Heterogeneous Velocity-Dependency Structures of Lithospheres as Inferred from a Friction to Flow Law

Toshihiko Shimamoto$^{1,2}$ and Hiroyuki Noda$^2$

$^1$State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration
$^2$Shimamoto Earth & Environment Laboratory (SEE-Lab) Ltd.
$^3$Disaster Prevention Research Institute, Kyoto University

An Outline of Talk

(1) A quick review on “Friction to flow law” (Shimamoto and Noda, 2014, JGR)

(2) Velocity-dependency: most heterogeneous in the transition zone (JpGU, 2018)
Frictional patches surrounded by deep-transitional and viscous patches.
$\Rightarrow$ Modeling of slow slip and low-frequency earthquakes

(3) Fault models: Friction to grain-size sensitive flow law, not to power law

(4) How to upscale friction to flow properties?
Complete transition from friction to fully plastic deformation across a lithosphere was produced only for halite, but not for other rocks!

I want to produce this for other important rocks.

Kawamoto and Shimamoto (1998)

Slip rates: 0.3 mm/yr to almost 10 mm/s.

We have not conquered “LITHOSPHERE” yet!
Five Important Steps towards a Friction to Flow Law

Frictional behavior changes to pressure-insensitive fully plastic deformation, through a transitional regime.

Step 1
Friction to exponential flow law
Shimamoto (1986, Science)

Step 2
Brittle def. (basal slip in phyllosilicates)
Plastic def. (slip systems less than 5) + brittle def. [Mylonitic def.]

Trading time with temperature!

Increase in slip rate
Decrease in temperature
Friction to power law
Kawamoto and Shimamoto (1997) Proc. of 30th IGC, Beijing

Pressure-dependence is lost!
An Empirical Friction to Plastic Flow Law

\[
\tau_{\text{friction}} = \mu_s \sigma = \text{steady-state friction, } \sigma : \text{normal stress}
\]

\[
\tau_{\text{flow}} = \text{steady-state flow stress}
\]

\[
\tau_{ss} = \text{real shear resistance}
\]

\[
\frac{\tau_{ss}}{\tau_{\text{flow}}} = \tanh \left( \frac{\mu_s \sigma}{\tau_{\text{flow}}} \right)
\]

\[\mu_s \sigma/\tau_{\text{flow}} : \text{small} \]

\[\tanh \left( \frac{\mu_s \sigma}{\tau_{\text{flow}}} \right) \sim \mu_s \sigma/\tau_{\text{flow}} \]

\[\tau_{ss} = \mu_s \sigma \]

\[\text{(Friction law)}\]

\[
\sigma_{ss} \sigma/\tau_{\text{flow}} : \text{large} \]

\[\tanh \left( \frac{\mu_s \sigma}{\tau_{\text{flow}}} \right) \sim 1 \]

\[\tau_{ss} = \tau_{\text{flow}} \]

\[\text{(Flow law)}\]

[1] An empirical mixing law connecting friction to flow smoothly
--- Only friction and flow parameters needed.
← No new deformation mechanisms

[2] Only new parameter: shear zone width \( w \)
This is needed to relate strain rate in flow law with velocity in friction law.

[3] The law is bound by friction and flow laws.
It cannot be completely wrong unless something strange happens in the transition.
Rate-and-State Flow Law

A step increase in slip rate from $V_1$ to $eV_1$:

$$\Delta(\ln(\tau_{flow})) = \ln(\tau_{flow}(V_1, \Psi_0)) - \ln(\tau_{flow}(eV_1, \Psi_0)) = 1/m$$

**Transient behavior:** an exponential increase from $\Psi_0$ to $\Psi$

$$\Psi = \Psi_{ss} + (\Psi_0 - \Psi_{ss}) \exp(-Vt/\gamma_c) = \Psi_{ss} + (\Psi_0 - \Psi_{ss}) \exp(-\gamma/\gamma_c)$$

Viscous Newtonian

Parameter $m \rightarrow$ Instantaneous response (determined only for halite)

Is the instantaneous response real?
Step 5

Fitting the halite data with the law

Friction to flow behavior can be described with the law.

\[
\frac{\tau_{ss}}{\tau_{flow}} = \tanh \left( \mu_{ss} \frac{\sigma}{\tau_{flow}} \right)
\]

\[
\dot{\gamma} = A (\tau_{flow})^n \exp(-O/RT)
\]

\[
\mu_{ss} = \mu_0 + (b-a) \ln v
\]

Shear zone = 0.7 mm

Least-square fit with Matlab

Good agreements with data!

Shimamoto and Noda (2014, JGR)
Step-Change Behavior from to Flow to Friction

(1) Velocity weakening to strengthening at the peak strength
(2) Instantaneous response followed by decay – beyond peak

Base of seismic zone: V. weakening to strengthening!?
Velocity Dependency versus Temperature

Granite & Qz gouge: Blanpied et al. (1995, JGR) \( \sigma_N = 400 \text{ MPa, } P_p = 100 \text{ MPa} \)

Quartzite shear zone, \( w = 300 \text{ m.} \)
Flow law from Hirth et al., (2001)

Friction to transitional!

1. Velocity-dependency increases with increasing flow stress.
2. Velocity-dependency increases sharply within the transitional regime.
3. Maximum rate dependency --- near the bottom of transitional regime
4. \( V \) has a large effects on the velocity dependency.

\[ \frac{d \tau_{\text{flow ss}}}{d \ln(V)} = \frac{\tau_{\text{flow ss}}}{n} \]
Heterogeneity Predicted from Friction to Flow Law

Rate-dependency = $\sigma(a - b)$ --- $\Delta\tau$ for $V \rightarrow eV$

Slip rate: $10^{-9}$ m/s, shear zone width: 300 m
Geothermal gradient: 25ºC

(1) Temperature for flow depends on rock/mineral types. → Transitional regime: most heterogeneous!

(2) Slow slip, low-frequency tremors!

---

Quartzite
Hirth et al., (2001)

Plagioclase
Rybacki & Dresen (2000)

Diabase
Caristan (1982)
A certain Pp distribution can make profiles flat. Similar velocity dependency still remains.

Rate-depenfency = $\sigma(a - b) - \Delta \tau$ for $V \rightarrow eV$

**Essential features of fault properties (a summary)**

1. Frictional and flow regimes are separated by transitional regime. The transitional regime has a high rate dependency of shear resistance and it can act as an very effective barrier of seismic fault motion.
2. Fault properties are most heterogeneous in the transitional regime.
Ando san’s Rheology Model for Slow Slip and LFE’s

Ando, Nakata & Hori (2010, GRL), Nakata, Ando, Hori & Ide (2011, JGR)

Brittle patches in viscous matrix
Growth to large EQs suppressed. Diffusion like rupture propagation.

[1] I had strong doubt about such possibility! But I was wrong!

[2] Friction to flow law →
Frictional patches in transitional/viscous matrix!

[3] Matrix is likely to be pelitic rocks (weakest) in subduction zones.
--- Flow laws of rocks in subduction zones are needed!
In nature, it is likely that friction changes to diffusion creep.
Grain-size sensitive flow law (linearly viscous).

To be precise, flow regime may be a composite system.
Diffusion creep for the core (ultramylonites)
Power law creep for the outside (protomylonite and mylonites)

Low-temperature mylonites form in the transitional regime.
How to attack the **scale issue**?

(1) Noda’s modeling of plate-boundary behaviors

\[
\frac{\tau_{ss}}{\tau_{flow}} = \tanh \left( \mu \sigma/\tau_{flow} \right)
\]

(2) Behaviors are very systematic
→ A macroscopic constitutive law \( \tau_{pl}(V_{pl}) \), describing system behaviors

(3) Same modeling can be done with heterogeneous fault zones → Apparent properties (**upscaling**)
→ More realistic EQ modeling
Thank you!

大同 (Daton, China)
[1] Plate boundaries are governed by a rate-strengthening power law. 
[2] Average shear stress at boundary $\tau_{pl}$ significantly depends on the maximum effective normal stress $\sigma_{e\text{max}}$. 


Noda (2017, Joint JpGU-AGU meeting)
A plate boundary may have “power-law friction” with significant apparent cohesion.

Plate boundaries have their own apparent properties, reflecting the friction to flow properties. --- *useful in analyzing plate interactions!*

The fault is overall frictional, having significant (apparent) cohesion. The friction coefficient is much smaller than the brittle part of the fault ($f_0 = 0.6$).
A simple friction to flow law is useful in describing fault properties across a lithosphere and in EQ modeling.

\[ \frac{\tau_{ss}}{\tau_{flow}} = \tanh \left( \frac{\mu \sigma}{\tau_{flow}} \right) \]

The flow regime in fault zones is probably dominated by diffusion creep or grain-size sensitive flow.

Velocity-dependency is most heterogeneous in the core of a lithosphere (transitional regime): important for SSL and LFT.

How to merge the friction to flow law with HV friction?

Mechanical properties of lithosphere itself are needed for modeling tectonic deformation including fault motions.

--- Friction to flow law has to be extended to describe brittle to ductile transition of rocks.
**Task 1: Friction to flow experiments for important rocks**

My dream machine: a rotary-shear anvil-type friction apparatus

**Flow regime: diffusion creep**

Transitional regime: power law

**Diffusion creep: dominant**

---

**Solenhofen limestone**

Grain size ~ 4 μm

Schmit (1977):

$10^{-5}$ mm/s --- 5 mm/5.8 days

---

**Feldspar (CaAl$_2$Si$_2$O$_8$)**

Grain size ~ 3.4 μm

Rybacki & Dresen (2000):
Task 2: Constitutive Law for Brittle-Plastic Transition (Lithosphere Rheology)

A similar law may hold. – First analyze existing data!

Early studies with a solid-pressure medium apparatus (IGCEA): Zhang et al. (1982)

\[
\frac{\sigma_d}{\tau_{\text{flow}}} = \frac{\tanh [(a + bP_c)/\tau_{\text{flow}}]}{\tau_{\text{flow}}} = A \exp \left( \frac{Q}{nRT} \right)
\]

- \(a = 381\) MPa, \(b = 3.4\)
- \(A = 1.6, Q/n = 28\) kJ/mole

Fitting is not good partly because of large error in experiments.

Fitting by H. Noda (2017)