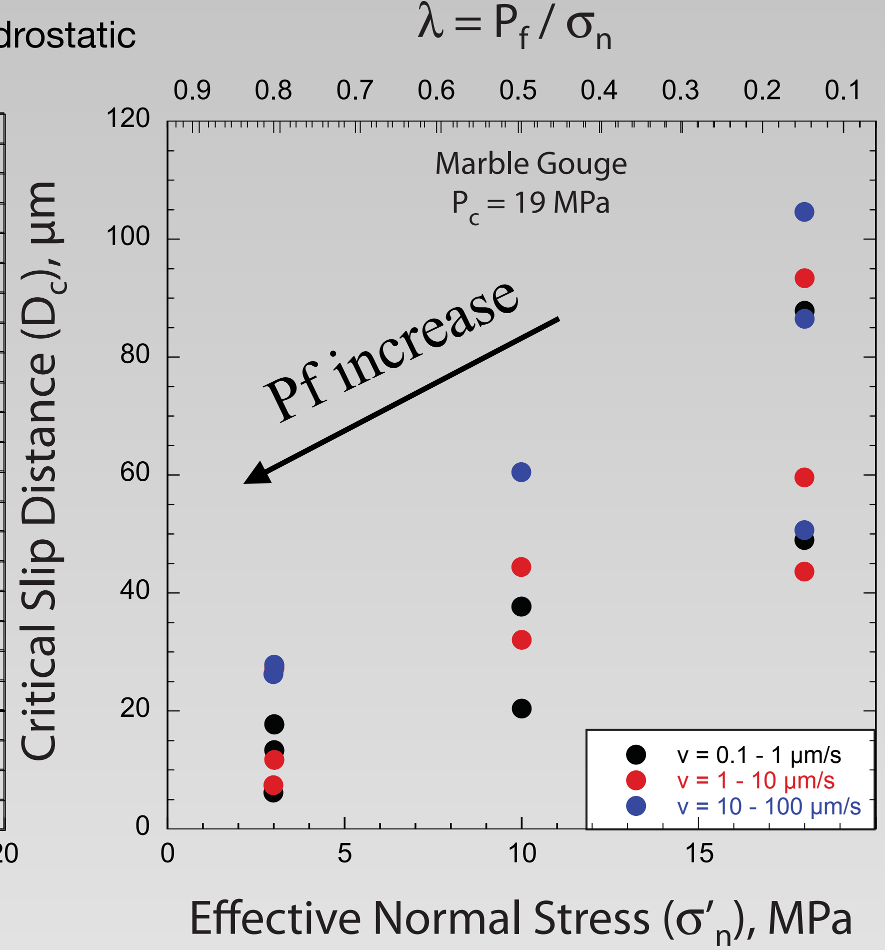
Porous Frits

Experimental curve for a typical experiment



Scuderi & Collettini, 2016 *Nat. Sci. Rep.*



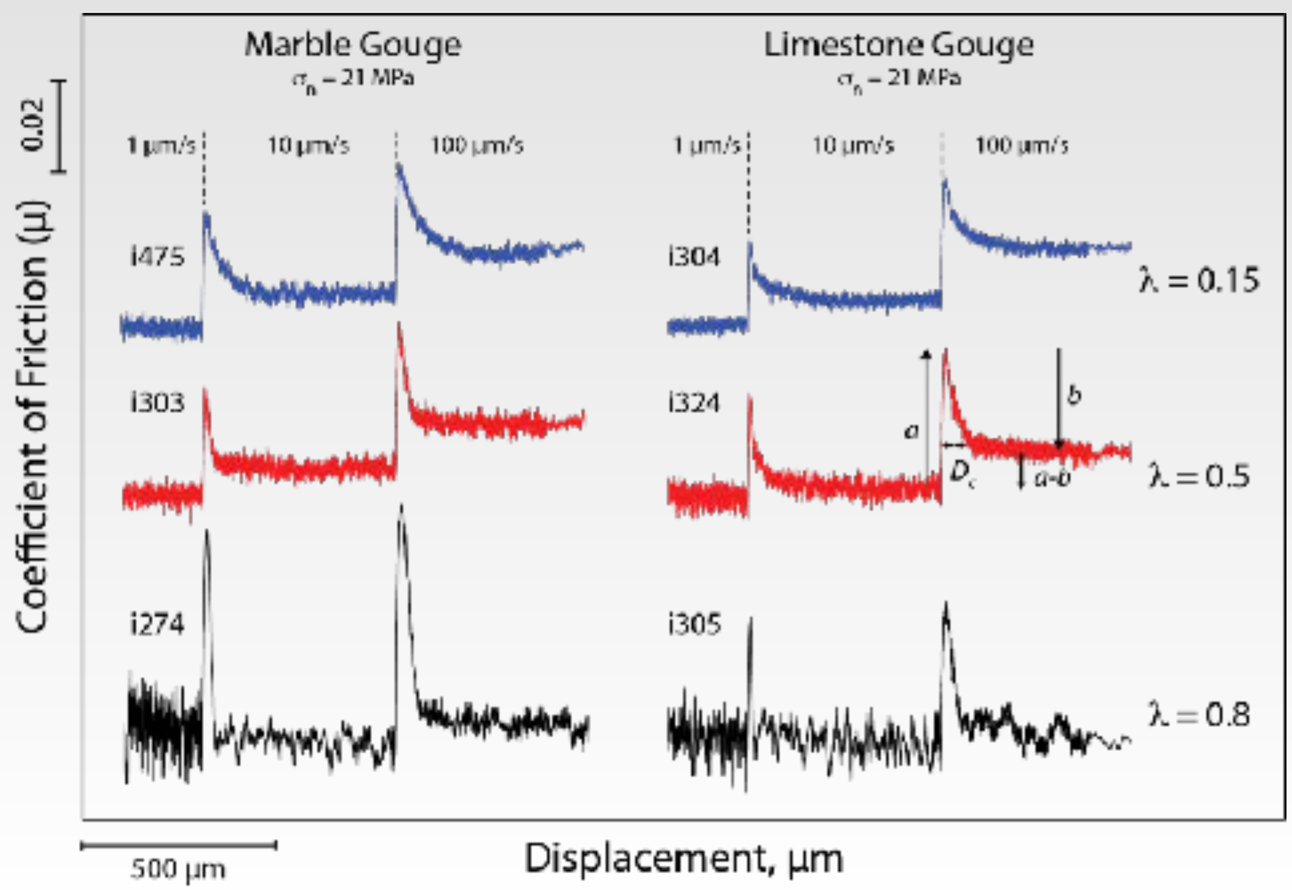


Velocity dependence of friction *(a-b)*

The friction rate parameter <u>(a-b) decreases as the pore fluid pressure is increased</u>

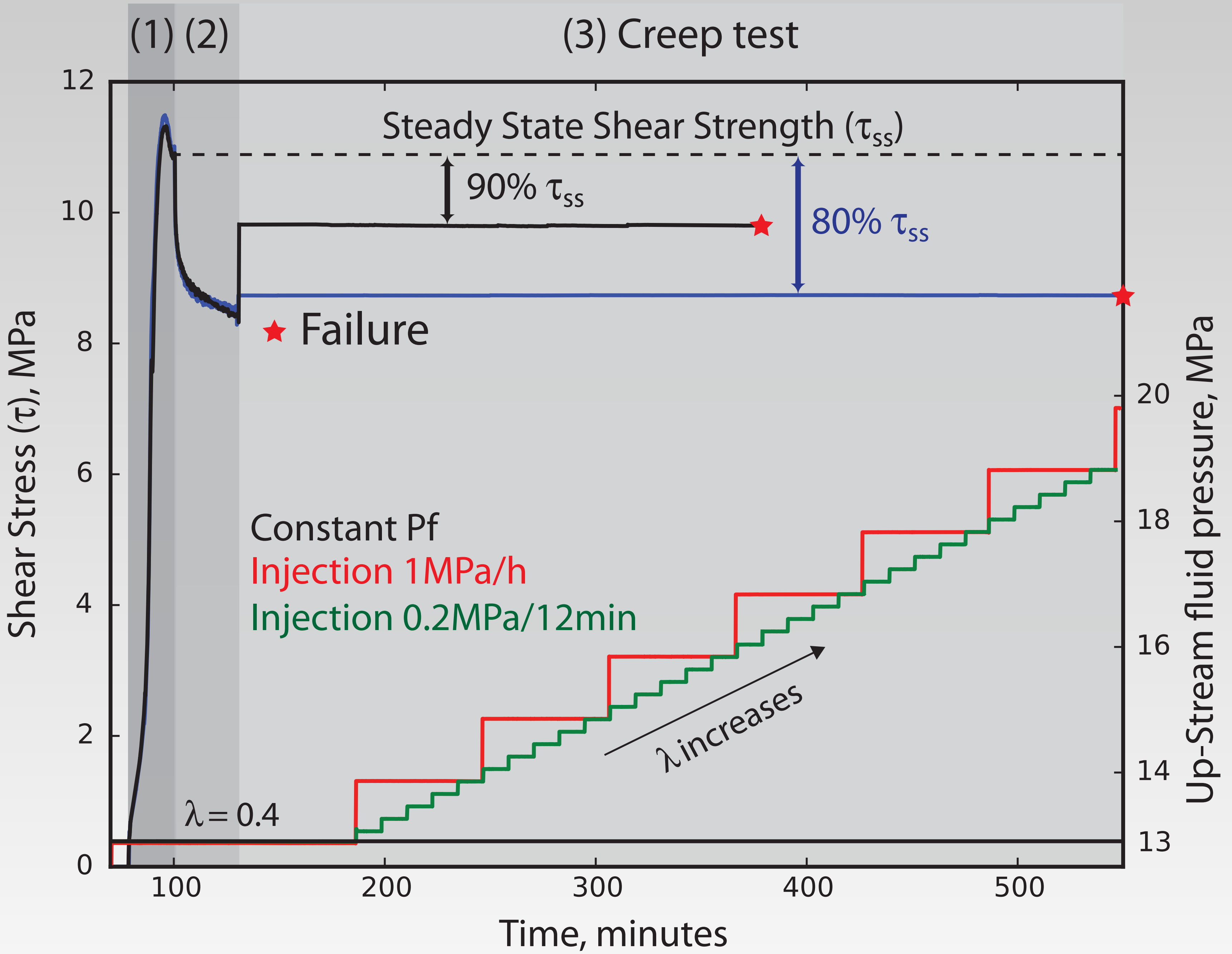
Critical Slip Distance - Dc

The parameter <u>Dc decreases as pore fluid pressure is increased</u> from sub-hydrostatic to near lithostatic conditions

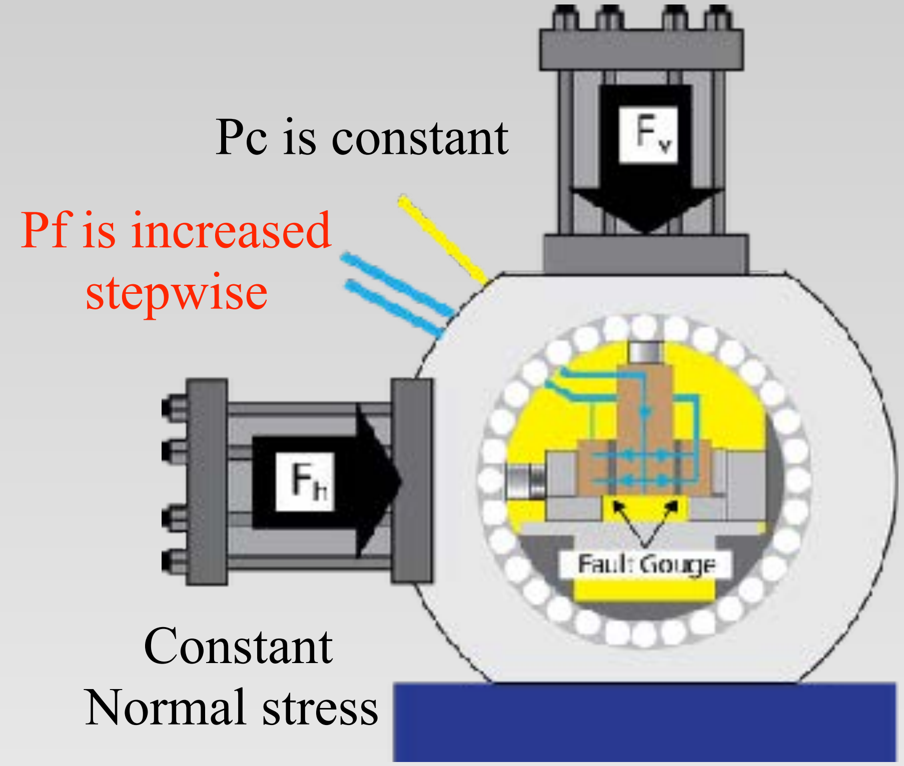


Scuderi & Collettini, 2016 *Nat. Sci. Rep.*

Creep experiments



Constant
Shear stress
We monitor fault slip



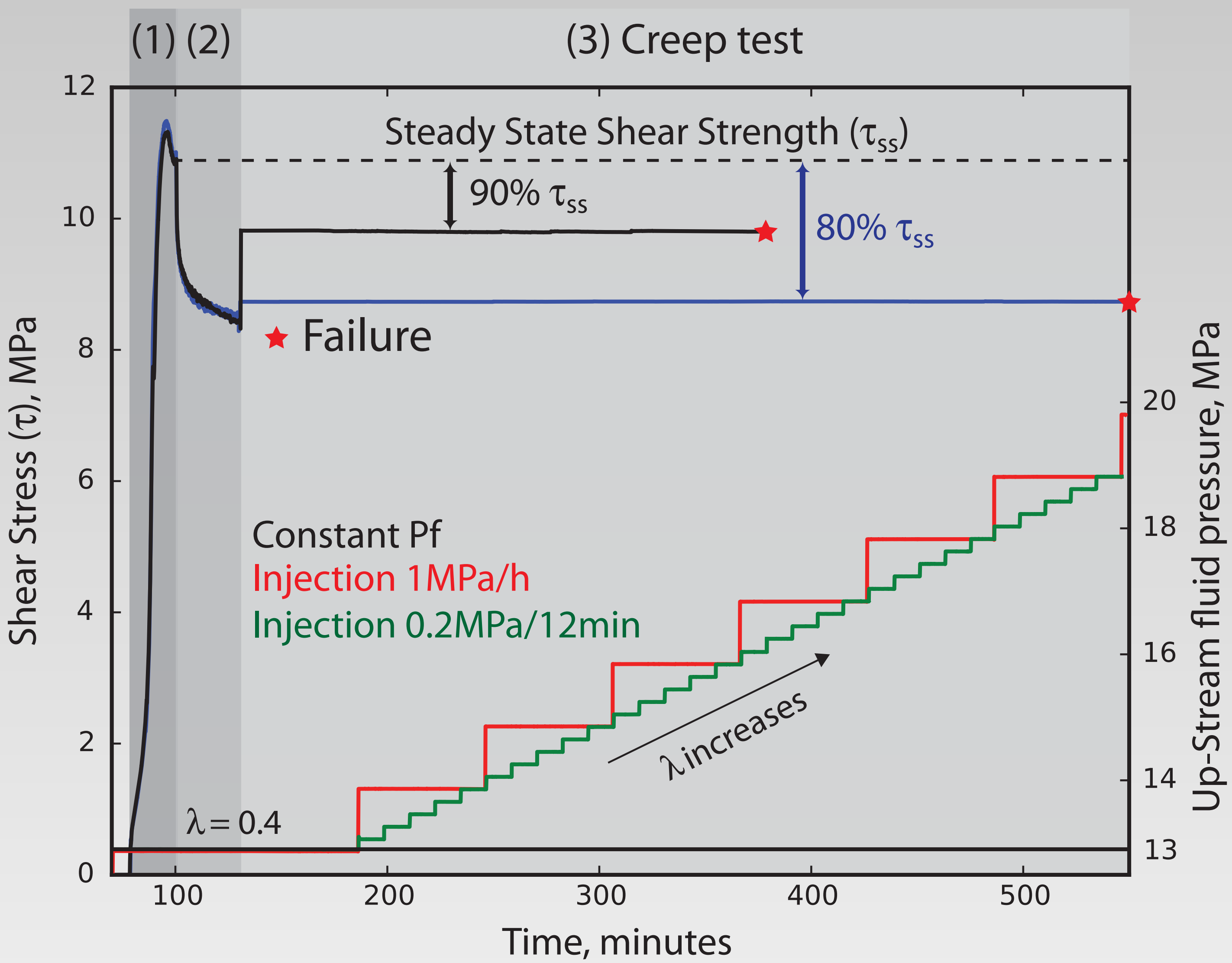
(1) Constant displacement rate of 10 μm/s to localize shear

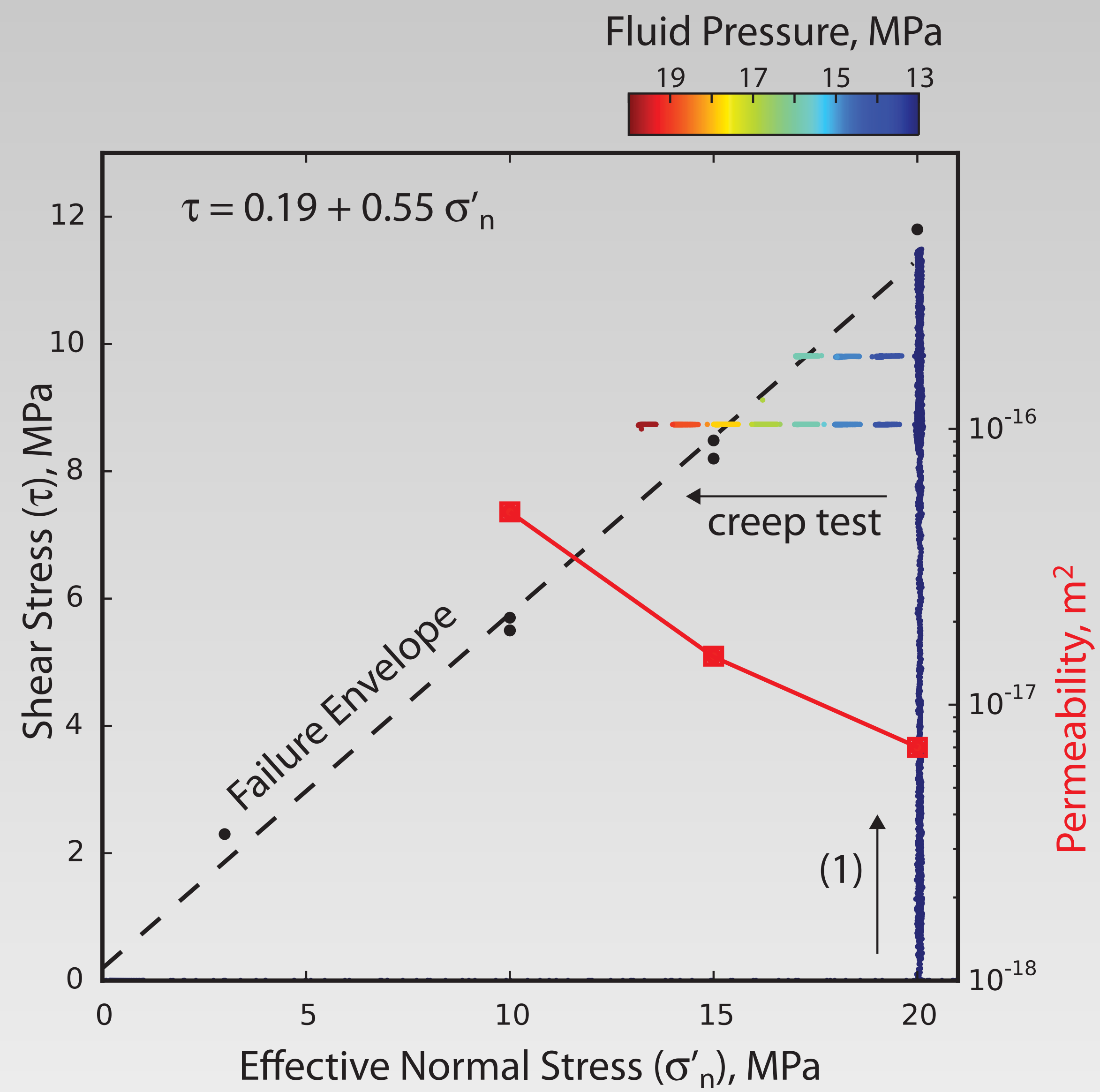
(2) Fault relaxation to residual strength

(3) Set the shear stress at the desired value in load control to monitor fault slip

Scuderi et al., 2017 *EPSL*

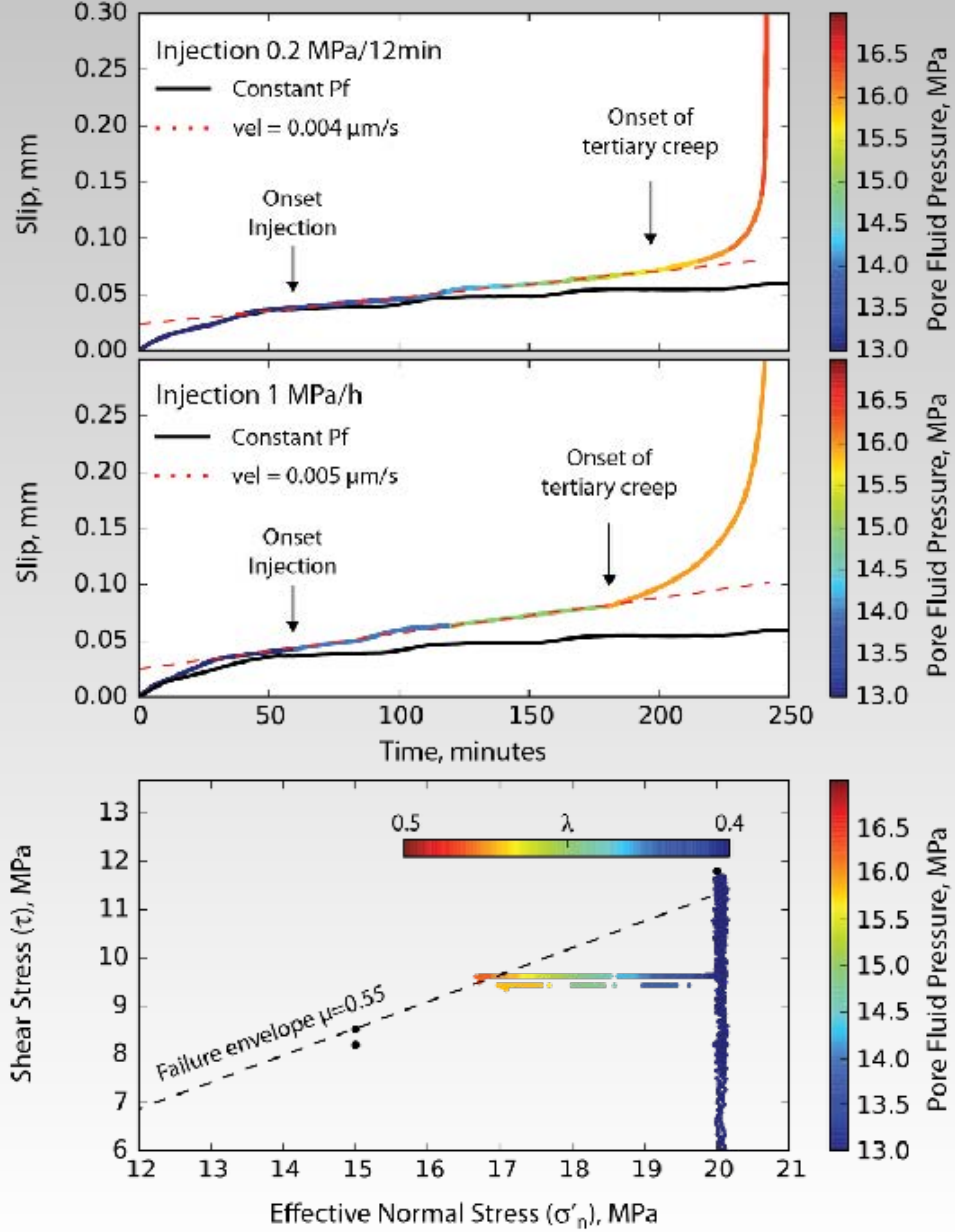
Creep experiments





Three types of experiments to characterize fault slip behavior:

1) Constant Pf to monitor undisturbed fault creep
2) Injection of fluids at 1 MPa every hour
3) Injection of fluids at 0.2 MPa every 12 min



Creep Experiments - 90%τ_{ss}

1) Primary creep
least for 35-40min in the experiment before injection begun

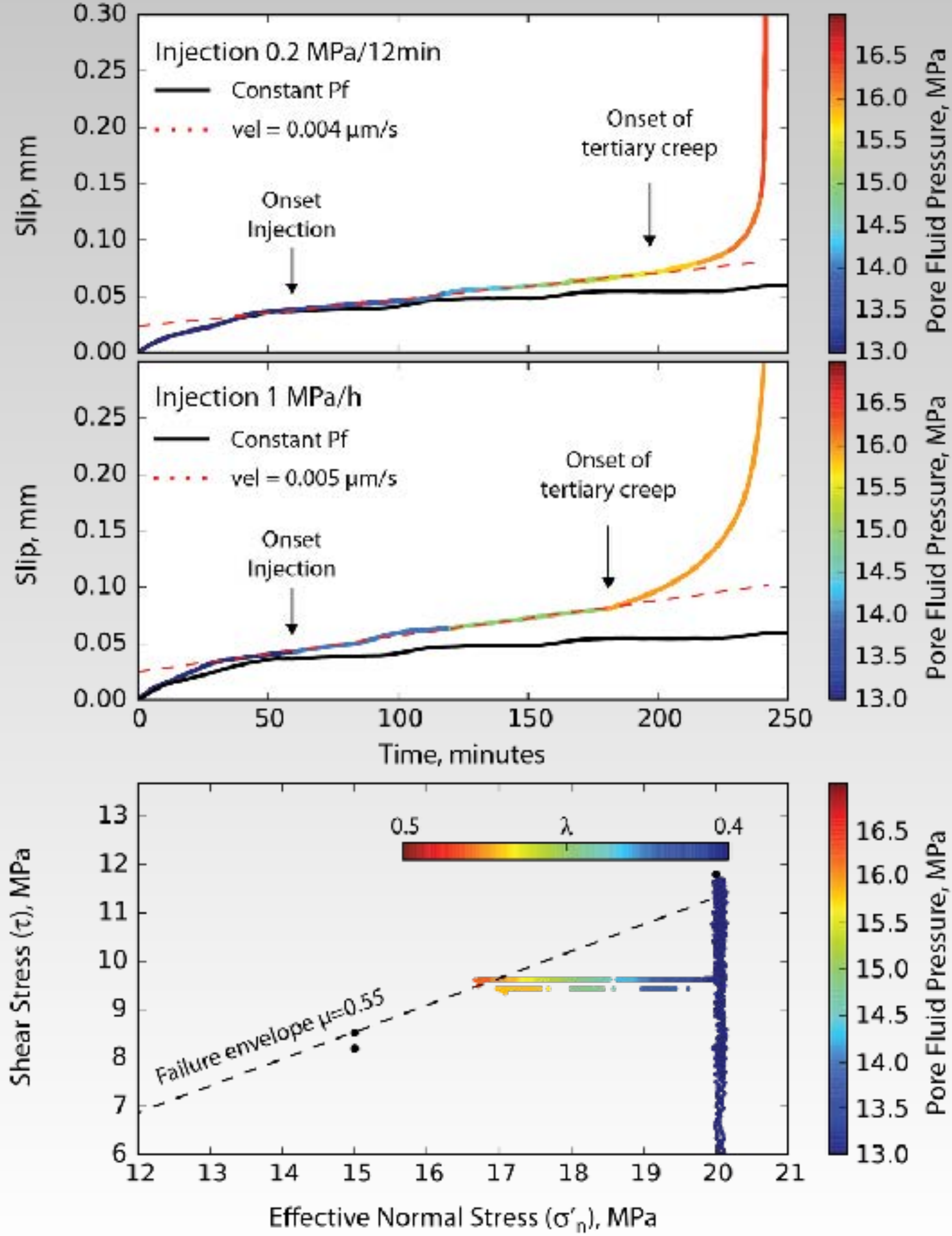
2) Secondary creep
aseismic creep at v~50nm/s corresponding to strain rates of 2×10^{-4} s^{-1}

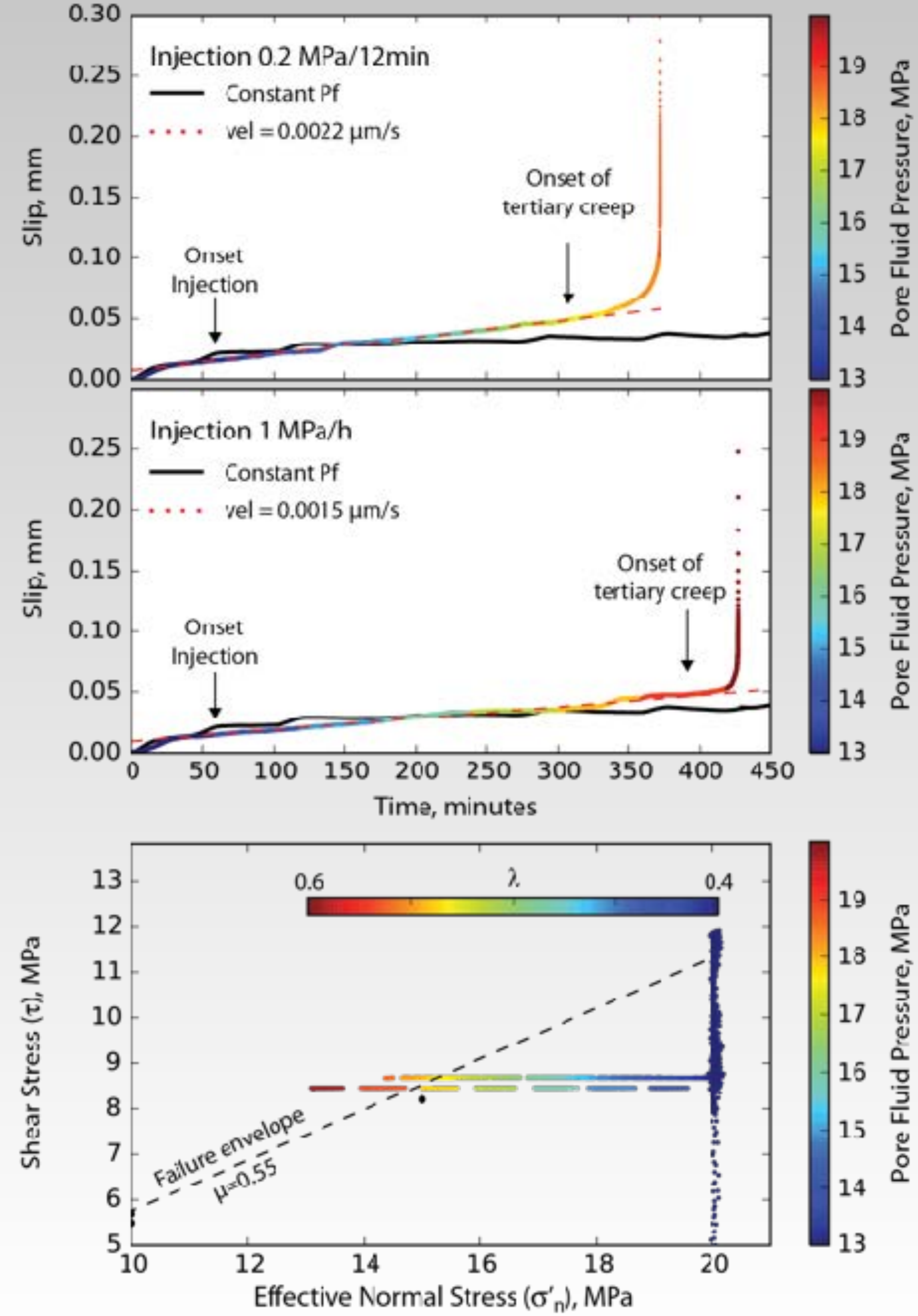
3) Tertiary creep
begin when we meet the criterion for reactivation
the acceleration preceding dynamic failure least for ~1h

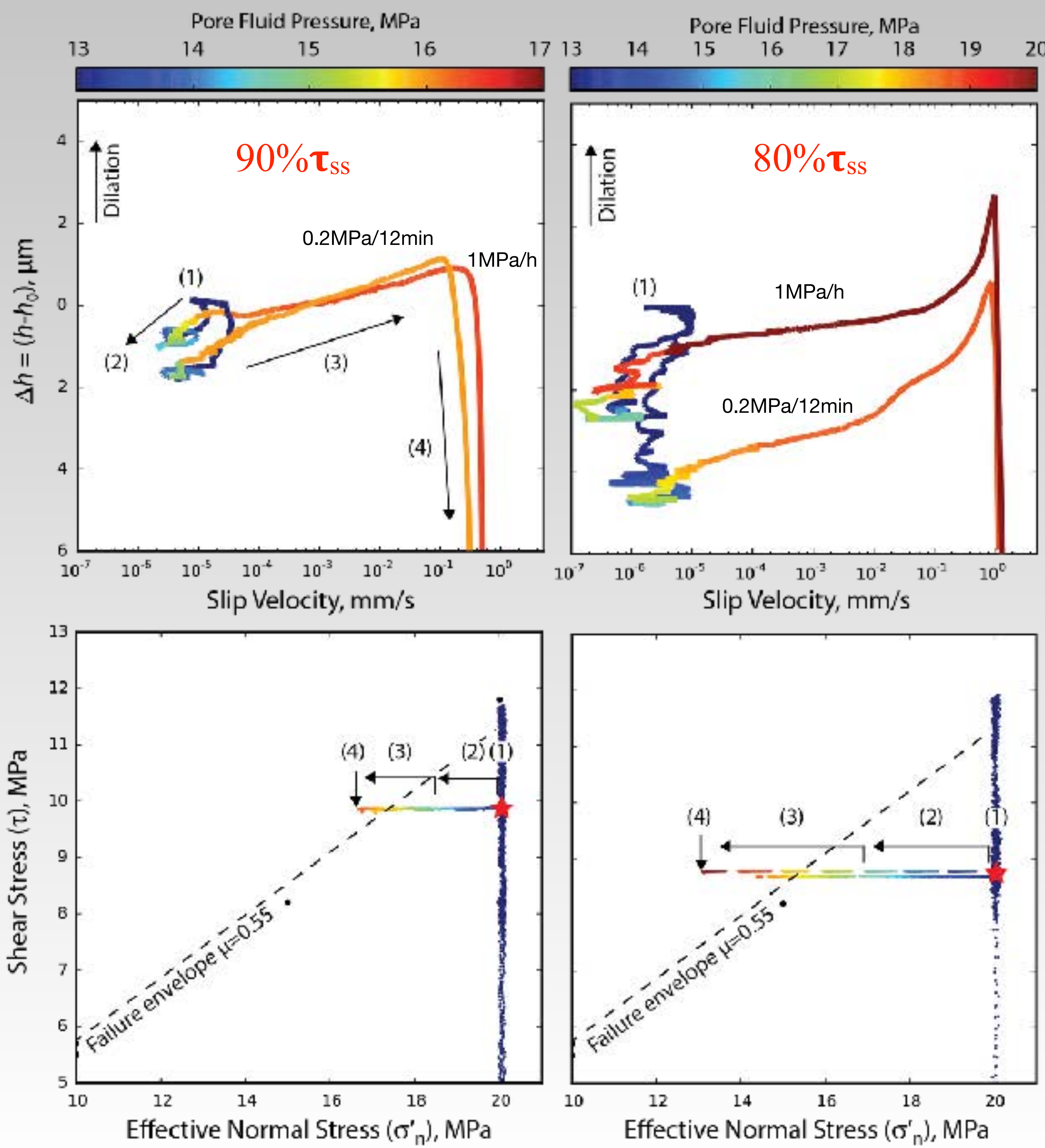
An increase in pore fluid pressure causes fault reactivation and failure with fault slip reaching slip velocities of 1 to 2 mm/s

Scuderi et al., 2017 *EPSL*

90%τ_{ss} / 80%τ_{ss}







Fault zone deformation characterized by:

(1-2) During aseismic creep fault gouge compacts

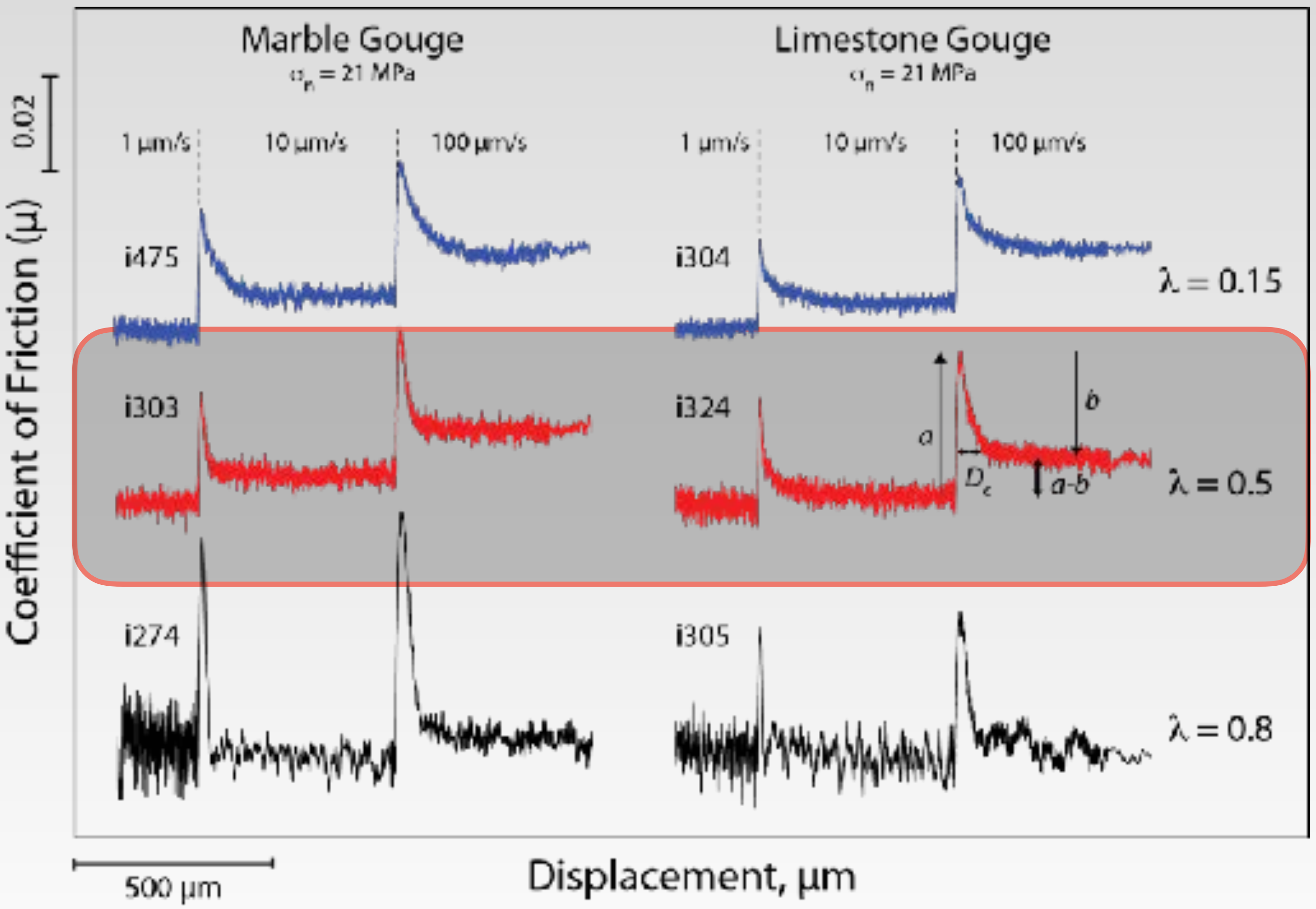
(3) Accelerated fault creep is associated with dilation

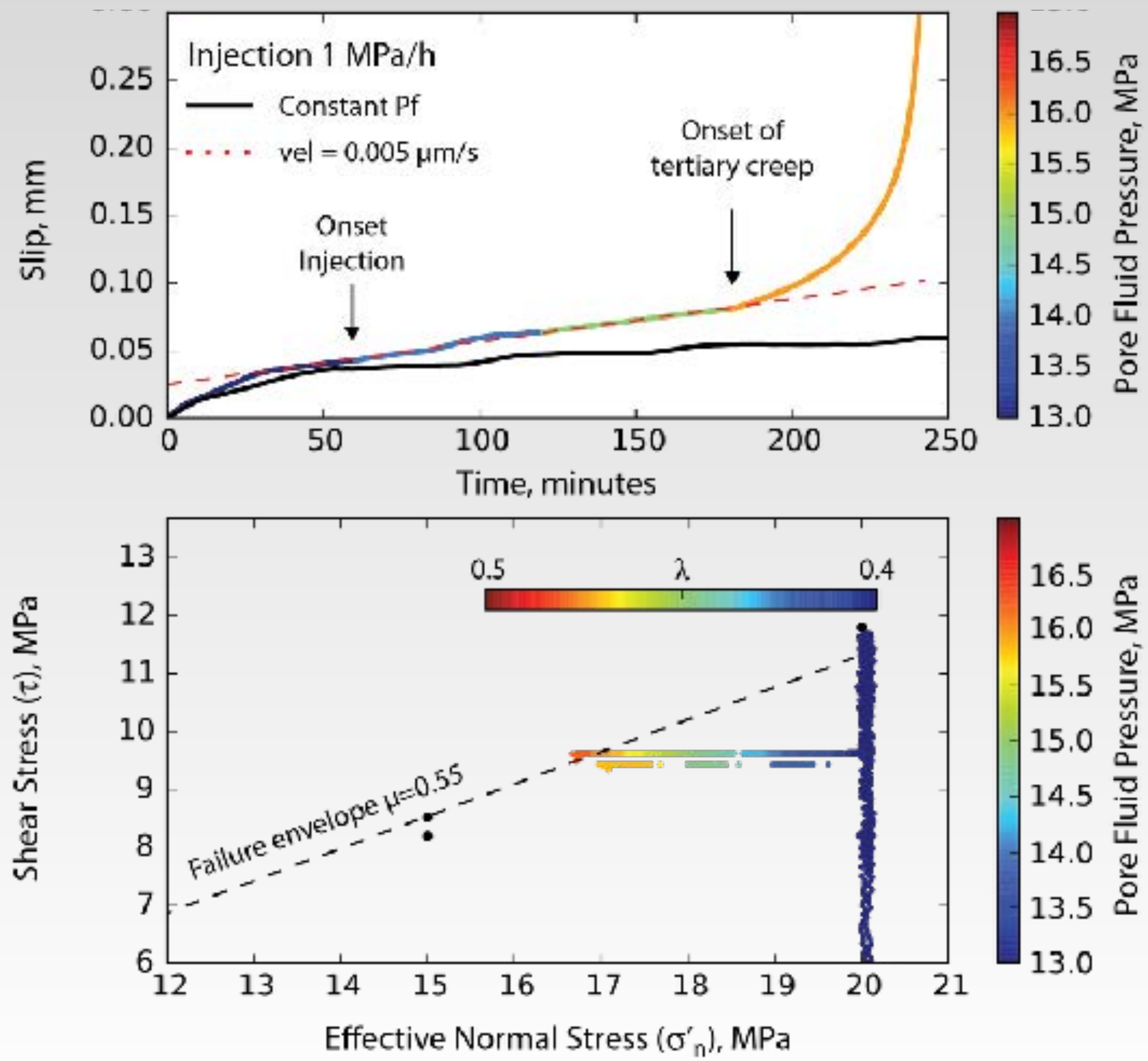
(4) During co-seismic slip fault gouge undergo compaction

Fault Reactivation vs. Frictional Slip Stability
The conundrum of fluid overpressure in earthquake triggering

Rate- and State- Friction analysis shows that at the same applied stress field and for similar values of pore fluid factor, λ, the fault has velocity strengthening behavior (i.e. aseismic behavior).

Creep tests show that over pressurized fluids cause accelerated creep leading to dynamic instability once the criterion for fault reactivation is met.





Micro-mechanical model for fault zone deformation

Energy balance for a representative unit volume of fault gouge

(Marone et al., 1990; Bos&Spiers, 2002)

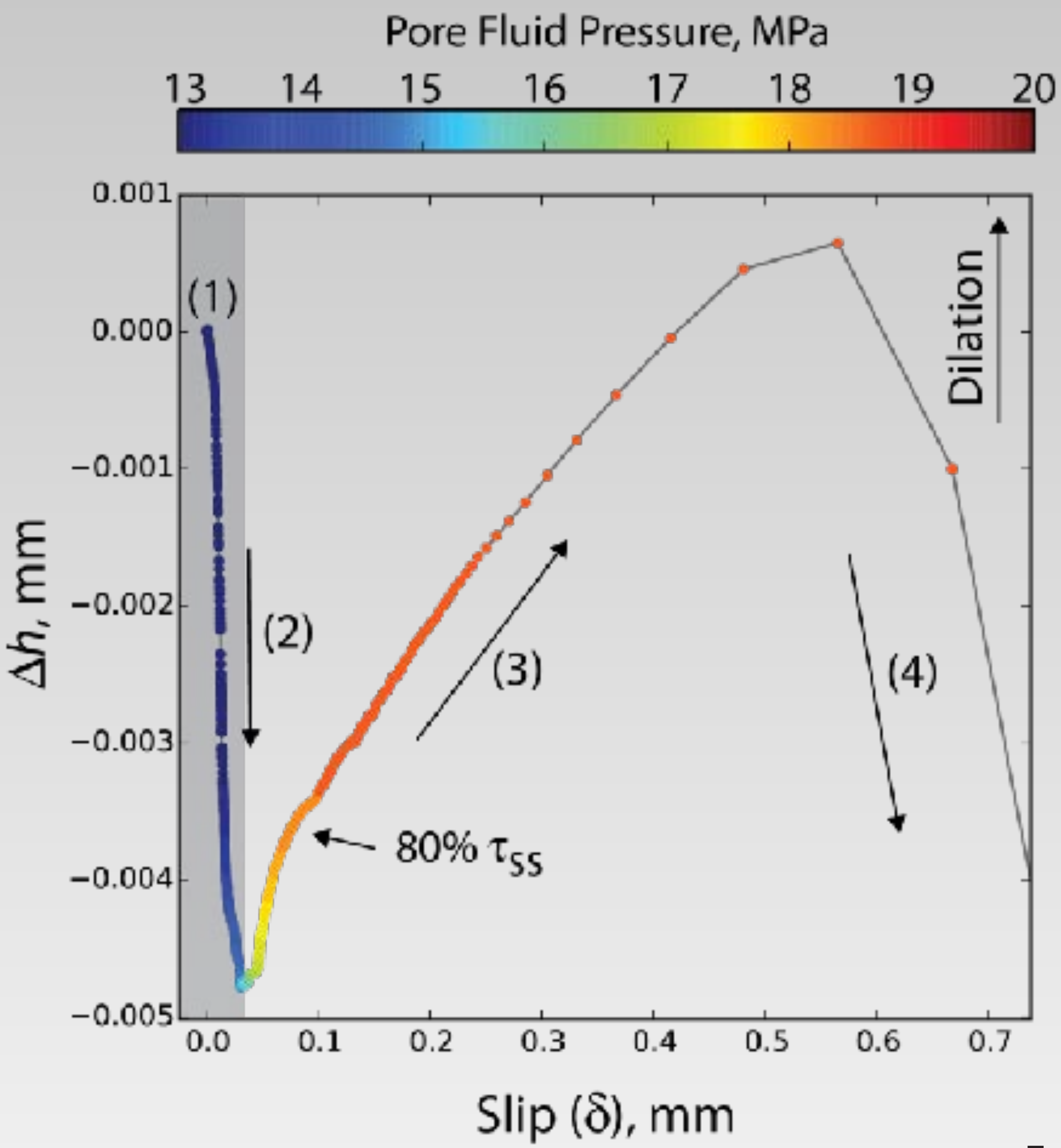
$$\tau = \tau_x + \frac{d\varepsilon}{d\gamma}\left(\sigma_n - P_f\right)$$

$d\varepsilon / d\gamma$ → For our experimental configuration → $dh / d\delta$

$$\tau = \tau_x + \frac{dh}{d\delta}\left(\sigma_n - P_f\right)$$

- τ: Shear Stress during creep experiments is imposed at constant values
- τ_x: represents the sum of all **microscale dissipative processes** per unit volume that include grain fracture, frictional sliding of grain contacts, pressure solution and crystal plasticity.
- $\frac{dh}{d\delta}$: Volumetric variations per unit of slip
- $\left(\sigma_n - P_f\right)$: Effective Stress

Micro-mechanical model for fault zone deformation



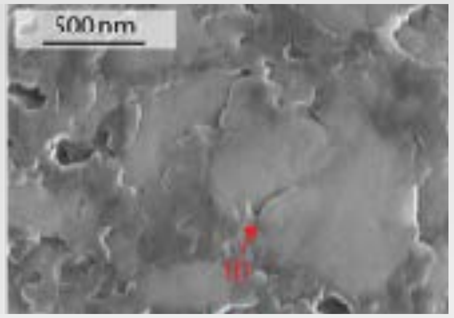
Energy balance for unit volume of fault gouge

(Marone et al., 1990; Bos&Spiers, 2002)

$$\tau = \tau_x + \frac{dh}{d\delta}\left(\sigma_n - P_f\right)$$

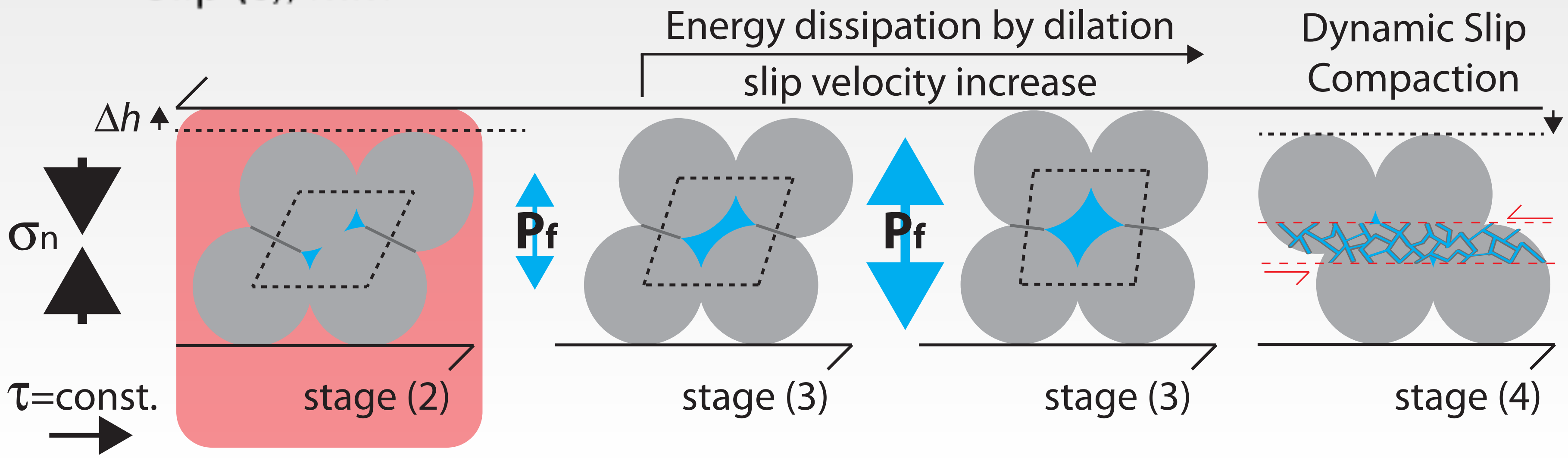
Constant

Increases due to microscale dissipative processes such as pressure solution

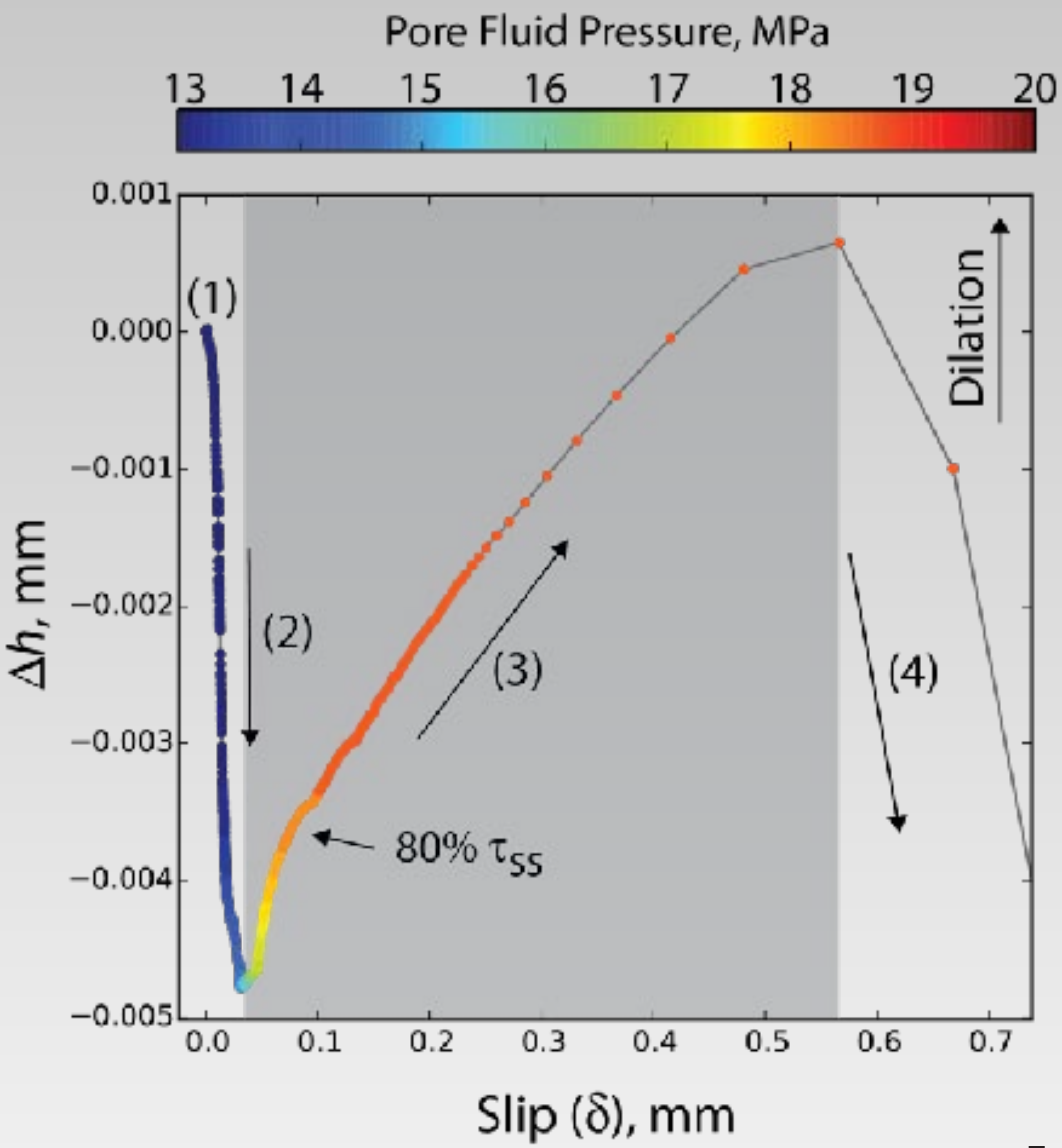


To maintain the energy balance fault gouge compacts

Constant



Micro-mechanical model for fault zone deformation



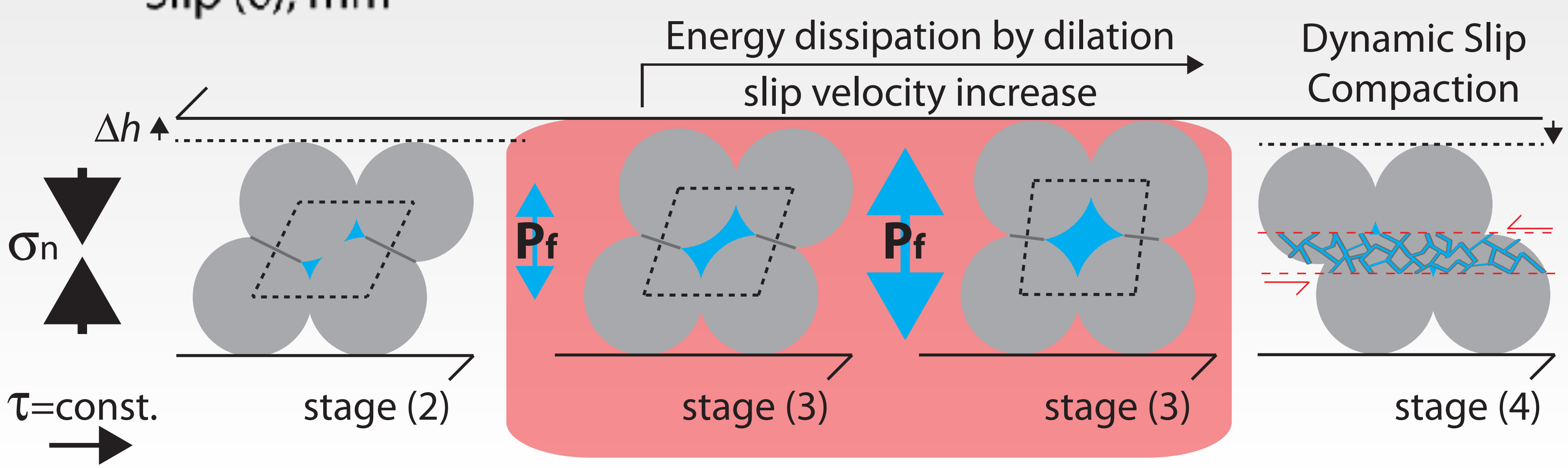
Energy balance for unit volume of fault gouge
(Marone et al., 1990; Bos&Spiers, 2002)

$$\tau = \tau_x + \frac{dh}{d\delta}\left(\sigma_n - P_f\right)$$

Constant

The fault must dilate to dissipate the energy

The effective stress decreases due to fault pressurization causing a energy imbalance



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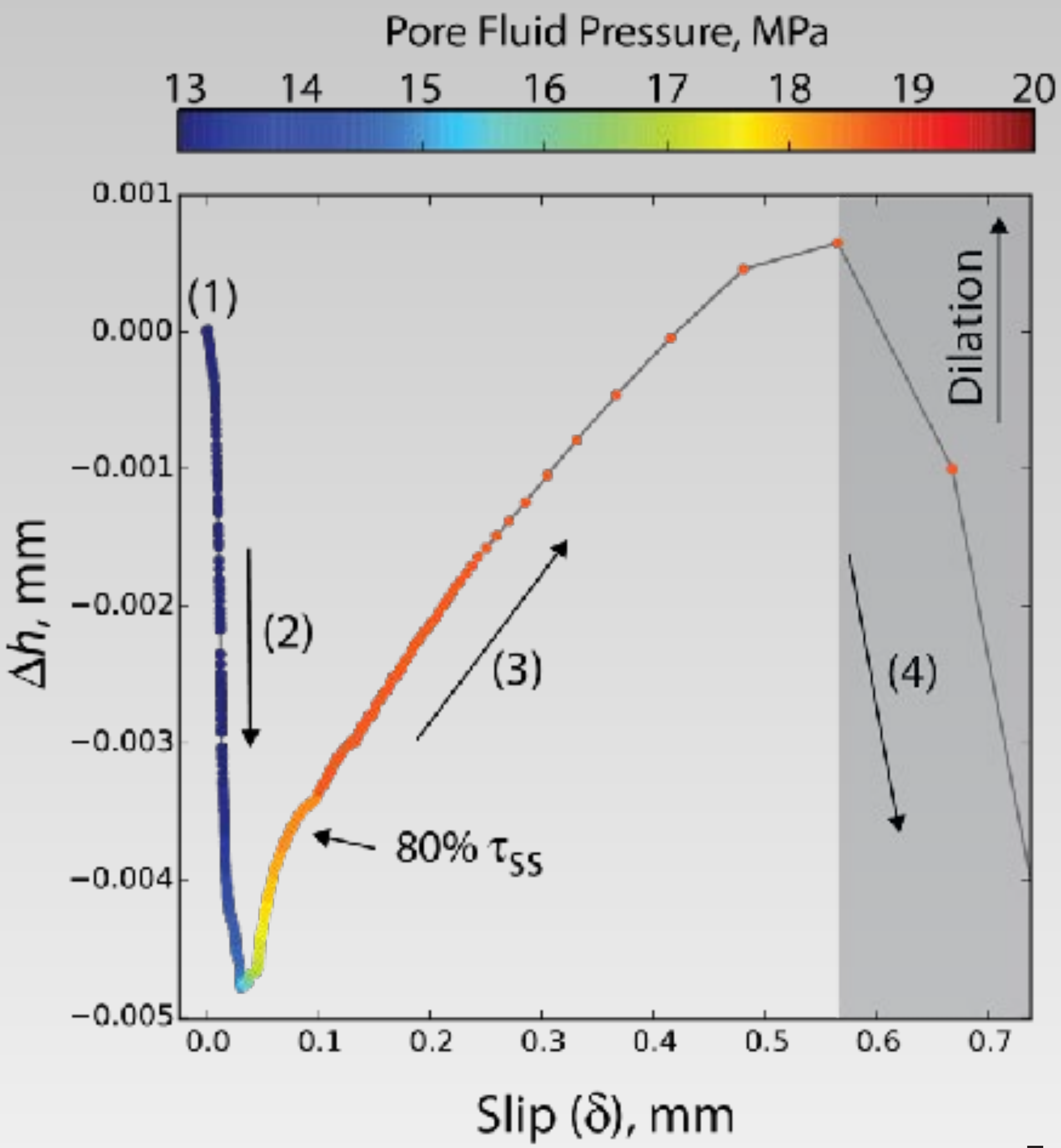
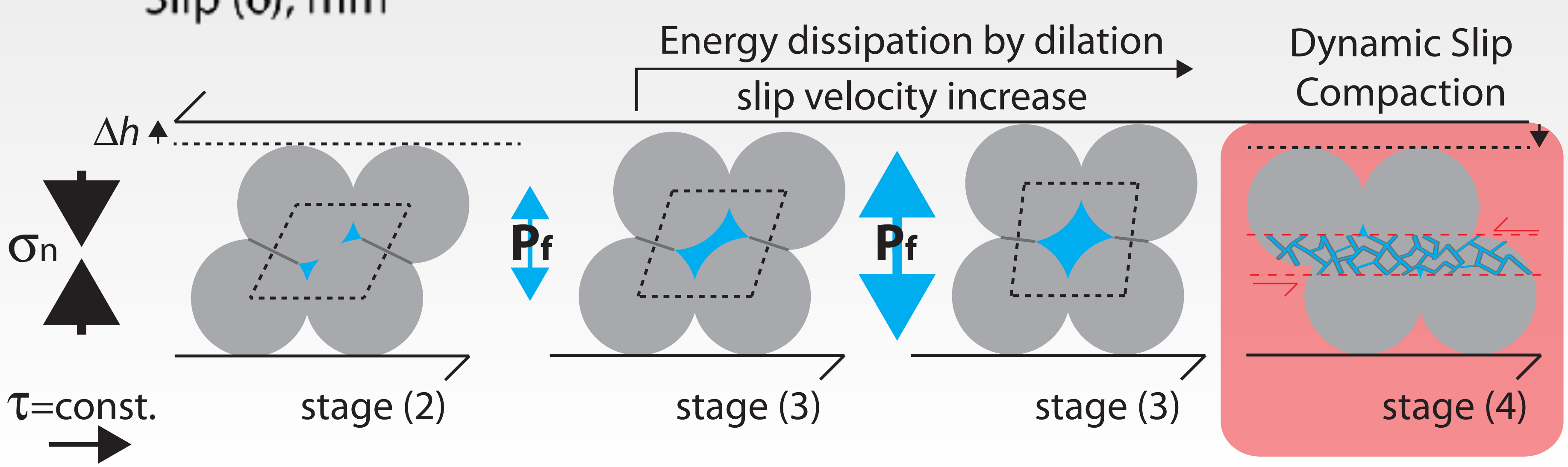


Energy balance for unit volume of fault gouge
(Marone et al., 1990; Bos&Spiers, 2002)

$$\tau = \tau_x + \frac{dh}{d\delta}\left(\sigma_n - P_f\right)$$

Constant

Fault dilation is no longer an efficient mechanism for energy dissipation, the fault system reacts with fracturing and shear localization resulting in dynamic slip propagation.



Summary:

- Pore fluid pressurization can promote accelerated fault slip in fault gouge that is characterized by velocity strengthening behavior (i.e. aseismic creep).
- Fault slip behavior is well described by an energy balance that consider the interaction between fault zone deformation and surrounding stress field .
- The duality between the rate strengthening behavior and the observed nucleation of dynamic instability can be interpreted by considering the different dynamics of micro mechanical processes and stress state evolution between creep experiments and constant displacement rate experiment used to retrieve RSF parameters.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M.M. Scuderi, C. Collettini, C. Marone

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