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

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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.

→ Modeling of slow slip and low-frequency earthquakes

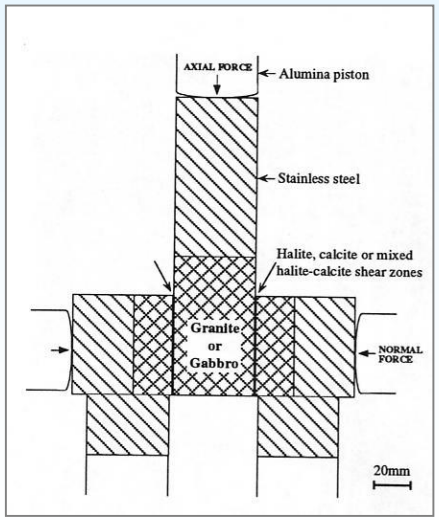
(3) Fault models: Friction to **grain-size sensitive flow law**, not to power law

(4) How to upscale friction to flow properties?

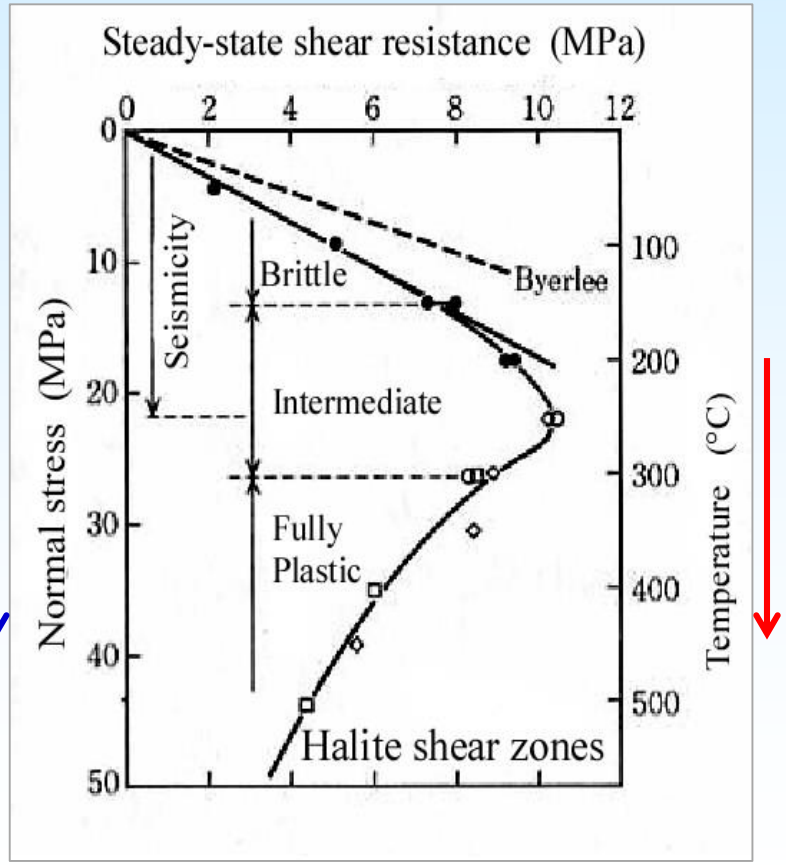
We have not conquered "LITHOSPHERE" yet!

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.

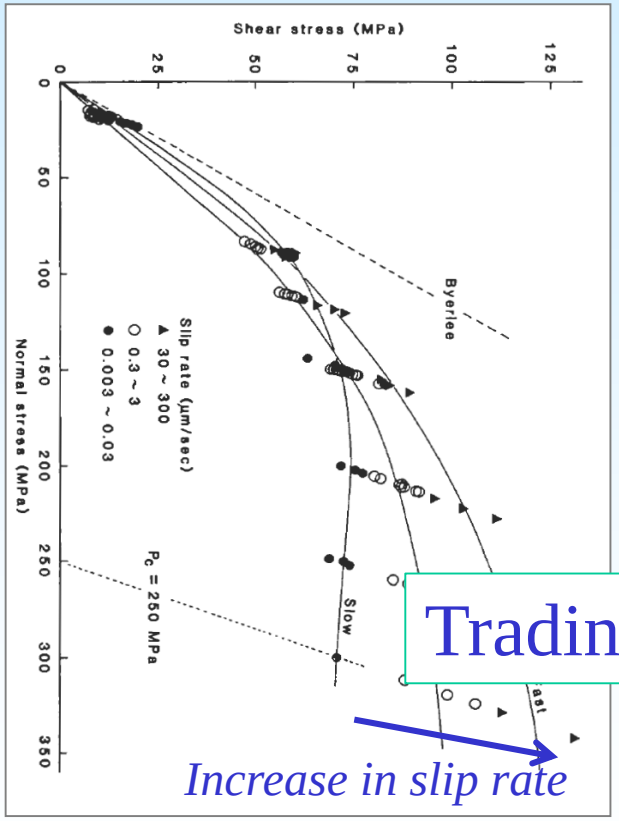
High-Temperature Biaxial Frictional Testing Machine

Five Important Steps towards a Friction to Flow Law

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

Step 1

Step 2



Increase in slip rate

Friction to exponential flow law

Shimamoto (1986, Science)

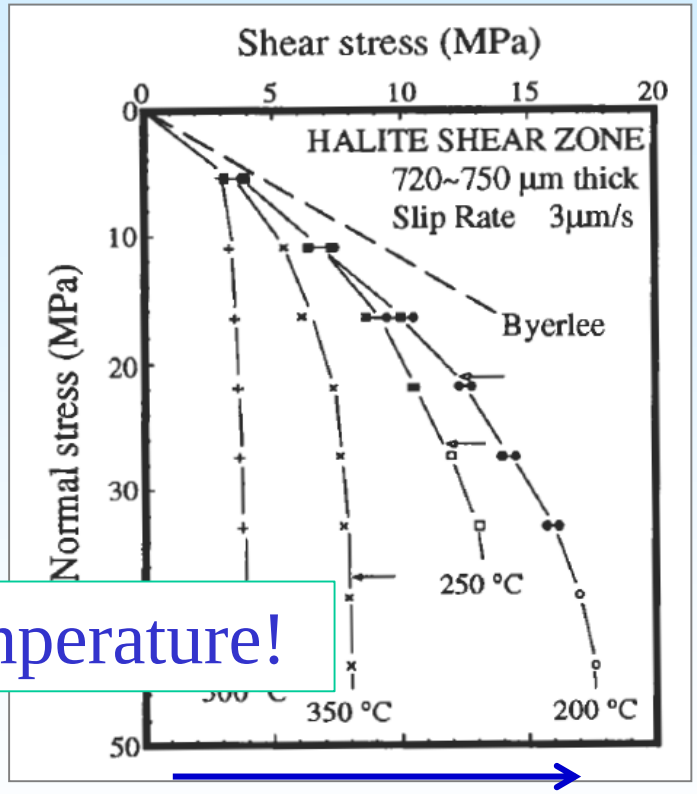
Brittle def.
(basal slip in phyllosilicates)

↓

Plastic def.
(slip systems less than 5) + brittle def.
[Mylonitic def.]

Trading time with temperature!

Fully plastic def.
(von Mises Criterion is satisfied.)
Pressure-dependence is lost!



Decrease in temperature

Friction to power law

Kawamoto and Shimamoto (1997)
Proc. of 30th IGC, Beijing

Step 3

An Empirical Friction to Plastic Flow Law

Shimamoto (2004, JpGU)

$\tau_{friction} = \mu_{ss}\sigma$ = steady-state friction, σ : normal stress

τ_{flow} = steady-state flow stress

τ_{ss} = real shear resistance

$$\tau_{ss} / \tau_{flow} = \tanh(\mu_{ss}\,\sigma/\tau_{flow})$$

$\mu_{ss}\sigma/\tau_{flow}$: small

$\tanh(\mu_{ss}\,\sigma/\tau_{flow}) \sim \mu_{ss}\,\sigma/\tau_{flow})$

$$\tau_{ss} = \mu_{ss}\,\sigma$$

(Friction law)

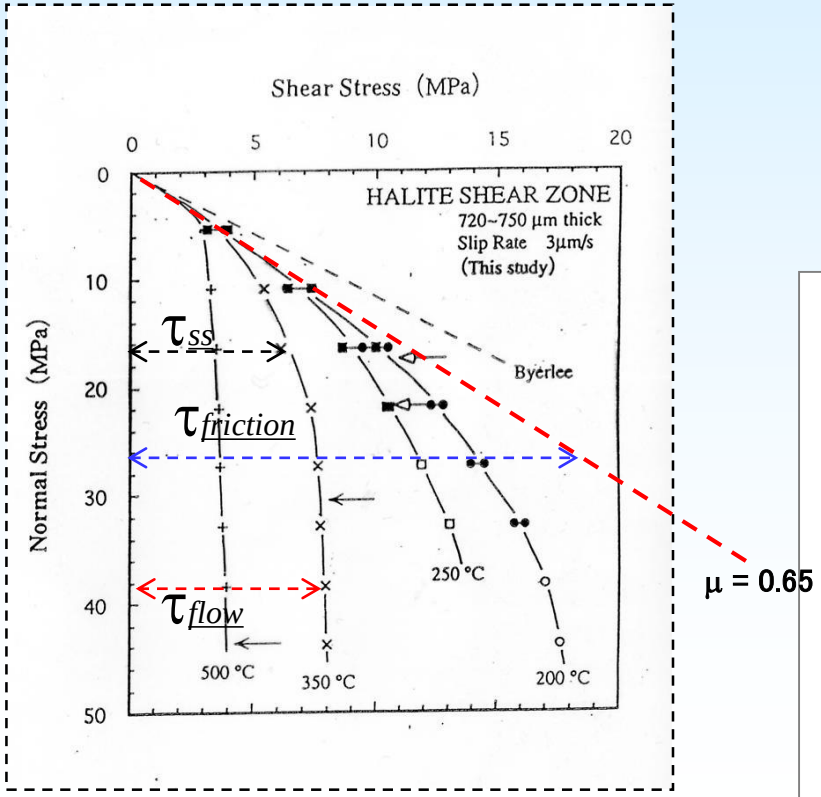
$\sigma_{ss}\sigma/\tau_{flow}$: large

$\tanh(\mu_{ss}\,\sigma/\tau_{flow}) \sim 1$

$$\tau_{ss} = \tau_{flow}$$

(Flow law)

Very similar to tanh curve!



Kawamoto & Shimamoto (1997)

[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.

Step 4

Rate-and-State Flow Law

Both transient & steady-state behaviors

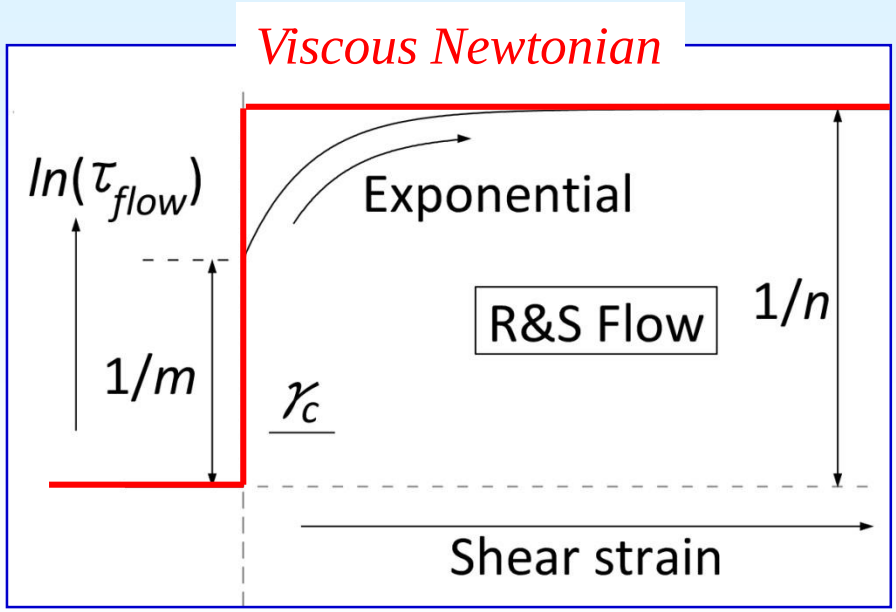
A step increase in slip rate from V_1 to eV_1:

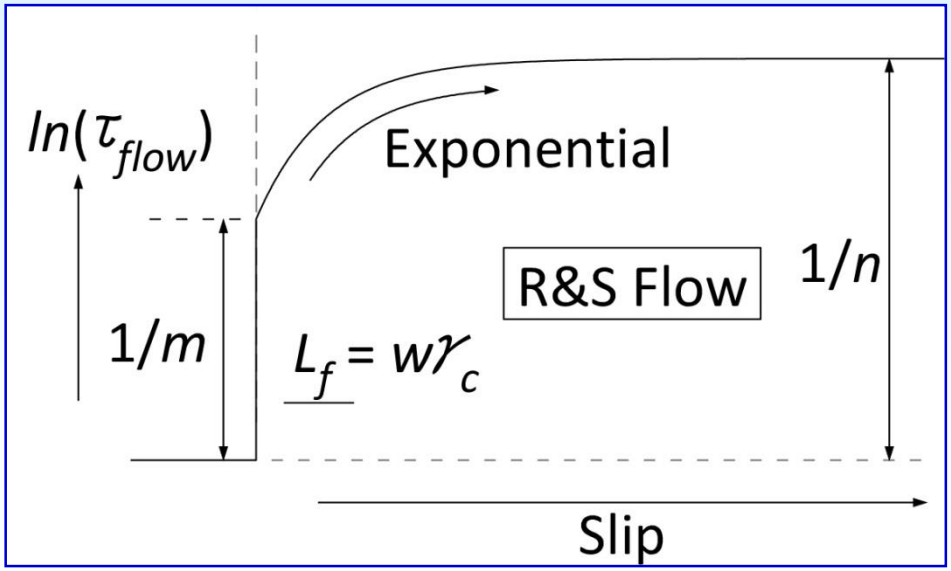
Noda & Shimamoto (2010, GRL)

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

Transient behavior: an exponential increase from Ψ_0 to Ψ

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





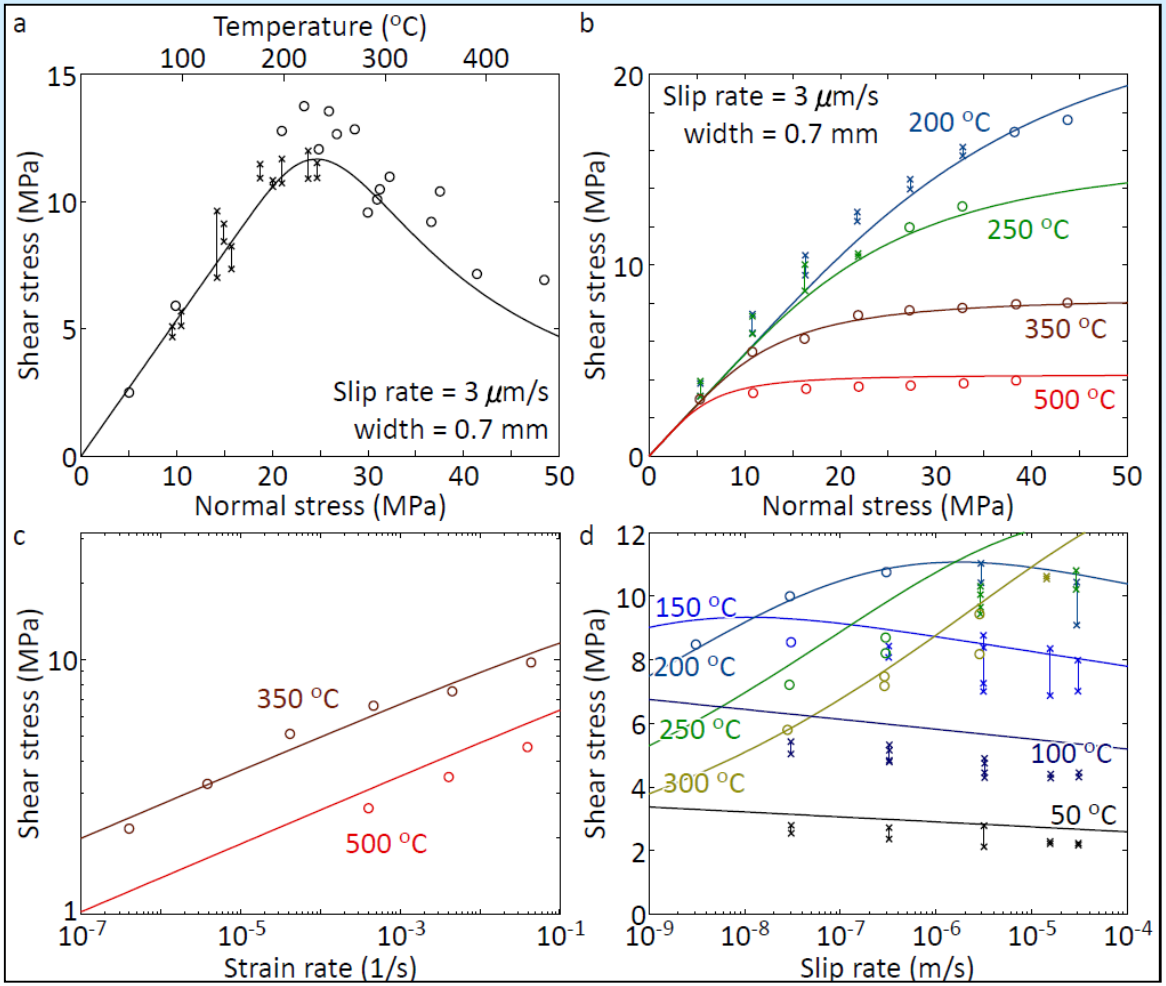
Parameter m → Instantaneous response (determined only for halite)

Is the instantaneous response real?

Step 5

Fitting the halite data with the law

Friction to flow behavior can be described with the law.



$$\tau_{ss} / \tau_{flow} = \tanh(\mu_{ss}\, \sigma / \tau_{flow})$$

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

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

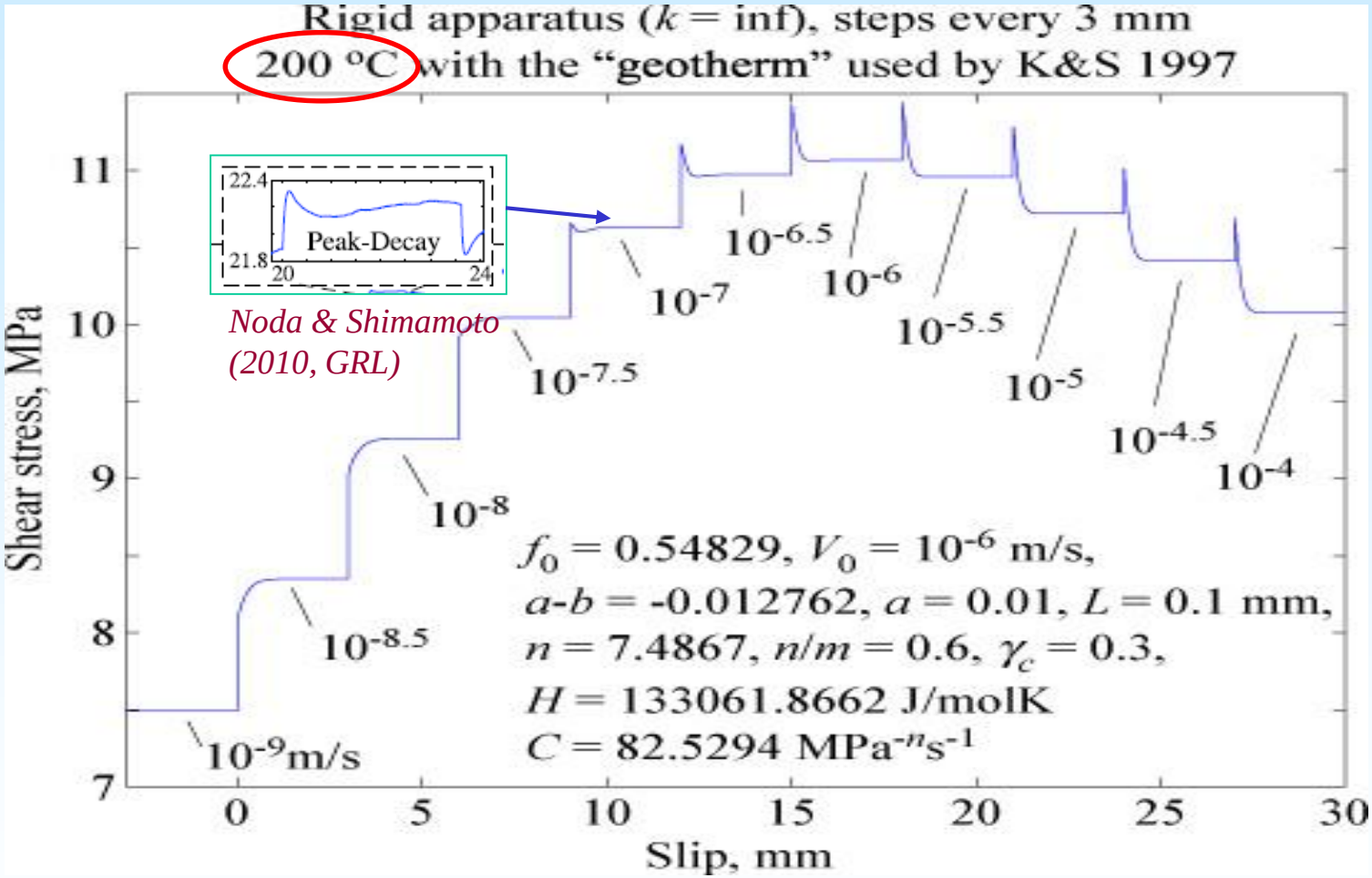
Shear zone = 0.7 mm

Least-square fit with Matlab

Good agreements with data!

Shimamoto and Noda (2014, JGR)

Step-Change Behavior from to Flow to Friction



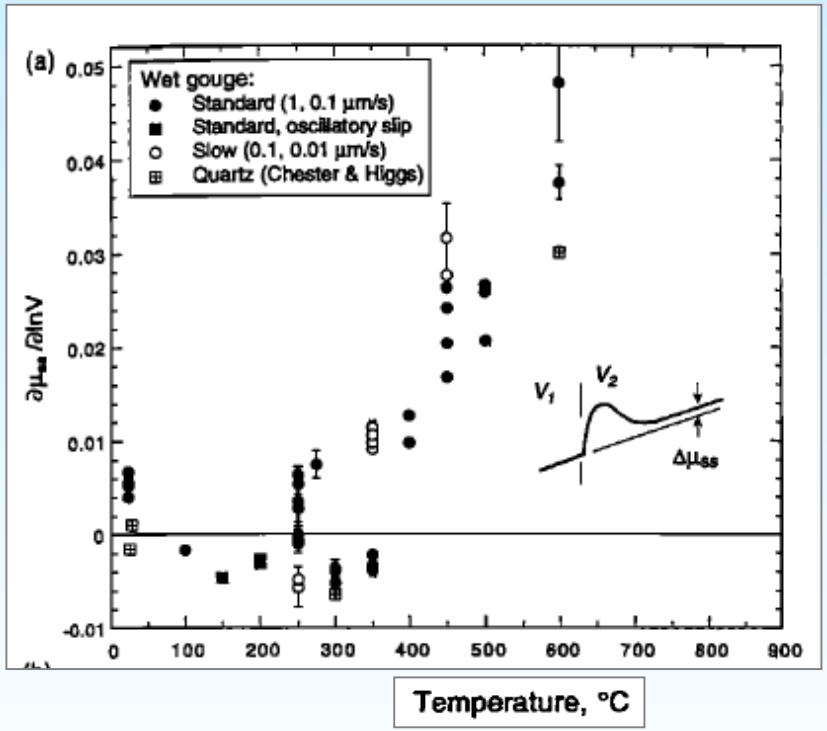
(1) Velocity weakening to strengthening at the peak strength

(2) Instantaneous response followed by decay – beyond peak

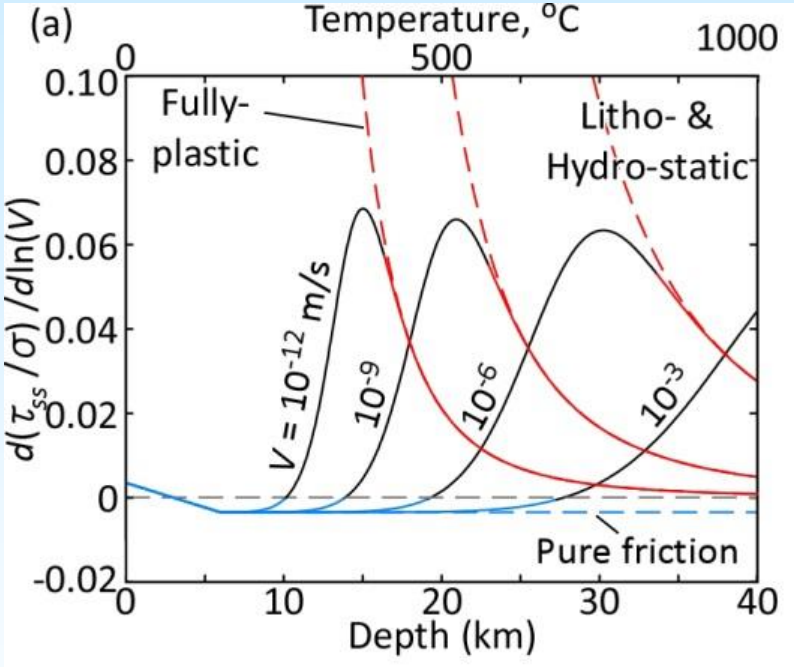
Base of seismic zone: V. weakening to strengthening!?

Velocity Dependency versus Temperature

Granite & Qz gouge: Blanpied *et al.* (1995, JGR) σ_N = 400 MPa, P_p = 100 MPa



Quartzite shear zone, w = 300 m.
Flow law from Hirth *et al.*, (2001)



$$d\tau_{flow\ ss} / d\ln(V) = \tau_{flow\ ss} / n$$

Friction to transitional!

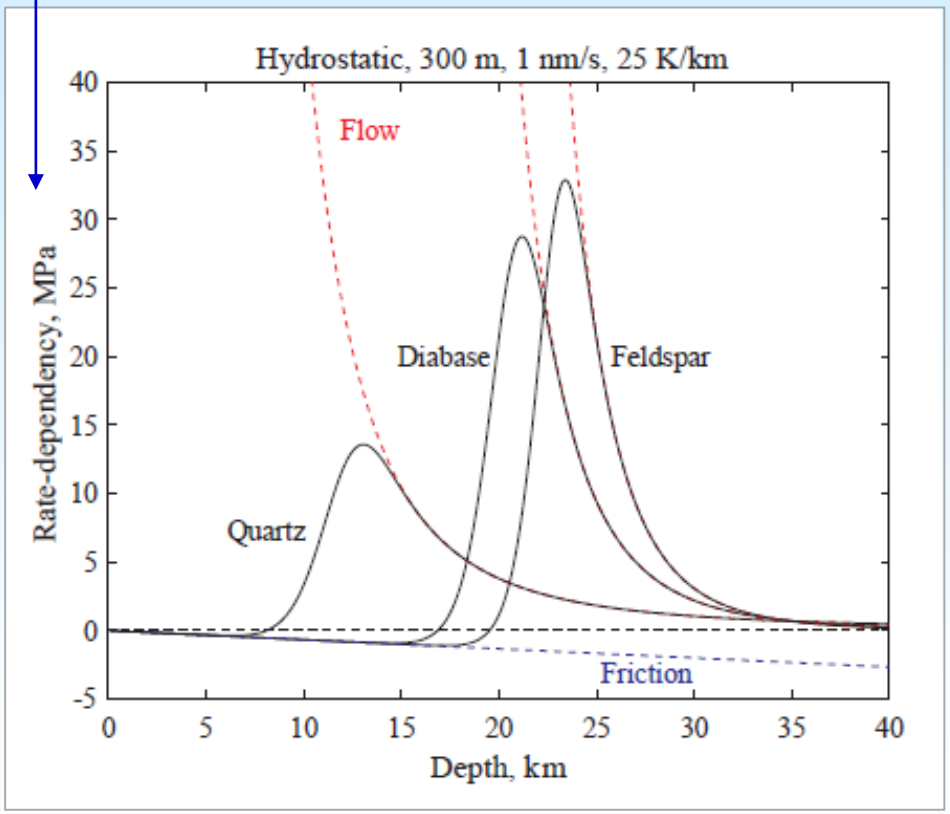
(1) Velocity-dependency increases with increasing flow stress.
(2) Velocity-dependency increases sharply within the transitional regime.
(3) Maximum rate dependency --- near the bottom of transitional regime
(4) *V* has a large effects on the velocity dependency.

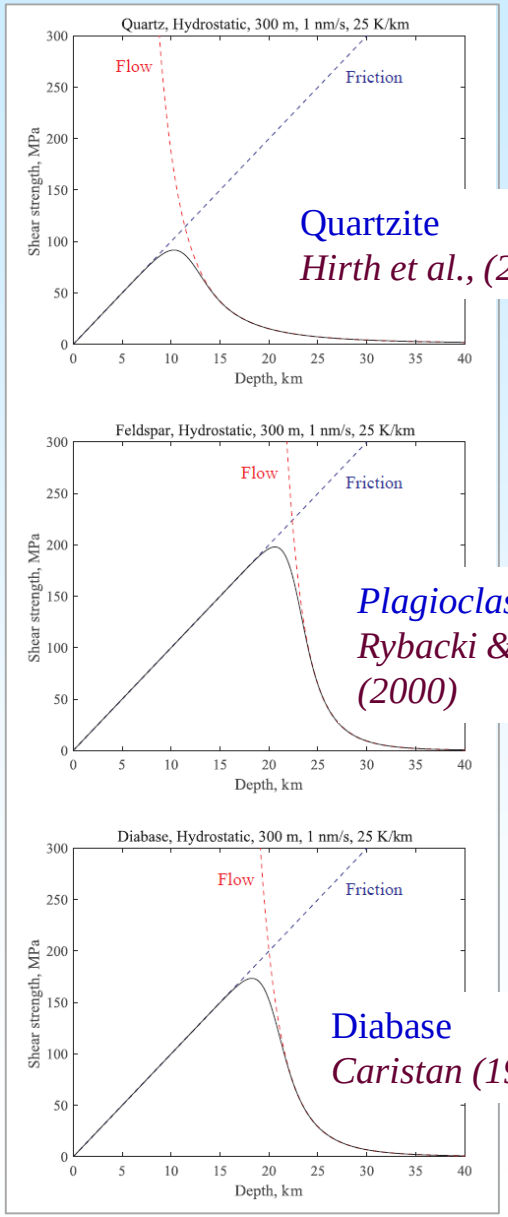
Heterogeneity Predicted from Friction to Flow Law

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





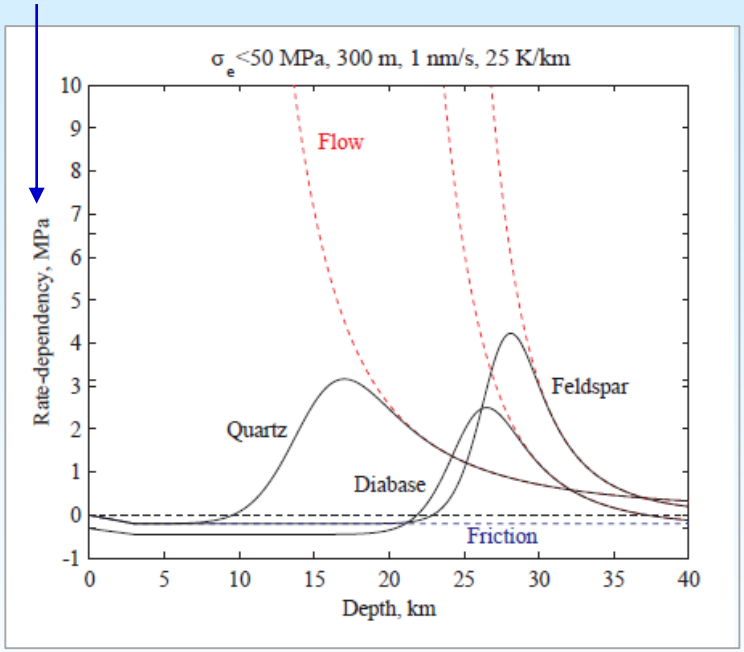
(1) Temperature for flow depends on rock/mineral types. → Transitional regime: *most heterogeneous!*

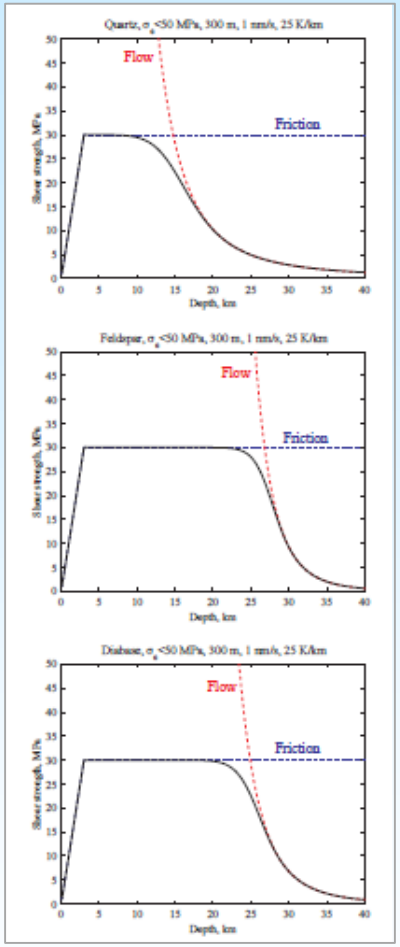
(2) Slow slip, low-frequency tremors!

Velocity Dependency for Flat Strength Profiles

A certain Pp distribution can make profiles flat.
Similar velocity dependency still remains.

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





Quartzite
Hirth et al., (2001)

Plagioclase
Rybacki & Dresen (2000)

Qiabase
Caristan (1982)

Essential features of fault properties (a summary)

[1] Frictional and flow regimes are separated by transitional regime.
The transitional regimes has a high rate dependency of shear resistance and it can act as an very effective barrier of seismic fault motion.

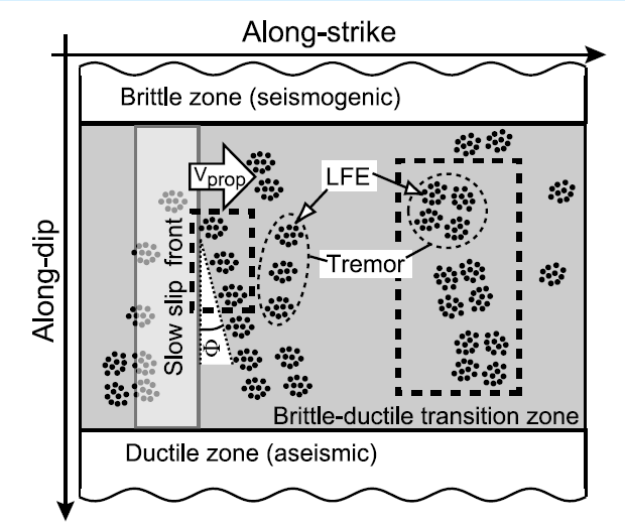
[2] Fault properties are most heterogeneous in the transitional regime.

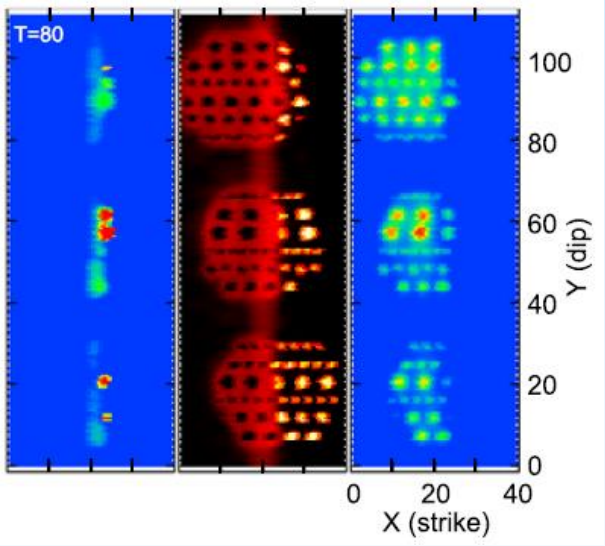
Ando san's Rheology Model for Slow Slip and LFE's

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!

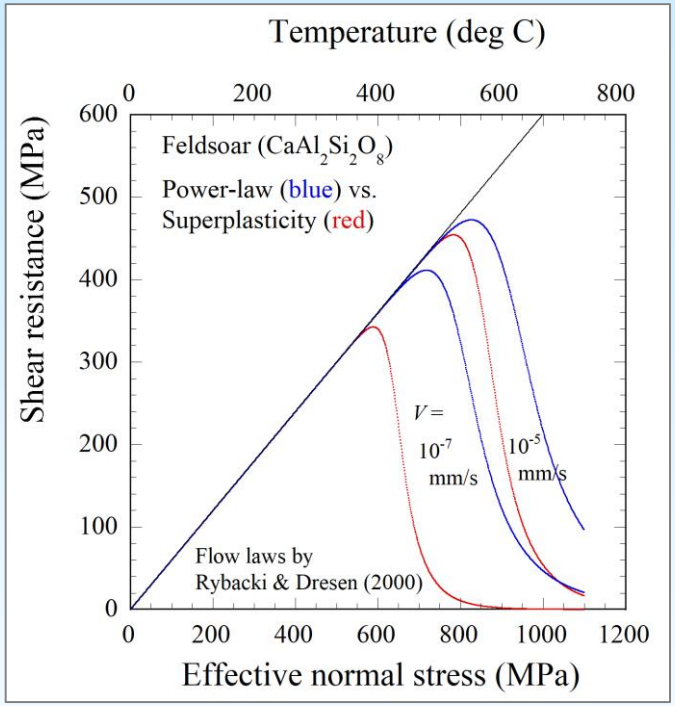
[2] Friction to flow law →

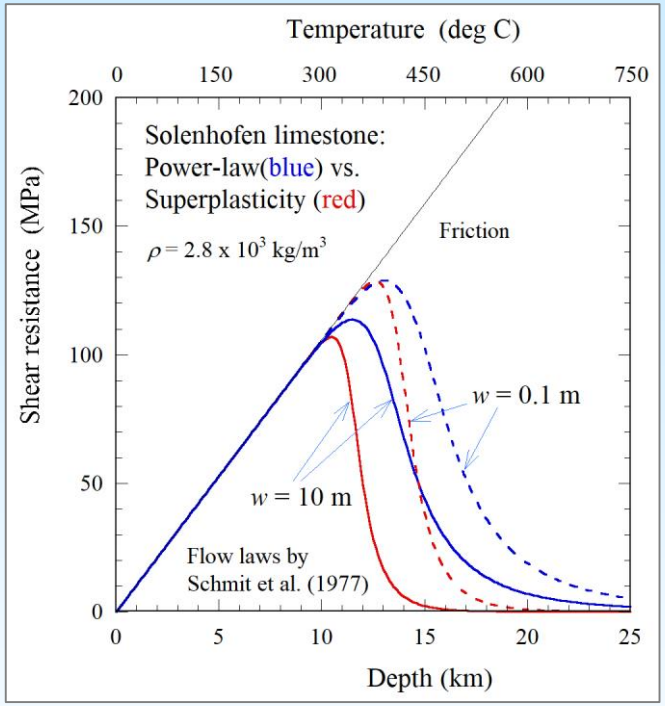
Frictional patches in transitional/viscous matrix!

[3] Matrix is likely to be pelitic rocks (weakest) in subduction zones.

--- Flow laws of rocks in subduction zones are needed!

Transition to Dislocation Creep or to Diffusion Creep?





[1] In nature, it is likely that friction changes to diffusion creep.
Grain-size sensitive flow law (linearly viscous).

[2] 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)

[3] Low-temperature mylonites form in the transitional regime.

How to attack the scale issue?

(An issue discussed at Caltech WS, Oct. 2018)

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

$$\tau_{ss} / \tau_{flow} = \tanh (\mu \sigma / \tau_{flow})$$

(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)

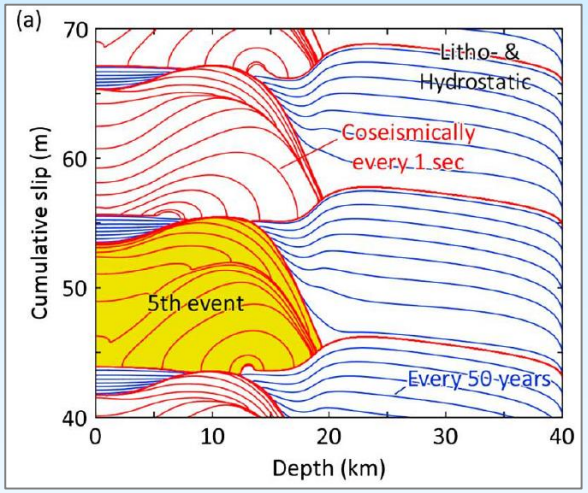
→ More realistic EQ modeling

Thank you!

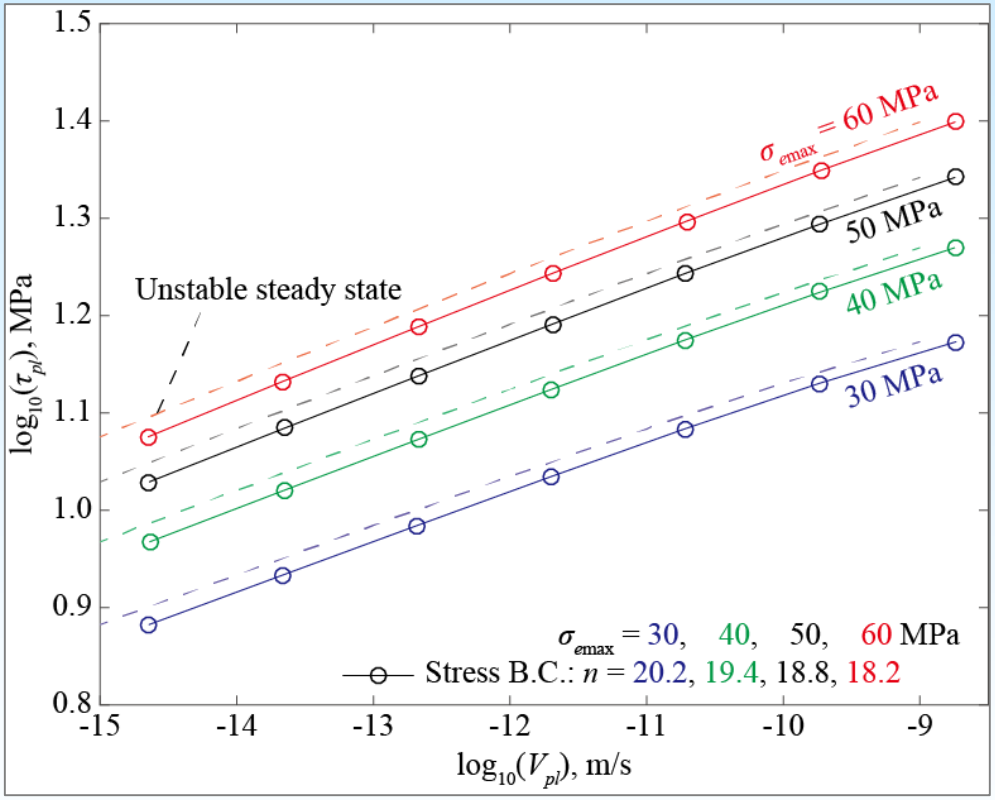
大同 (Daton, China)

Numerical Modeling on Plate Motion

Noda (2017~2018): What determines plate velocities?



Noda (2017, Joint JpGU-AGU meeting)



[1] Plate boundaries are governed by a rate-strengthening power law.

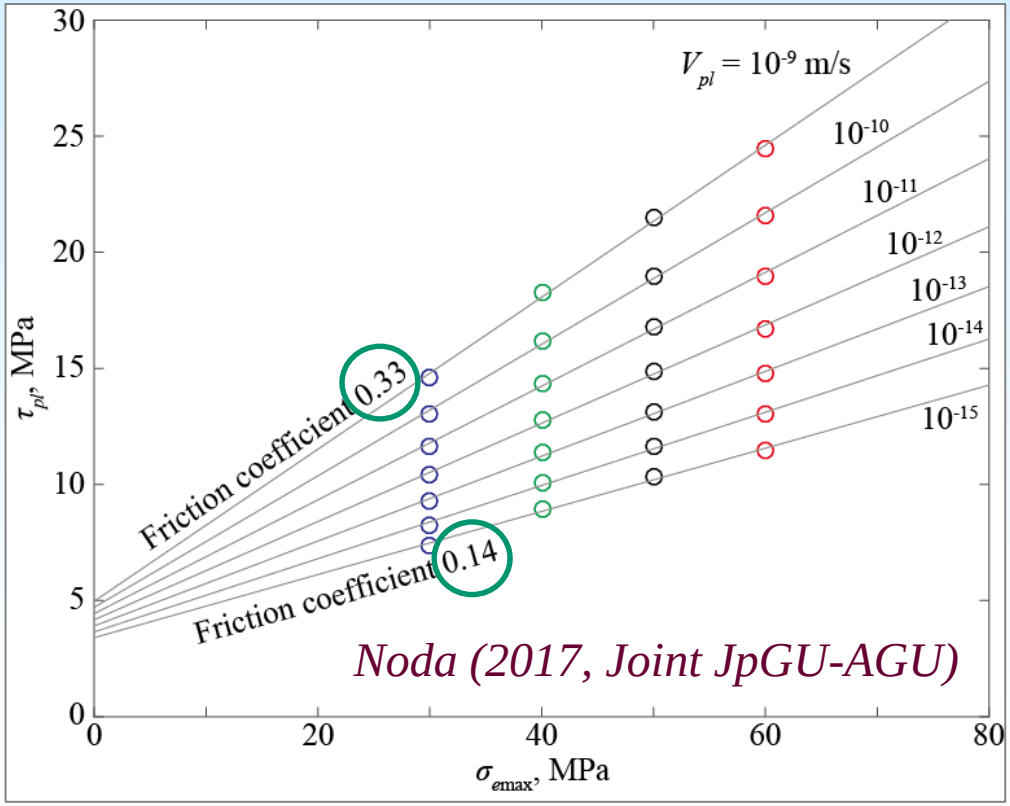
[2] Average shear stress at boundary τ_{pl} significantly depends on the maximum effective normal stress σ_{emax}.

Dependency of τ_{pl} on σ_{emax}

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 over all frictional, having significant (apparent) cohesion.
The friction coefficient is much smaller than the brittle part of the fault (f_0 = 0.6).

Friction to Flow: Summary and Tasks

[1] A simple friction to flow law is useful in describing fault properties across a lithosphere and in EQ modeling.

$$\tau_{ss} / \tau_{flow} = \tanh (\mu \sigma / \tau_{flow})$$

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

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

[4] How to merge the friction to flow law with HV friction?

[5] 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*.

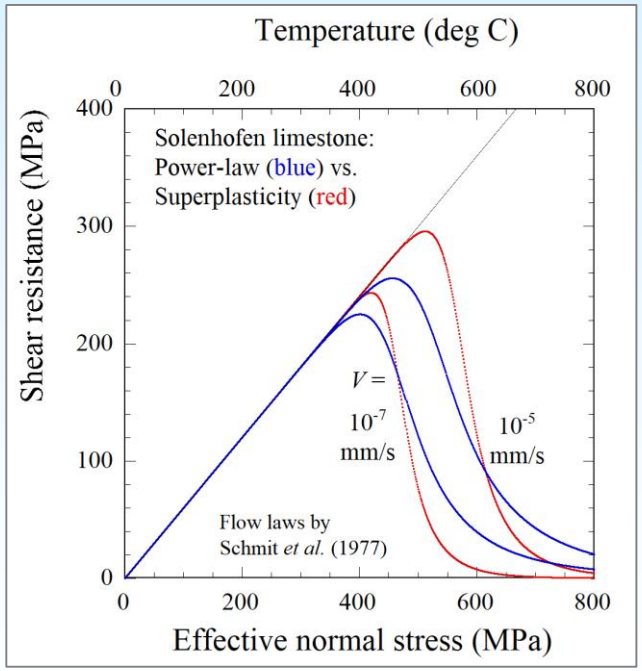
Task 1: Friction to flow experiments for important rocks

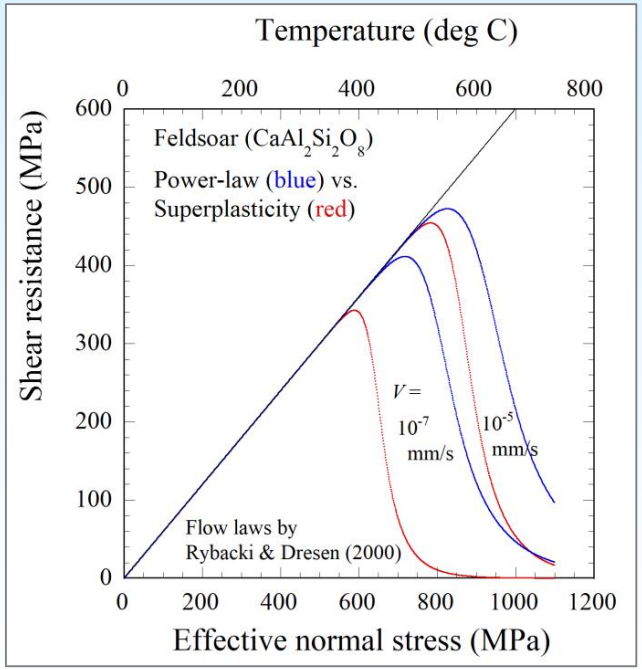
My dream machine: a rotary-shear anvil-type friction apparatus

2 GPa, 1,200ºC

Transitional regime: power law
Flow regime: diffusion creep

Diffusion creep: dominant





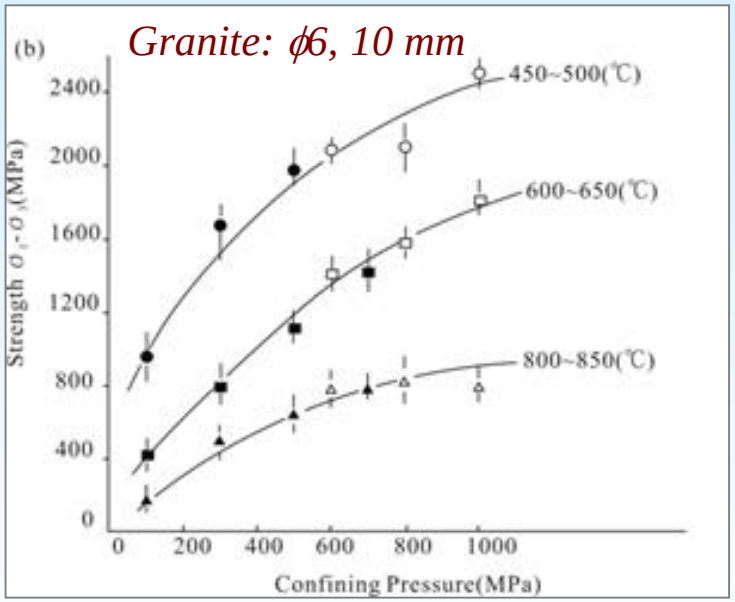
Solenhofen limestone
Grain size ~ 4 μm
Schmit (1977):

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

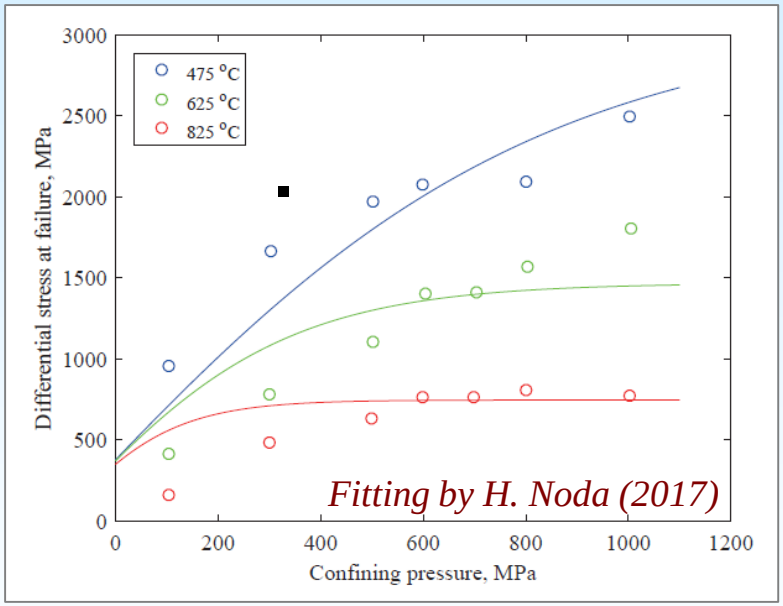
Feldspar ($CaAl_2Si_2O_8$)
Grain size ~ 3.4 μm
Rybacki & Dresen (2000):

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)



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

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.