On the possibility of unstable slip on clay-rich faults

Dan Faulkner

Thanks to: John Bedford, Julia Behnsen, Carolyn Boulton, Sabine den Hartog, Takehiro Hirose, Tom Mitchell, Marieke Rempe, Catalina Sanchez Roa, Toshi Shimamoto, Marion Thomas

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Here comes the sun

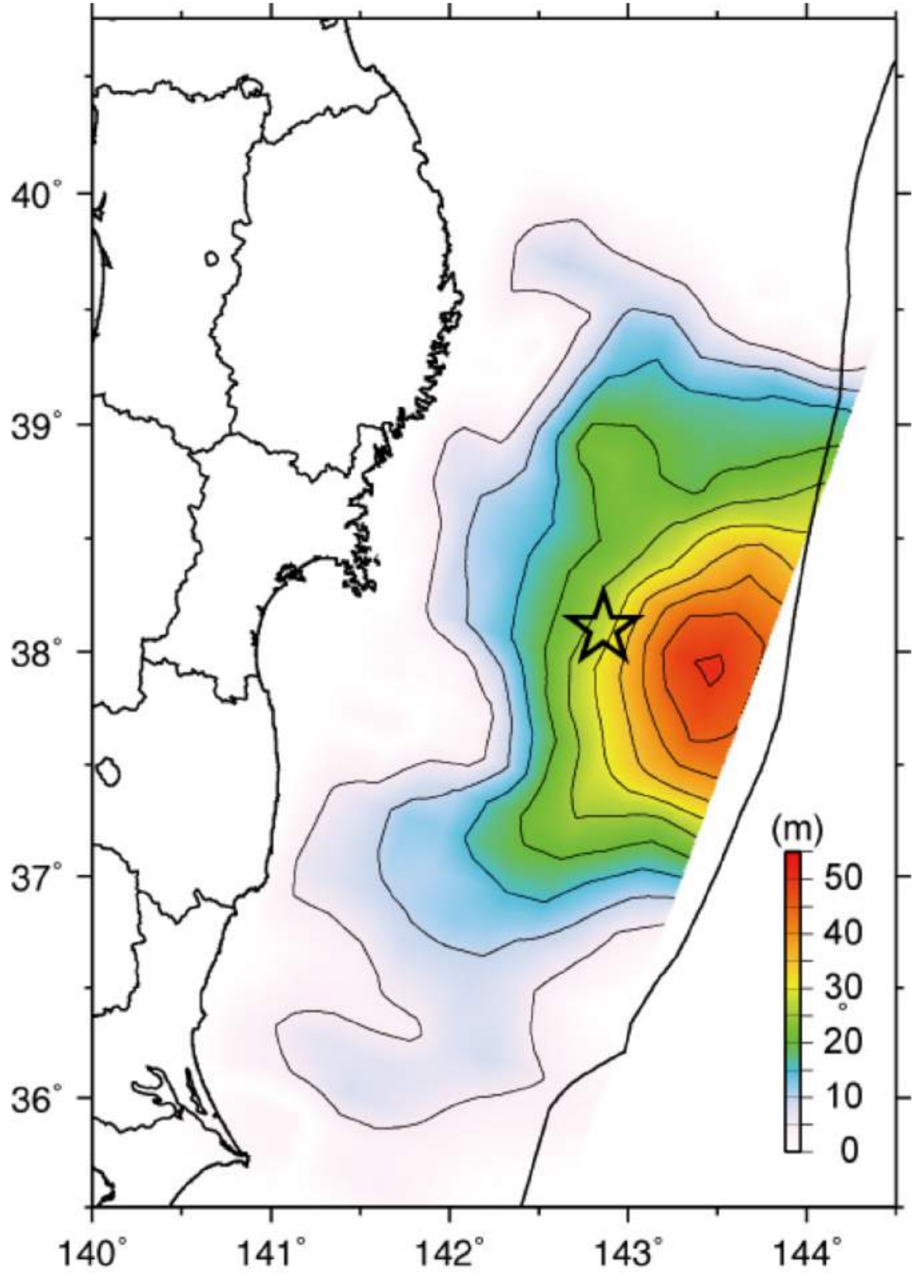
Outline

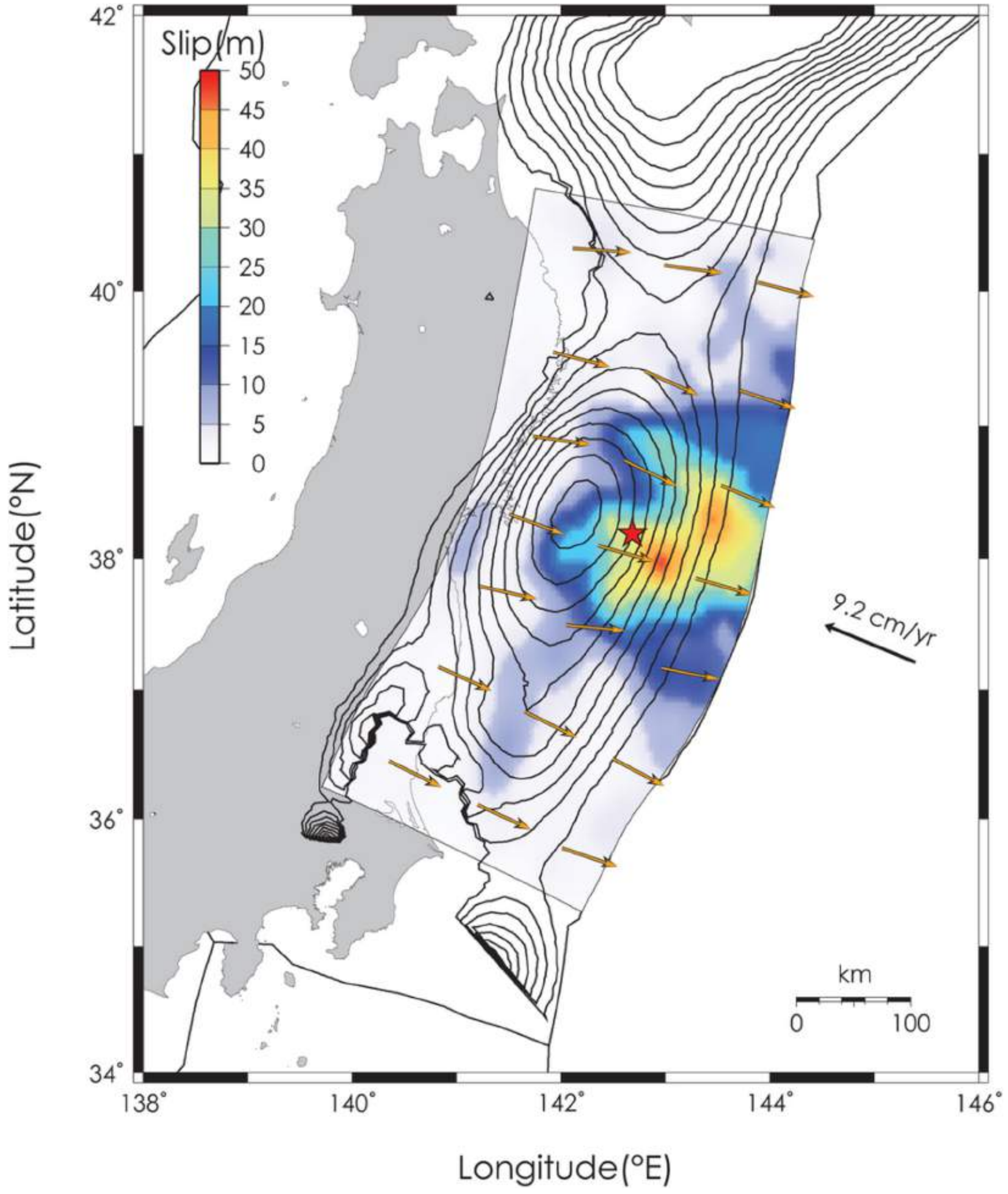
- The character of major faults in the field
- Clay friction in the lab
- Possibility of clay faults becoming unstable
  - Temperature
  - Pore fluid pressure
- Rupture propagation through clay-rich faults

Evidence that this might be an issue

- Slip deficit on the creeping section of the SAF
  - Ellsworth and Malin, 2011, Geological Society, London, Special Publications, 359, 39–53.
  - Michel et al., 2018, BSSA
- The Tohoku earthquake 2011
  - Interseismic aseismicity in the trench, huge co-seismic slip

Tohoku-Oki earthquake, March 2011



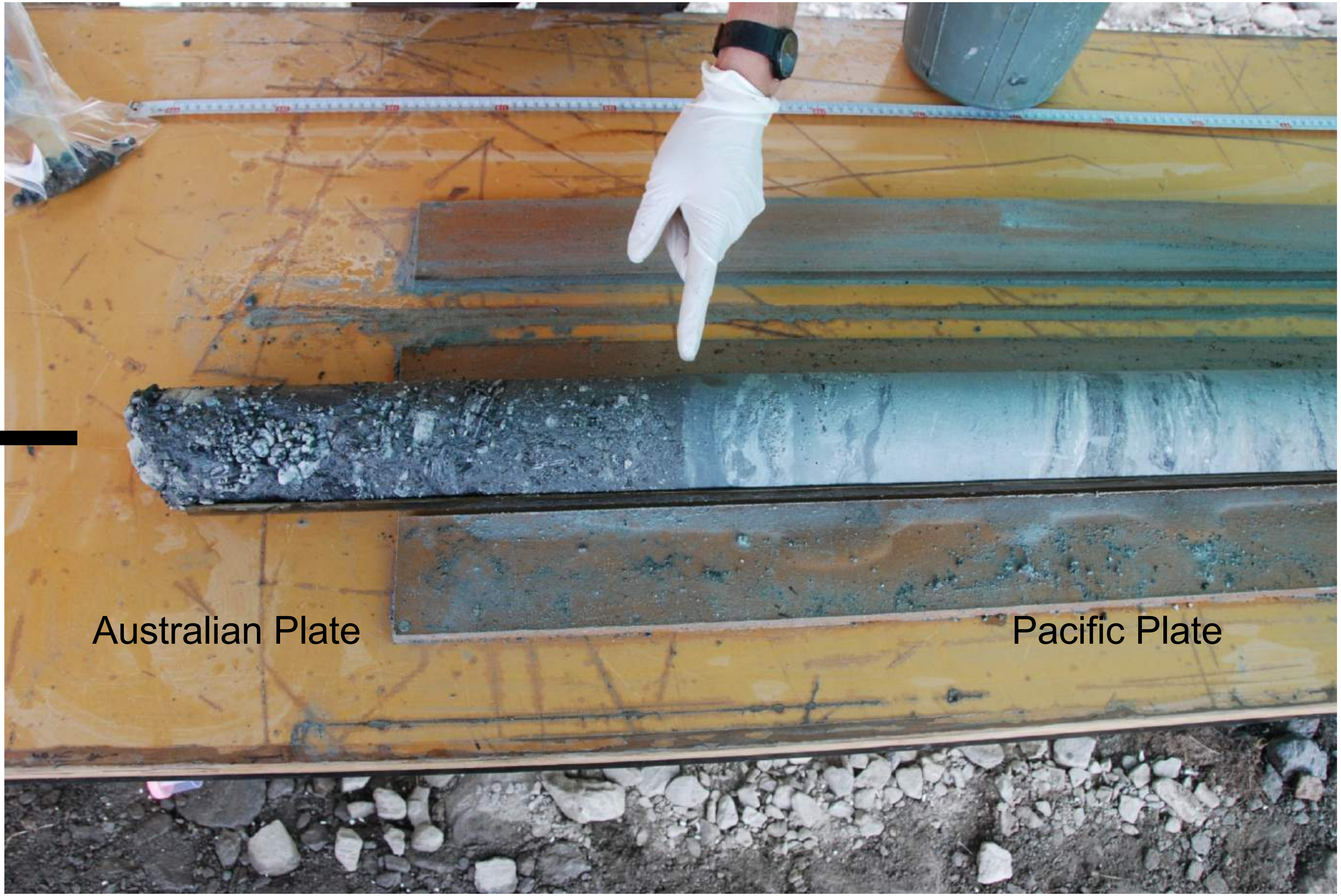


Major faults in the nature

DFDP2 drill site, Westland, New Zealand

DFDP 1a - The Fault

Liverpool,
~12,742km away




Median Tectonic Line, Japan

From the field:

Major faults typically display a fault core that contains significant proportions of clay minerals

Friction and frictional stability of clays

- Weak
- Velocity strengthening

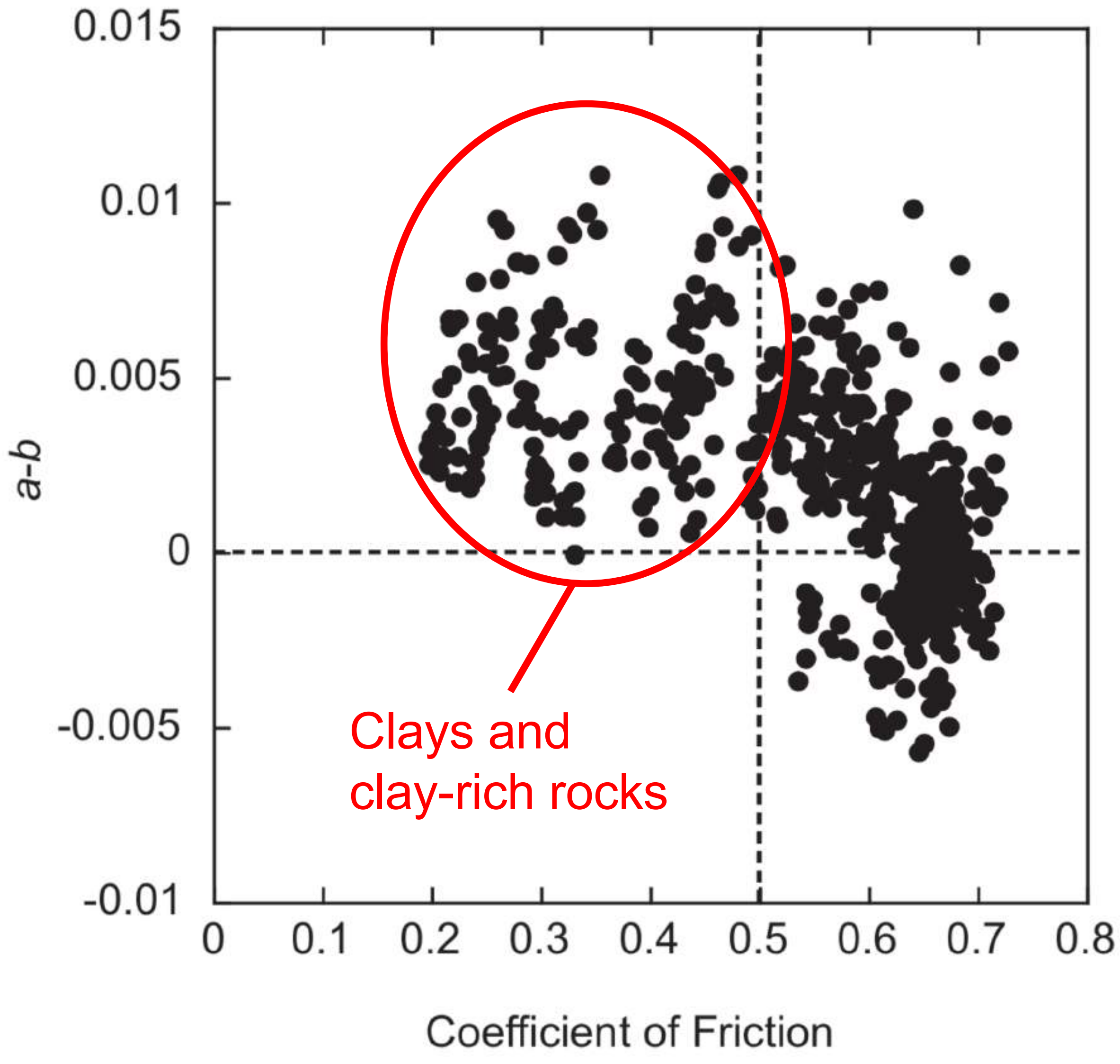
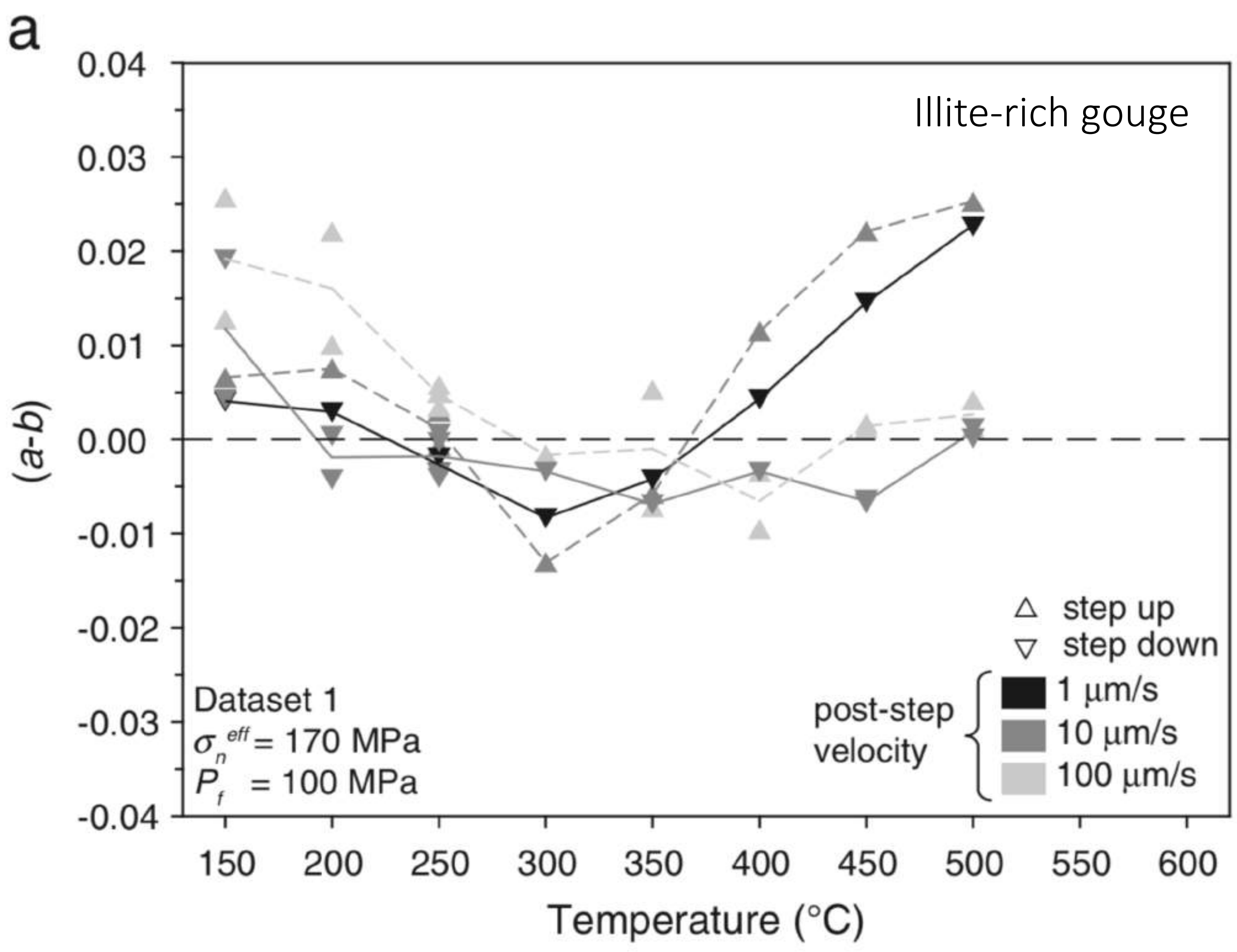
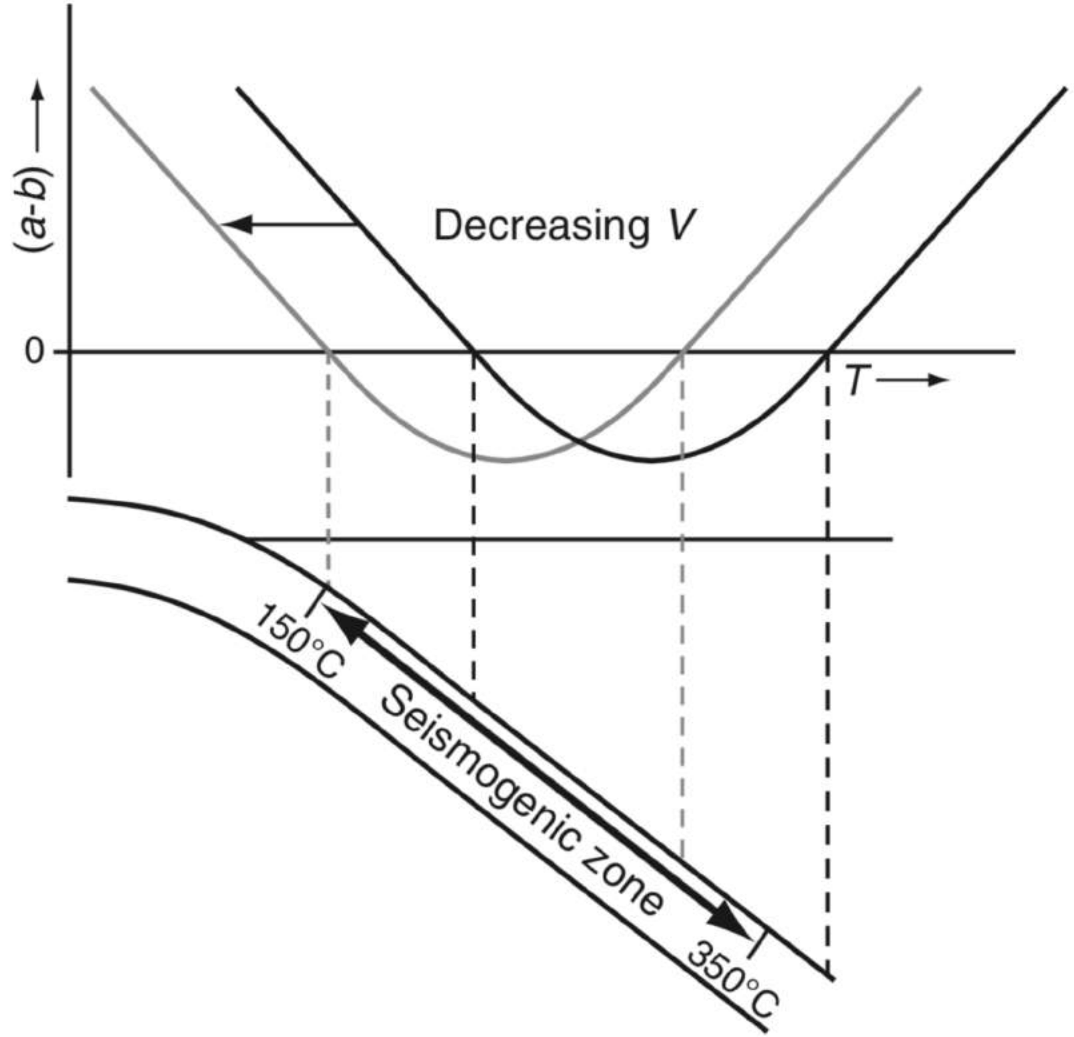


Figure 2. Friction rate parameter *a-b* as function of coefficient of friction for all gouges in this study.

Ikari et al. 2011

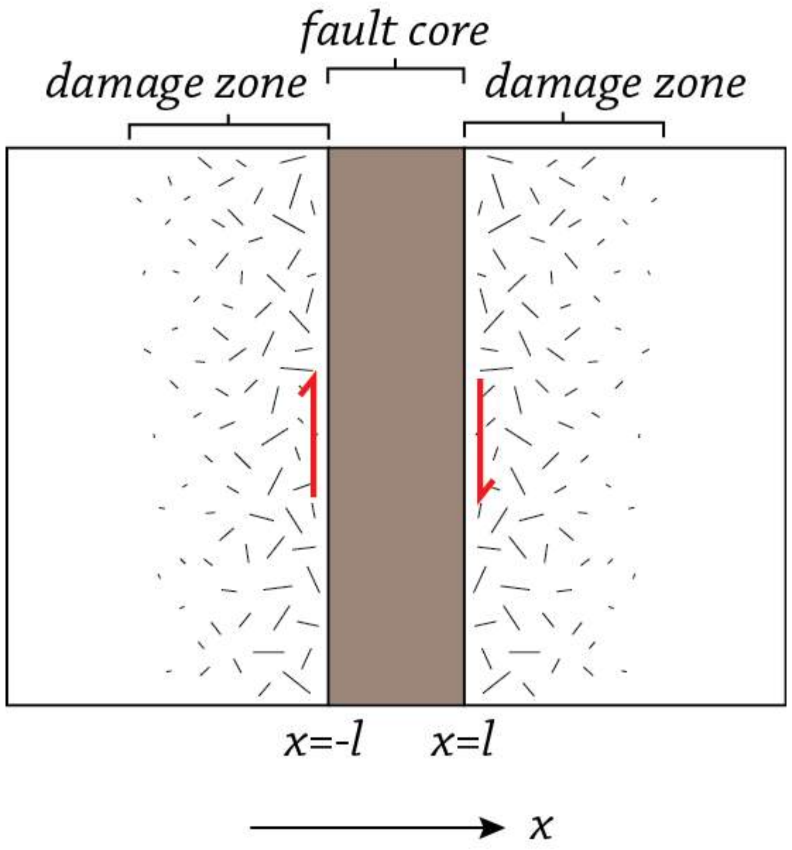
Earthquake nucleation on clay-rich faults – T effects





den Hartog et al. 2013 EPSL; 2013 Tectonophysics; 2018 unpublished data

Fluid pressure weakening in faults



$$\frac{\partial p}{\partial t} = \kappa \frac{\partial^2 p}{\partial x^2} + A$$

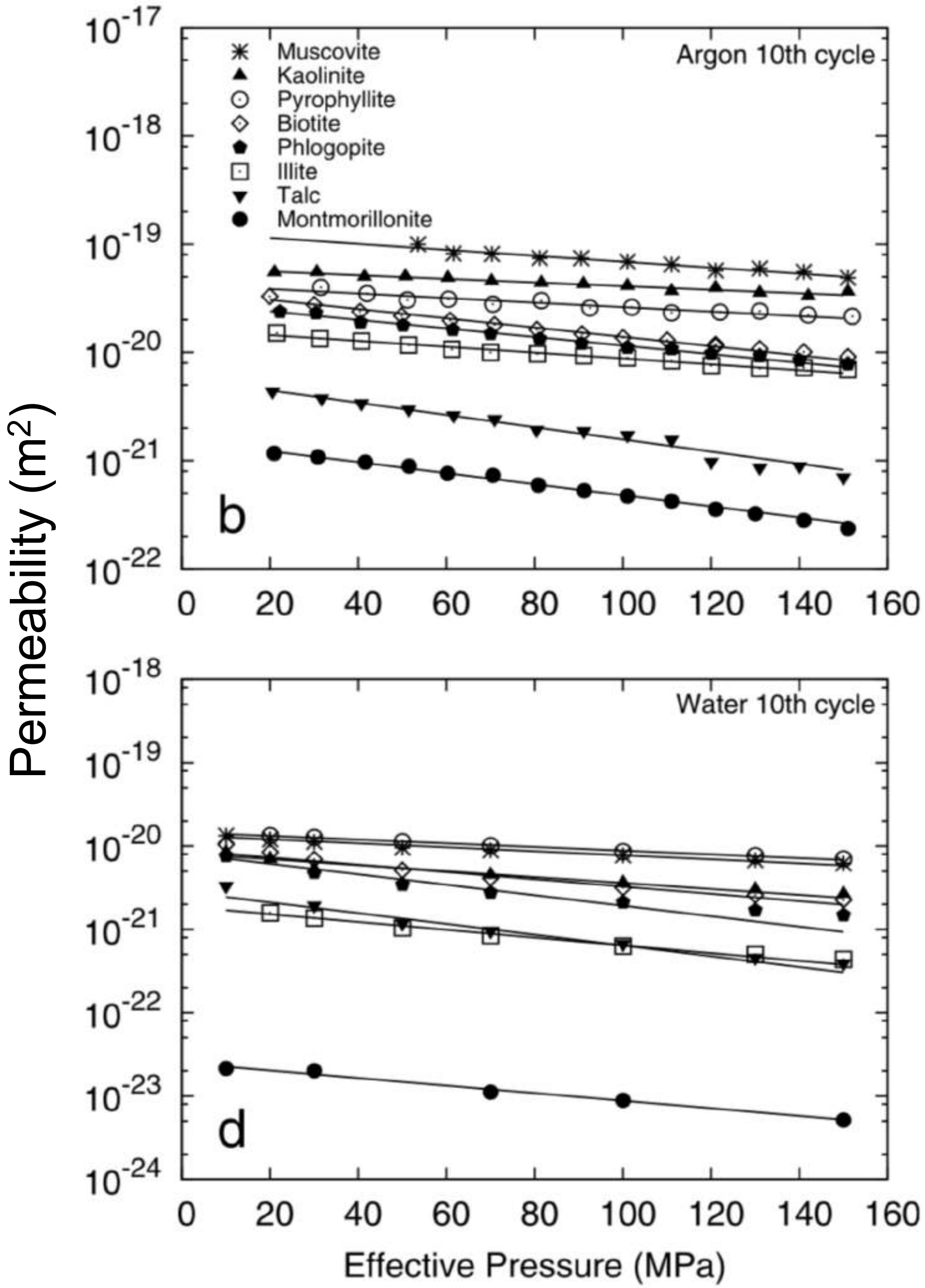
p = pressure (Pa)
t = time (s)
κ = hydraulic diffusivity (m^2/s)
x = distance (m)

$$\kappa = \frac{k}{\beta_c \eta}$$

k = permeability (m^2)
β_c = storage capacity (Pa^{-1})
η = viscosity (Pa.s)

Compaction produced by shear produces high pore-fluid pressure which is mediated by fluid loss out of the gouge layer

Faulkner et al. 2018

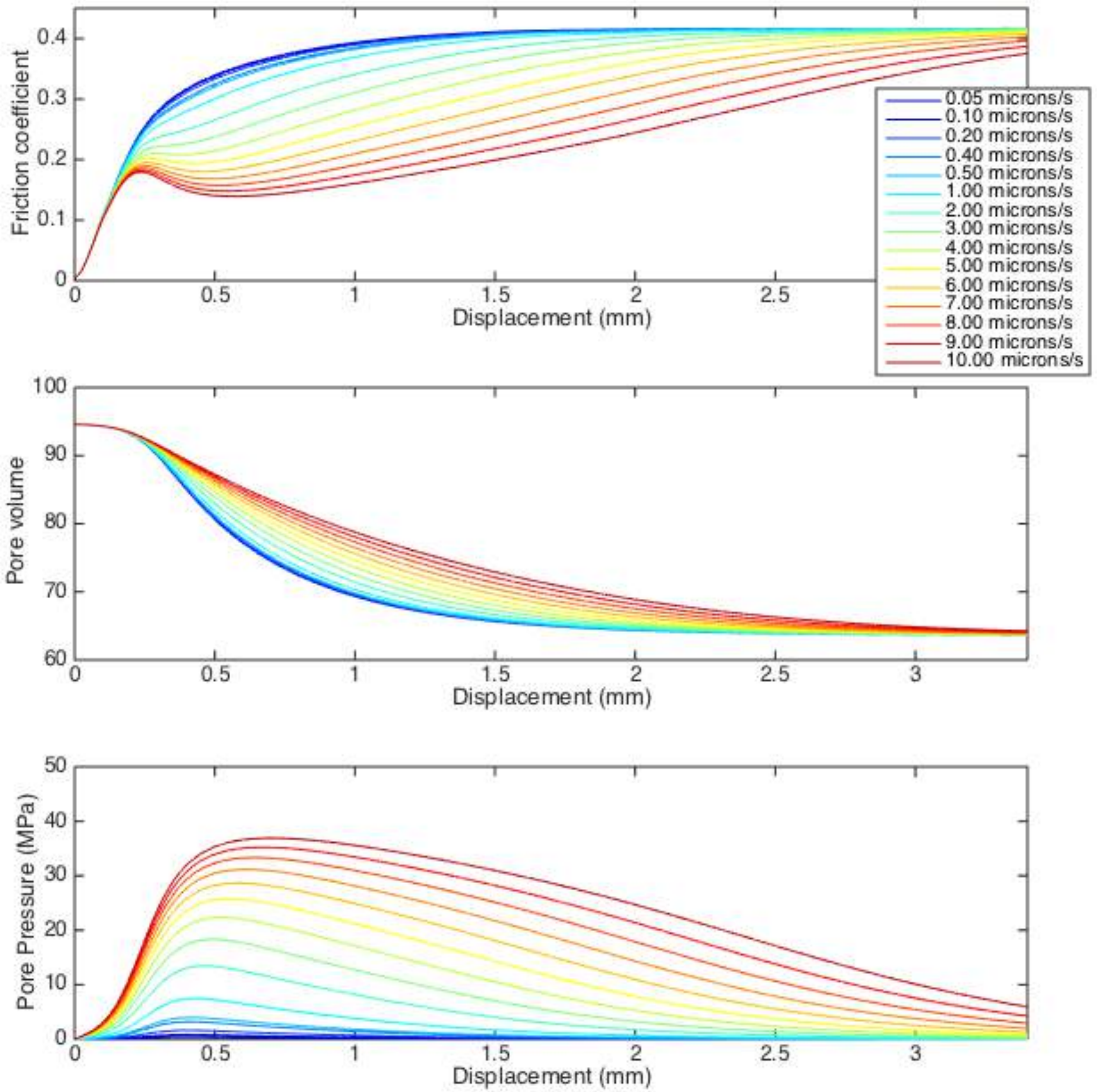


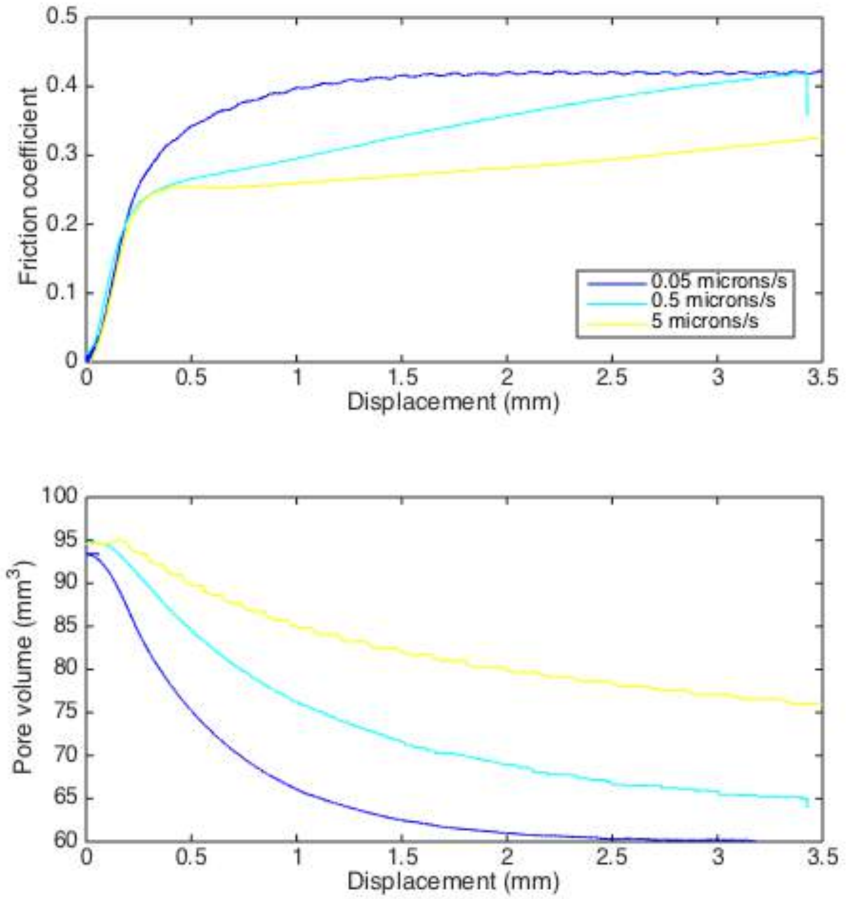
Permeability of clays typically found in fault gouge

Behnsen and Faulkner 2011 JGR

Natural fault gouges also;
Morrow et al. 1981 - SAF
Chu et al. 1981 - SAF
Faulkner and Rutter 1998; 2000; 2003 – Carboneras Fault, Spain
Wibberley and Shimamoto, 2003 – Median Tectonic Line, Japan
Allen et al. 2017 – Alpine Fault, New Zealand

Compaction weakening in experiments

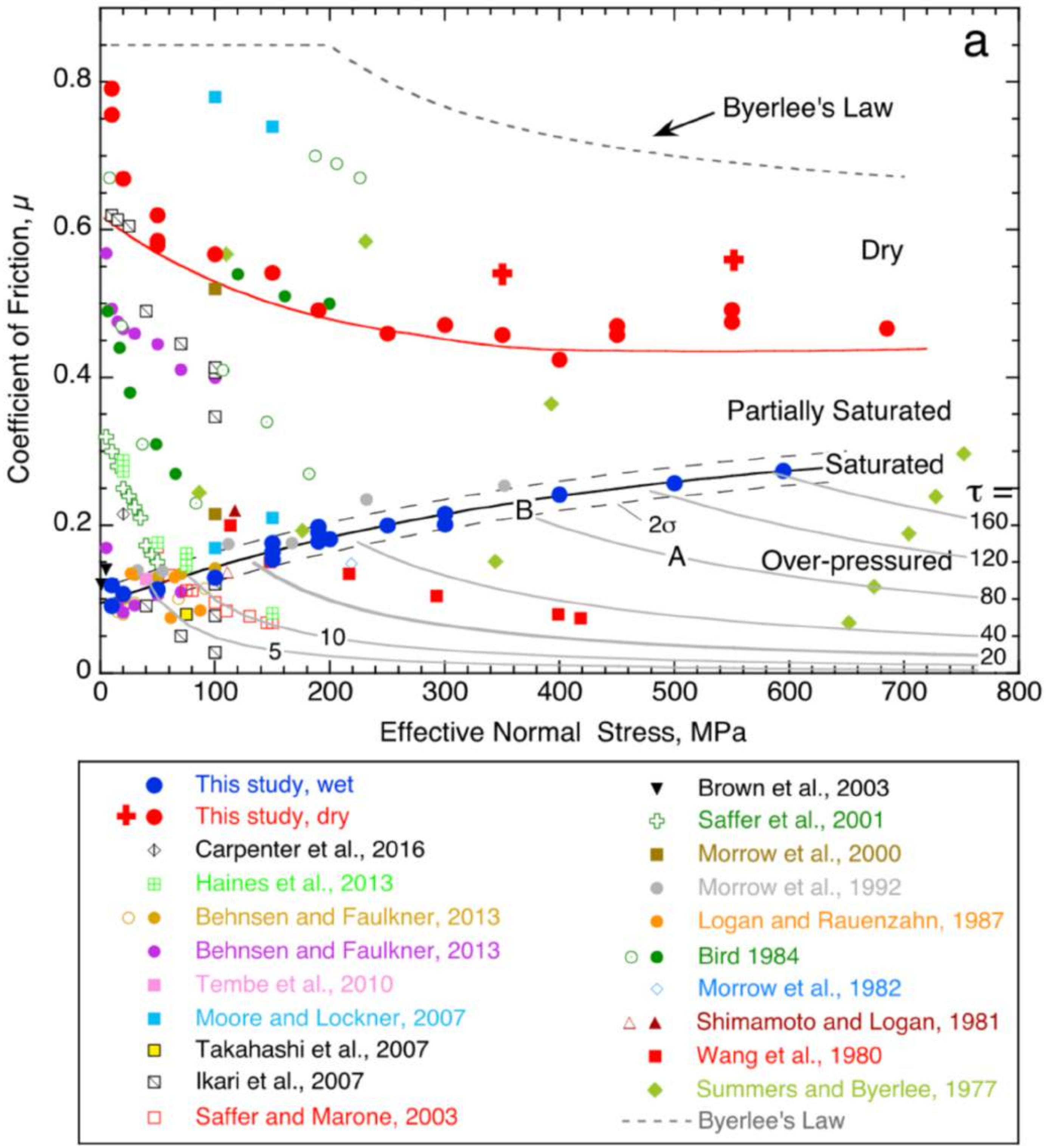




Fluid pressure development can produce apparent velocity weakening behaviour

Faulkner et al. 2018 JGR

Compilation of friction data for montmorillonite in experiments

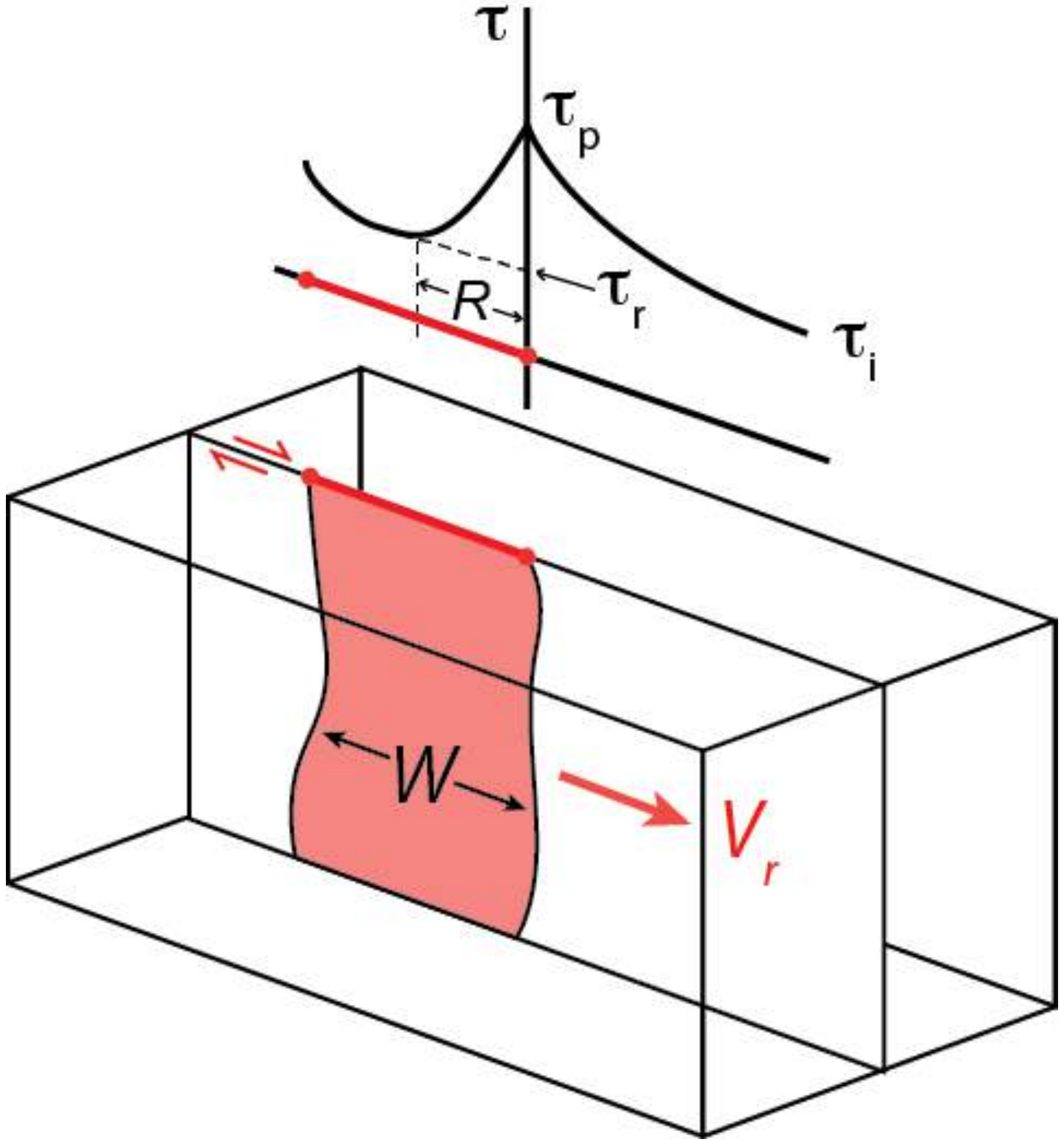


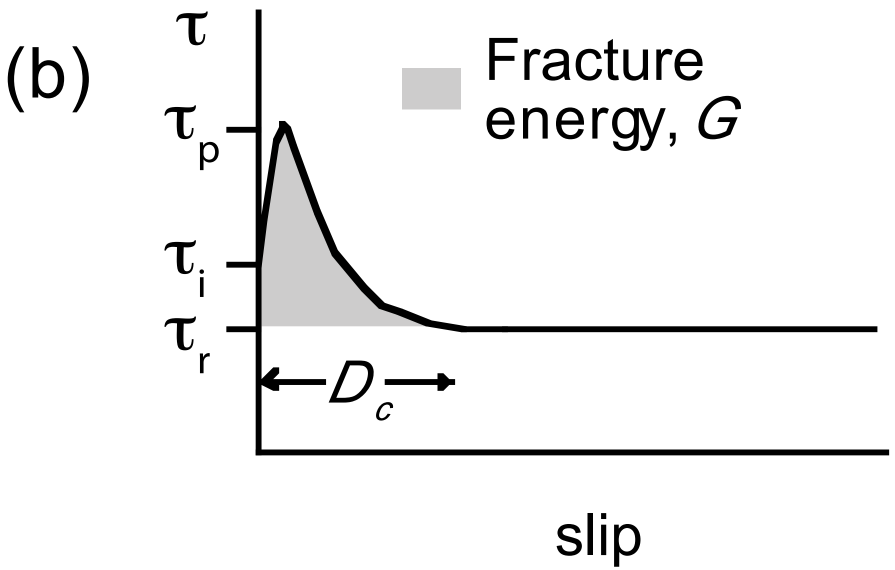
Morrow et al. 2017 JGR

From the lab (slow slip velocity):

- Clay-rich gouge is inherently velocity strengthening but under certain circumstances can become velocity weakening
- Future tests should establish
  - dilatant/compactive behaviour from ‘steady state’ pore volume conditions
  - Effects of temperature

Earthquake mechanics

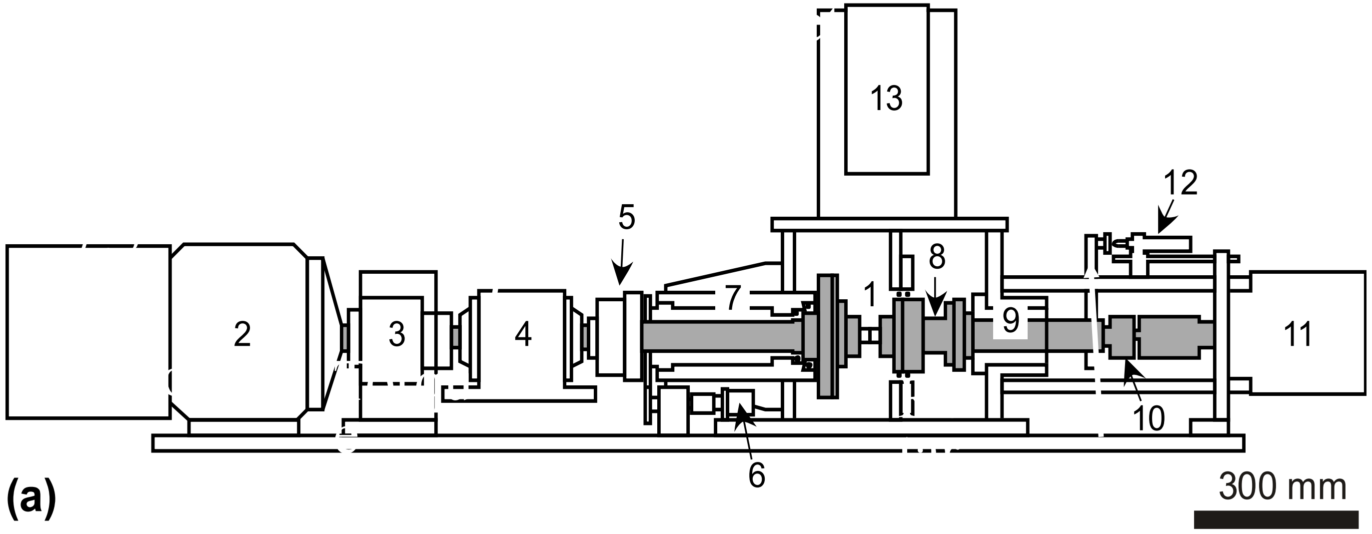


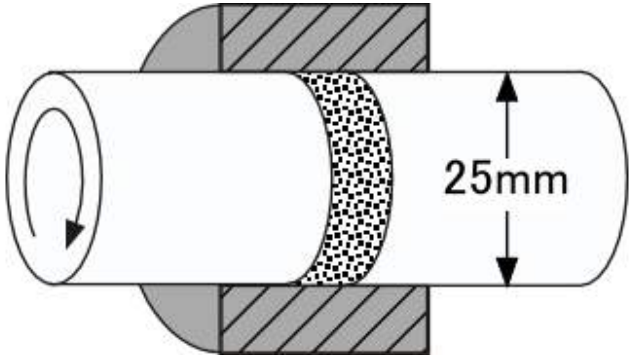


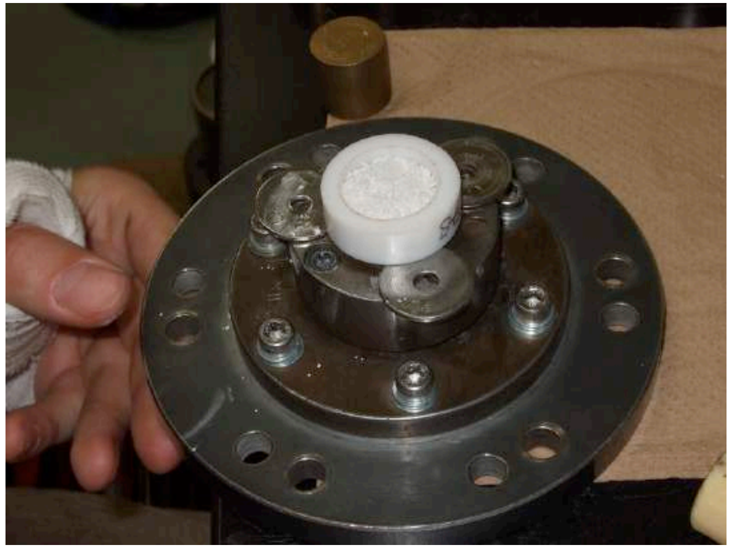
Note: no energy dissipation in the bulk

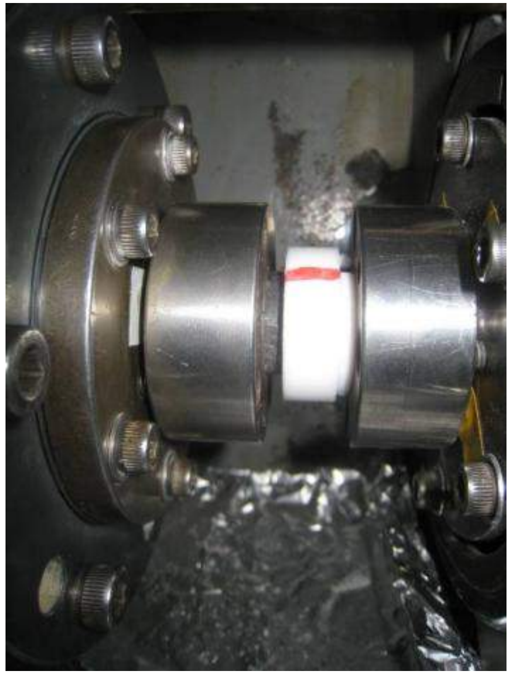
High velocity tests (1.3 m/s)

- Pyrophyllite
- Illite/quartz
- Sericite
- Talc
- Montmorillonite





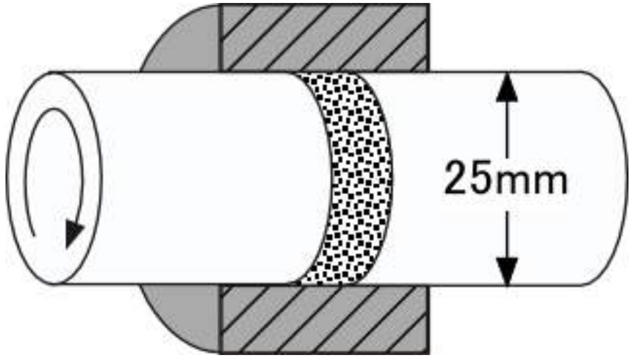




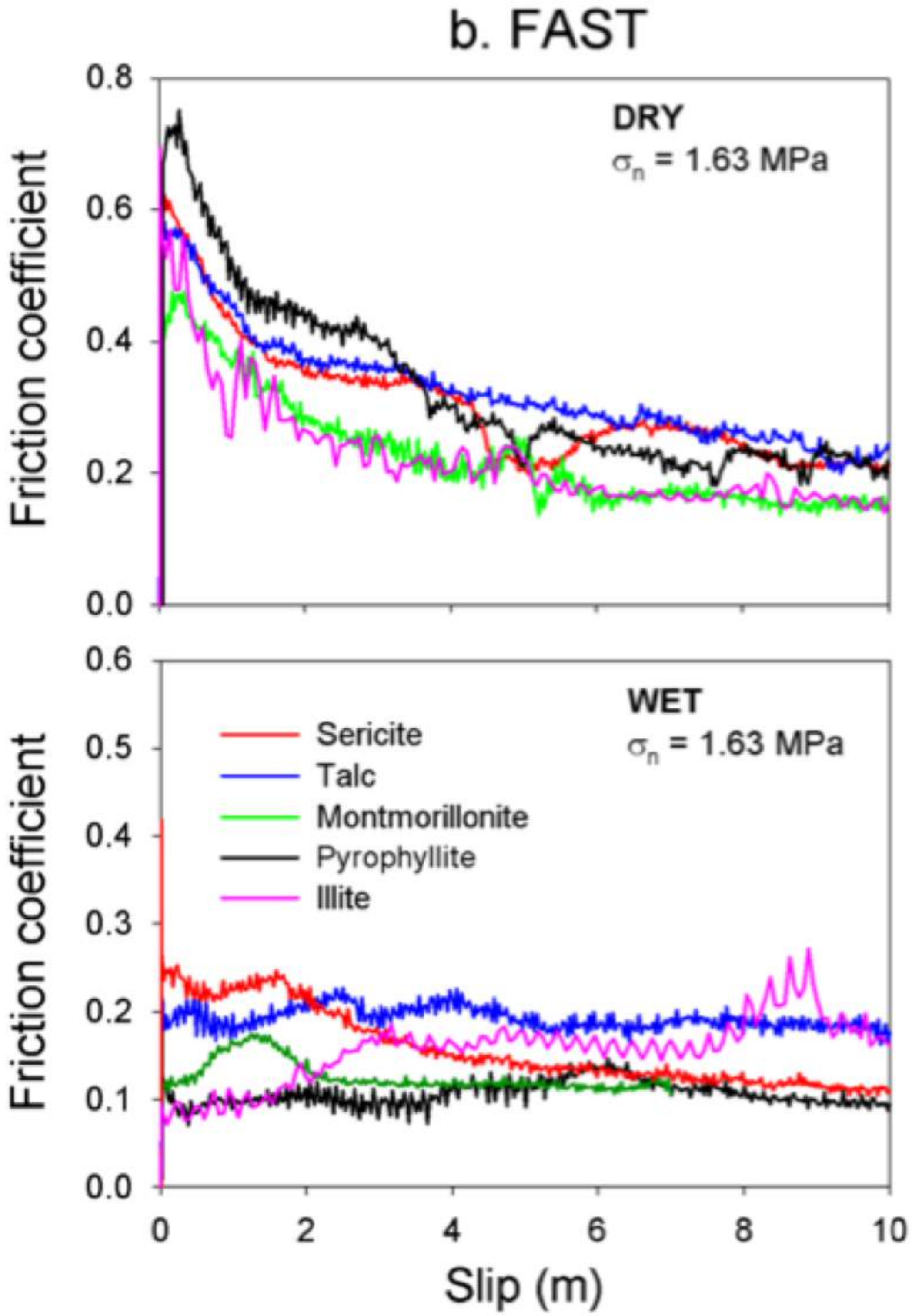
High velocity friction tests (1.3 m/s)

Loss of fracture energy in wet tests

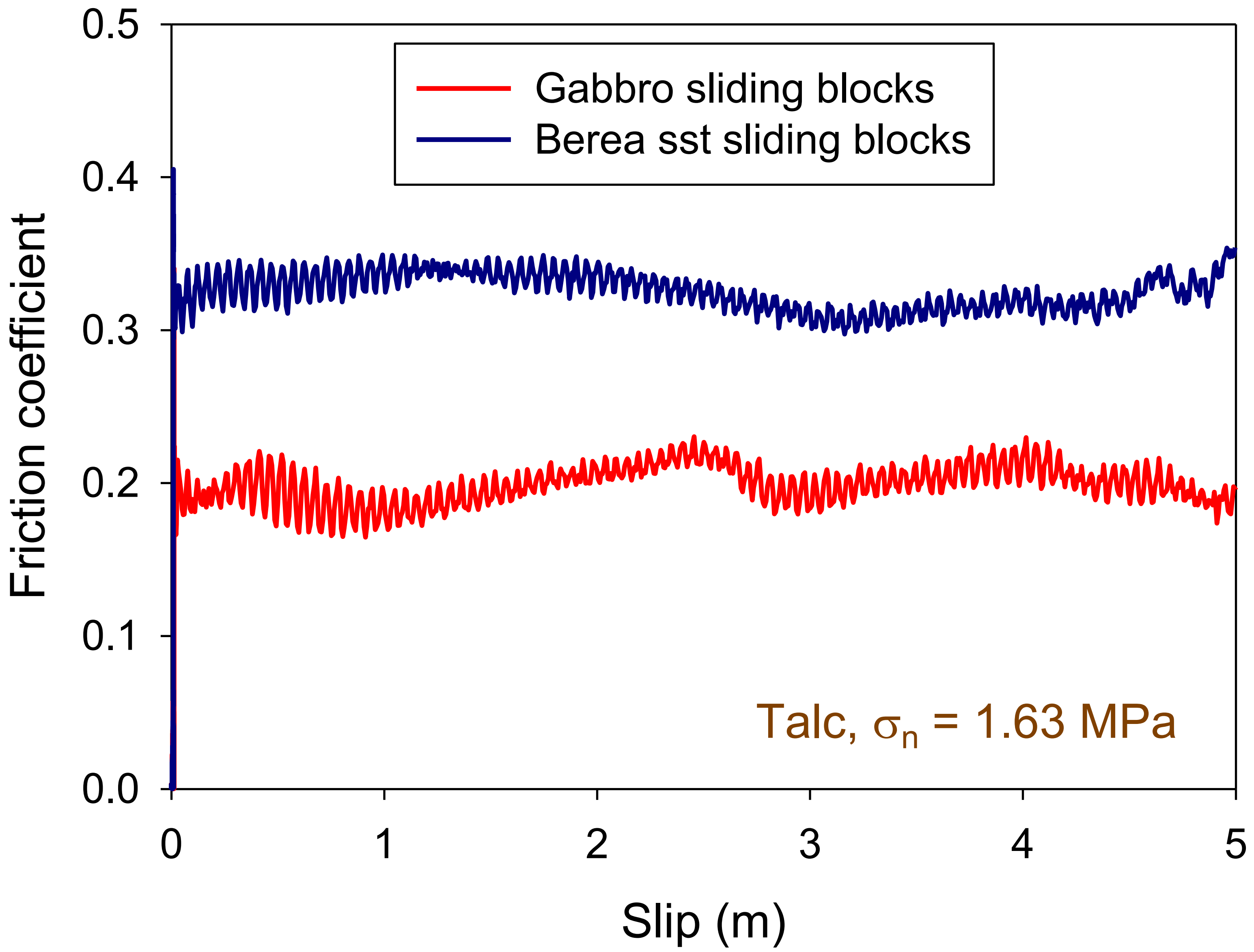
- energetically easier to propagate earthquake
- radiation efficiency ~1 (ignoring off-fault dissipation)

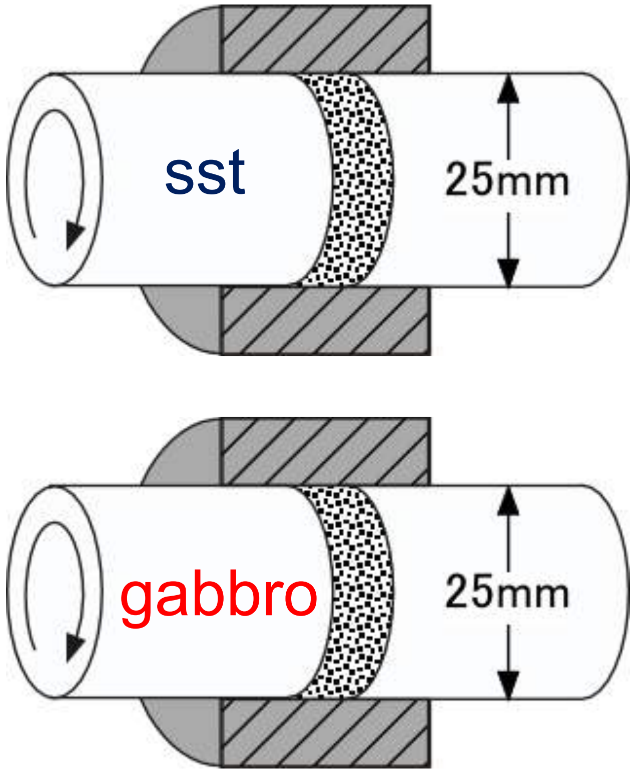


- Gabbro forcing blocks (v. low permeability)

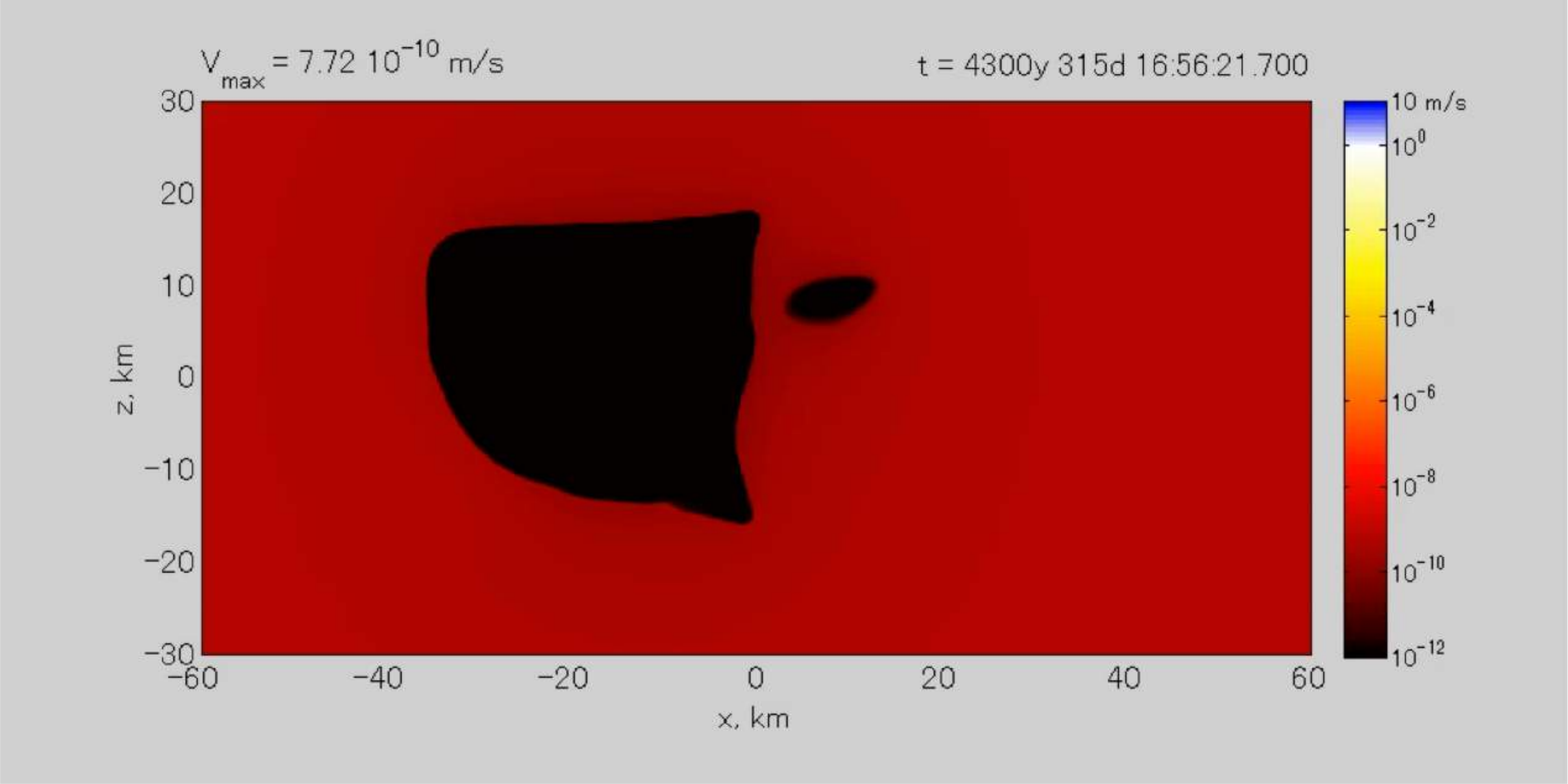


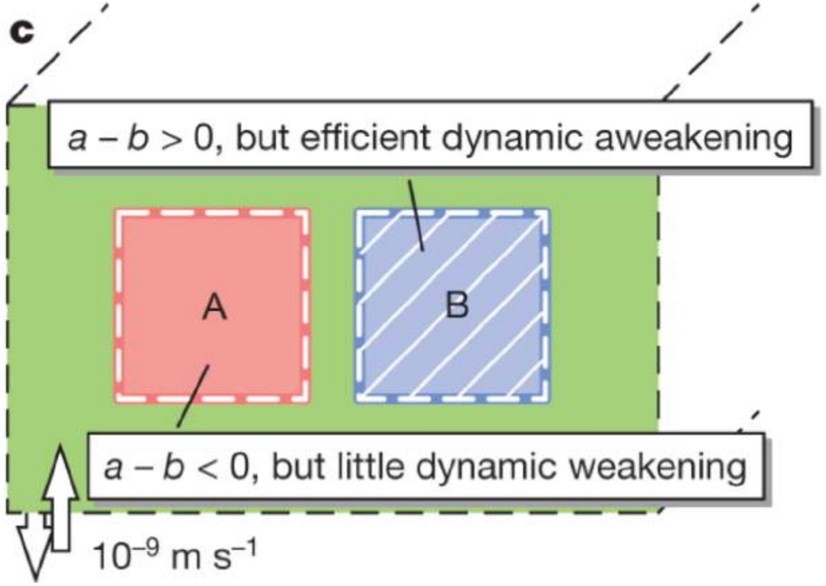
Thermal pressurization





Faulkner et al. 2011, GRL, cf. Ujiie et al. 2013 Science





A = velocity weakening
B = velocity strengthening

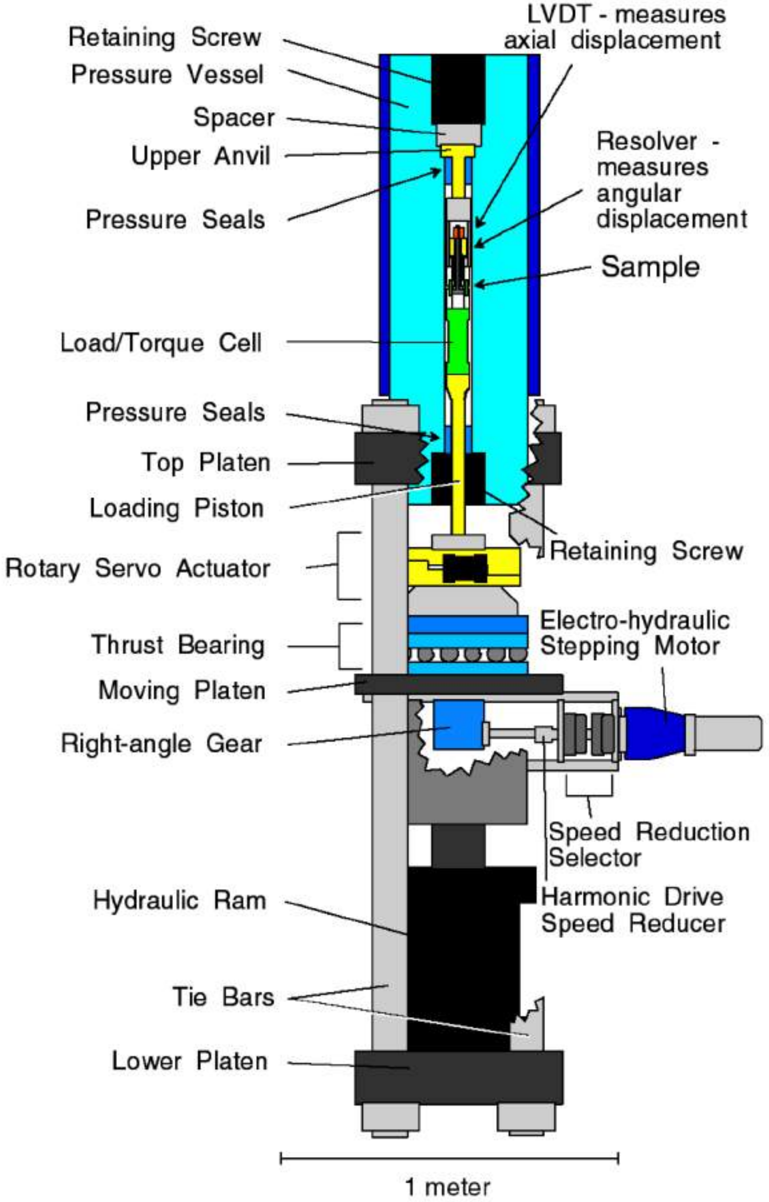
Noda and Lapusta 2013 Nature

From the lab (high slip velocity):

- We need to constrain the properties and behaviour of clay-rich fault gouge at elevated slip velocity and higher normal stress
  - This requires confined high-velocity rotary shear experiments

There will be an answer…

Liverpool



Overall rotary shear apparatus

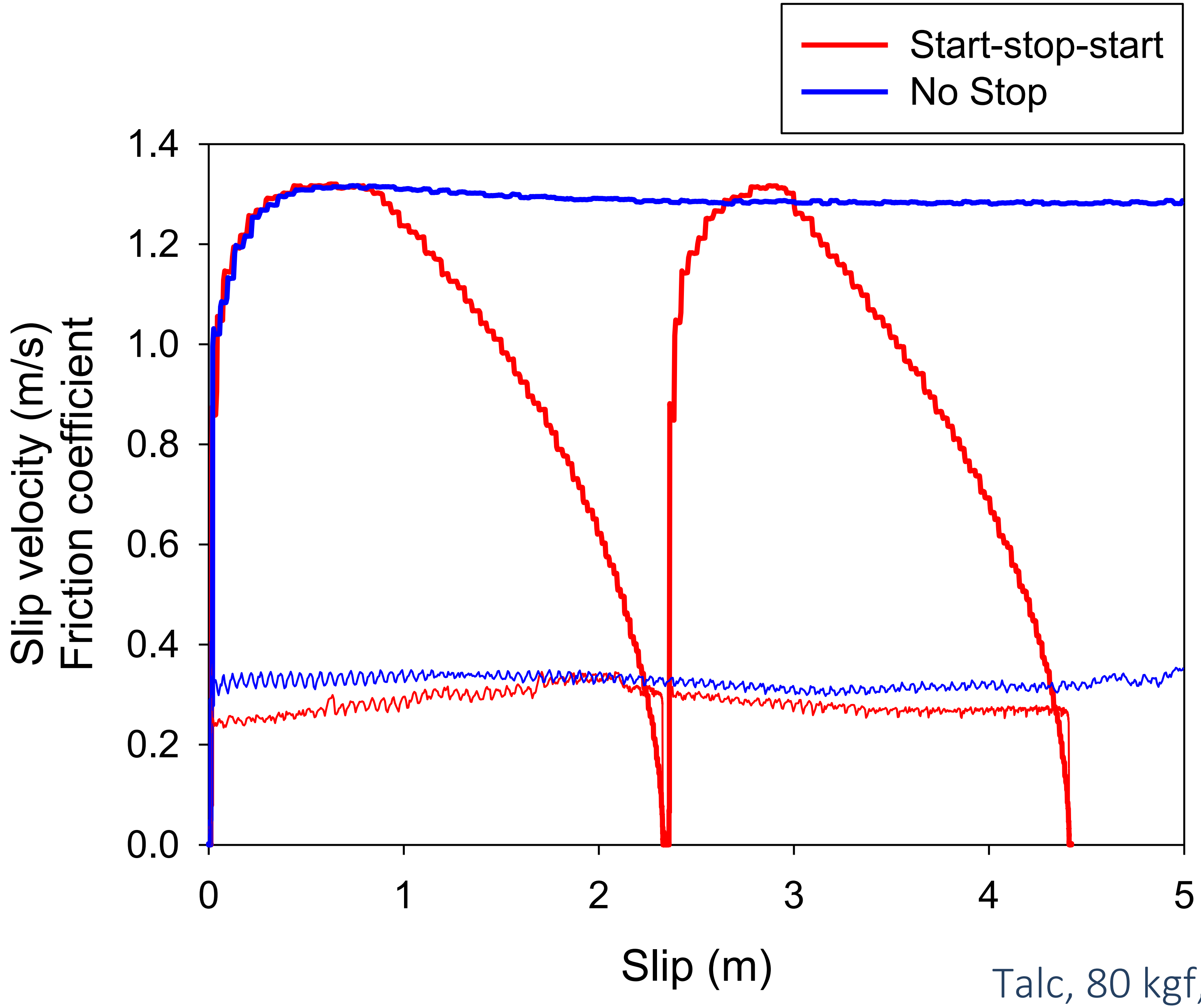
Brown

…let it be

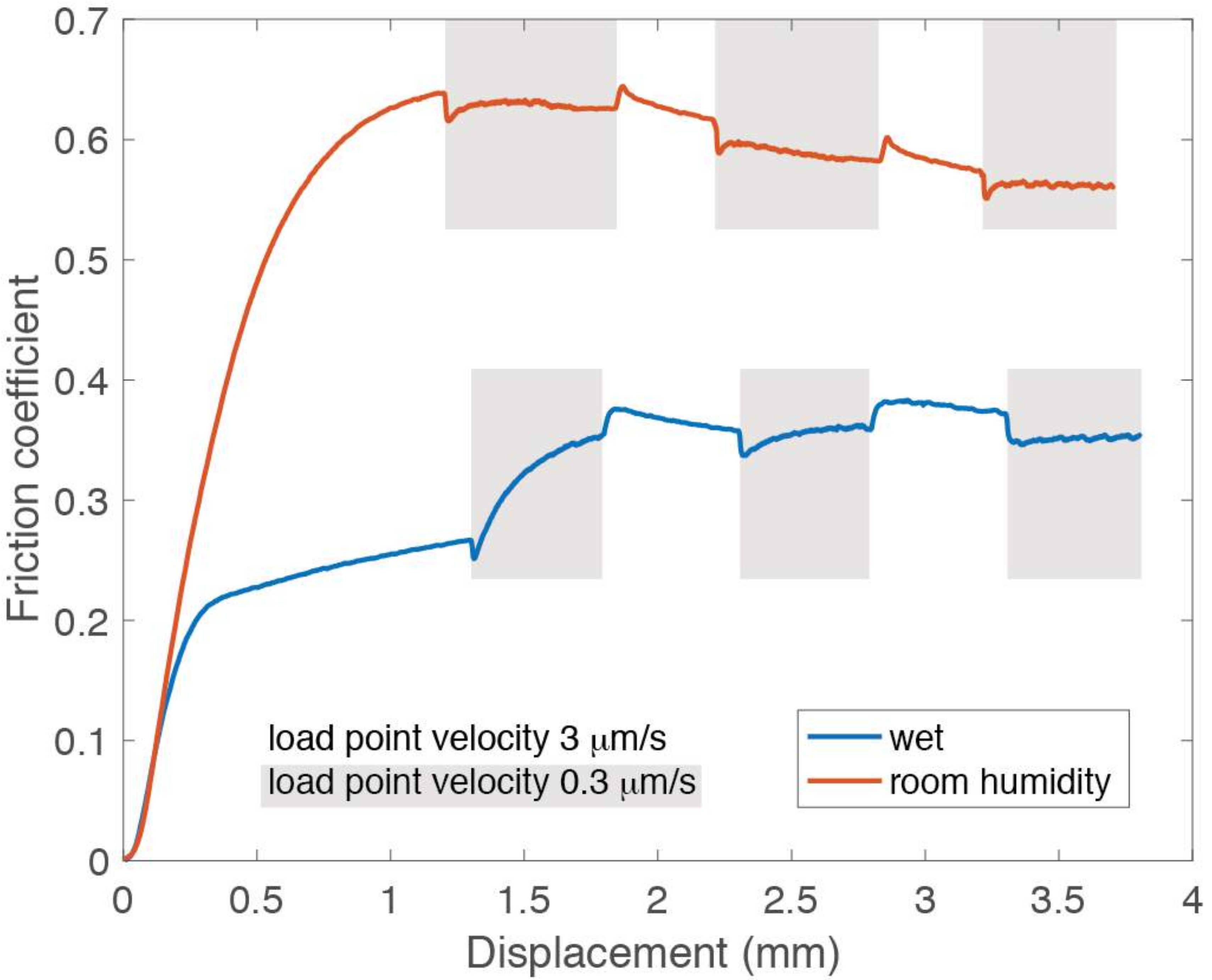
Conclusions

- Clays are common in faults and frictionally weak
- Earthquake nucleation difficult on clay-rich faults
- Rupture propagation on clay-rich faults is possible with fluid involvement

Initial compaction?



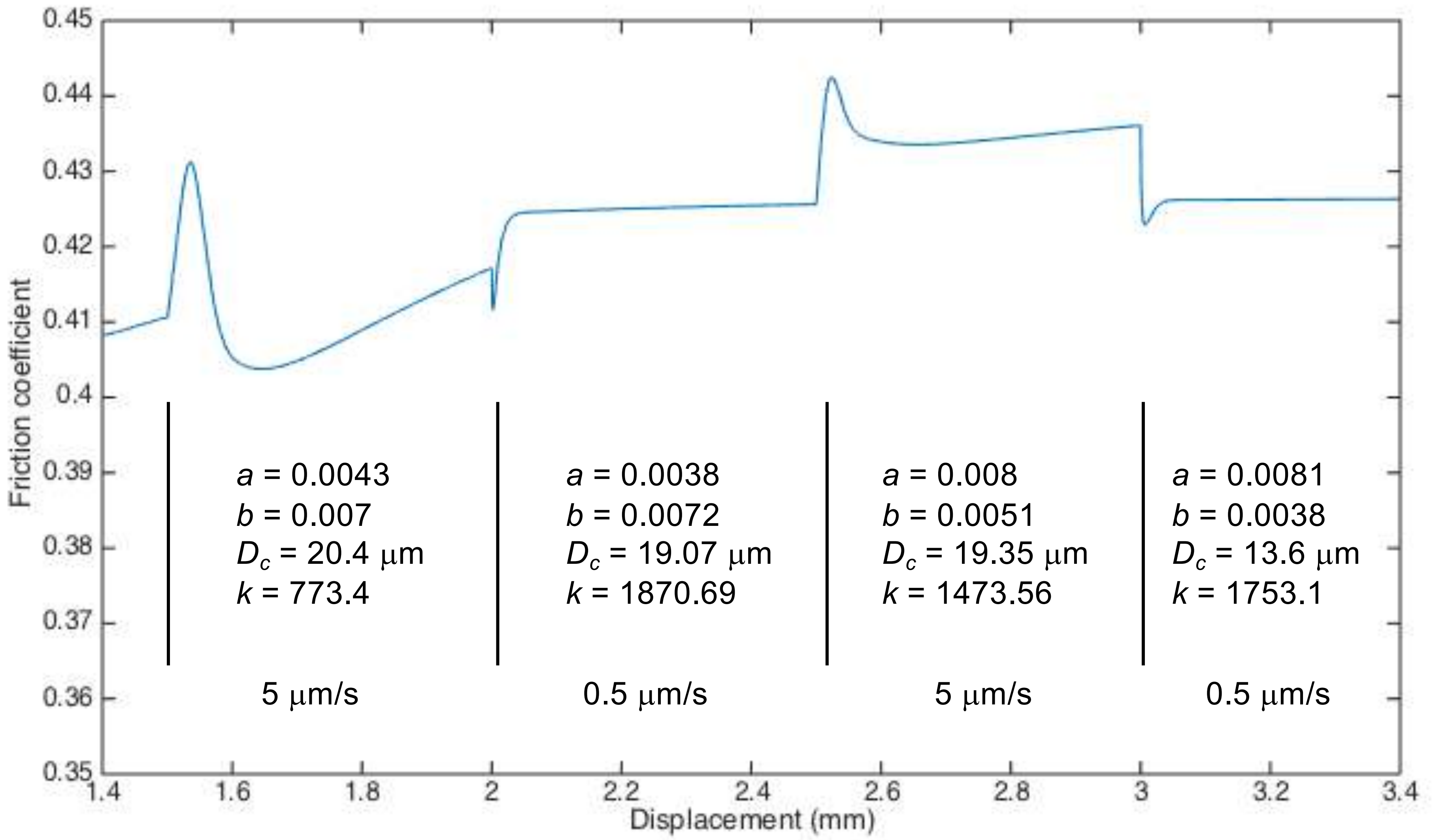
Talc, 80 kgf, sst sliding blocks



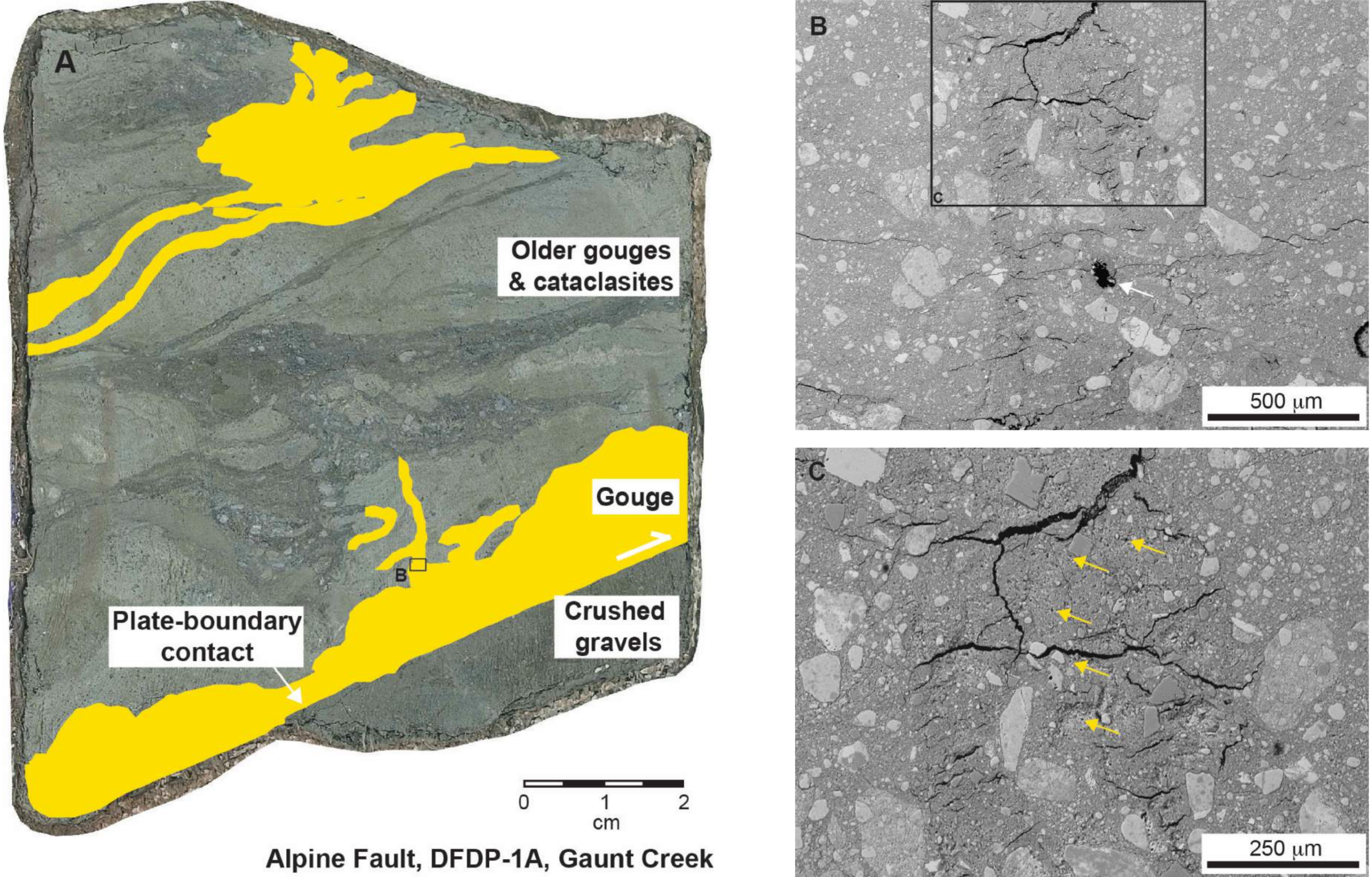
Initial lab observations

Sepiolite gouge
(Mg-silicate)

Velocity stepping, with pore fluid pressure



- a = 0.01; b = 0.004; D_c = 10 microns; *stiffness* = 1500 m^{-1} (friction units)



A
Older gouges
& cataclasites
Gouge
B
Crushed
gravels
Plate-boundary
contact
0
1
2
cm
Alpine Fault, DFDP-1A, Gaunt Creek
B
c
500 μm
C
250 μm