On the possibility of unstable slip on clay-rich faults

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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
  • 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

Australian Plate

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den Hartog et al. 2013 EPSL; 2013 Tectonophysics; 2018 unpublished data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

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

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

\[
\kappa = \frac{k}{\beta_c \eta}
\]

- \( p \) = pressure (Pa)
- \( t \) = time (s)
- \( \kappa \) = hydraulic diffusivity (m\(^2\)/s)
- \( x \) = distance (m)
- \( k \) = permeability (m\(^2\))
- \( \beta_c \) = storage capacity (Pa\(^{-1}\))
- \( \eta \) = viscosity (Pa.s)

Faulkner et al. 2018
Permeability of clays typically found in fault gouge

Behnse 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
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

\[ \tau \]

\[ \tau_p \]

\[ \tau_r \]

\[ \tau_i \]

Fracture energy, \( G \)

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

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?

Slip (m)

0 1 2 3 4 5

Slip velocity (m/s)

Friction coefficient

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

Start-stop-start
No Stop

Talc, 80 kgf, sst sliding blocks
Initial lab observations

Sepiolite gouge (Mg-silicate)
Velocity stepping, with pore fluid pressure

- $a = 0.0043; b = 0.007; D_c = 20.4 \, \mu m; k = 773.4$
- $a = 0.0038; b = 0.0072; D_c = 19.07 \, \mu m; k = 1870.69$
- $a = 0.008; b = 0.0051; D_c = 19.35 \, \mu m; k = 1473.56$
- $a = 0.0081; b = 0.0038; D_c = 13.6 \, \mu m; k = 1753.1$

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