Thermo-Poro-Mechanics of Strain Localization in Rapidly Sheared Granular Rock, and Implications for Earthquake Source Physics

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Underlying studies done collaboratively with some of:

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Quandary in seismology:

- Lab (J. Byerlee et al.) and field (M. D. Zoback et al.) estimates of friction coefficient are usually high, \( f \sim 0.6-0.8 \).

  \[ \tau = f \times (\sigma_n - p) \]

  Shear strength \( \tau \) = normal stress clamping the fault shut
  \( \sigma_n \) = normal stress clamping the fault shut
  \( p \) = pore pressure in infiltrating fluid phase

- Fault slip zones are thin (despite wide damage zones of 1-10^3 m).

  \[ \Rightarrow \text{If those } f \text{ prevail during seismic slip, and } p \sim \text{hydrostatic, we should find} \]

  - measurable heat outflow near major faults, and/or
  - extensive melt signatures along exhumed faults.

Neither effect is generally found.
Chester & Chester

[Tectonophys., 1998]
Earthquake shear is highly localized!

Punchbowl PSS, composite based on Chester & Chester [Tectonophys ‘98] & Chester & Goldsby [SCEC ‘03]

Figure 1. Principal slip surface (PSS) along the Punchbowl fault. (a) From Chester and Chester [1998]: Ultracataclasite zone with PSS marked by black arrows; note 100 mm scale bar. (b) From Chester et al. (manuscript in preparation, 2005) [also Chester et al., 2003; Chester and Goldsby, 2003]: Thin section; note 5 mm scale bar and ~1 mm localization zone (bright strip when viewed in crossed polarizers due to preferred orientation), with microshear localization of most intense straining to ~100–300 μm thickness.
Core retrieved across the Chelungpu fault, which hosted the 1999 Mw 7.6 Chi-Chi, Taiwan, earthquake: Suggests slip at 328 m depth traverse was accommodated within a zone ~ 50–300 μm thick.
Two other Chelungpu Fault, Taiwan boreholes [Boullier et al., GGG 2009, GSL 2011]:
Principal Slip Zone (PSZ) localized within black gouges

• Hole A, fault at 1111 m depth: PSZ is ~2 cm thick

• Hole B, fault at 1136 m depth: PSZ is ~3 mm thick
PSZ layering defined by variations in concentrations of clay minerals and clasts, comparable to structures produced in high-rate rotary shear exp’s.
This study: Primary source of data we use for gouge porosity, compressibility and permeability as functions of effective confining stress (and its history).
\[ \tau = f \times (\sigma_n - p) \]

Statically strong but dynamically weak faults, e.g., due to thermal weakening in rapid, large slip:

- **Process expected to be important from start of seismic slip:**
  - Thermal pressurization of in-situ pore fluid, reduces effective stress.

- **Process that may set in at large enough rise in \( T \):**
  - Thermal decomposition, fluid product phase at high pressure (e.g., CO\(_2\) from carbonates; H\(_2\)O from clays or serpentines).

- **Ultimately:**
  - Melting at large slip, if above have not limited increase of \( T \).
Shear of a fluid-saturated gouge layer

- Two non-yielding half-spaces are moved relative to each other at a speed $V$ (typically, $V \sim 1 \text{ m/s}$).

- All inelastic deformation accommodated in gouge layer, leading to a nominal strain rate $\dot{\gamma}_0 = \frac{V}{h}$. 
Thermo-mechanical model in gouge layer

- To model the deforming gouge layer we use,

Mechanical equilibrium
\[
\frac{\partial \tau}{\partial y} = 0, \quad \frac{\partial \sigma_n}{\partial y} = 0
\]

Conservation of energy
\[
\frac{\partial T}{\partial t} - \alpha_{th} \frac{\partial^2 T}{\partial y^2} = \frac{\tau \dot{\gamma}}{\rho c}
\]

Conservation of fluid mass
\[
\frac{\partial p}{\partial t} - \alpha_{hy} \frac{\partial^2 p}{\partial y^2} = \Lambda \frac{\partial T}{\partial t}
\]

- Shear stress modeled using the effective stress and rate-strengthening friction,

\[
\tau = f(\dot{\gamma})(\sigma_n - p) \quad f(\dot{\gamma}) = f_0 + (a - b) \log \left( \frac{\dot{\gamma}}{\dot{\gamma}_0} \right)
\]

\(\left(\text{We assume } a - b \equiv \left(\dot{\gamma} \frac{df(\dot{\gamma})}{d\dot{\gamma}}\right)_{\dot{\gamma} = \dot{\gamma}_0} > 0 \right)\)
Shear between moving rigid blocks of perfectly insulating, impermeable material:

Exact homogeneous shear solution (Lachenbruch, JGR, 1980, version ignoring dilatancy):

\[ \tau(t) = f_o (\sigma_n - p(t)) = f_o (\sigma_n - p_a) \exp \left( -f_o \frac{\Lambda}{\rho c} \frac{V t}{h} \right), \]

(Exponential decay of strength with slip)

Linearized perturbation analysis:

Is that solution stable to small perturbations? Not unless \( h \) is very small!

Stable only if \( h \leq W_{\text{crit}} = \frac{\pi^2}{2 + \frac{f_o}{a-b}} \rho c \left( \alpha_{\text{th}} + \alpha_{\text{hy}} \right) \left( \frac{\Lambda}{V} \right) \).

\[
\left( \text{Typically, } \frac{f_o}{a-b} \gg 2 \Rightarrow W_{\text{crit}} \approx \pi^2 \frac{a-b}{f_o^2} \rho c \frac{\alpha_{\text{th}} + \alpha_{\text{hy}}}{\Lambda} \right).
\]

\[ W_{\text{crit}} = \lambda_{\text{shr}} / 2, \text{ where } \lambda_{\text{shr}} = \text{ longest wavelength } \lambda \text{ for stable linearized response to infinitesimal } \exp(2\pi iy / \lambda) \text{ perturbation]}

Rice, Rudnicki & Platt (JGR 2014)
Estimates of maximum stable shear layer thickness (i.e., localized zone width) \( W_{\text{crit}} \)

Results, using \( f_o = 0.4, \frac{f_o}{a-b} = 20, V = 1 \text{ m/s}, \alpha_{th} = 0.7 \text{ mm}^2/s, \rho_c = 2.7 \text{ MPa}^\circ\text{C} \):

Corresponding to ~ 7 km depth:

Low estimate (Based on lab properties of intact Median Tectonic Line gouge [Wibberley and Shimamoto, 2003] at effective confining stress = 125 MPa and \( T = 200^\circ\text{C} \)):

\[ \Lambda = 0.70 \text{ MPa}^\circ\text{C}, \quad \text{and} \quad \alpha_{hy} = 1.5 \text{ mm}^2/s \quad \Rightarrow \quad W_{\text{crit}} = 3-5 \mu\text{m} \]

High estimate (Accounts very roughly for fresh damage of the initially intact fault gouge, introduced at the rupture front just before and during shear, by increasing permeability \( k \) to \( k^{\text{dmg}} = 5-10 \) \( k \), and increasing drained compressibility \( \beta_d \) to \( \beta_d^{\text{dmg}} = 1.5-2 \beta_d \)):

\[ \Lambda \approx 0.34 \text{ MPa}^\circ\text{C}, \quad \text{and} \quad \alpha_{hy} \approx 3.5 \text{ mm}^2/s \quad \Rightarrow \quad W_{\text{crit}} \approx 25-40 \mu\text{m} \]

Corresponding to ~ 1 km depth:

Low estimate: \( W_{\text{crit}} \sim 25 \mu\text{m} \)  
High estimate: \( W_{\text{crit}} \sim 200 \mu\text{m} \)

Rice, Rudnicki & Platt (JGR 2014)
Two non-yielding half-spaces are moved relative to each other at a speed $V$ (typically, $V \sim 1$ m/s).

All inelastic deformation accommodated in gouge layer, leading to a nominal strain rate $\dot{\gamma}_0 = V/h$.
Strain localization

• Full nonlinear numerical simulations (vs. linear perturbations), using representative physical values predict that strain localization does occur.

\[ W << h \quad (43 \mu m << 1,000 \mu m). \]

\[ W_{\text{nonlin. calc.}} \quad \text{is comparable to} \quad W_{\text{lin. pert.}}. \]
Implications, dynamic weakening

- Weakening of a gouge layer during localization

\[
\tau = \frac{\sigma_n - p_a}{f_o} \exp \left( \frac{V_t}{L^*} \right) \text{erfc} \left( \frac{\sqrt{V_t}}{L^*} \right)
\]

where

\[
L^* = \left( \frac{2 \rho c}{f_o \Lambda} \right)^2 \left( \sqrt{\alpha_{hy}} + \sqrt{\alpha_{th}} \right)^2 \frac{V}{V_t}
\]

Closely follows Lachenbruch \([JGR,1980]\) sol’n (Here, transport at boundary allowed).

Closely follows “slip on a plane” Rice \([JGR, 2006]\) sol’n, generalizing Mase & Smith \([JGR,1987]\) sol’n.

- Localization leads to additional weakening.
Statically strong but dynamically weak faults, e.g., due to thermal weakening in rapid, large slip:

- Process expected to be important from start of seismic slip:
  - Thermal pressurization of in-situ pore fluid, reduces effective stress.

- Process that may set in at large enough rise in $T$:
  - Thermal decomposition, fluid product phase at high pressure (e.g., CO$_2$ from carbonates; H$_2$O from clays or serpentines).

- Ultimately:
  - Melting at large slip, if above have not limited increase of $T$. 

$\tau = f(\sigma_n - p)$
Examples, thermal decomposition:


- At $T \sim 550^\circ$C, dolomite decomposes to calcite, periclase, and carbon dioxide:
  \[
  \text{CaMg(CO}_3\text{)}_2 \rightarrow \text{CaCO}_3 + \text{MgO} + \text{CO}_2
  \]
- At $T \sim 700$-900$^\circ$C, the calcite further decomposes to lime and carbon dioxide:
  \[
  \text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2
  \]

**Many clays and hydrous silicates** (Brantut et al., *J. Geophys. Res.*, 2010):

- At $T \sim 500^\circ$C (~300$^\circ$C for smectite, ~ 800$^\circ$C for chlorite), decomposition releasing H$_2$O starts.

**Gypsum, CaSO$_4$(H$_2$O)$_2$** (Brantut et al., *Geology*, 2010):

- At $T \sim 100^\circ$C, gypsum dehydrates to form bassanite:
  \[
  \text{CaSO}_4(\text{H}_2\text{O})_2 \rightarrow \text{CaSO}_4(\text{H}_2\text{O})_{0.5} + 1.5 \text{H}_2\text{O}
  \]
- At $T \sim 140^\circ$C, bassanite turns into anhydrite
  \[
  \text{CaS}_4(\text{H}_2\text{O})_{0.5} \rightarrow \text{CaSO}_4 + 0.5 \text{H}_2\text{O}
  \]
Example, recent version of Toshi Shimamoto’s rotary shear apparatus (at Institute of Geology, Peking University)
[Han, Shimamoto, Hirose, Ree & Ando, Sci., 2007]:

**Carbonate Faults**

Simulated faults in Carrara Marble at subseismic to seismic slip rates

\[ f, \text{ in sustained slip at a fixed rate } V, \text{ vs. that } V \]

\[ \tau = 0.60 (\pm 0.01) \sigma_n \]

At onset of slip

\[ \tau = 0.06 (\pm 0.01) \sigma_n \]

Sustained slip at ~ 1 m/s
Model for decomposing gouge material

- To model the deforming gouge layer we use, based on J. Sulem, I. Vardoulakis, and co-workers (Brantut, Ghabezloo, Famin, Lazar, Noda, Schubnel, Stefanou, Veveakis, …),

\[
\frac{\partial T}{\partial t} = \frac{\tau \dot{\gamma}}{\rho c} + \alpha_{th} \frac{\partial^2 T}{\partial y^2} - E_r \frac{\partial \xi}{\partial t}
\]

\[
\frac{\partial p}{\partial t} = \Lambda \frac{\partial T}{\partial t} + \alpha_{hy} \frac{\partial^2 p}{\partial y^2} + P_r \frac{\partial \xi}{\partial t}
\]

- We assume that the reaction follows an Arrhenius kinetic law,

\[
\frac{\partial \xi}{\partial t} = A (1 - \xi) \exp \left( -\frac{Q}{RT} \right)
\]

Platt, Brantut & Rice (JGR, 2015)
**Table 2. List of reaction parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Decarbonation reaction</th>
<th>Dehydration reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-exponential factor, log₁₀(Å) (Å in 1/s)</td>
<td>Calcite⁴</td>
<td>Lizardite⁵</td>
</tr>
<tr>
<td>Activation energy, Q (kJ/mol)</td>
<td>15.47</td>
<td>17.80</td>
</tr>
<tr>
<td>Fluid mass, m_{100%} (kg/m³),</td>
<td>319</td>
<td>328</td>
</tr>
<tr>
<td>Enthalpy, ΔH (MJ/kg)</td>
<td>1140</td>
<td>240</td>
</tr>
<tr>
<td>Solid volume change, φ (x10⁻³ m³/kg)</td>
<td>7.25</td>
<td>2.56</td>
</tr>
<tr>
<td>Fluid density, ρf (m³/kg)</td>
<td>0.46</td>
<td>0.88</td>
</tr>
<tr>
<td>Tr (°C)</td>
<td>418</td>
<td>267</td>
</tr>
<tr>
<td>Er (°C)</td>
<td>960 °C</td>
<td>885 °C</td>
</tr>
<tr>
<td>Pr (GPa)</td>
<td>3.06 × 10³</td>
<td>275</td>
</tr>
<tr>
<td>W^{HT}</td>
<td>7.42</td>
<td>2.80</td>
</tr>
<tr>
<td>W</td>
<td>5.1 μm</td>
<td>1.2 μm</td>
</tr>
<tr>
<td></td>
<td>12.7 μm</td>
<td>6.8 μm</td>
</tr>
</tbody>
</table>

**Linear perturbation results:** very rough estimates of localization zone widths:

High T, fast reaction rate limit:  \( W^{HT} \approx \frac{\pi^2 \alpha_{hy}}{V} \frac{(a-b) \rho c E_r}{f_o^2 Pr} \)

Low T, pre-reaction thermal press.:  \( W \approx \frac{\pi^2}{f_o^2 \Lambda} \frac{a-b \rho c \alpha_{th} + \alpha_{hy}}{V} \)

\([W = \lambda / 2, \text{ where } \lambda = \text{ longest wavelength for stable linearized response to infinitesimal } \exp(2\pi iy/\lambda) \text{ perturbation}]\)
Representative simulations: thermal pressurization of in-situ fluids, followed by thermal decomposition

Supports concept that faults may be strong but brittle (quickly lose strength after slip is initiated at a place of localized stress concentration)
- Numerical solutions for a 1 mm wide gouge layer.

- When the reaction becomes important, we observe significant strain localization ($W_{\text{nonlin. calc.}}$ of order $\sim 2 \times W_{\text{lin. pert.}}$).
Independence of reaction rate

- Our linear stability analysis predicts the localized zone width is independent of kinetic parameters. To test this we increase $A$ by three orders of magnitude.

- The localized zone width has only decreased by a factor of two.

Platt, Brantut & Rice (AGU, Fall 2011; JGR 2015)
Now we investigate a case for which **depletion of reactant** is important.

- Depletion causes the zone of localized straining to migrate. The strain rate and reaction rate profiles are strongly coupled.  

Platt, Brantut & Rice *(AGU, Fall 2011; JGR 2015)*
Localized zone migration

- This localized zone migration leads to a complex, non-monotonic, strain history.

- Possible end result: Laminations in gouge.

Platt, Brantut & Rice (AGU, Fall 2011; JGR 2015)
Observation suggesting migration (in rotary shear of carbonate sample)

from T. Mitchell, Univ. Col. London (private comm.)
• Another *weakening process expected to be important from start of seismic slip*:

  - Flash heating of asperity contacts, reduces $f$ in rapid slip.

Most studied so far for bare surfaces in contact; recent extensions to fault gouge
**Flash heating of microscopic frictional asperity contacts**


\[ V = \text{slip rate} \]

\[ T = \text{asperity temperature} \]

\[ T_f = \text{average temperature of fault surfaces} \]

\[ \sigma, \tau \]

\[ \sigma_c, \tau_c \]

\[ V_w = \pi \frac{\alpha_{th} (T_w - T_f)^2}{D} \left( \frac{\tau_c}{\rho c} \right) \]

When \( V > V_w \), asperity is weak for some of its life; suggests friction coeff

\[ f \approx f_{\text{slow}} \frac{V_w}{V} + f_{\text{weak}} \left( 1 - \frac{V_w}{V} \right) \]

\[ = f_{\text{weak}} + (f_{\text{slow}} - f_{\text{weak}}) \frac{V_w}{V} \]

when \( V > V_w \).
Arkansas novaculite (~100% quartzite)

Rotary shear, 1.2 mm pre-slip at ~10 μm/s, followed by rapid slip for remaining 43 mm.

At low $V$, $f \approx 0.65$

At $V > 0.3$ m/s, $f \approx 0.30$

$V_w \approx 0.14$ m/s

[Tullis & Goldsby, SCEC, 2003; EOS, 2003]
Torsional Kolsky bar apparatus
[Yuan & Prakash, Int. J. Solids & Structures, 2008]

Slip at $V \approx 2-4$ m/s, resulting in $f \approx 0.20$. 

Arkansas novaculite (quartzite)

(Experiment becomes uninterpretable after small slip, marked, due to cracking in wall of specimen.)
Goldsby & Tullis [Sci., 2011]:
Test of simple flash weakening model,
\[ f = f_o \text{ for } V < V_w, \quad f = f_w + (f_o - f_w) \frac{V_w}{V} \text{ for } V > V_w \]

Such rate weakening promotes rupture propagation in the self-healing pulse mode!
Flash heating and weakening in gouge?

Some relevant studies:

Beeler, N., T. E. Tullis, and D. L. Goldsby (JGR, 2008): Constitutive relationships and physical basis of fault strength due to flash heating


The role of gouge and temperature on flash heating and its hysteresis

Major points:

Building on Beeler et al. [2008], total slip rate assumed to be shared between multiple frictional contacts.

Solving for the contact temperatures, flash heating occurs when the strain rate exceeds a critical rate. For a deforming zone 100 microns wide, \( V_w \) is \( \sim 4 \text{ m/s} \) (vs. \( \sim 0.1 \text{ m/s} \) for bare surfaces) → flash heating much less efficient in gouge than for bare surfaces.

The lower contact slip rate → longer contact lifetimes → wider thermal boundary layer thickness \( W \) at contact

When \( W \sim D \) (spacing between contacts) flash heating begins at much lower slip rates, and friction decreases slowly as the slip rate increases.

Hysteresis commonly seen in bare surface experiments, with higher friction observed during acceleration than deceleration. Accounting for the sensitive dependence of \( V_w \) on sliding surface temperature \( T_f \) allows to match some data for both acceleration and deceleration over a wide range of slip rates.
Some Consequences for Earthquake Dynamics
Dynamic rupture simulations, incorporating flash heating of asperity contacts and thermal pressurization of pore fluid, with parameters constrained (to the extent possible) by laboratory observations

[Noda, Dunham & Rice, JGR 2009]

\[ \tau^b = \sigma e f = (\sigma_n - p \bigg|_{z=0}) f \]
**Flash heating**  (in dynamic rupture simulations, Noda, Dunham & Rice, JGR 09)

**Effective stress law:**

\[ \tau = \sigma_e f = (\sigma_n - p |_{z=0}) f \]

- given, fixed compressive normal stress
- friction coefficient
- pore pressure on slip surface

**Rate and state friction concepts, together with flash heating at microscopic contacts during rapid slip:**

\[
\frac{df}{dt} = \frac{a}{V} \frac{dV}{dt} - \frac{V}{L} \left[ f - f_{ss}(V) \right]
\]

- \( f_{ss}(V) = \begin{cases} f_{LV}(V), & V \leq V_w, \\ f_w + \left( f_{LV}(V) - f_w \right) \frac{V_w}{V}, & V \geq V_w, \end{cases} \)

- with \( V_w = \pi \frac{\alpha_{th} \left( T_w - T \right)}{D \left( \frac{T_w - T}{\tau_c/\rho c} \right)^2} \)

- \( f_{LV}(V) = f_o + (a - b) \ln \left( \frac{V}{V_o} \right) \)
Based on Tullis and Goldsby [SCEC, `03] parameters $f_o'$, $f_w$ and $V_w$ for granite.

Figure 1. Steady state frictional shear stress, $\tau_{ss}$, normalized by initial effective normal stress, $\bar{\sigma}_0$, as a function of slip velocity, $V$. $\tau^{\text{pulse}}$ is defined for the initial ambient conditions at 7 km depth ($T = 210 ^\circ C$, $\sigma = 196$ MPa, $\rho = 70$ MPa) by the radiation-damping line which fits tangentially to $\tau_{ss}(V)$ at $V = V^{\text{pulse}}$ (= 1.487 m/s). The weakening slip rate is $V_w = 0.170$ m/s. Due to extreme velocity weakening at elevated slip rates, $\tau^{\text{pulse}}$ is very small ($0.2475 \bar{\sigma}_0$).

Based on Zheng & Rice (BSSA, 1999), sustained rupture propagation expected to be possible, once nucleated, for background stress $\tau^b > \tau^{\text{pulse}} \approx 0.25 \bar{\sigma}_0$. 

$V_{w0} = 0.170$ m/s  
$T_0 = 210 \ ^\circ C$ 
$\bar{\sigma}_0 = 126$ MPa 
$V^{\text{pulse}} = 1.487$ m/s
Thermal pressurization (in dynamic rupture simulations, Noda, Dunham & Rice, JGR 09)

Effective stress law:

\[ \tau = \sigma_n f = (\sigma_n - p\big|_{z=0})f \]

given, fixed compressive normal stress

friction coefficient

pore pressure on slip surface

Thermal pressurization, finite thickness of slipping zone, with Gaussian shear distribution having \( r.m.s. \) width \( w \):

Conservation of energy (first law of thermodynamics):

\[
\frac{\partial T}{\partial t} = \alpha_{th} \frac{\partial^2 T}{\partial z^2} + \frac{\tau}{\rho c \sqrt{2\pi}} \frac{V}{w} \exp \left( -\frac{z^2}{2w^2} \right)
\]

Conservation of fluid mass (neglecting dilatancy):

\[
\frac{\partial p}{\partial t} = \alpha_{hy} \frac{\partial^2 p}{\partial z^2} + \Lambda \frac{\partial T}{\partial t}
\]

\( \alpha_{th} \sim 0.7 \text{ mm}^2/\text{s}; \ \alpha_{hy} \sim 0.9 - 6 \text{ mm}^2/\text{s} \) at mid-seismogenic depths; \( \rho c \sim 2.7 \text{ MJ/m}^3\text{K} \);

\( \Lambda \sim 0.3 - 1.0 \text{ MJ/m}^3\text{K} \) (Rice \[JGR 2006\] & Rempel & Rice \[ibid\], based on Wibberley \[EPS 2002, priv comm 2003\] & Wibberley & Shimamoto \[JSG 2003\], and estimates of damage)
High $\tau^b$ favors crack-like solution, thermal pressurization does too.
Effect of hydrothermal properties

\[ \tau_{\text{per}} = 30\text{MPa} \]
\[ D_{\text{per}} = 5\text{cm} \]

Mode III, Different \( \alpha_{\text{th}} \) and \( \Lambda \)

**Shown:**
The case \( w = 0 \), slip on a plane.

High \( \tau^b \) favors crack-like solution, thermal pressurization does too.
Effect of hydrothermal properties

$\tau_{\text{per}} = 30\text{MPa}$
$D_{\text{per}} = 5\text{cm}$

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High $\tau^b$ favors hydrothermal pressurization, but hydrothermal pressurization does too.
Effect of hydrothermal properties

\[ \tau_{\text{per}} = 30 \text{MPa} \]
\[ D_{\text{per}} = 5 \text{cm} \]

\[ \text{H.T. diffusivity Factor, mm}^2/\text{s} \]

\[ \text{Slip distribution every 5 \mu s} \]

\[ \text{Slip distribution every 25 \mu s} \]

\[ \text{Damaged} \]

\[ \text{Arrested pulse} \]

\[ \text{Growing pulse} \]

\[ \text{Crack-like} \]

Shown: The case \( w = 0 \), slip on a plane.

High \( \tau^b \) favors hydrothermal pressurization does too.
Effect of hydrothermal properties

\[ \tau_{\text{per}} = 30 \text{MPa} \]
\[ D_{\text{per}} = 5 \text{cm} \]

Shown: The case \( w = 0 \), slip on a plane.

High \( \tau^b \) favors crack-like solution, thermal pressurization does too.
Comparing a growing slip pulse at $\tau^b = 0.230 \ (\sigma_0 - p_0)$ to an enlarging shear crack at $\tau^b = 0.238 \ (\sigma_0 - p_0)$

Both predict (if projected to circular fault) Seismic Moment $M_o \ [\text{Nm}] \approx \lambda \times 10^{17} \ (t \ [\text{s}])^3$; $\lambda \approx 1.7$ for *slip pulse*, $\lambda \approx 10.5$ for *crack*; compare, $\lambda \approx 2$ for Parkfield 2004 [Uchide]

[Using $\delta^{3D}/\delta^{2D} = 0.73$, $\mu=35 \ \text{GPa}$, $\rho=2800 \ \text{kg/m}^3 \ (c_s = 3.5 \ \text{km/s})$, and $v_r = 0.8c_s$]
Simulations show growing pulse for ~ 0.22-0.24
Steady-state pulse solutions, from Dmitry I. Garagash, "Seismic and Aseismic Slip Pulses Driven by Thermal Pressurization of Pore Fluid", to JGR, 2012:

Assumes:
- Friction coefficient $f = \text{const.}$
- Shear zone thickness $W = \text{const.}$
Steady-state pulse solutions, from Dmitry I. Garagash, "Seismic and Aseismic Slip Pulses Driven by Thermal Pressurization of Pore Fluid", JGR, 2012:

\[ f (\sigma_n - p_{amb}) = \tau_0 \]

**Maximum T rise is "low":**

\[ \Delta T_{\text{max}} \leq \frac{\sigma_n - p_{amb}}{\Lambda} \]

\[ \Lambda \approx 0.3 \text{ to 1.0 MPa/°C} \]

**Assumes:**
- Friction coefficient \( f = \text{const.} \)
- Shear zone thickness \( W = \text{const.} \)

**Shows:**
- \( W > 0 \) needed for healing.  
- \( W \) scales slip lengths in the early weakening process.
- \( \alpha/W \) scales the rupture velocity.  
- Thin/thick shear zones support seismic/aseismic pulses.
Conclusions:

• \( \tau_{\text{static}} \) much larger than \( \tau_{\text{seismic}} \).

• Documented weakening (and localization) processes:
  - flash heating;
  - thermal pressurization, in-situ & decomp product;
  - nanoparticle-related \( \rightarrow \) (physics remains unclear);
  - melting.

• Static strength \( \tau_{\text{static}} = f_s \sigma_n \) is unreliable predictor of pre-earthquake stress on major, well-slipped, smooth faults.

• Such faults may operate near or slightly above \( \tau_{\text{pulse}} \) (a \( \tau \) at which a small event, once nucleated, propagates indefinitely).

• Roughness may keep less mature faults from full benefit of dynamic weakening; to slip, side-walls must be deformed.

• The fact that a segment is creeping does not preclude it from having large coseismic slip (Chi-Chi, 1999, Tohoku-Oki, 2011).
Particle size distribution for Ultracataclasite gouge hosting the Punchbowl pss [Chester et al., *Nature*, 2005]

- \( N(D)/A = \) number of particles per unit sample area with \( 2D/3 < \text{diameter} < 4D/3 \).

- \( N(D)/A \approx c/D^2 \) for \( 30 \text{ nm} < D < 70 \text{ \( \mu \)}\text{m} \).
  
  In 3D: \( \hat{N}(D)/V \approx \hat{c}/D^3 \)

- \( D_{50} (= \text{size such that 50\% by mass are larger/smaller}) \sim 1 \text{ \( \mu \)}\text{m} \).

- Standard granular material guideline (for narrow size range): thinnest possible shear zone \( \sim 5 \text{ to } 10 \times D_{50} \sim 5 \text{ to } 10 \text{ \( \mu \)}\text{m} \)