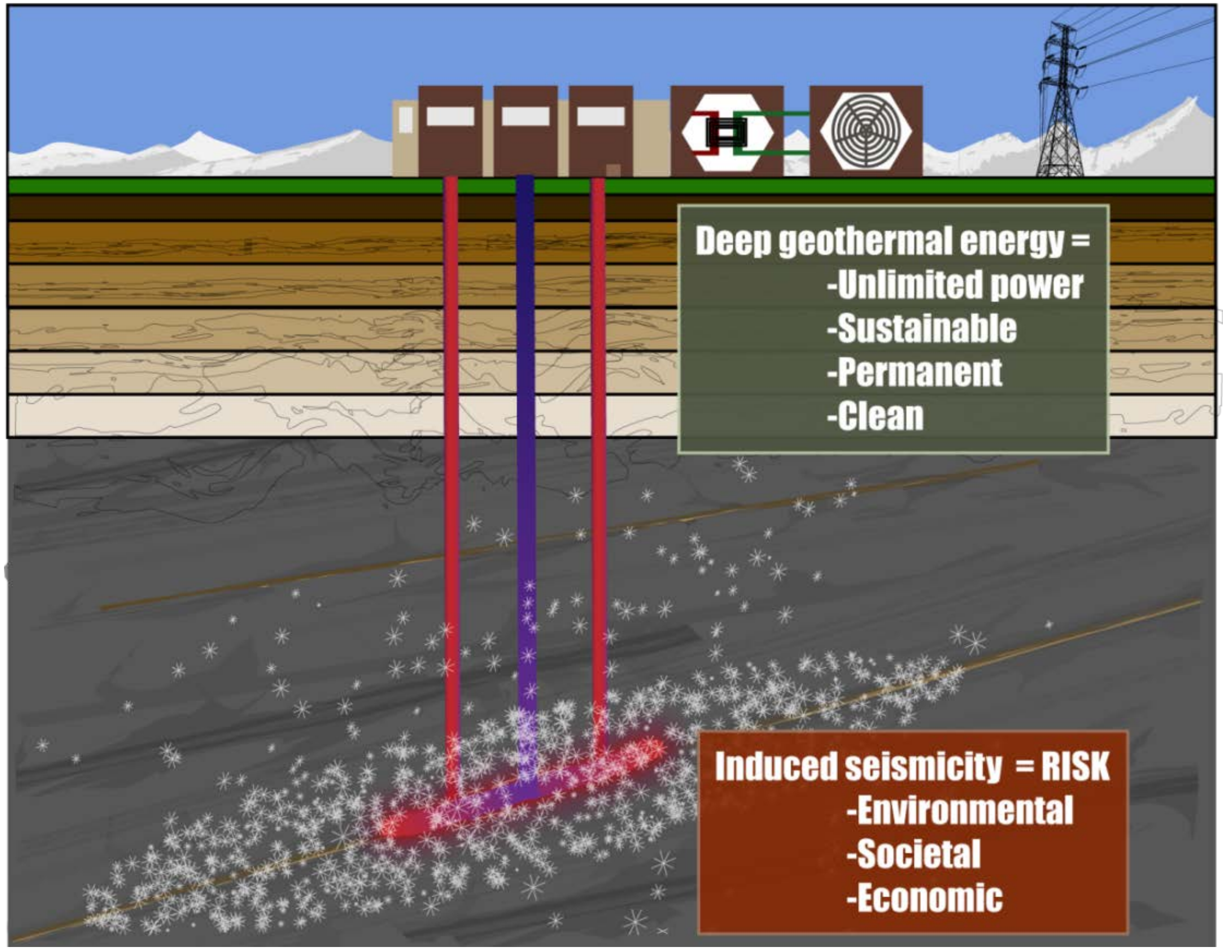
Rock and fluid thermodynamics control the dynamics of induced earthquakes

M. Acosta, F. Passelègue, A. Schubnel et M. Violay

(mateo.acosta@epfl.ch)

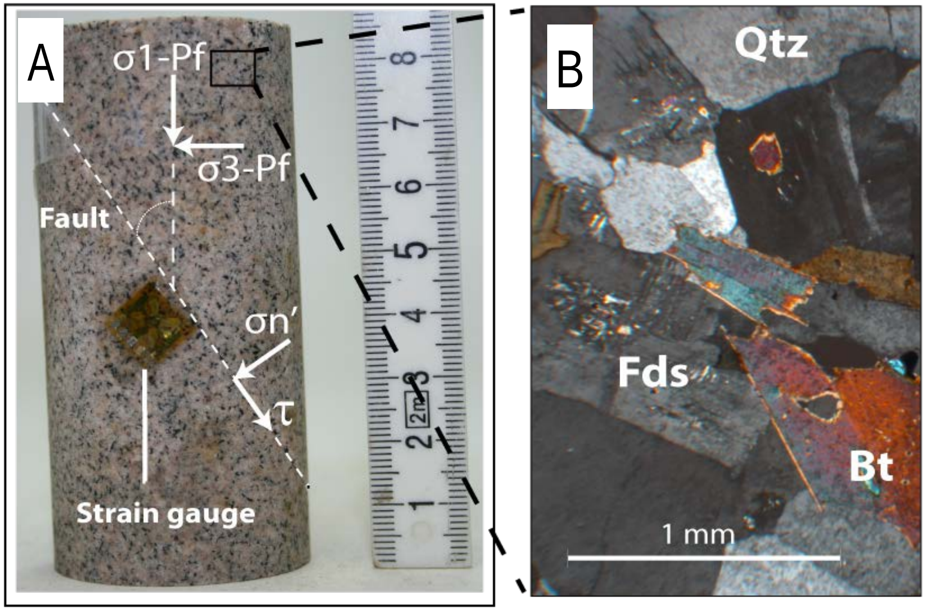
Context – Induced Seismicity in Enhanced Geothermal Systems



UNDERSTAND THE MICROPHYSICAL INTERACTIONS BETWEEN PORE FLUID AND RESERVOIR FAULTS DURING INDUCED EARTHQUAKES

Stick-Slip experiments under Triaxial stress conditions

$$\sigma_1 > \sigma_2 = \sigma_3$$



➢ **Samples:**

30 ° Saw cut westerly granite cylinders (φ=40 mm ; H=88 mm)

➢ ***Instrumentation:***

- **External measurements:**

  $\sigma_1 ; \sigma_3 ; p_f ; \varepsilon_1$

- **Internal sensors:**

  Near fault strain gauges

Best analogue for earthquakes

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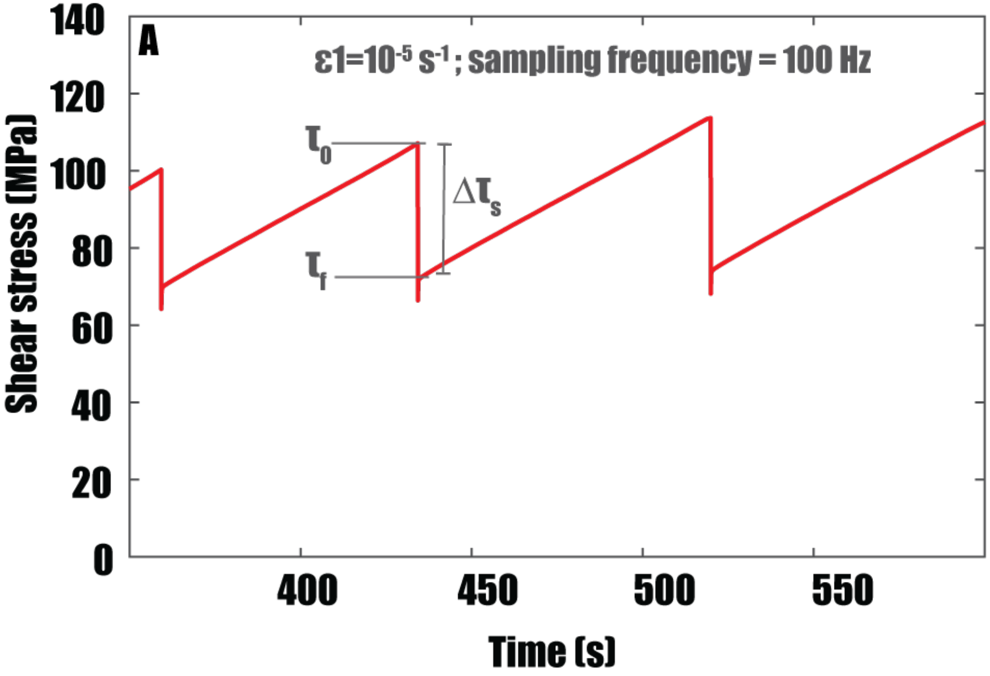
Methods- Stick-slip experiments



Elastic loading until shear strength is reached

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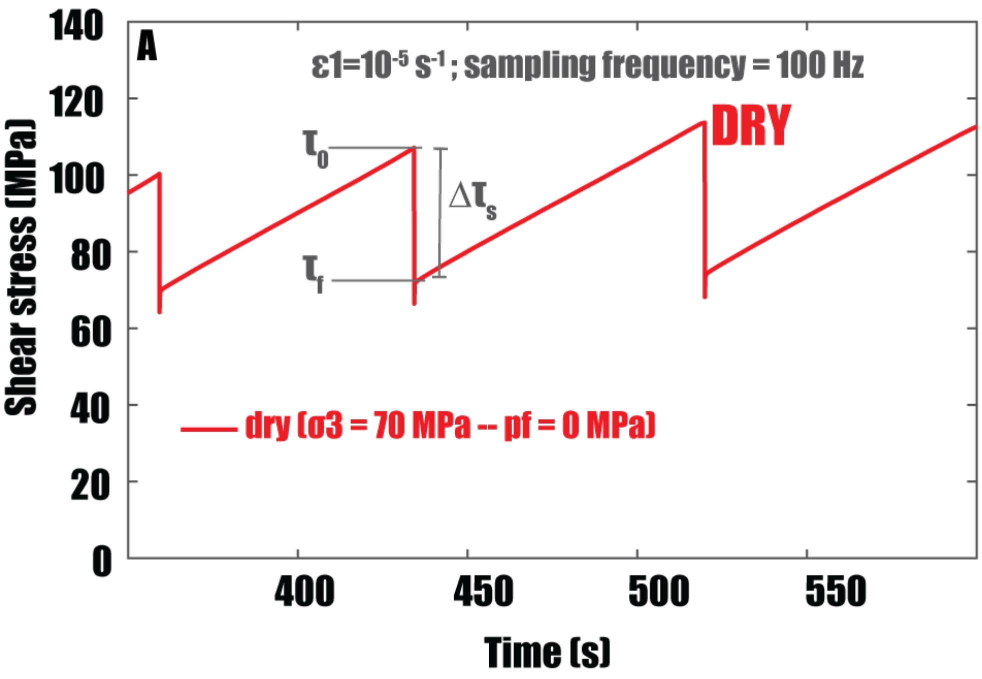
Results- 100 Hz measurements



Pceff=Pc-Pf= 70 MPa

Pf held constant during experiment

Three pore pressure configurations (**DRY**, **Low Pf**, **High Pf**)

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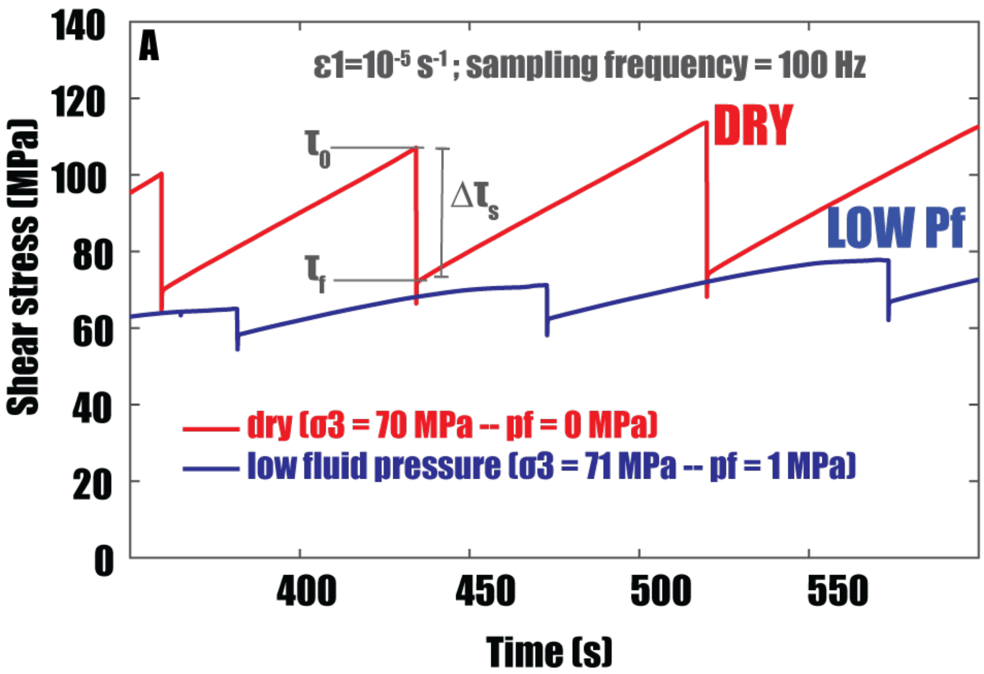
Results- 100 Hz measurements



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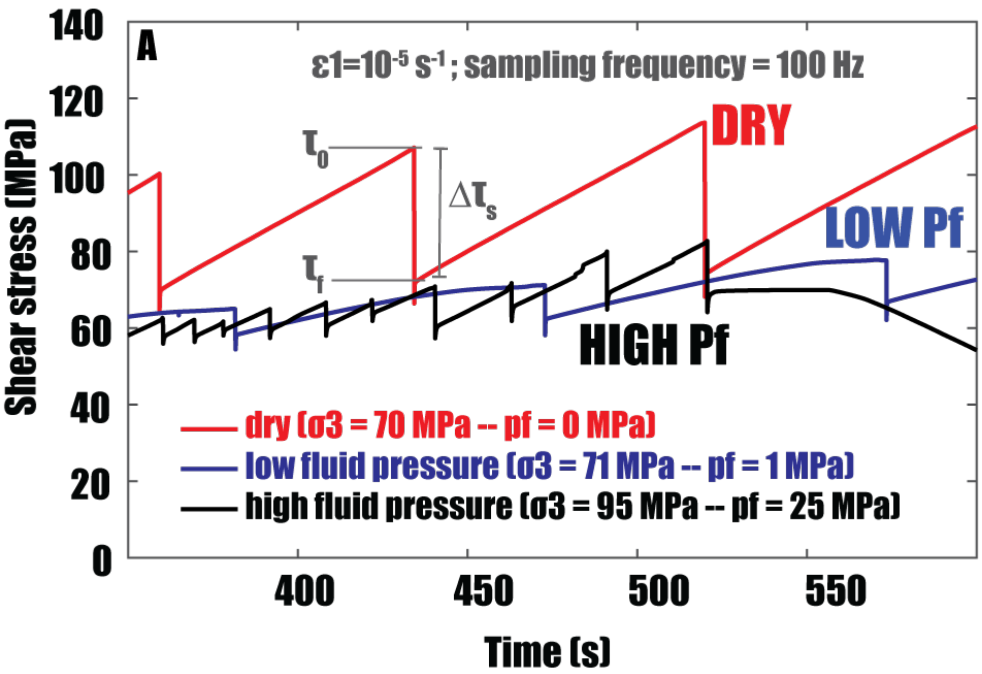

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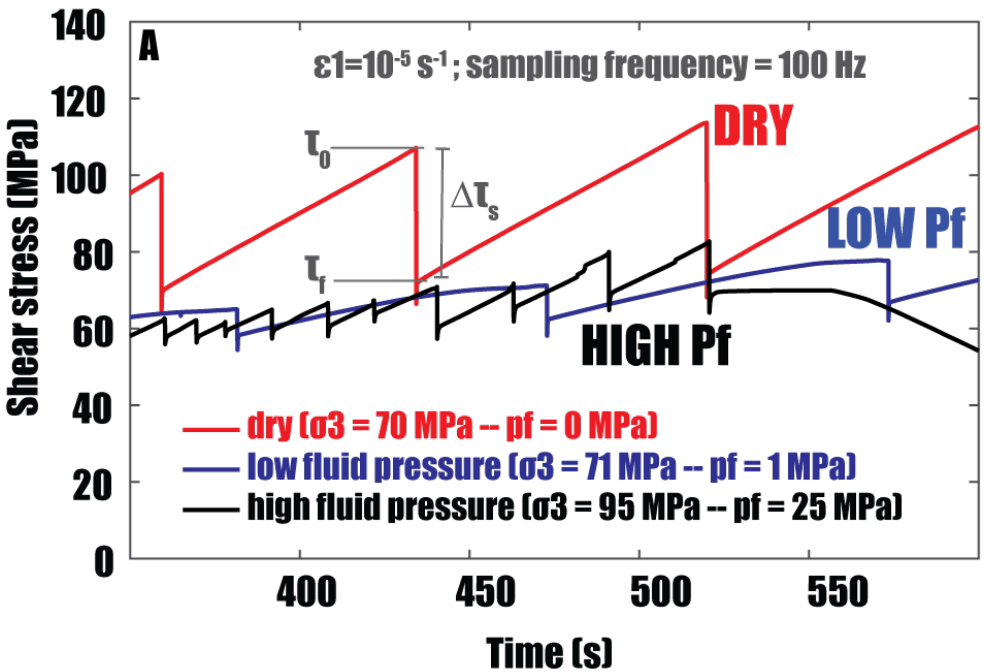

Water Pressure

==

Lower coulomb strength.

Pceff=Pc-Pf= 70 MPa

Pf held constant during experiment

Three pore pressure configurations (**DRY**, **Low Pf**, **High Pf**)

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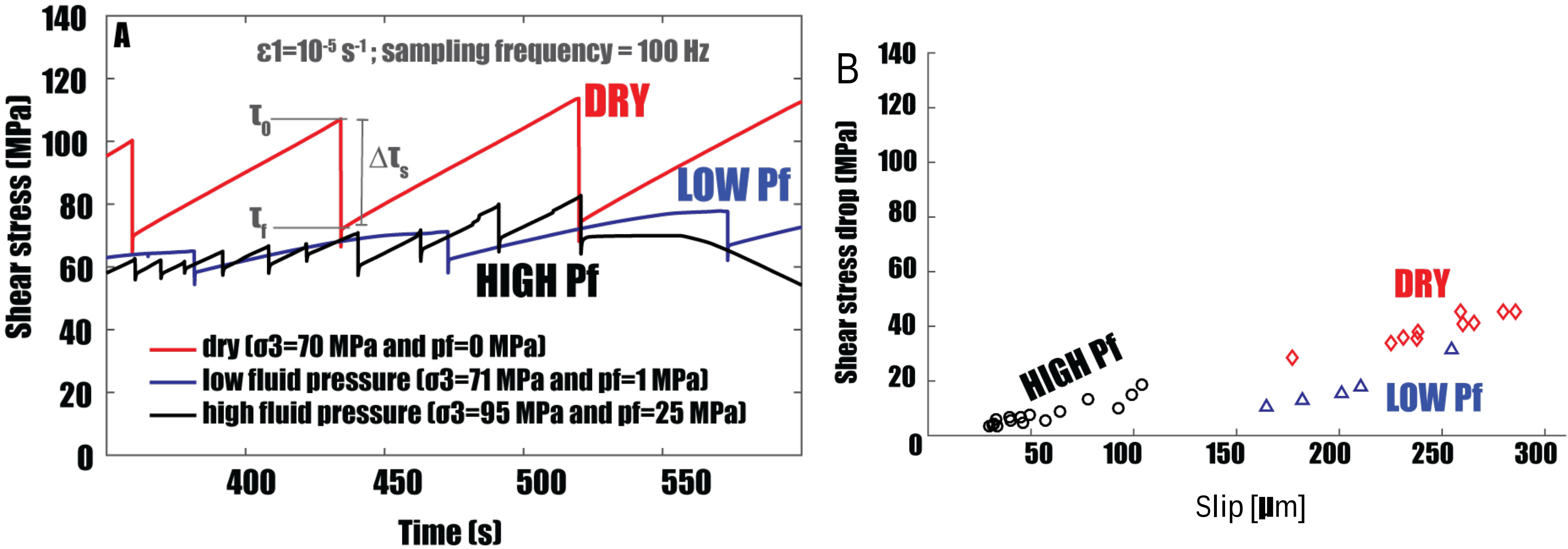
Results- Static stress drop .Vs. Slip



Pceff=Pc-Pf= 70 MPa

Pf held constant during experiment

Pore pressure = low <u>static</u> stress drops

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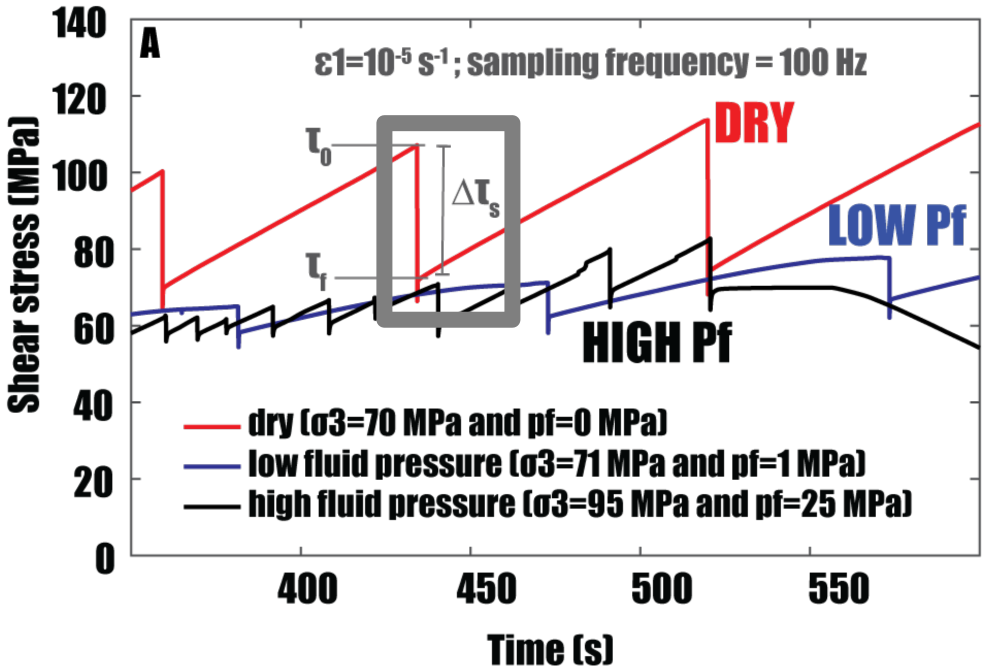
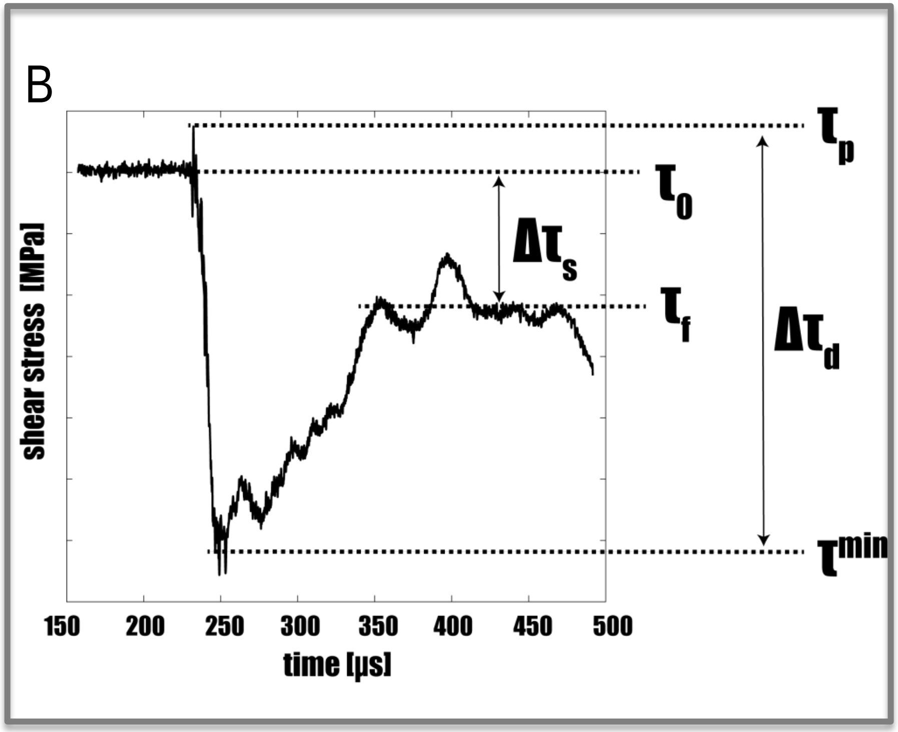
Results – Dynamic stress drop





Pceff=Pc-Pf= 70 MPa

Pf held constant during experiment

Dynamic recording of near fault stress

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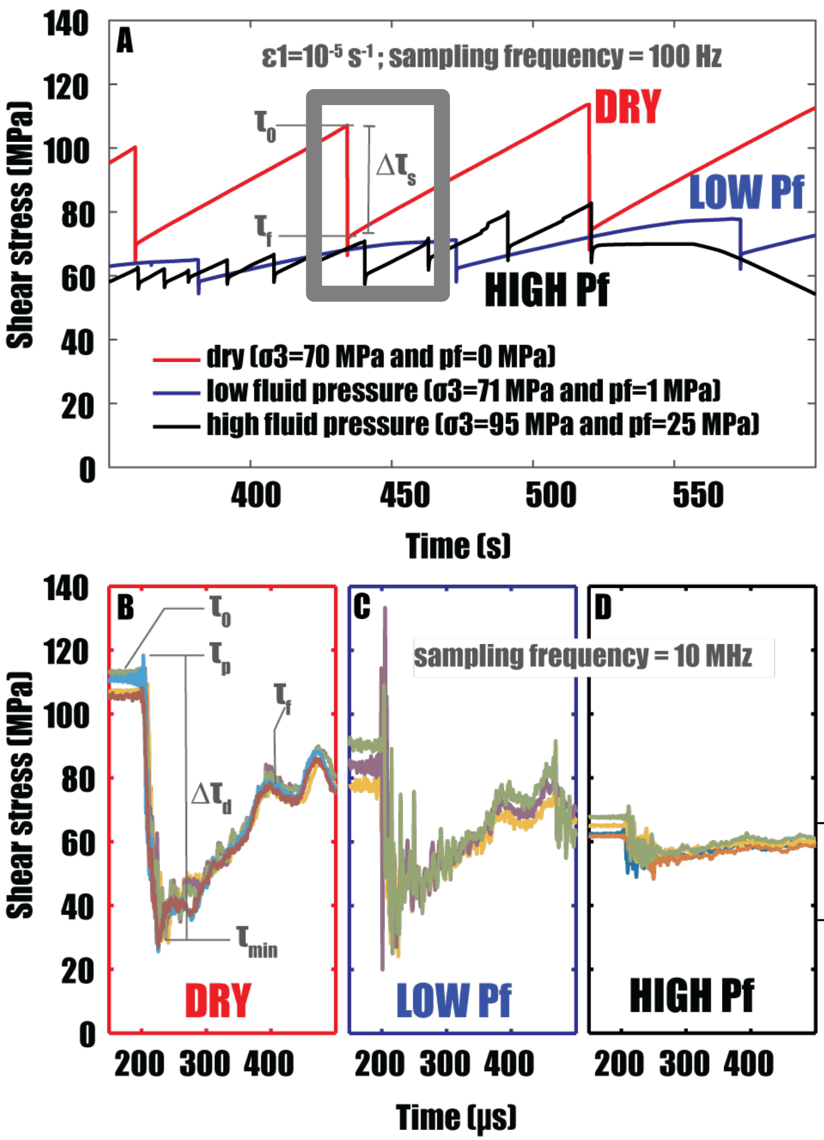
Results – Dynamic stress drop



1 curve = 1 dynamic event

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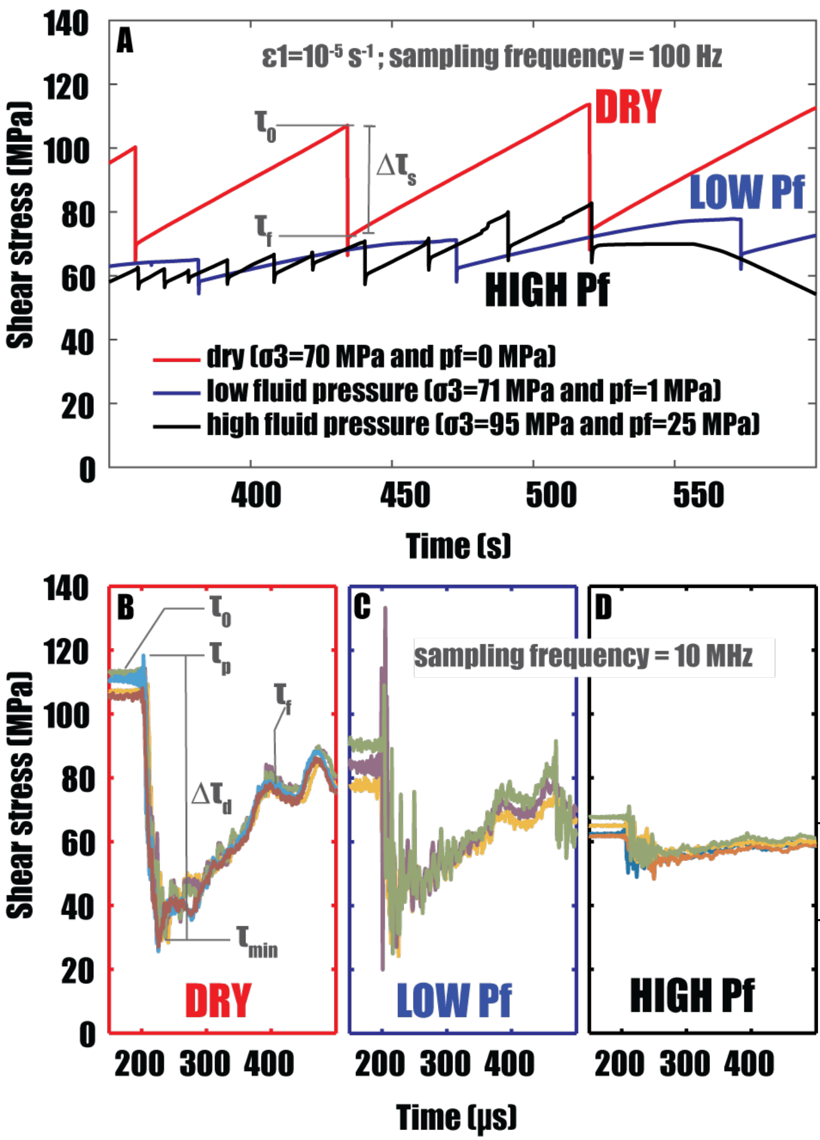
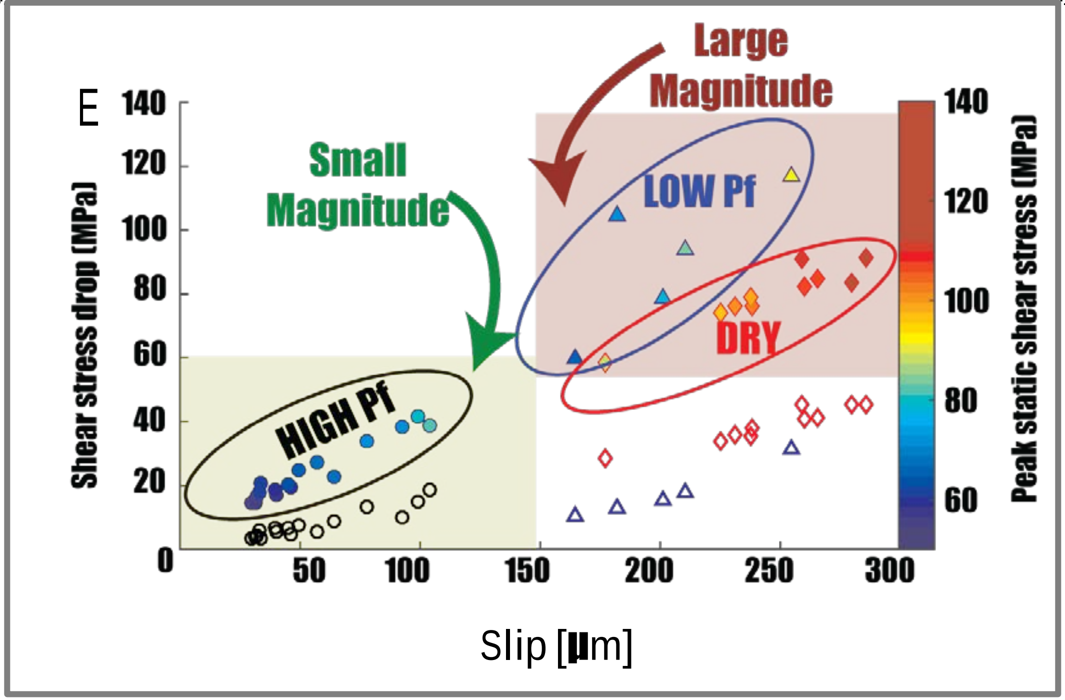
Results – Dynamic stress drop .Vs. Slip





Largest dynamic stress drops at **Low Pf**

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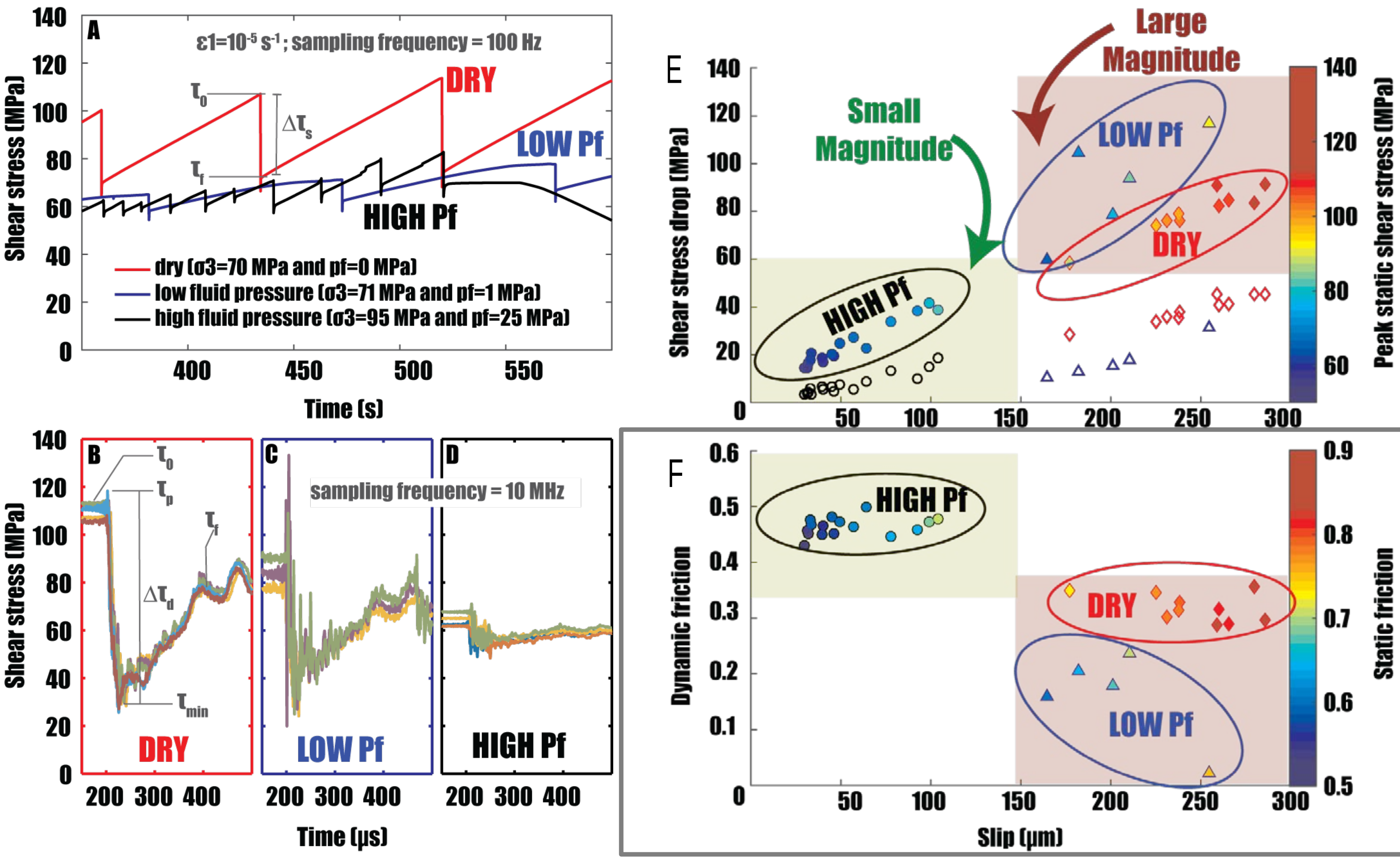
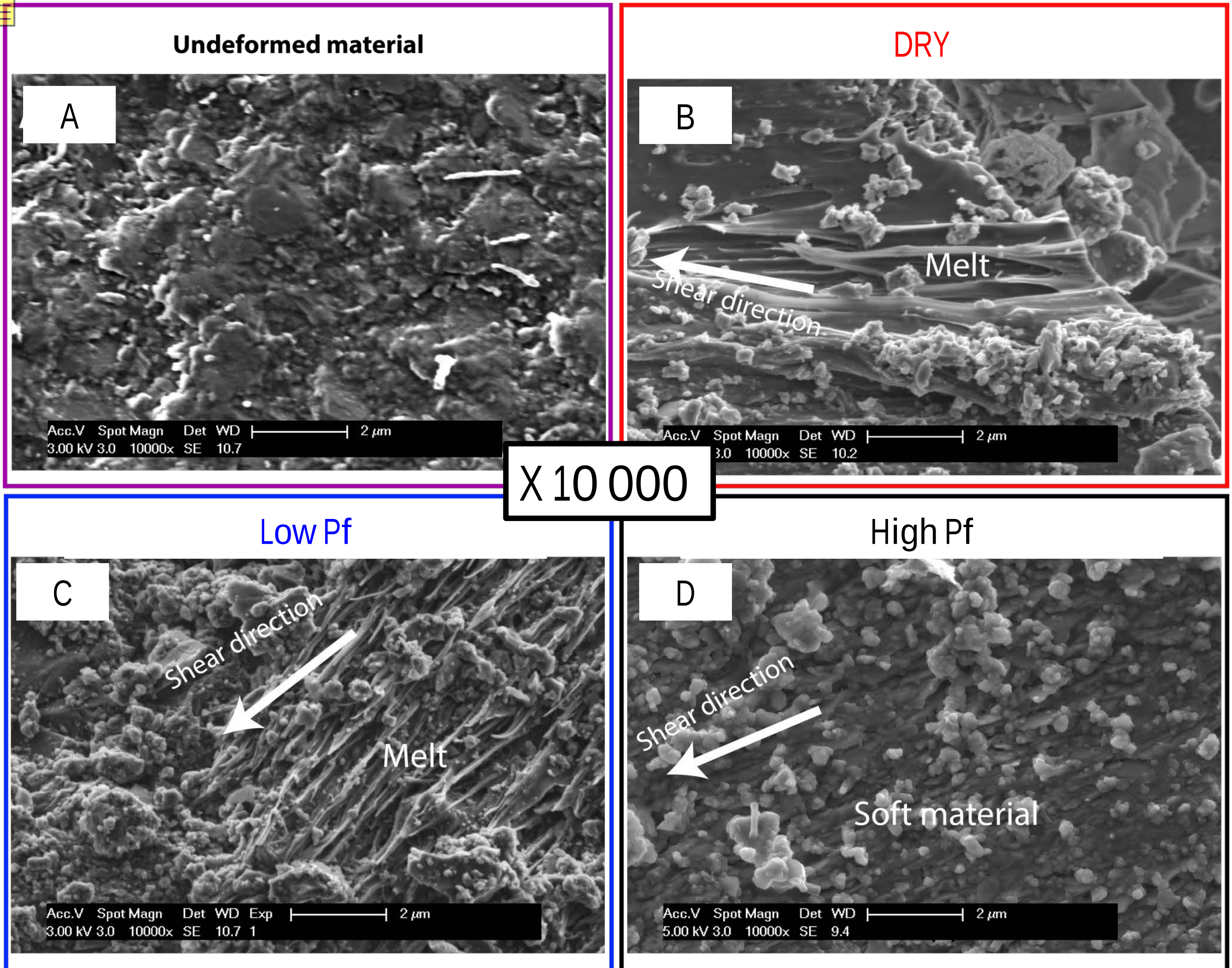
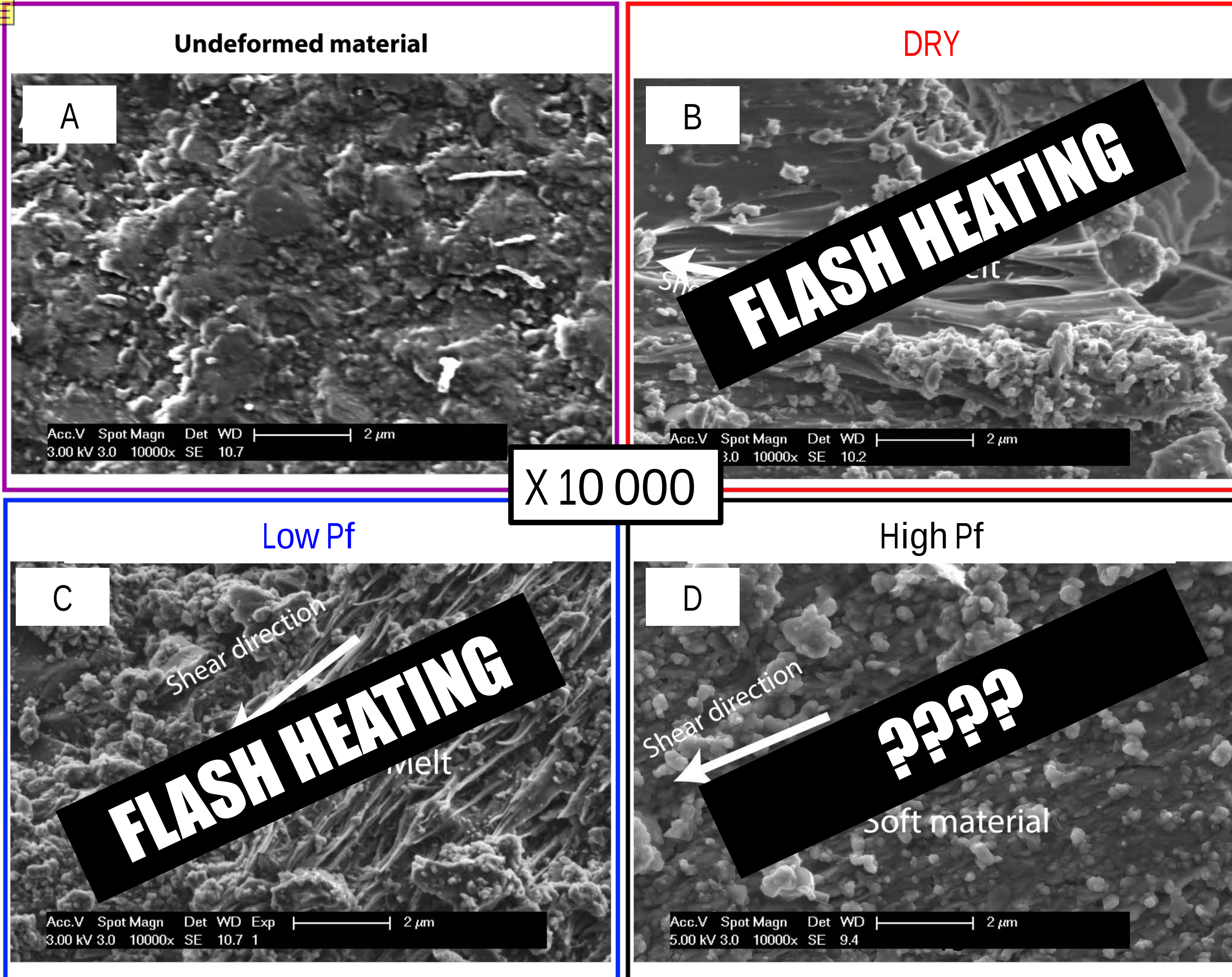
Results – Dynamic Friction




Undeformed material
A
Acc.V Spot Magn Det WD 2 µm
3.00 kV 3.0 10000x SE 10.7
DRY
B
Melt
Shear direction
Acc.V Spot Magn Det WD 2 µm
3.0 10000x SE 10.2
X 10 000
Low Pf
C
Shear direction
Melt
Acc.V Spot Magn Det WD Exp 2 µm
3.00 kV 3.0 10000x SE 10.7 1
High Pf
D
Shear direction
Soft material
Acc.V Spot Magn Det WD 2 µm
5.00 kV 3.0 10000x SE 9.4

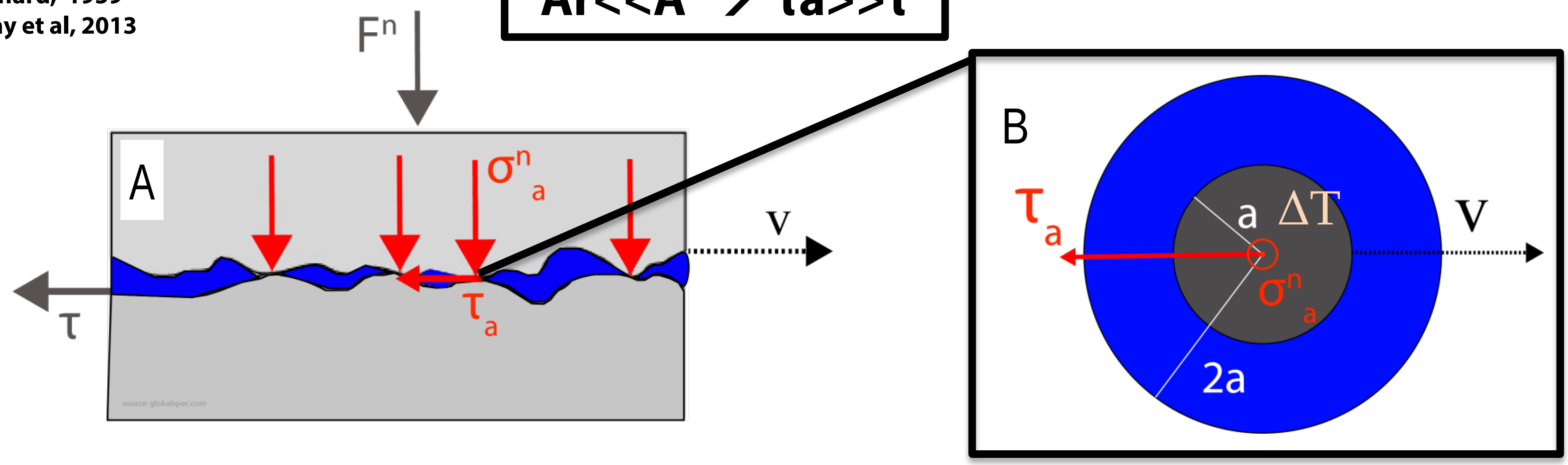


Undeformed material
A
Acc.V Spot Magn Det WD 2 µm
3.00 kV 3.0 10000x SE 10.7
DRY
B
FLASH HEATING
Acc.V Spot Magn Det WD 2 µm
3.0 10000x SE 10.2
X 10 000
Low Pf
C
Shear direction
FLASH HEATING
Melt
Acc.V Spot Magn Det WD Exp 2 µm
3.00 kV 3.0 10000x SE 10.7 1
High Pf
D
Shear direction
????
Soft material
Acc.V Spot Magn Det WD 2 µm
5.00 kV 3.0 10000x SE 9.4

Asperity temperature model - Description

Bowden and Tabor, 1969
Archard, 1959
Violay et al, 2013

Ar<<A → τa>>τ



$$\Delta T = f\left(\tau_a, v\right) - g\left(T, \rho_w\left(P,T\right), C_{pw}\left(P,T\right)\right)$$

Heat source rate **Temperature buffering**

Flash Temperature = maximum transient temperature responsible for weakening

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Asperity temperature model - Description

Bowden and Tabor, 1969
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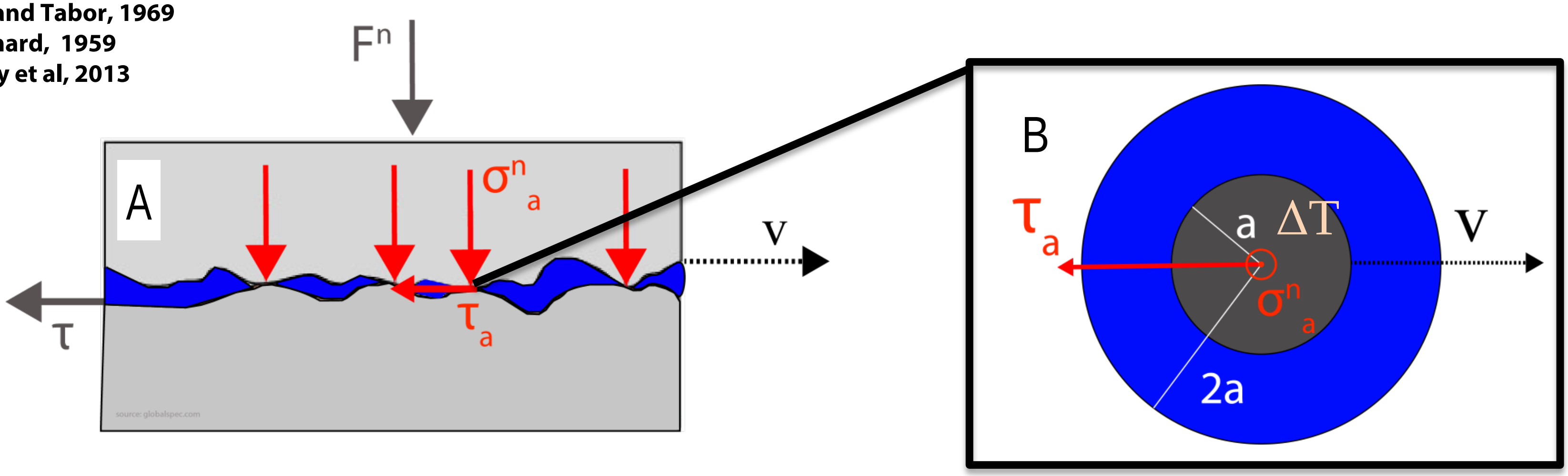

$$\Delta T = f\left(\tau_a, v\right) - g\left(T, \rho_w\left(P,T\right), C_{pw}\left(P,T\right)\right)$$

Heat source rate

Temperature buffering

Dependence on P & T !

Thermophysical properties of fluid depend on Pressure & Temperature

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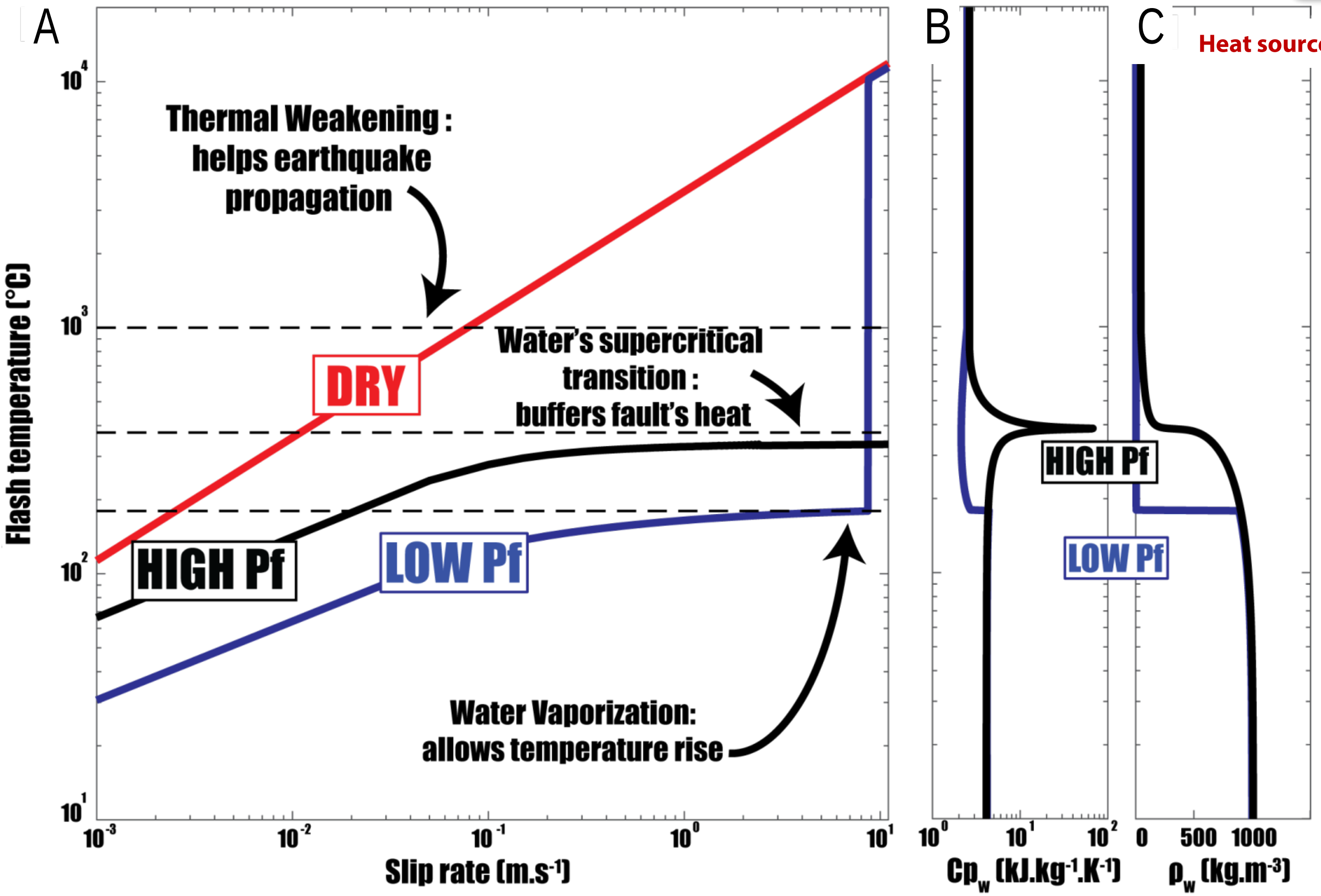
Asperity temperature model - Results

$$\Delta T = \frac{1}{\rho_{Q_z} C_{p_{Q_z}} \sqrt{k\pi}} \left(\tau_a v \sqrt{t_c} - \frac{V_w \rho_w}{t_c \pi a^2} \left(T C_{p_w} + L_w \right) \sqrt{t_c} \right)$$

Heat source rate

Temperature buffering



Thermodynamic phase transitions control Temperature rise

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Thermal pressurization model

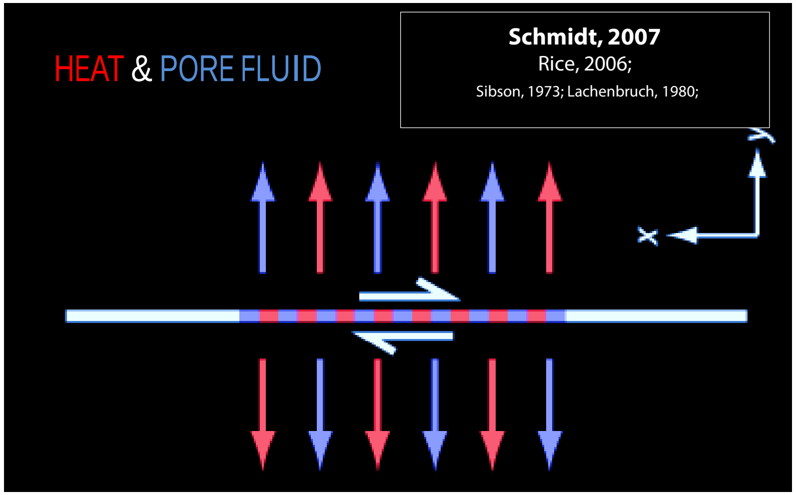
- Difference DRY and LOW Pf ??

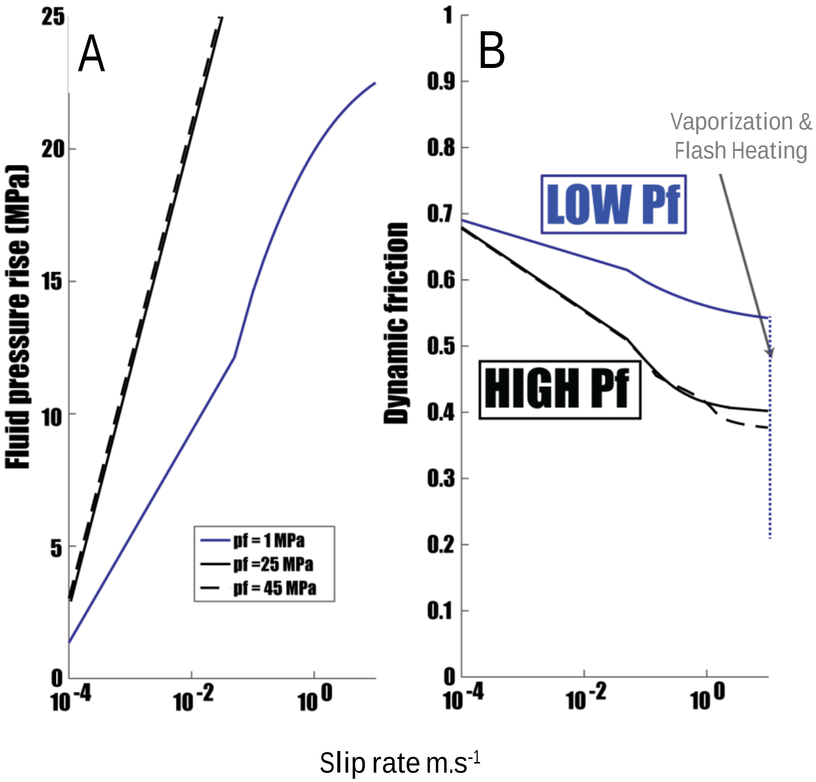
- Stress drop at HIGH PF ??

THERMAL PRESSURIZATION.

Rice, 2006

$$\Delta p = \frac{\Lambda}{1+\sqrt{\frac{\alpha_{hyd}}{\alpha_{th}}}}\Delta T$$





Thermal pressurization accounts for reduction in dynamic friction

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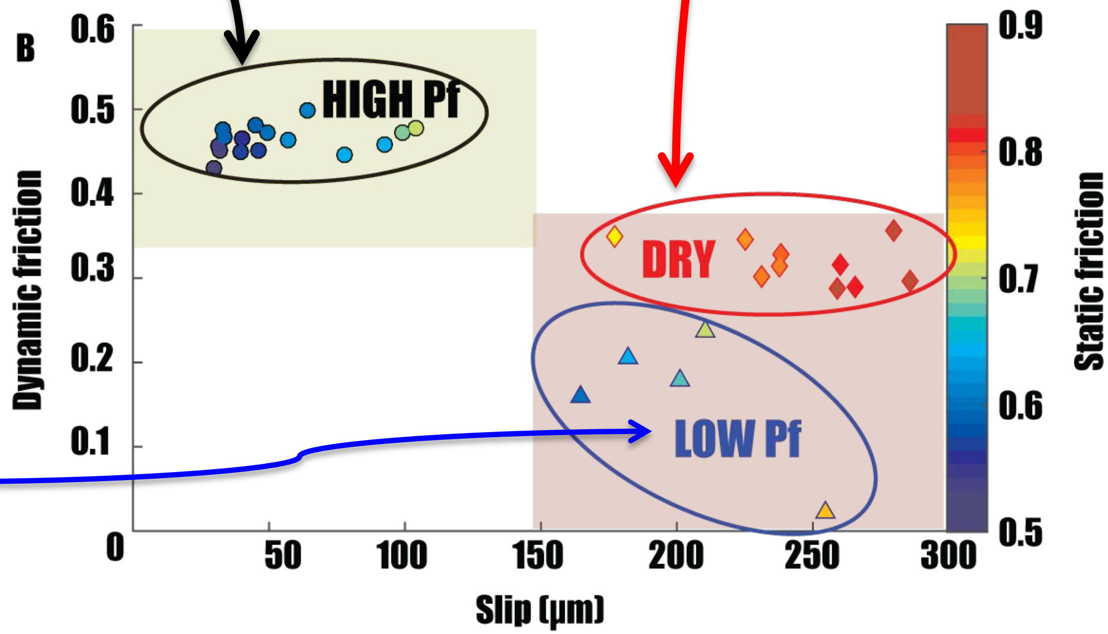
CONCLUSIONS.

Reduced THERMAL WEAKENING
=
THERMAL PRESSURIZATION

THERMAL WEAKENING
=
FLASH HEATING
(decomposition of contacts)

Enhanced THERMAL WEAKENING
=
FLASH HEATING + THERMAL PRESSURIZATION



Thermodynamics control dynamic weakening processes during earthquake rupture.

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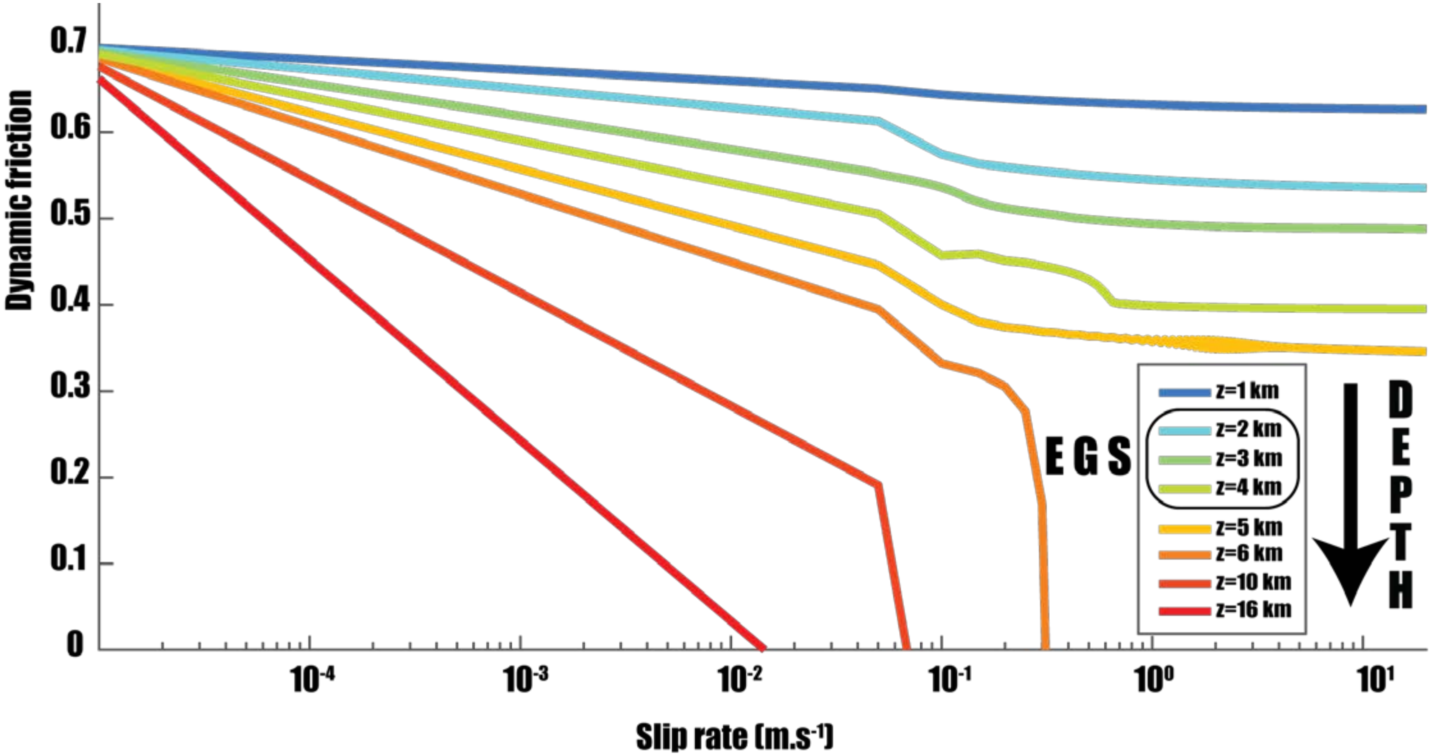
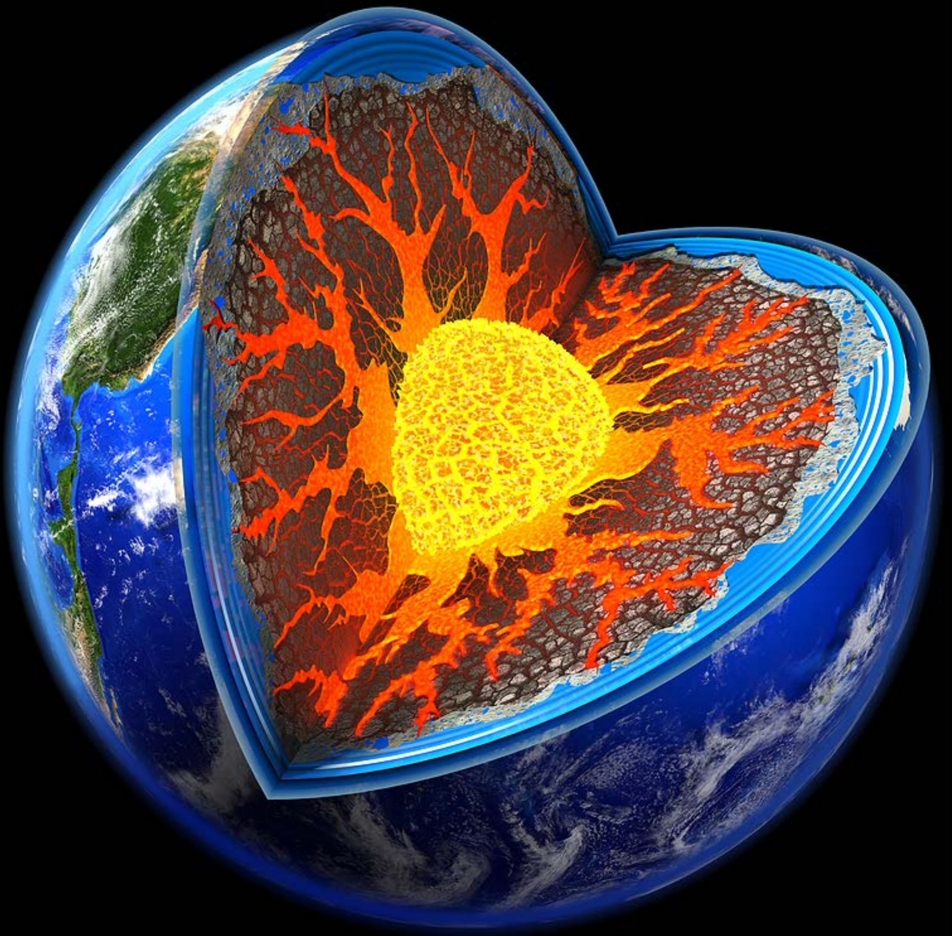
Careful! – σ_N Evolves with depth!

High Depth => **Higher stress** => **FLASH HEATING**



Thermophysical properties of water and rock
should be taken into account in physics based models



QUESTIONS ?

Asperity temperature model – Parameter description

$$\Delta T = \frac{1}{\rho_{Qz} C_{p_{Qz}} \sqrt{k\pi}} \left(\tau_a v \sqrt{t_c} - \frac{V_w \rho_w}{t_c \pi a^2} \left(T C_{p_w} + L_w \right) \sqrt{t_c} \right)$$

$\boldsymbol{\Delta T}$ in $^{\circ}C$ is the temperature rise at the contacting asperities.

$\boldsymbol{v}$ in $m.s^{-1}$ is the slip rate relative to the contacting asperities.

$\boldsymbol{t_c}$ in s is the average contacting time between asperities which is defined as $t_c = \sqrt{\frac{a}{v}}$ by *Rice,2006*.

$\boldsymbol{\tau_a}$ in MPa is the shear stress acting on a single asperity at the onset of instability.

$\boldsymbol{a}$ in m is the average size of asperities defined as $a = \sqrt{\frac{F}{M\pi Pm}}$. Where:

F in N is the normal force applied to the surface.

M is the number of asperities in contact as defined by *Dietrich and Kilgore, 1994* and calculated for our surface.

Pm in Pa the critical yield stress or penetration hardness of Quartz.

$\boldsymbol{\rho_{Qz}}$ in $kg.m^{-3}$, $\boldsymbol{C_{p_{Qz}}}$ in $J.kg^{-1}.K^{-1}$ and $\boldsymbol{k}$ in $m^2.s^{-1}$ are respectively the density, specific heat and thermal conductivity of Quartz.

$\boldsymbol{\rho_w (P,T)}$ in $kg.m^{-3}$ and $\boldsymbol{C_{p_w} (P,T)}$ in $J.kg^{-1}.K^{-1}$ are respectively the density and specific heat of water.

$\boldsymbol{V_w}$ in m^3 is water volume interacting with asperities during shear heating defined in the same manner as *Violay et al, 2013* over a thickness of 100 μm.