Experimental investigation of dehydration weakening and embrittlement of hydrous minerals

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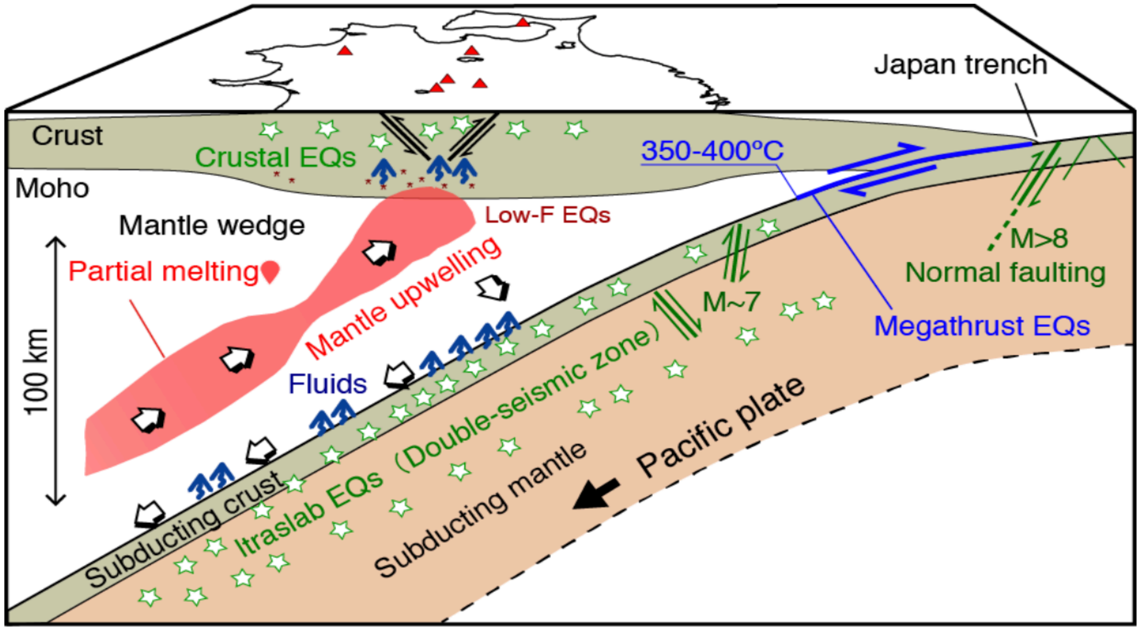
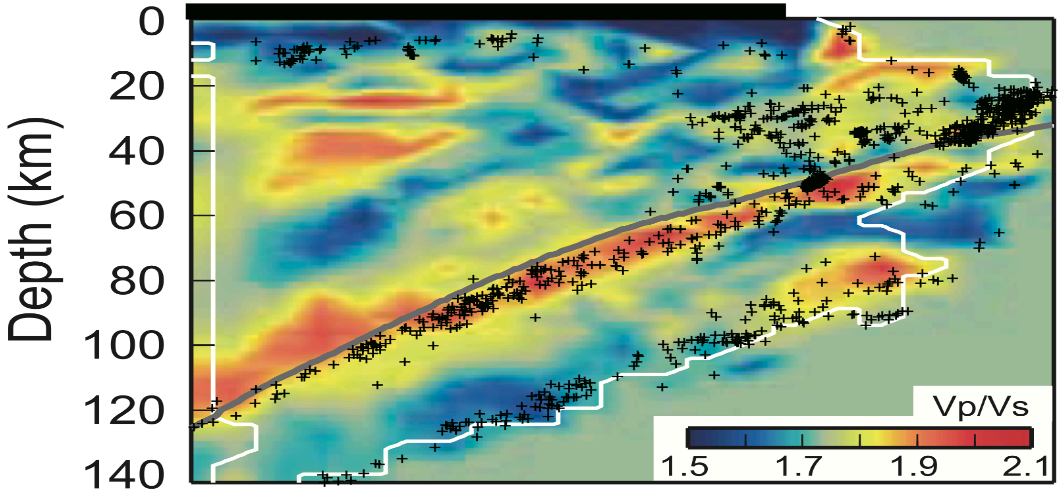


figure from Junichi Nakajima (titech)

Intra-slab seismicity: cold vs hot

Cold subduction zone (Tsuji et al., 2008)



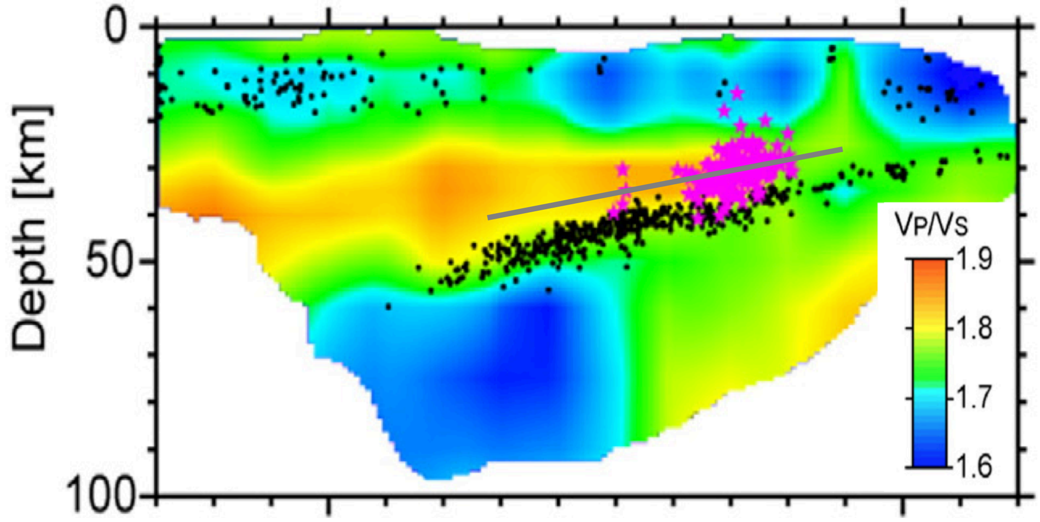
Cold subduction zones:

(e.g., Tohoku, NE Japan)

Double seismic zone

- crustal earthquake
- no deep slow earthquake

Hot subduction zone (Matsubara et al., 2009)



Hot subduction zones:

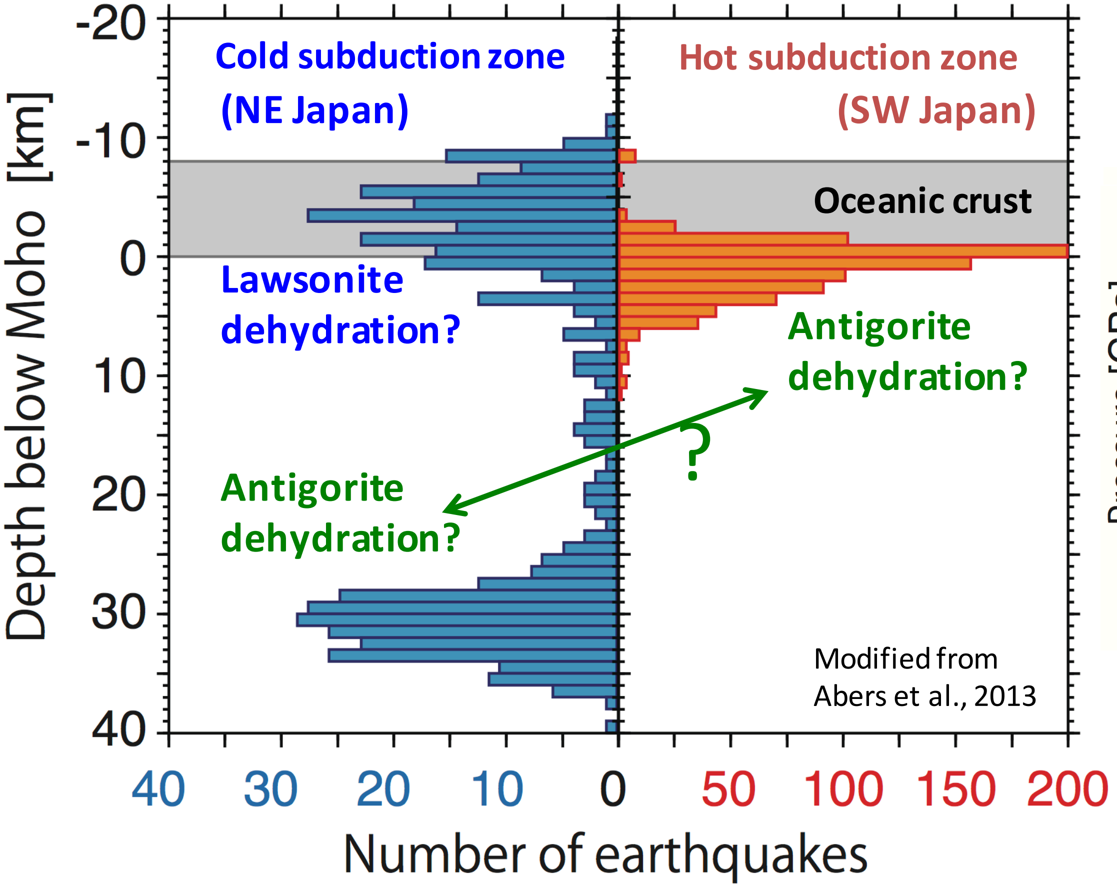
(e.g., Nankai, SW Japan)

Single seismic zone

- few crustal earthquake
- slow earthquake

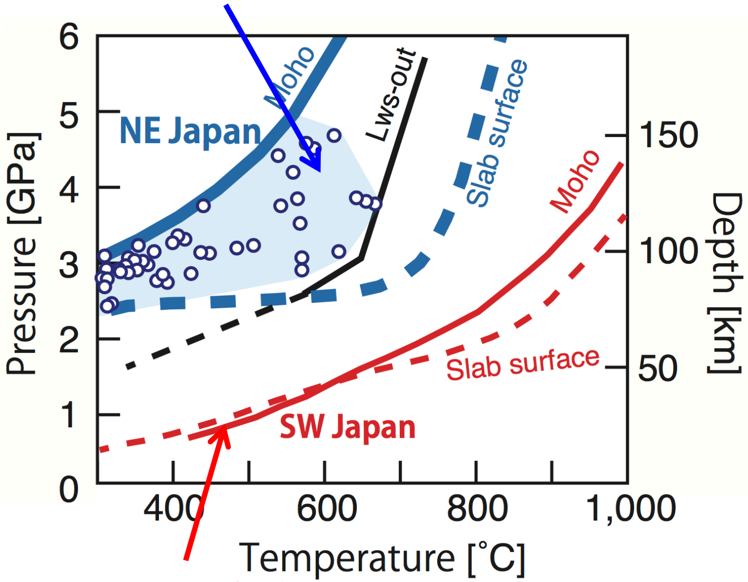
Intra-slab seismicity: Dehydration embrittlement?

while some alternative ideas are proposed,
Kelemen & Hirth, 2007, Ohuchi et al., 2017, etc.



Modified from Abers et al., 2013

Cold subduction zones: Lawsonite blueschist



Hot subduction zones: Epidote greenschist

Lawsonite ($CaAl_2Si_2O_7(OH)_2 \cdot H_2O$): major water carrier in the crust

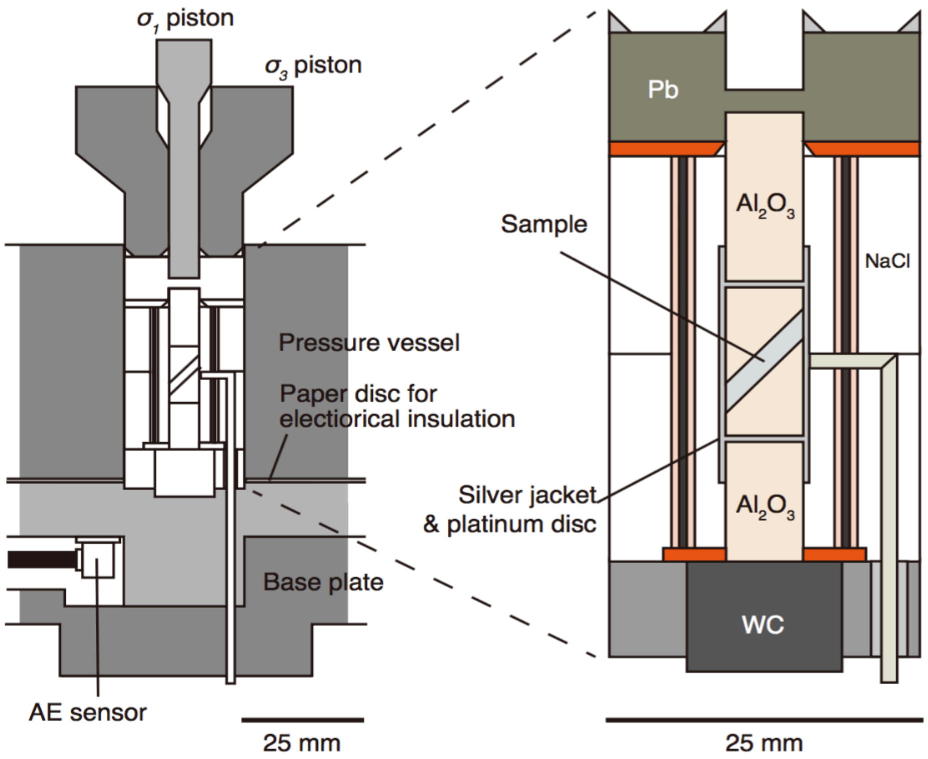
Antigorite ($Mg_3Si_2O_5(OH)_4$) : major water carrier in the mantle

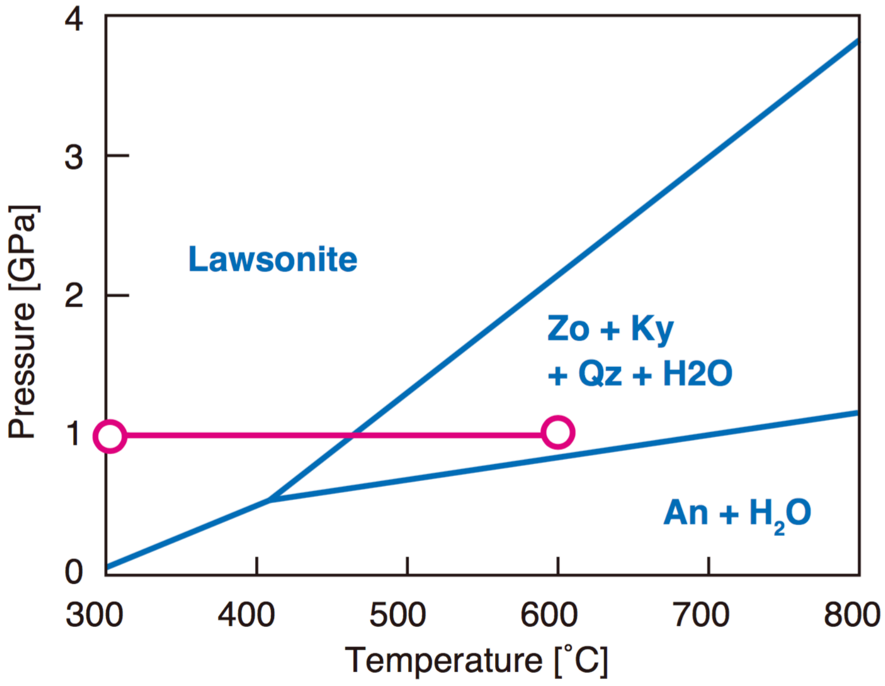
Can dehydration reactions really trigger earthquake?

“Temperature ramping” experiments of lawsonite, antigorite and Al metal samples

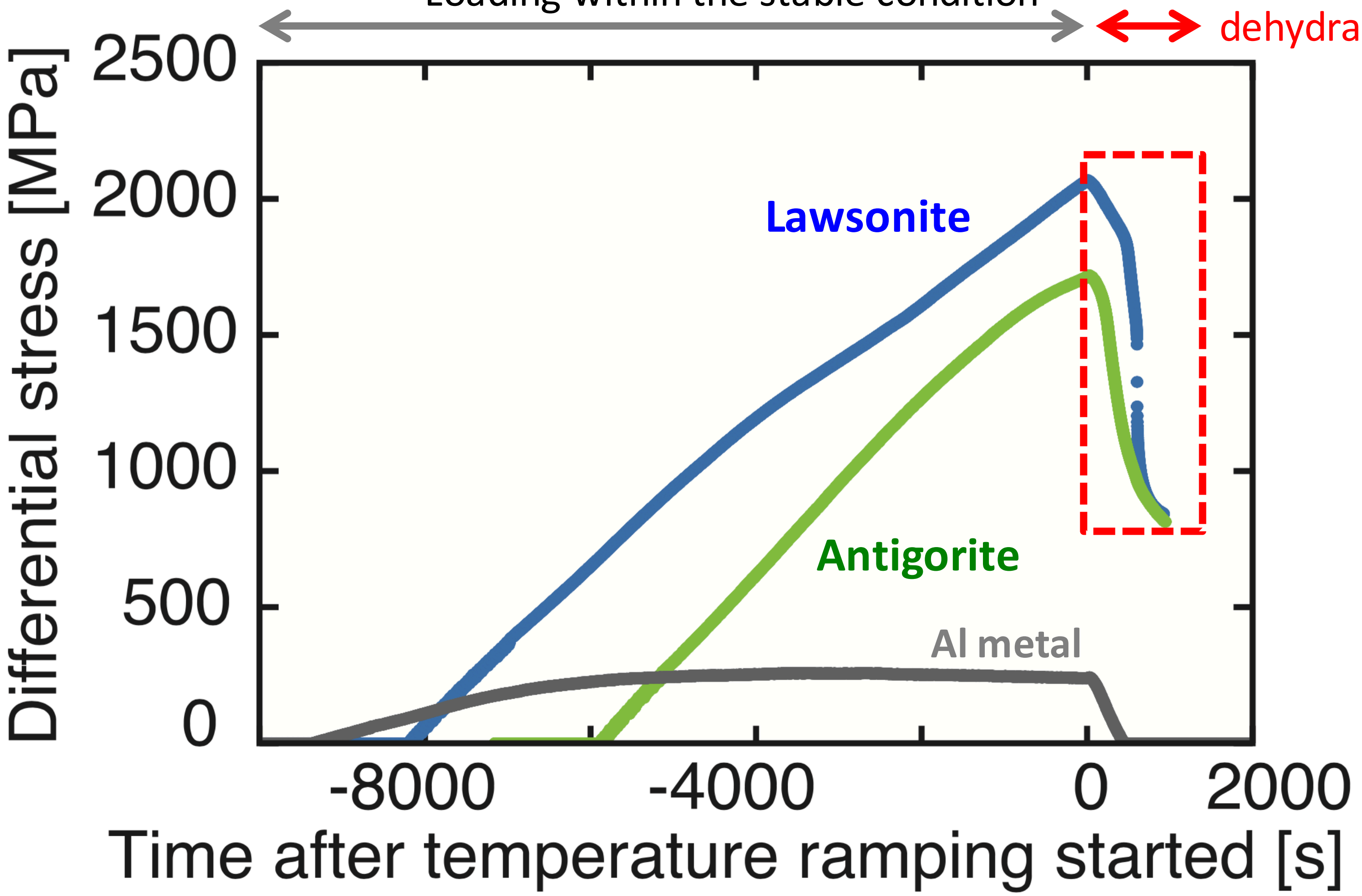
Experimental conditions:

- Confining pressure: 1 (+0.2) GPa
- Strain rate: 10^{-5} – 10^{-7} 1/s (v ~600 – 6 cm/yr)
- Temperature: **300˚C => 600˚C for lawsonite**, **400˚C => 700˚C for antigorite**.
- Temperature ramping rate: 0.5˚C, 0.05˚C/s
- AEs were recorded with f = 2.5 MHz, and then high pass filtered f > 100 kHz.

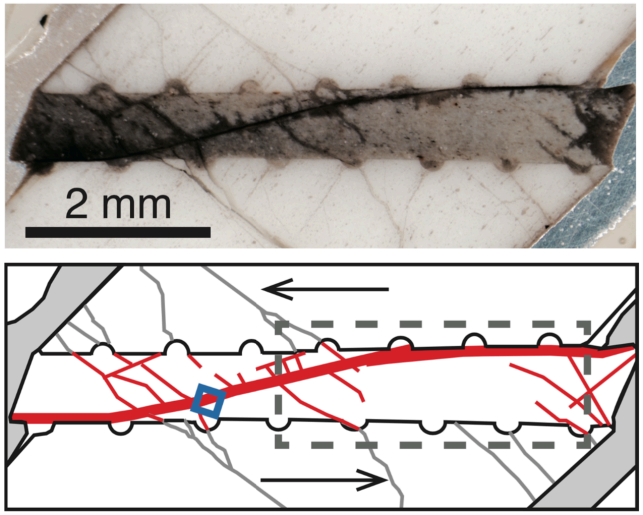




Mechanical data: Weakening during temperature ramping


Loading within the stable condition

Weakening during dehydration



Lawsonite:

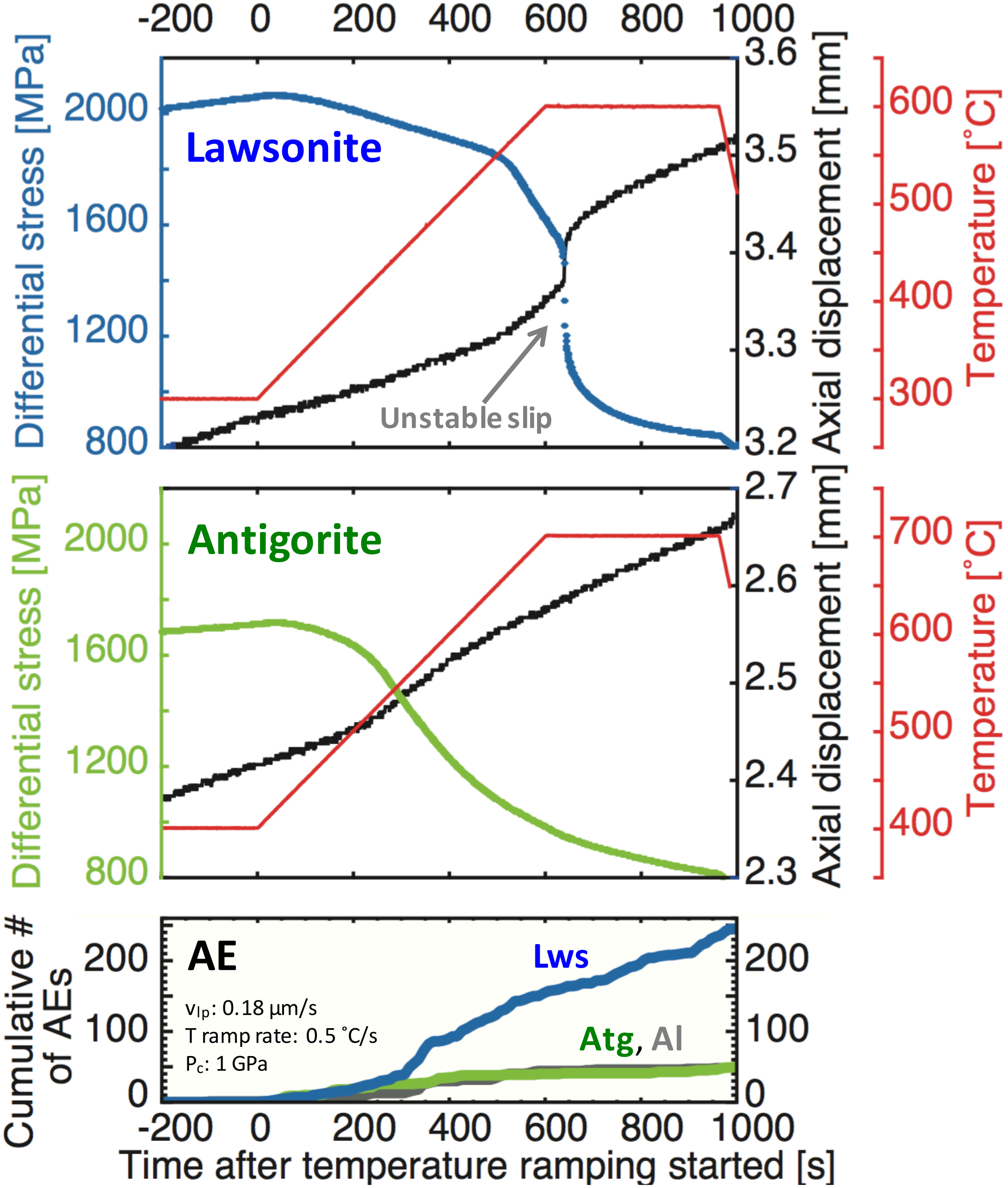
Unstable fault slip

(Okazaki & Hirth, 2016, Nature)

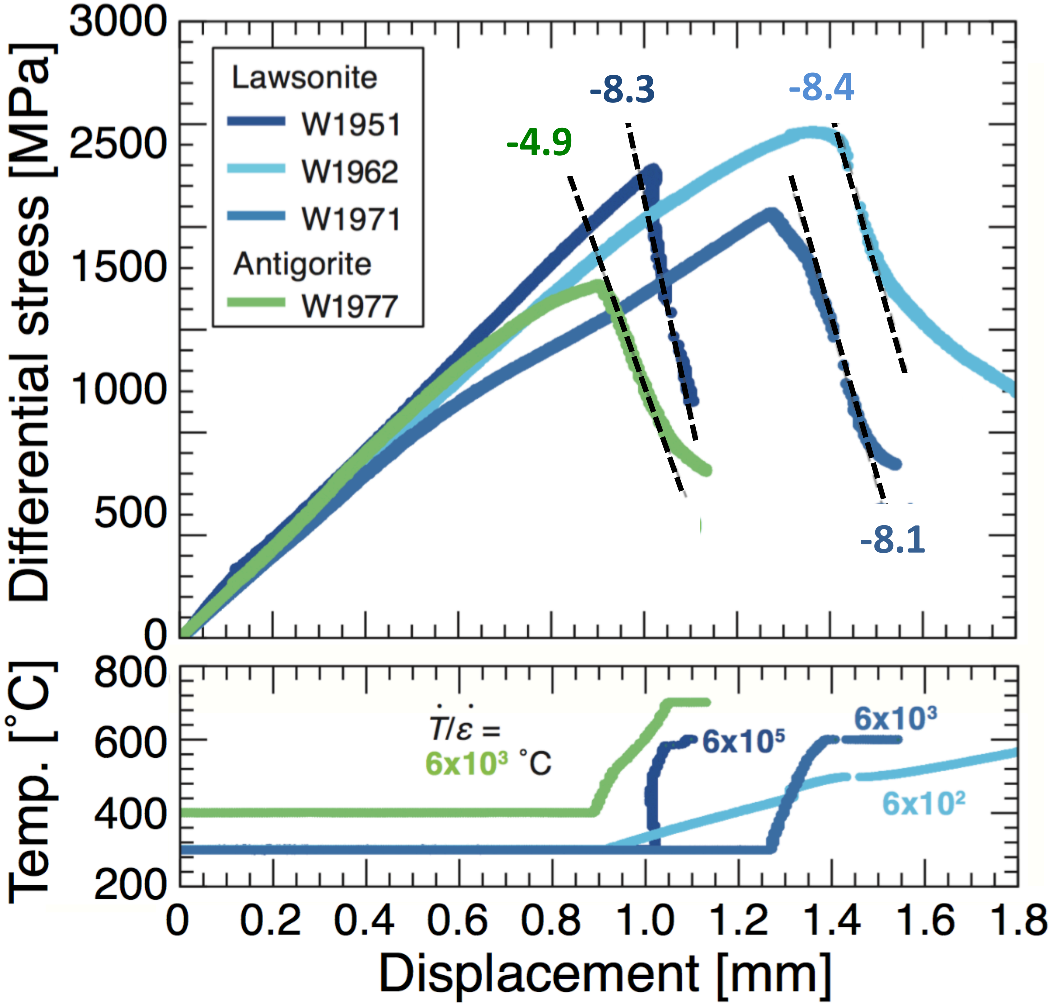
Antigorite serpentine:

Stable fault slip

(Chernak & Hirth, 2011, Geology; Proctor & Hirth, 2015, JGR; Gasc et al., 2017, EPSL)



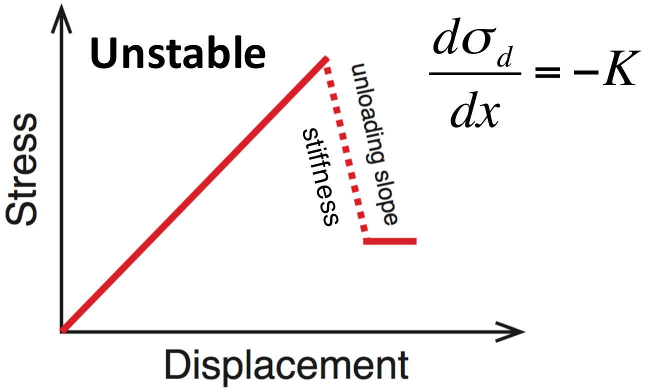
Unloading slopes: consistent with unstable slip



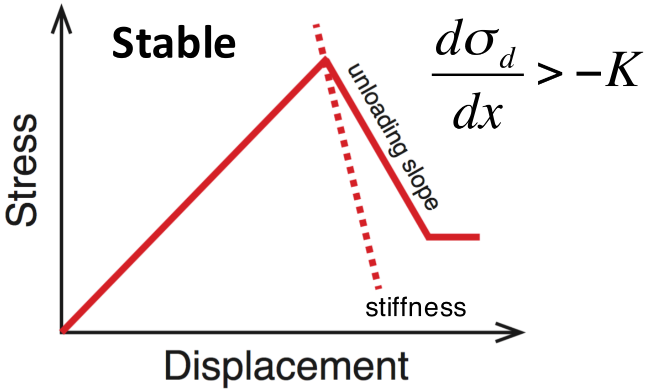
Unloading stiffness of the apparatus:

***K* = 8.8 GPa/mm**

(280 kN/mm, Chernak & Hirth, 2011)



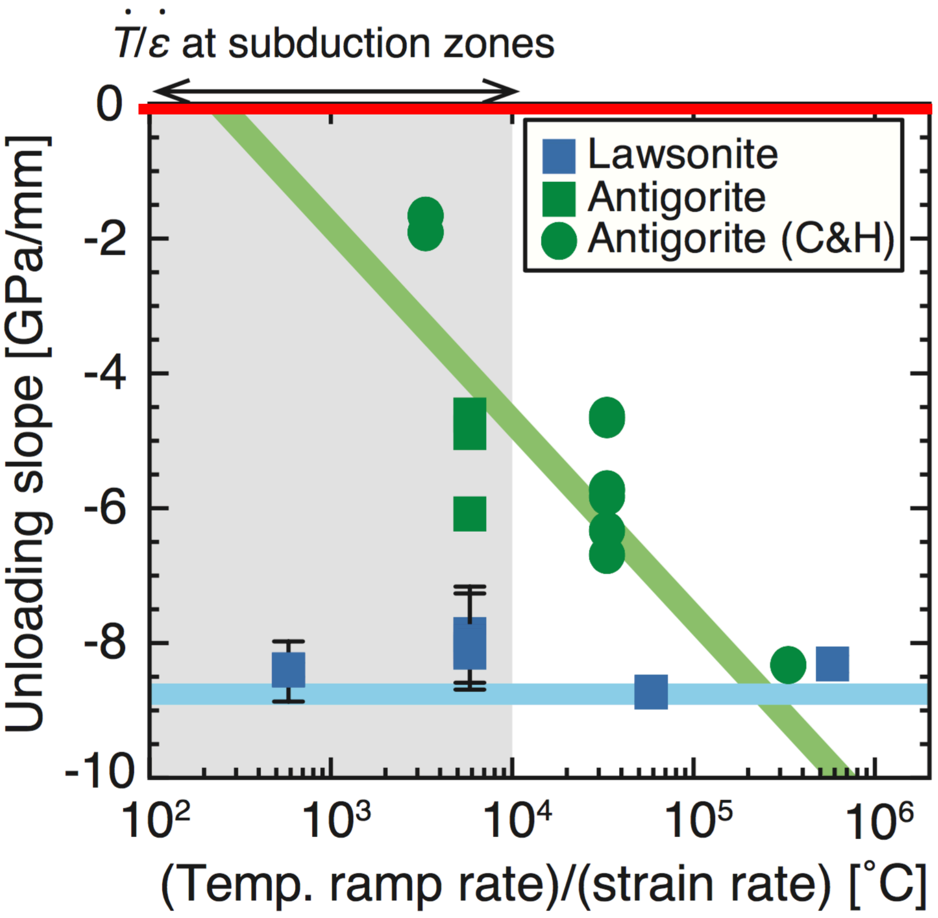
$$\frac{d\sigma_d}{dx} = -K$$



$$\frac{d\sigma_d}{dx} > -K$$

Unloading slope for lawsonite: nearly constant and similar to the effective unloading stiffness of the apparatus.

Scale to natural conditions: Temp. ramp rate/strain rate



Stiffness of the apparatus:
K = 8.8 GPa/mm

Stiffness of natural fault zones:
$K_f \sim$ 2 MPa/mm

$K_f = G/2/(1-\nu)/L$ (Scholz, 2002)
G: the shear modulus: 30 GPa,
ν : the Poisson's ratio: 0.25
L: the length of the slipping region
≈ 10 m for a M1 earthquake

Unstable when $K < K_c$

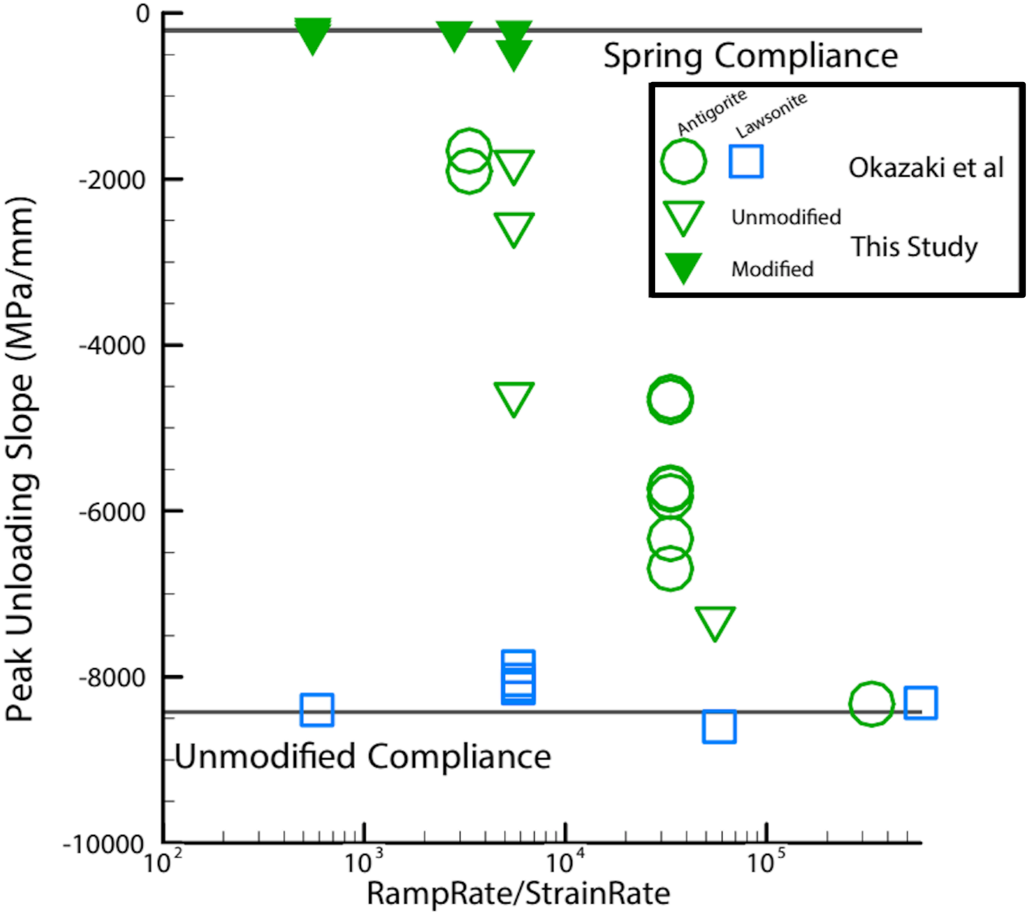
Unstable slip in lawsonite will occur even more easily in natural subduction zones.

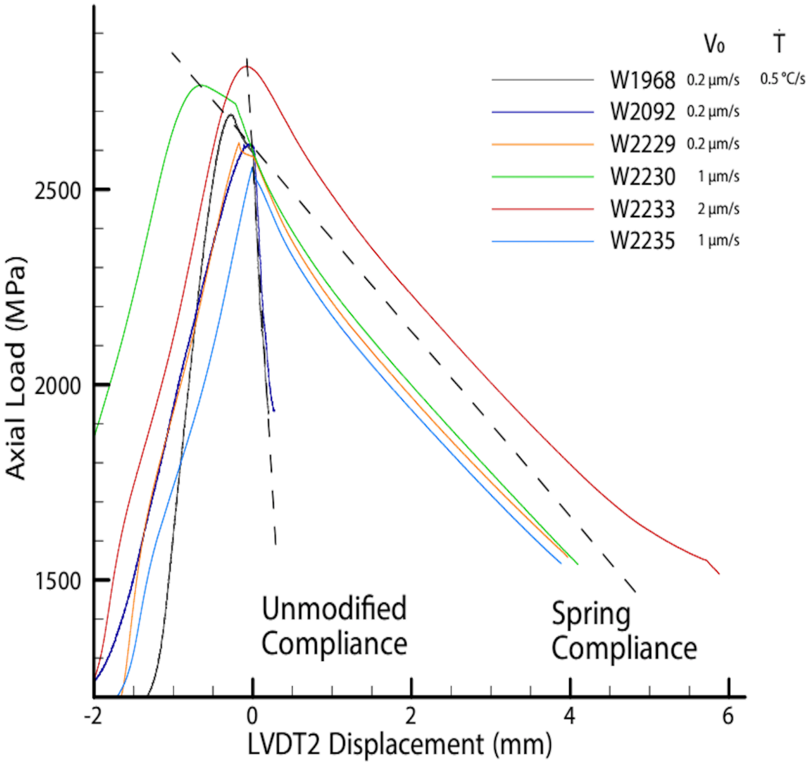
Lawsonite (*a*-*b*<0): Unstable fault slip can happen in natural time scale.

Antigorite (*a*-*b*>0): Reaction-controlled stable slip. Slow earthquakes?

Temp. ramp experiment with K ~1/35K$_{std}$

~250 MPa/mm





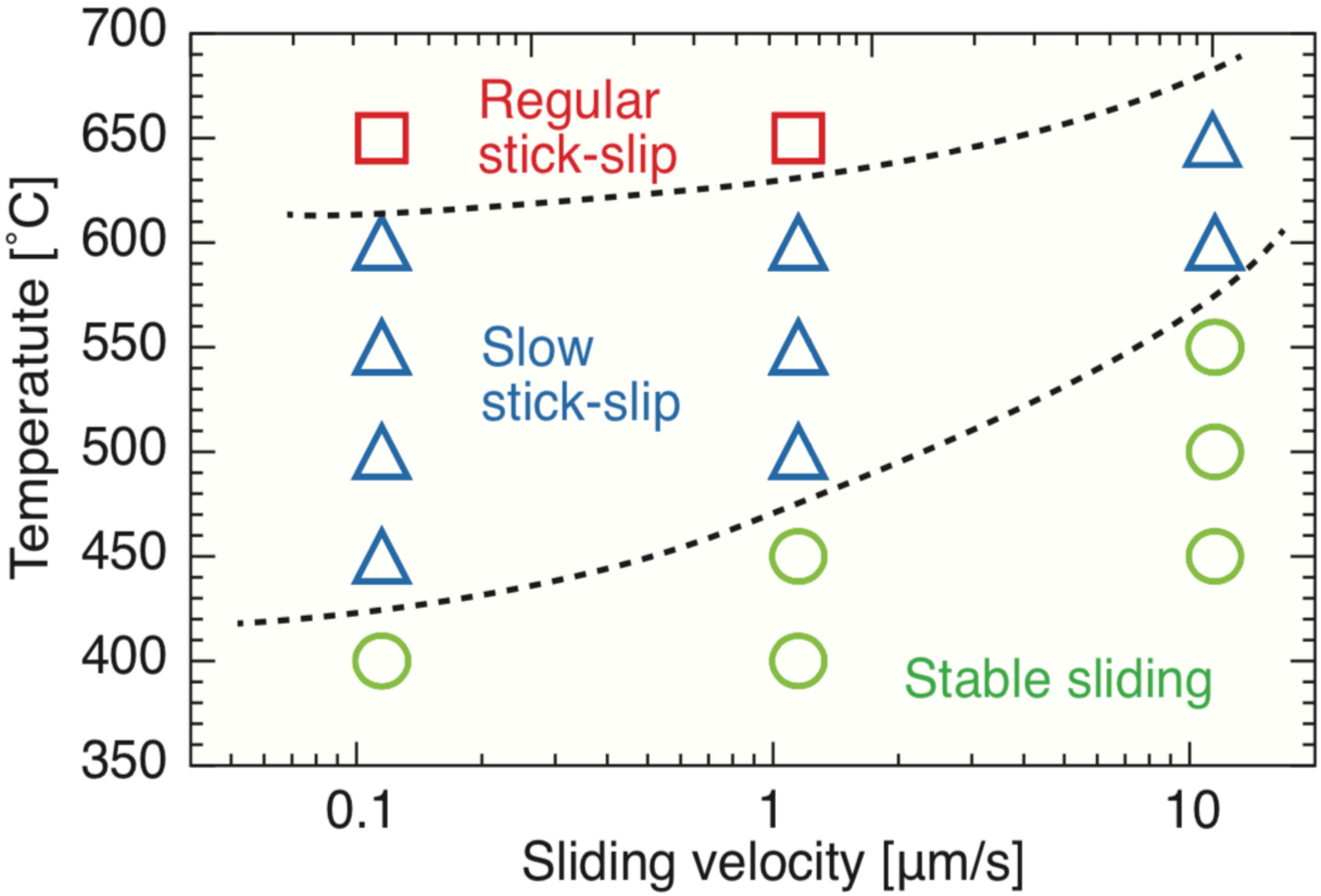
Burdette et al., in prep.

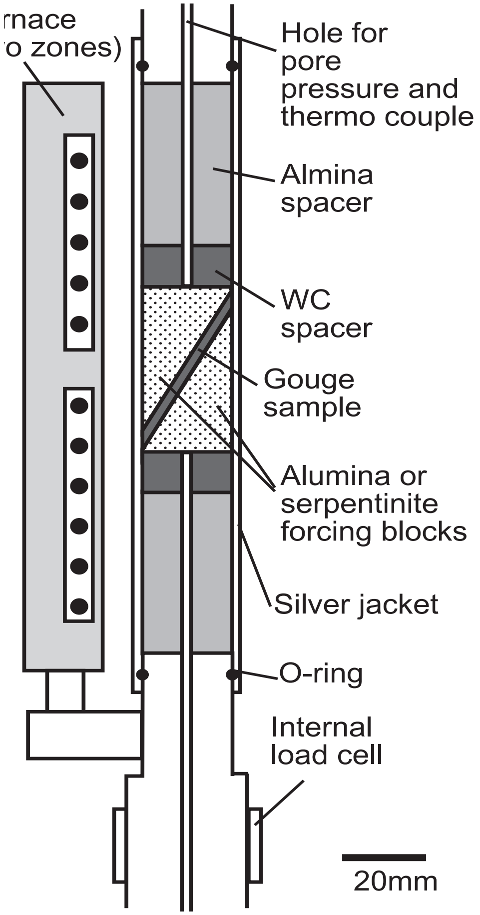
Antigorite (*a*-*b*>0): Reaction-controlled stable slip.

Partially serpentinized peridotite, not pure serpentine (Ferrand et al., 2017; Gasc et al., 2017)?

Serpentinite friction with more compliant system but low pressure (Pc ~200MPa)

~58 MPa/mm





🟩 400℃: stable sliding

🟧 450℃–550℃: slow stick-slip（longer duration of slip, smaller stress drop）

🟥 600℃–650℃: violent stick slip

Okazaki et al., in prep.
Okazaki & Katayama, 2015
Takahashi et al., 2013

Dehydration-kinetics-controlled critical stiffness

(simplified from Brantut and Sulem, 2013)

Unstable slip happens when:

$$\boxed{\underline{K} < K_c}$$

$$\tau = \mu\left(\sigma_n - P_p\right)$$

$\dot{T}/\dot{\varepsilon}$

$$\boxed{K_c^{deh} = \frac{d\tau}{dx} \approx \frac{dP_p}{dx} = \frac{dP_p}{dt}\frac{dt}{dx}}$$

$$\frac{dP_p}{dt} = \frac{1}{Ss}\frac{\partial}{\partial z}\left(\frac{k}{\mu}\frac{\partial}{\partial z}P_p\right) + \frac{1}{Ss}\left(\phi\alpha_f\frac{\partial T}{\partial t} + Q_{deh}\right)$$

$$Q_{deh} = \frac{C_{H_2O}\rho_m}{t_{1/2}\rho_f}$$

$$\boxed{K_c^{deh+RSF} \approx \frac{1}{Ss}\frac{C_{H_2O}\rho_m}{t_{1/2}\rho_f}\frac{1}{v}} + \underline{\frac{(b-a)\left(\sigma_n - \alpha P_p\right)}{D_c}}$$

$$t_{1/2}^{-1} = \exp\left(12 - \frac{15400}{RT}\right)$$

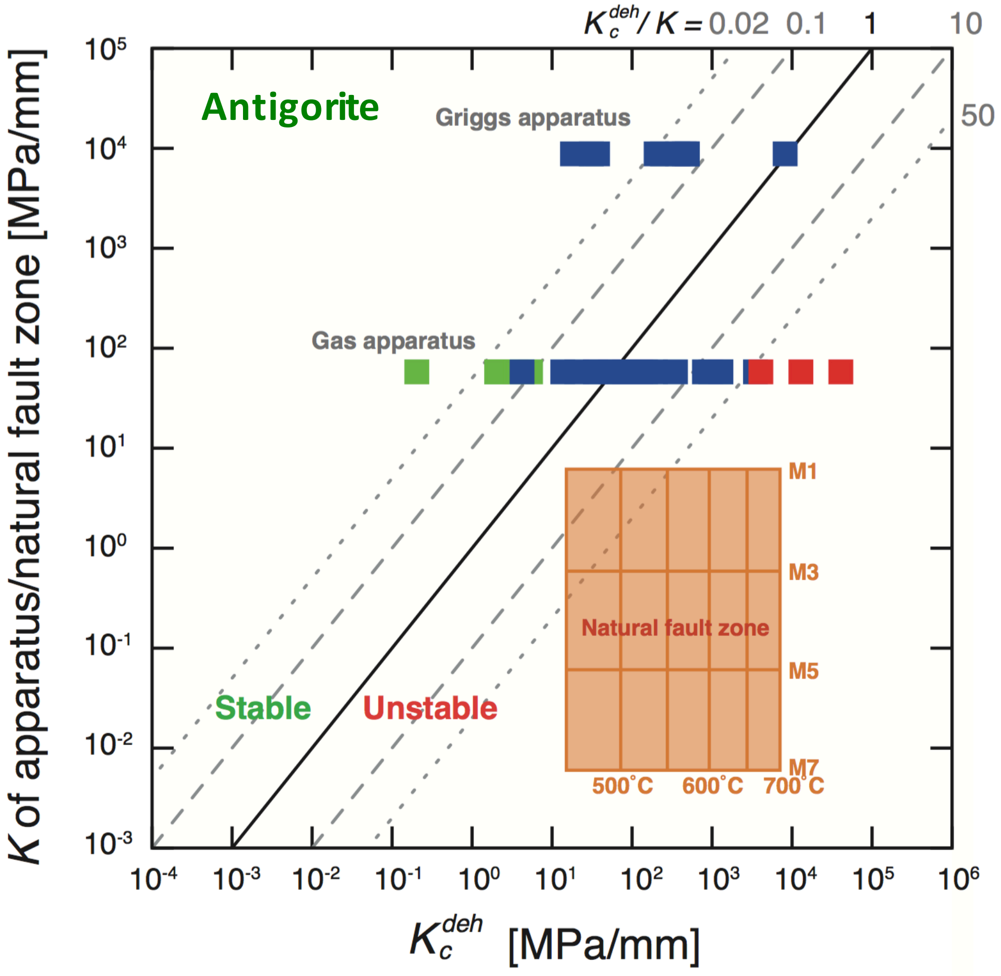
for antigorite from Sawai et al., 2013 and Chollet et al., 2009

K: stiffness, MPa/mm
x: slip, m
v: sliding speed, m/s
Ss: specific storage, Pa^{-1}
k: permeability, m^2
μ: viscosity of the fluid, Pa s
φ: porosity
α_f: coeff. of thermal expansion, $^\circ C^{-1}$
Q_{deh}: fluid release rate, $m_{fluid}^3\ m_{rock}^{-3} s^{-1}$
C_{H2O}: water content in the mineral ~ 0.13
ρ_m: density of the mineral, kg m^{-3}
ρ_f: density of the fluid, kg m^{-3}
t: half life-time of mineral, s

Ss, k, ϕ values are taken from Wibberly & Shimamoto, 2006 and Okazaki et al., 2013 for lowP, from Katayama et al., 2013 for highP.

Okazaki et al., in prep.

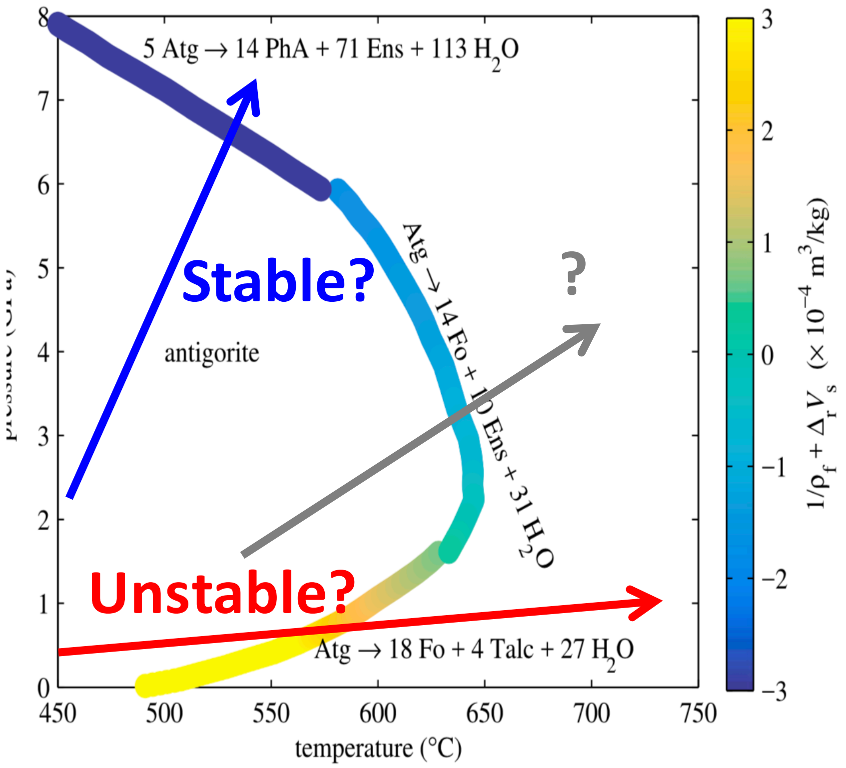
fault stiffness K vs critical stiffness *K_c^{deh}*



Stiffness of natural fault zones:
K_f ∼0.006–6 MPa/mm

Okazaki et al., in prep.

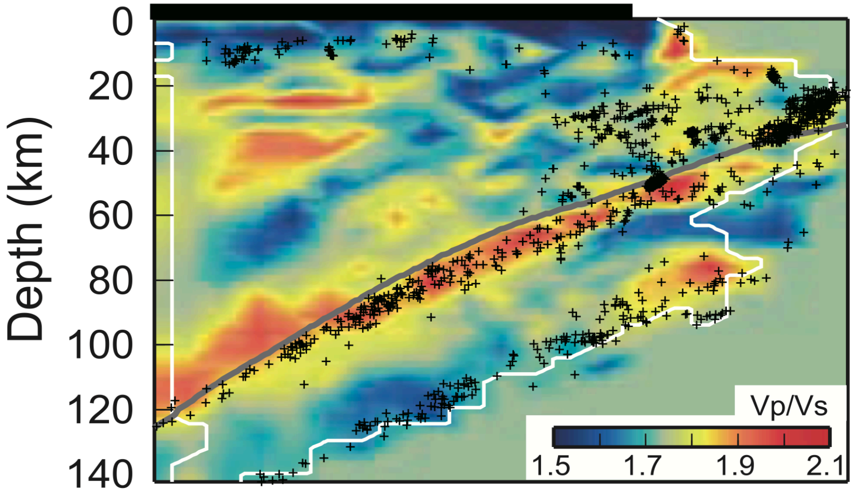
Unstable slip (earthquake) happens when K << Kc.
Intermediate conditions: slow earthquake?
(e.g., Ruina 1983; Liu & Rice, 2007)



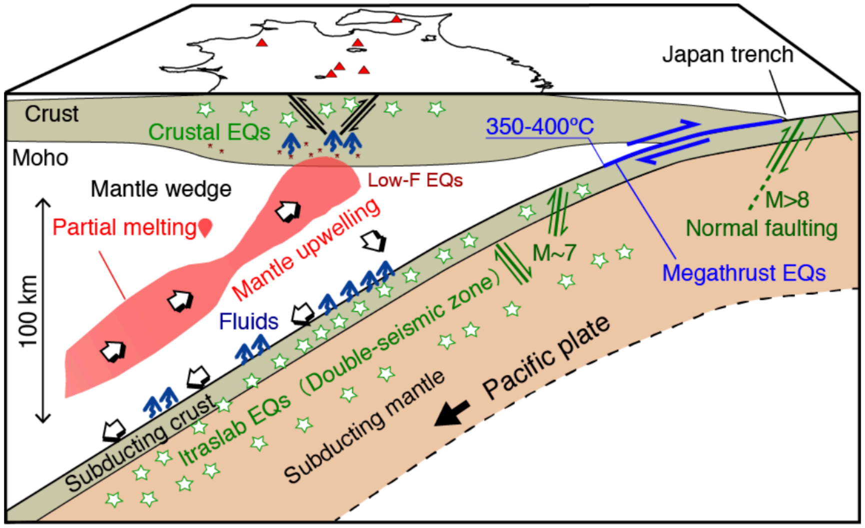
Brantut et al., 2017

Summary & further questions

- Lawsonite dehydration can nucleate EQs at conditions within cold subducting oceanic crusts. (dehydration weakening & a–b <0)
- Antigorite dehydration could give us a variety of slip behavior (stable to seismic slip) depending on the PT condition. →regional characteristics of intraslab seismicity?
- High pressure rock deformation apparatus could be too stiff to nucleate an unstable slip in the lab.
- How much & how deep are subducting plates hydrated? →Outer-rise?
- How deep does the effective pressure law work?



Tsuji et al., 2008



from Junichi Nakajima (titech)