Frictional properties of megathrust fault gouges at low sliding velocities: New data on effects of normal stress and temperature

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Introduction

• Subduction megathrust earthquakes and associated tsunamis present some of the most destructive natural hazards on the planet.

• nondestructive slow slip events (SSEs; e.g. Peng and Gomberg, 2010)

① southwestern Japan (Hirose et al., 1999)
② Cascadia (northwestern US; Dragert et al., 2001)
③ southern Alaska (Ohta et al., 2006)
④ Mexico (Lowry et al., 2001)
⑤ Chile (Pritchard and Simons, 2006)
⑥ New Zealand (Douglas et al., 2005)
⑦ Costa Rica (Davis et al., 2011)
• In the hope of improving *seismic and tsunami hazard evaluation*, there is presently intense interest

(i) in megathrust *earthquake nucleation* processes

(e.g. Faulkner et al., 2011; Kaneko and Lapusta, 2008)

(ii) in *SSEs* as possible precursors to major subduction zone earthquakes

(Dragert et al., 2001; Shibazaki et al., 2010)

**SSEs**

~15-20 km

~$10^{-9}$-$10^{-7}$ m/s

(Iio et al., 2002; Liu and Rice, 2005)
Material

- Muroto Transect across the Nankai Trough, cored during ODP Leg (in & out)
- simulated illite-rich gouge consisting of crushed Rochester Shale (Folk, 1962)
Biaxial experiments

1.5g sample material
completely wet
room temperature 14~16°C
effective normal stresses 5, 10, 15, 30MPa
sliding velocity 0.16, 1.6, 16 μm/s or 0.18, 1.8, 18μm/s
Ring shear experiments

~0.5g sample material
temperature 200, 250, 300°C
pore-fluid pressure 100MPa
effect normal stress 170MPa
sliding velocity 1, 10, 100μm/s

graphite powder
MOLYKOTE® spray
\( \mu = \frac{\tau}{\sigma} \)

\[
(a - b) = \frac{\Delta \mu_{ss}}{\Delta \ln V}
\]

> 0 velocity strengthening

< 0 velocity weakening

(Dieterich, 1978, 1979; Ruina, 1983)
10mm
\( \mu = 0.3 \sim 0.41 \)
Biaxial machine (illite gouge)

300°C

Ring shear machine (illite gouge) 250°C

FIB-SEM

FIB-SEM

FEG-SEM

10 MPa
Implications for seismogenesis

DP gouges showed velocity agreement with previous studies (Saffer, 2011; Ikari et al., 2009a; Tembe et al., 2010)

- On the basis of their results, Saffer and Marone (2003) rejected the hypothesis put forward by Vrolijk (1990) that the dehydration of smectite to illite may be responsible for the updip seismogenic limit in subduction zones.

120~150°C
Implications for seismogenesis

• At levels well within the seismogenic zone, muscovite-rich fault rocks must ultimately replace illite-rich gouge, since at temperatures of 200~300°C illite starts to transform into muscovite.

  (Merriman and Frey, 1999)

• Nonetheless, further work is clearly needed on both muscovite and illite to confirm this.
• All of these trends will tend to promote unstable slip behaviour at low effective normal stresses and at low sliding velocities, thus favouring nucleation of both regular earthquakes and SSEs when effective normal stresses are low.
Implications for modelling studies

room temperature transition

modeling
Conclusions

• ODP material showed velocity strengthening behaviour
  \( \mu = 0.33 \sim 0.41, \) 10 mm, 10\~{}15 MPa, room temperature
  \( \mu \) was found to increase with increasing normal stress

• illite gouge also showed velocity strengthening behaviour
  \( \mu = 0.30 \) to 0.43, 10 mm, 5\~{}30 MPa, room temperature
  The velocity strengthening behaviour became more marked with increasing effective normal stress and sliding velocity.
Conclusions

• The ring shear experiments performed on simulated illite gouge $\mu=0.36$–$0.57$, 2–10 mm, 200–300°C

  Above $\sim250$°C, a transition from velocity strengthening to velocity weakening behaviour was observed.

• A microscale shear mechanism is initially controlled by distributed deformation and passive clay rotation, forming a foliation, and later by P- and R1-shearing with minor Y-shear activity at shear strain $>1$ or 2.
Our data for illite at 200~300℃ suggest that key transitions between velocity strengthening and weakening in megathrust faults may occur at significantly different slip rates and temperatures.

ODP and illite gouges showed slip hardening at a rate that increased with applied normal stress and sliding velocity. This behaviour favours earthquake nucleation and SSE activity at low effective stresses.

Conclusions
Thank you!
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Material</th>
<th>$\sigma_n^{(eff)}$ (MPa)</th>
<th>$T$ (°C)</th>
<th>$P_T$ (MPa)</th>
<th>$V$ (μm/s)</th>
<th>Initial gouge thickness (mm)</th>
<th>Final gouge thickness (mm)</th>
<th>Final displacement (mm)</th>
<th>Final $\gamma$</th>
<th>$\mu$ at 10 mm displacement (or $\gamma = 20$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BODP-IN-A01</td>
<td>BODP-IN-A</td>
<td>15</td>
<td></td>
<td>14.1 atm.</td>
<td>18–1.8–0.18–1.8–1.8–1.8–0.18–1.8</td>
<td>0.22</td>
<td>0.14</td>
<td>18.20</td>
<td>130</td>
<td>0.38</td>
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<td>0.23</td>
<td>0.18</td>
<td>19.15</td>
<td>106</td>
<td>0.41</td>
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<td>BODP-IN-B02</td>
<td>BODP-IN-B</td>
<td>15</td>
<td></td>
<td>n.d. atm.</td>
<td>18–1.8–0.18–1.8–1.8–1.8–0.18–1.8</td>
<td>0.13</td>
<td>0.09</td>
<td>20.31</td>
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<td>18–1.8–0.18–1.8–1.8–1.8–0.18–1.8</td>
<td>0.19</td>
<td>0.10</td>
<td>19.54</td>
<td>195</td>
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<td>BODP-OUT02</td>
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<td>15.1 atm.</td>
<td>18–1.8–0.18–1.8–1.8–1.8–0.18–1.8</td>
<td>0.18</td>
<td>0.09</td>
<td>19.18</td>
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<td>BRS06</td>
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<td>5</td>
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<td>16.0 atm.</td>
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<td>0.45</td>
<td>0.39</td>
<td>9.98</td>
<td>26</td>
<td>0.37</td>
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<td>Illite</td>
<td>5</td>
<td></td>
<td>13.5 atm.</td>
<td>18–1.6–0.16–1.6</td>
<td>0.22</td>
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<td>13.5 atm.</td>
<td>18–1.6–0.16–1.6–1.6</td>
<td>0.34</td>
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<td>0.32</td>
<td>0.14</td>
<td>18.19</td>
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<td>15.4 atm.</td>
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<td>0.18</td>
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<td>0.34</td>
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<td>15.7 atm.</td>
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<td>0.36</td>
<td>0.23</td>
<td>19.17</td>
<td>83</td>
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<td>15.6 atm.</td>
<td>18–1.8–0.18–1.8–1.8–1.8–0.18–1.8</td>
<td>0.25</td>
<td>0.17</td>
<td>19.54</td>
<td>115</td>
<td>0.39</td>
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<td>BRS17</td>
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<td>15.8 atm.</td>
<td>18–1.8–0.18–1.8–1.8–1.8–0.18–1.8</td>
<td>0.22</td>
<td>0.13</td>
<td>19.91</td>
<td>159</td>
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<td>200 atm.</td>
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<td>0.46</td>
<td>49.95</td>
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<td>0.47 (0.47)</td>
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<tr>
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<td>300 atm.</td>
<td>18–1.8–0.18–1.8–1.8–1.8–0.18–1.8</td>
<td>0.32</td>
<td>0.23</td>
<td>25.39</td>
<td>110</td>
<td>0.51 (0.51)</td>
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<td>0.59</td>
<td>40.65</td>
<td>69</td>
<td>0.42 (0.43)</td>
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