Fluid pressure and frictional-viscous transition in the megathrust

So Ozawa (U-Tokyo), Eric M. Dunham (Stanford), Cailey B. Condit (U-Washington)

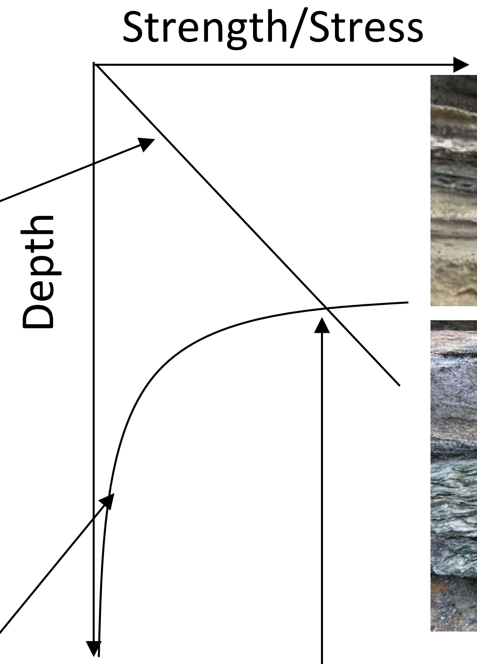
Topical workshop Fluids in Cascadia. April 25, 2025

Frictional-viscous control of stress profile

Friction/brittle

$$\tau_f = f\,(\sigma - p)$$
$$= f(1-\lambda)\rho_r g z$$

λ =Pore pressure/ lithostatic pressure

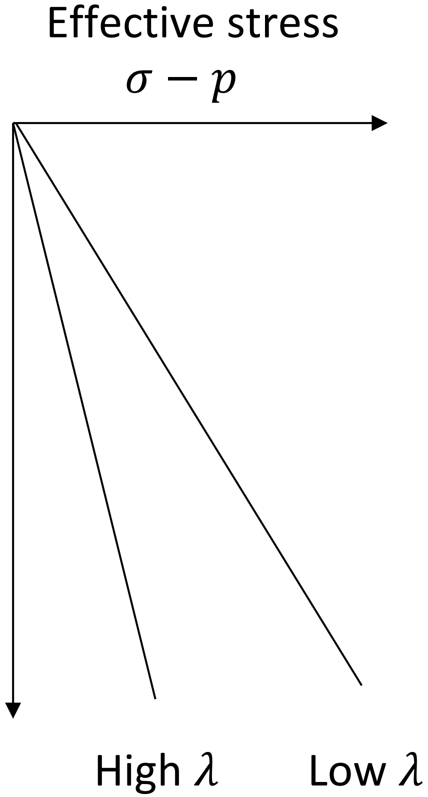


frictional-viscous transition

Viscous/ductile

$$\tau_v = A\exp\left(\frac{Q}{RT}\right)$$

temperature



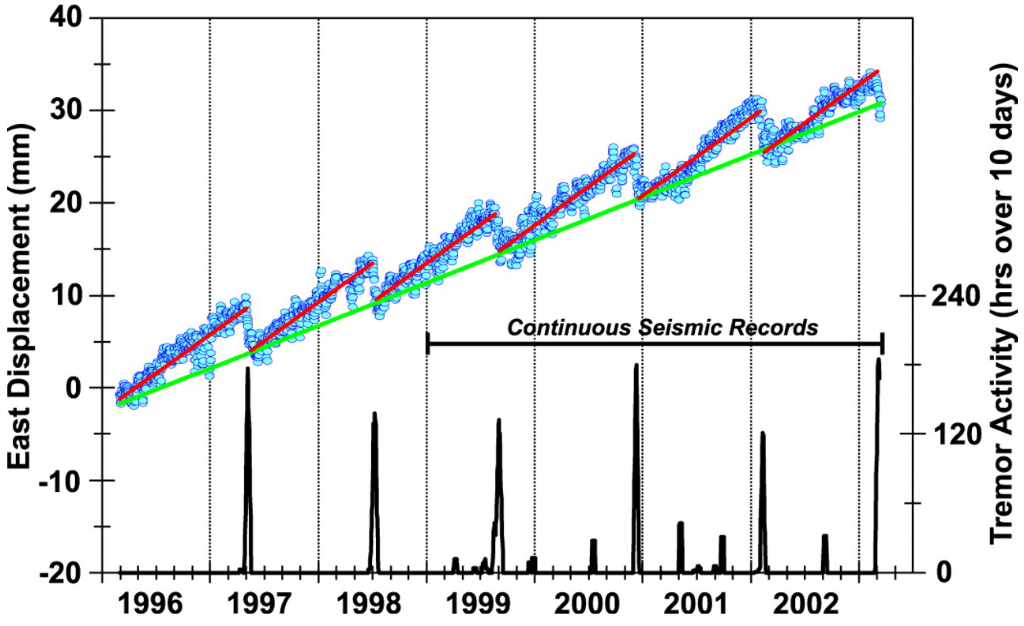
Depth-independent λ is assumed in thermal models and geodynamic models

Depth-dependent $\boldsymbol{\lambda}$ is assumed in earthquake cycle simulations

Direct measurement of effective stress is only possible in upper few km

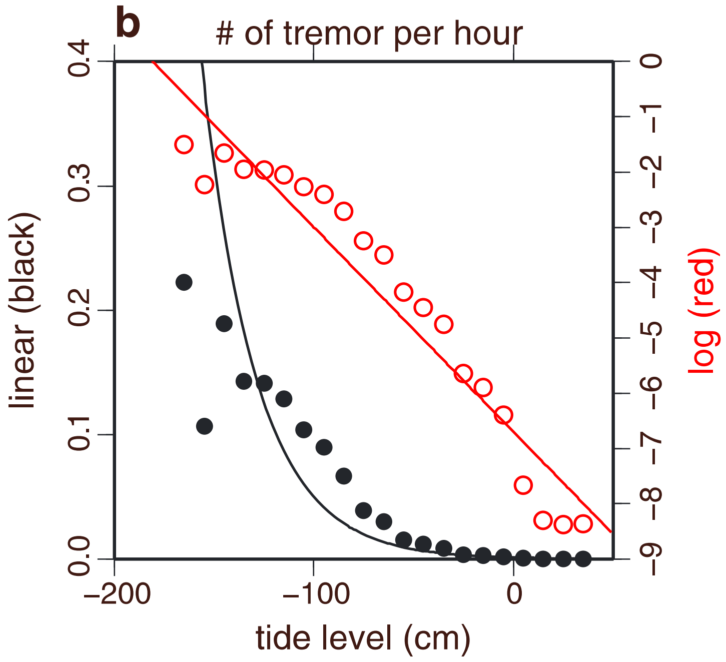
Slow earthquakes as evidence for near-lithostatic fluid pressure

Short recurrence interval compared with regular earthquakes



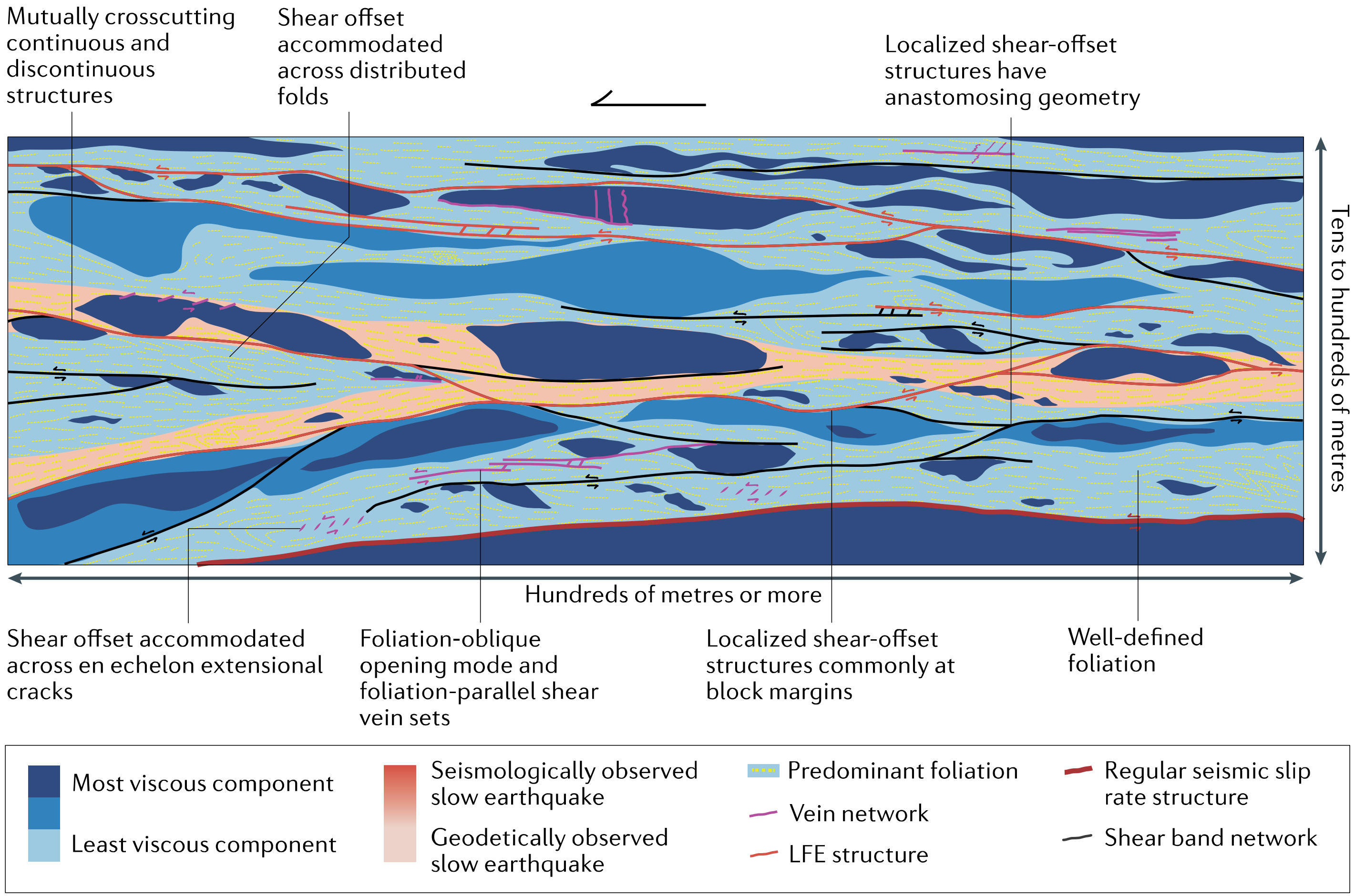
Rogers & Dragert, 2003

Tidal sensitivity of tremor



Ide & Tanaka, 2014

Is Episodic Tremor and Slip (ETS) mixed frictional-viscous behavior?



Frictional mechanism is consistent with

- Radiation of seismic waves from tremor
- Periodic occurrence of slow slip

Viscous mechanism is consistent with

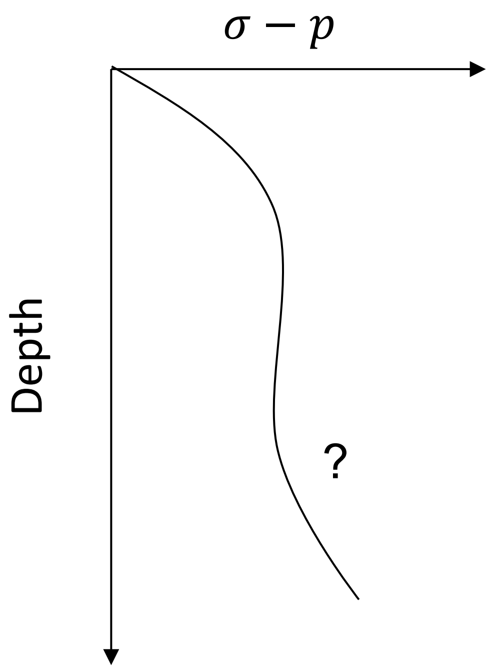
- Diffusive migration of slow slip

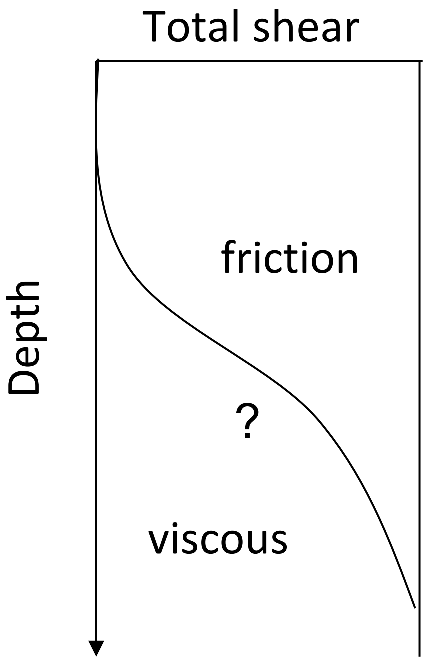
To activate both mechanisms, both strengths must be comparable

Kirkpatrick et al. (2021)

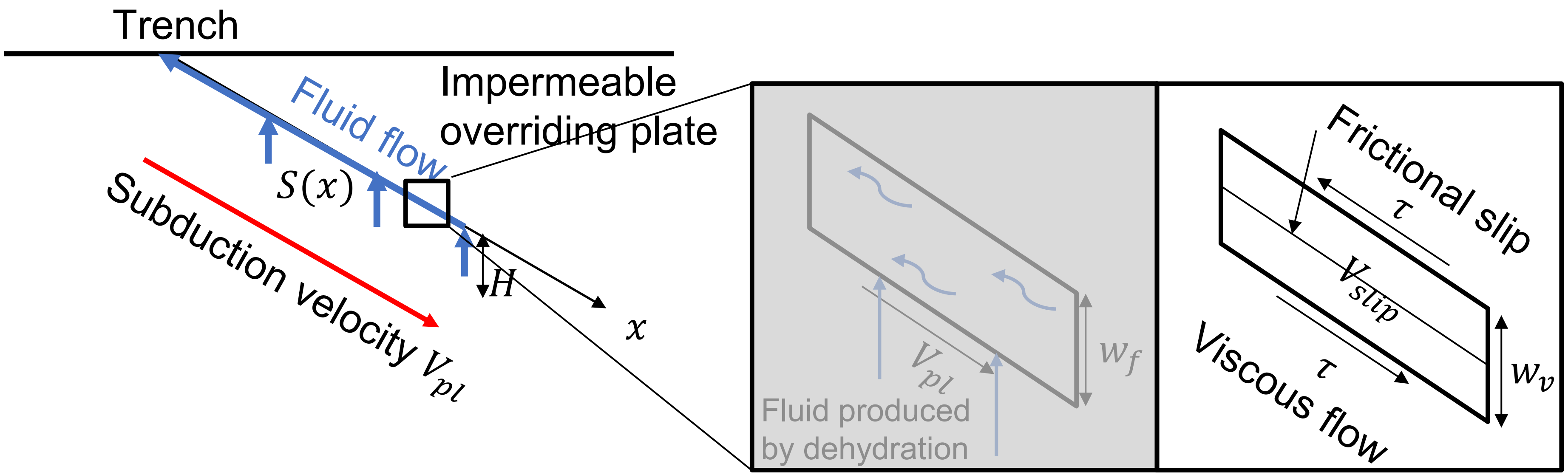
Goal of this work

- We calculate the partition of friction and viscous deformation by quantifying the fluid pressure by dehydration fluid production
- We apply this modeling framework into Cascadia and discuss the parameter by comparing the result with megathrust earthquakes and ETS





Partitioning of deformation



$$V_{slip} + V_{flow} = V_{pl}$$

- Friction law (rate and state)

$$\tau = \left(f_0 + a \ln \frac{V_{slip}}{V_0}\right)(\sigma - p)$$

Velocity dependence 0.01

Friction coefficient = 0.5

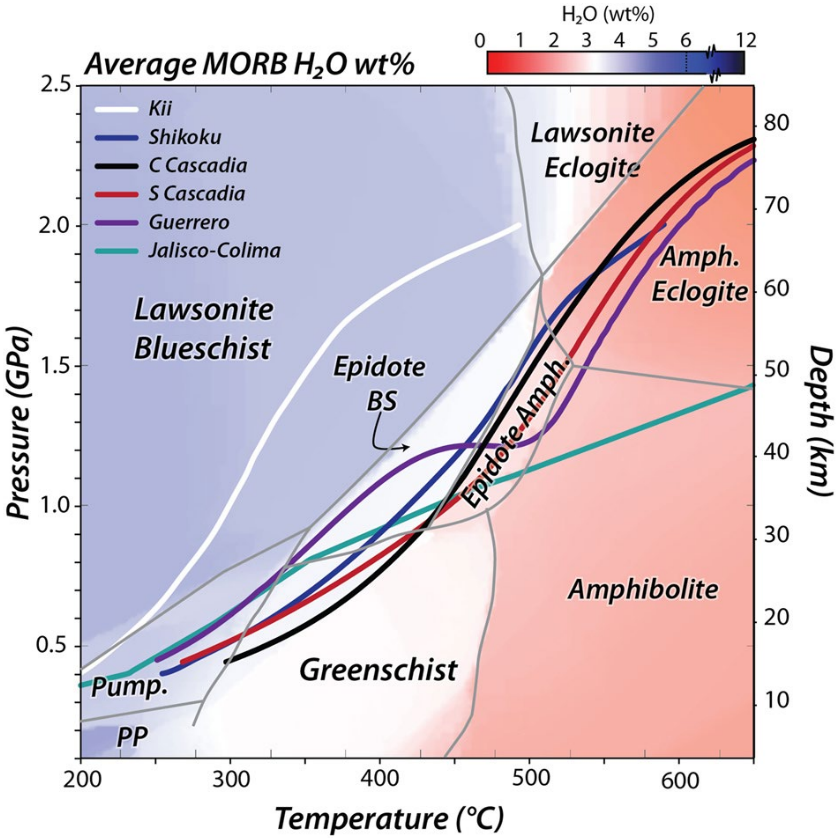
- Viscous flow law

$$\tau = \frac{\eta_s V_{flow}}{w_v}$$

$$\eta_s = A\exp\left(\frac{Q}{RT}\right)$$

Similar to pressure solution creep by Fisher and Hirth (2024)

Where do fluids come from?



Condit et al. (2020)

Perple_X

Input: PT path and chemical composition (Mid-Ocean Ridge Basalt)

Output: Mineral bounded water in subducting oceanic crust as a function of depth

Fluid production rate

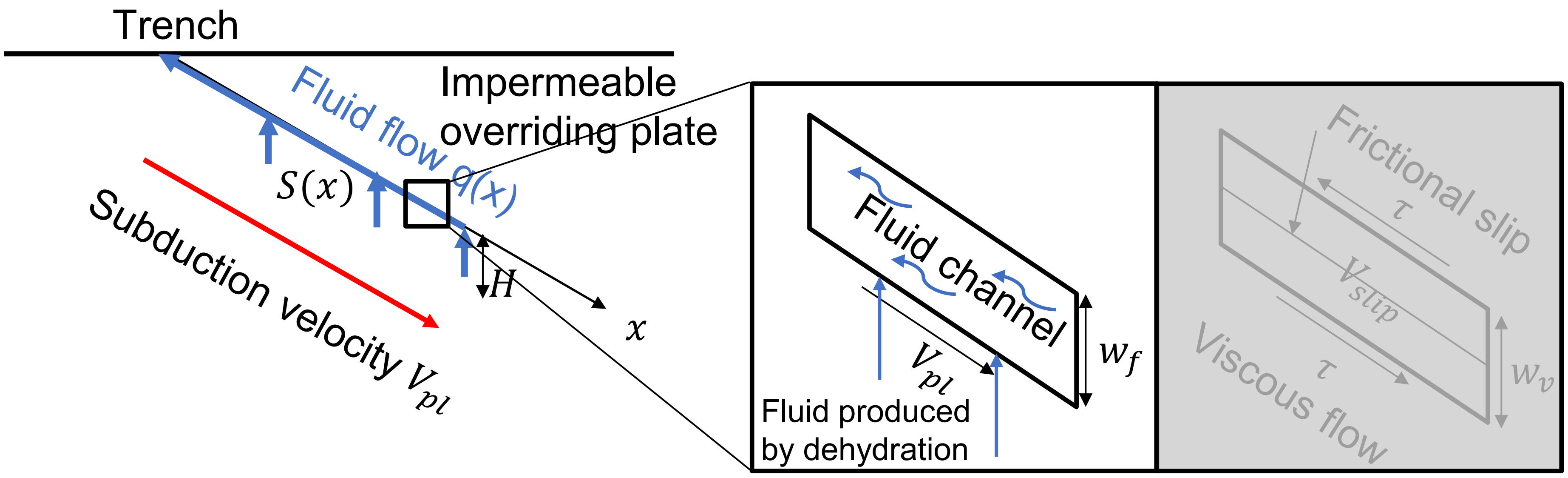
Mineral-bounded water (%)

$$s(x) = HV_{pl}\frac{\mathrm{d}\chi(P,T;x)}{dx}$$

Thickness of dehydrating layer (2km)

Plate velocity

Fluid flow along the megathrust



Fluid mass balance

Flux

$$q(x) = \int^x dx\, s(x)/w_f$$

Source Channel width

Darcy law: Fluid flux depends on overpressure gradient

Permeability (variable)

dip

$$q(x) = \frac{k}{\eta_f}\left(\frac{dp}{dx} - \rho_f g \sin\theta\right)$$

fluid density

fluid viscosity

Permeability is not constant

Pressure dependence

$$k = k^* \exp\left(-\frac{\sigma - p}{\sigma_0}\right)$$

David et al. 1994

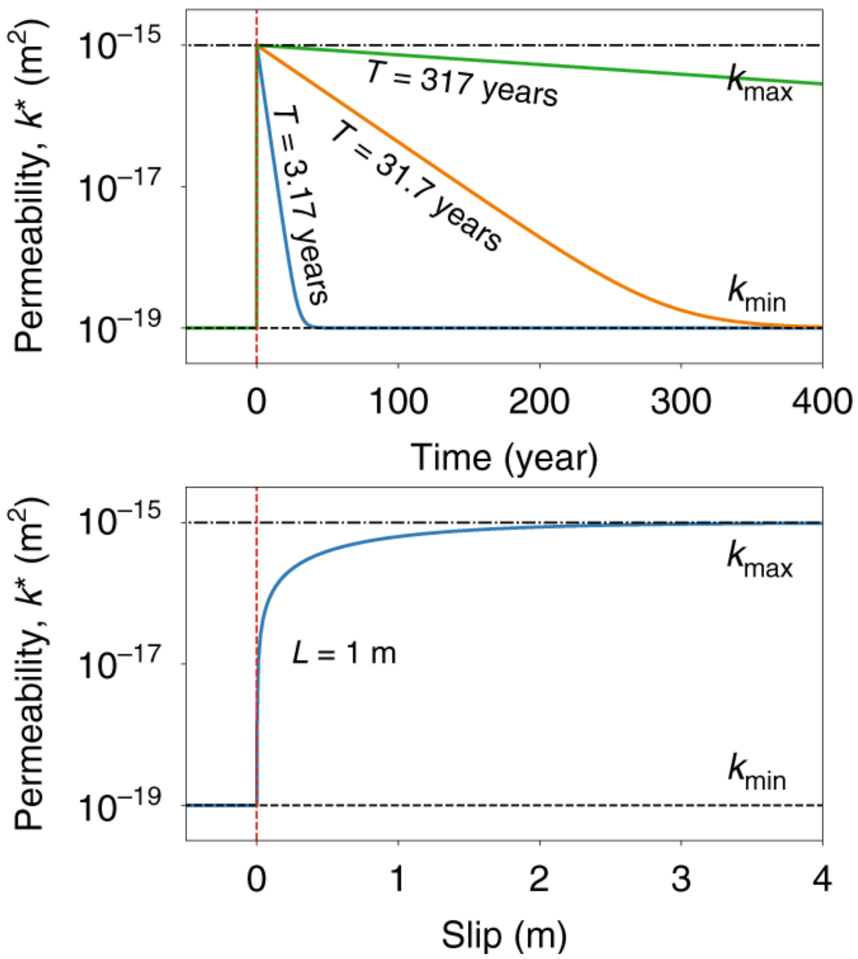
Steady state permeability: $k = \frac{k_{max} \exp\left(-\frac{\sigma - p}{\sigma_0}\right)}{1+\frac{L}{V_{slip} t_h}}$

Slip and time dependence

$$\frac{dk^*}{dt} = -\frac{1}{t_h}(k^* - k_{min}) - \frac{V_{slip}}{L}(k^* - k_{max})$$

Sealing/healing

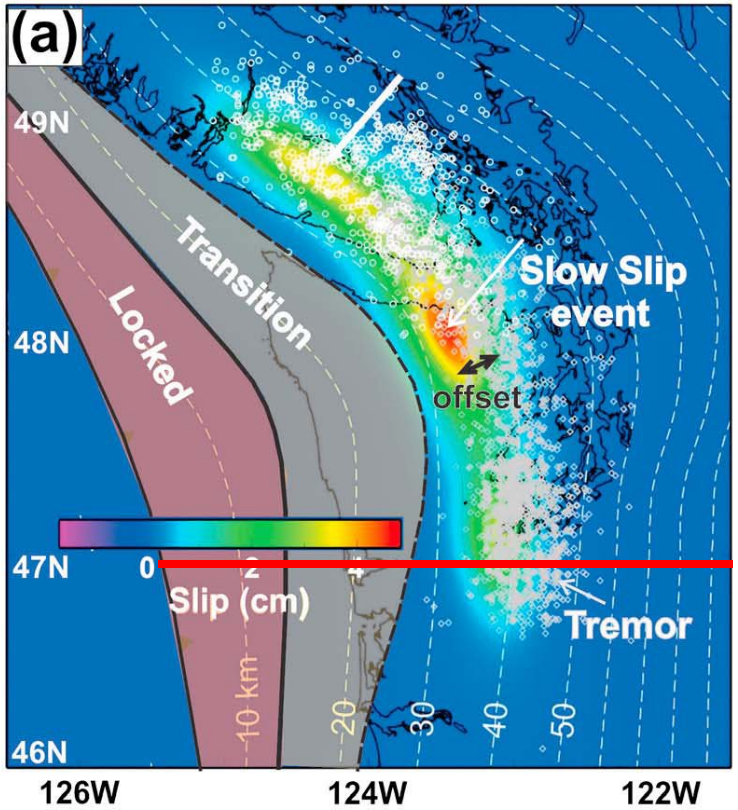
Slip induced increases



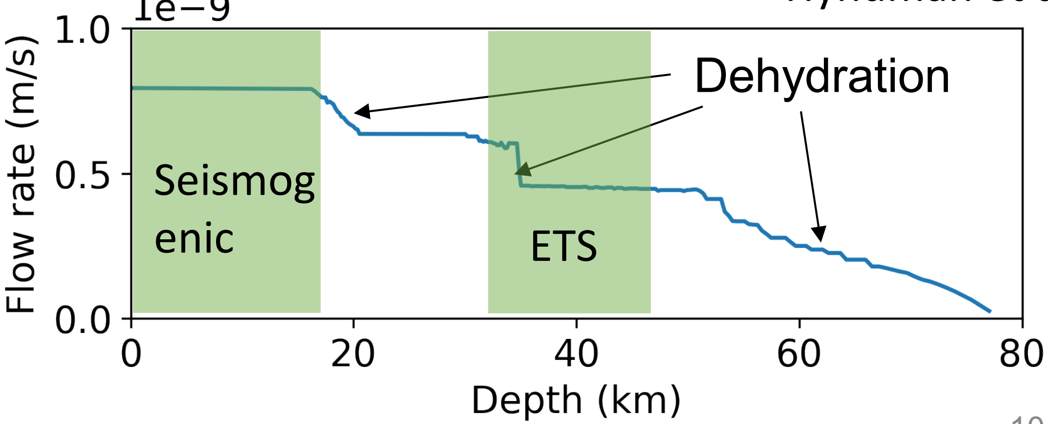
Zhu et al. 2020

Application to Cascadia subduction zone

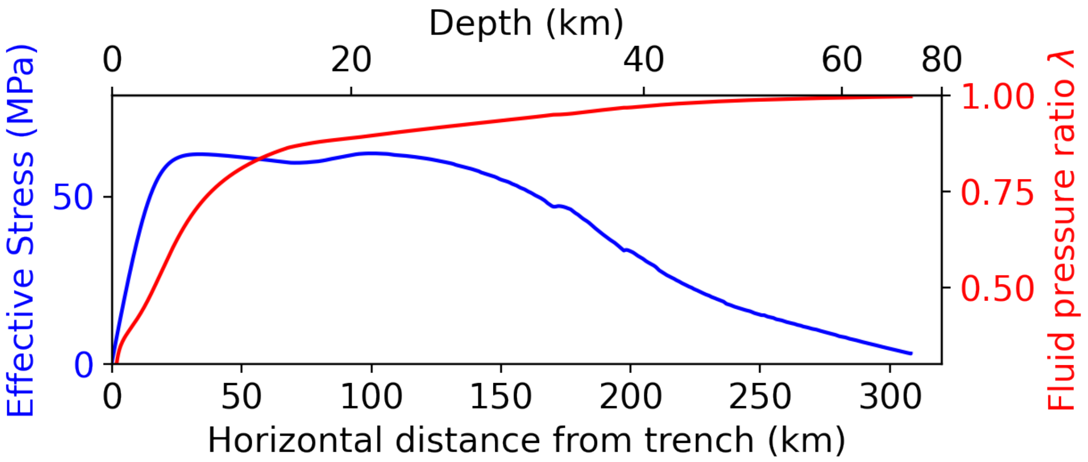
- Warm subduction zone
- Large earthquake (M9) recurrence :
  ~200-500 years
- Seismically quiet (uniformly locked until 15 - 20 km depth)
- Episodic Tremor and Slip (ETS) event at 35 – 45 km depths
- Shear stress in the seismogenic zone is estimated to be 20-30 MPa from stress rotation, topography, and heat flow (Li et al. 2018; Lamb 2006; Gao and Wang, 2014)
- Punctuated dehydration of subducting crust are 20 km, 35 km, and 50~ km

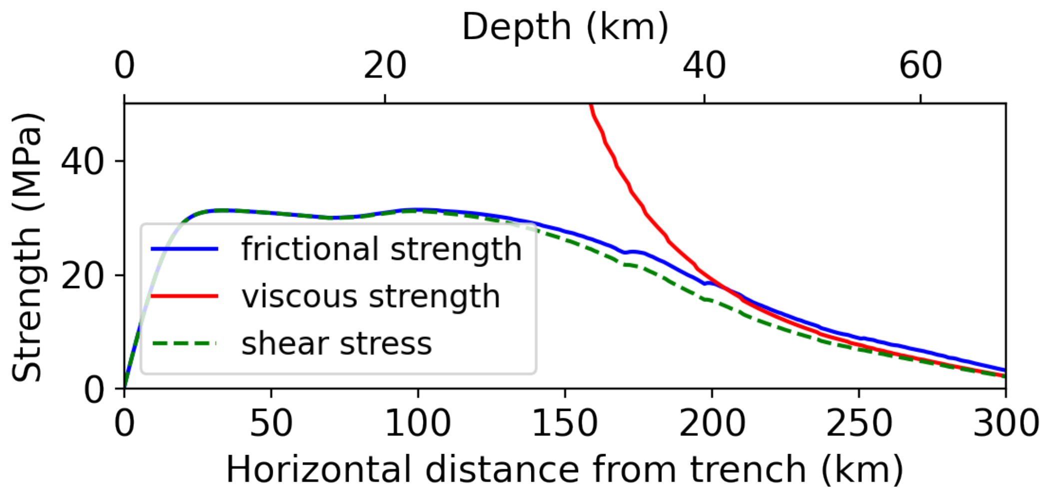


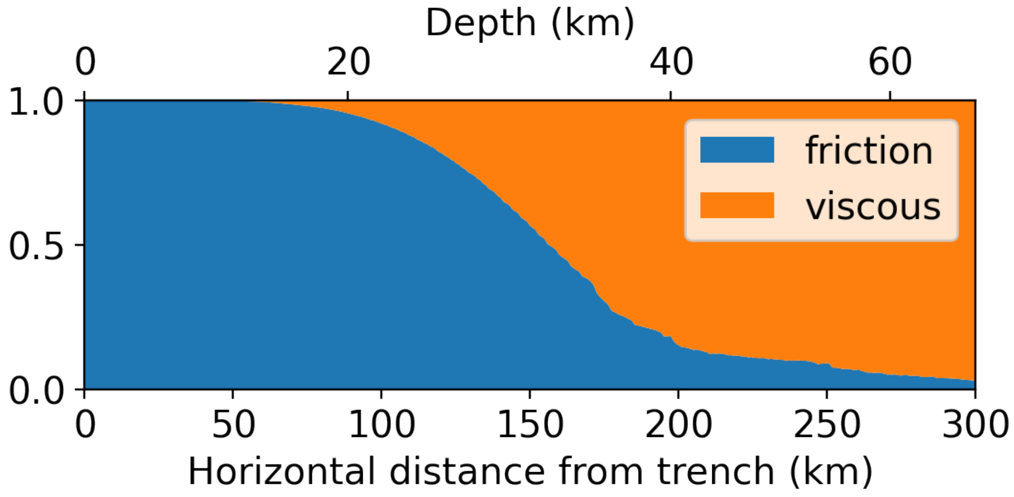
Hyndman et al. 2015



Overview of the results





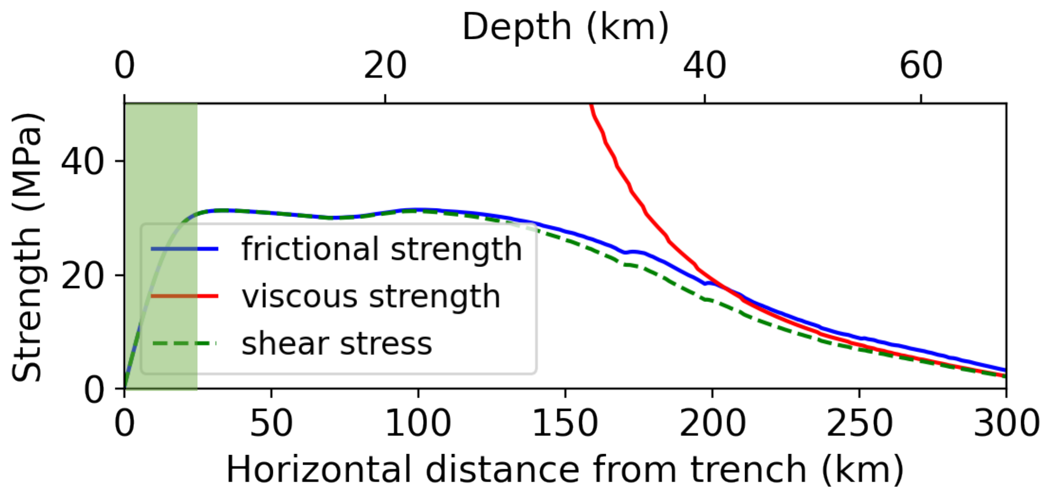


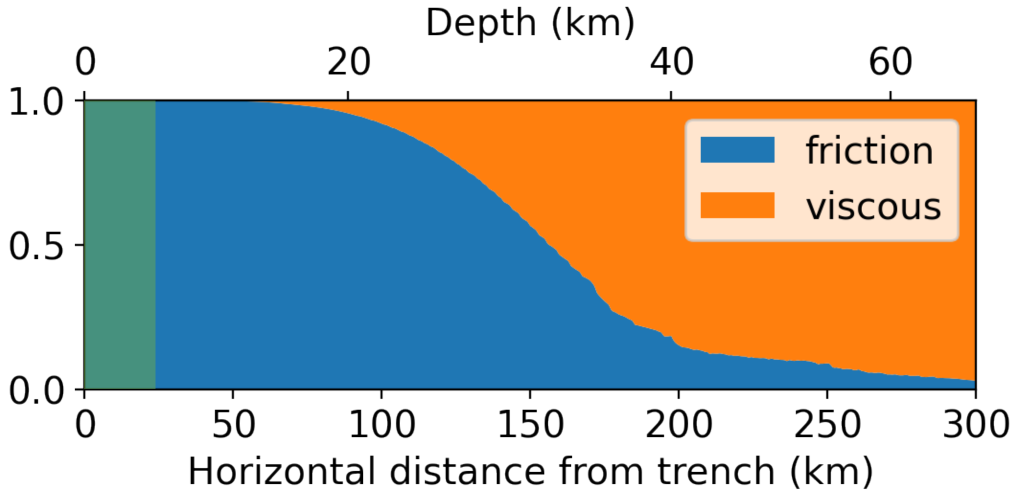
Overview of the results

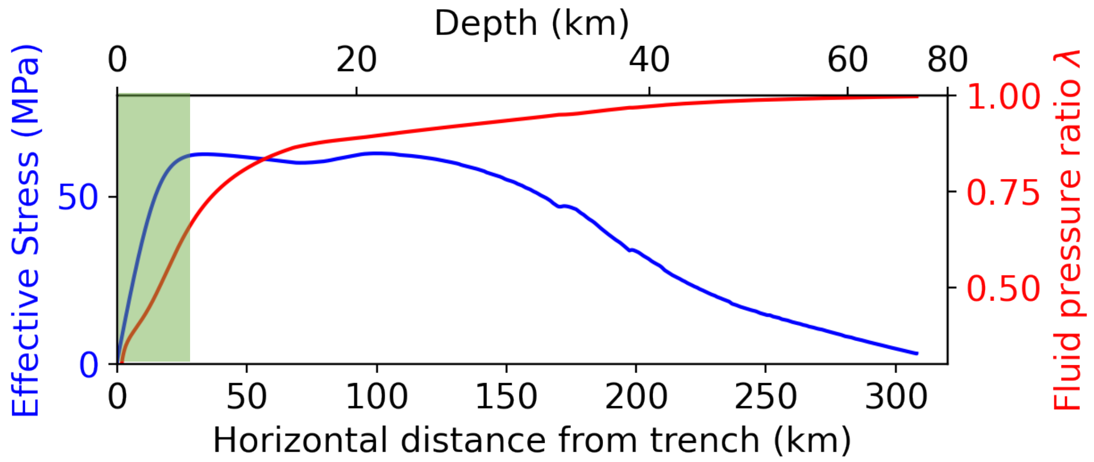
- Shallow (<5 km)

Frictional slip only

Effective stress increases with depth







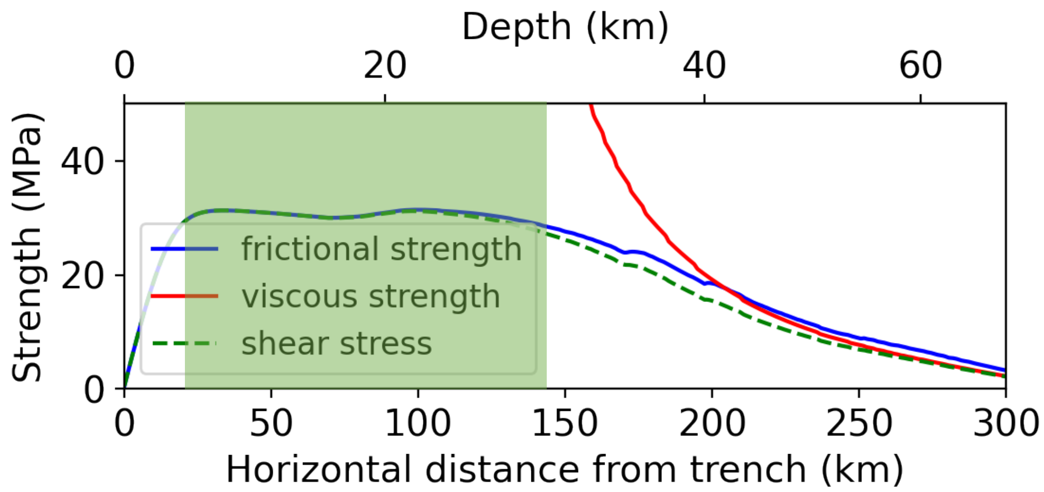
Overview of the results

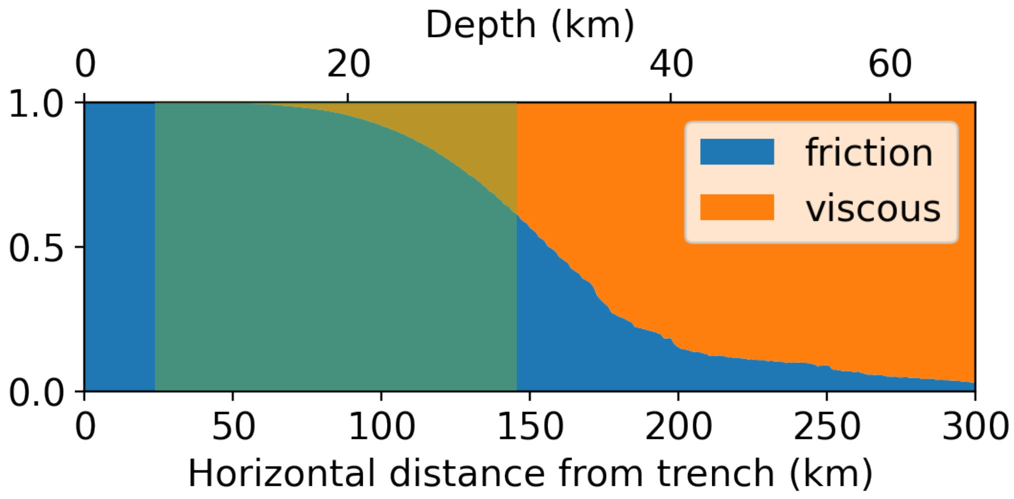
- Shallow (<5 km)

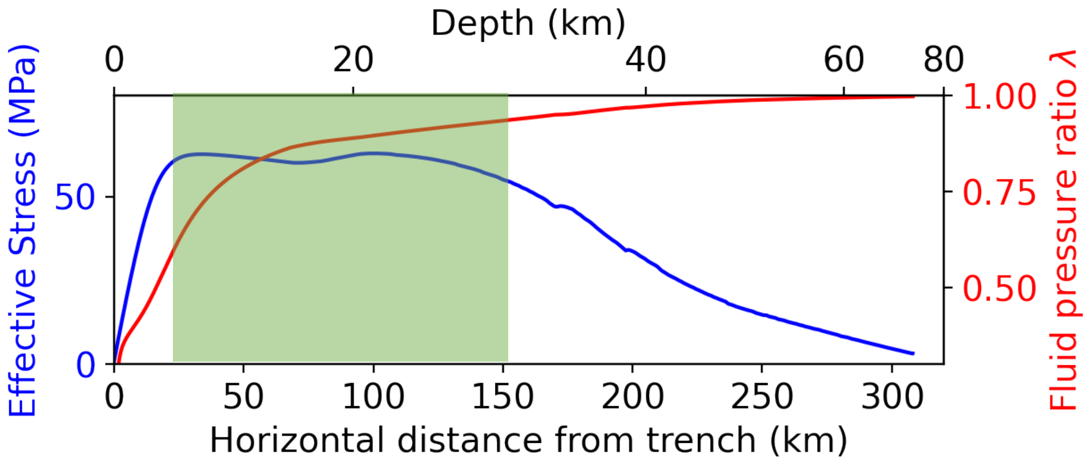
Frictional slip only
Effective stress increases with depth

- Intermediate (5 km - 30 km)

Friction slip dominant with nonzero viscous flow
Uniform effective stress and shear stress







Overview of the results

- Shallow (<5 km)

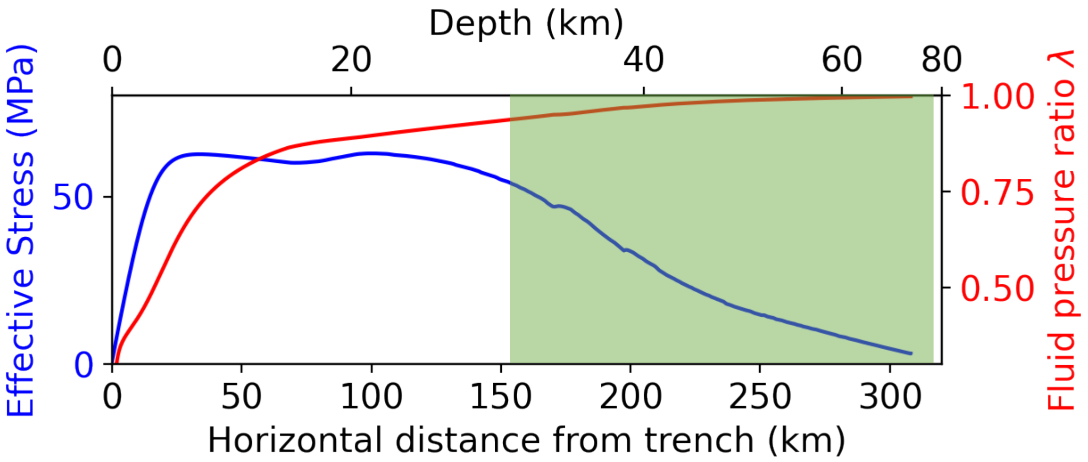
Frictional slip only
Effective stress increases with depth

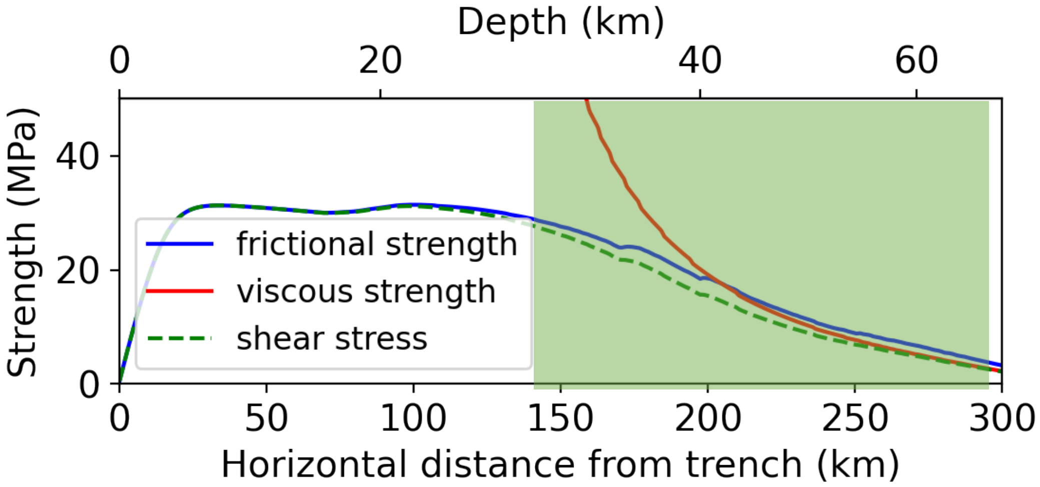
- Intermediate (5 km - 30 km)

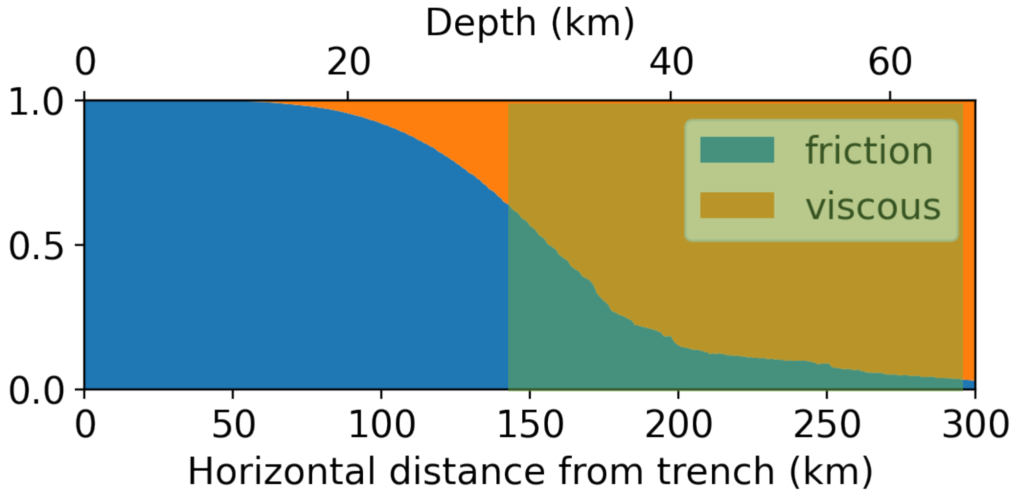
Friction slip dominant with nonzero viscous flow
Uniform effective stress and shear stress

- Deep (>30 km)

Viscous flow dominant with nonzero frictional slip
Effective stress decreases with depth
Frictional and viscous strengths are comparable







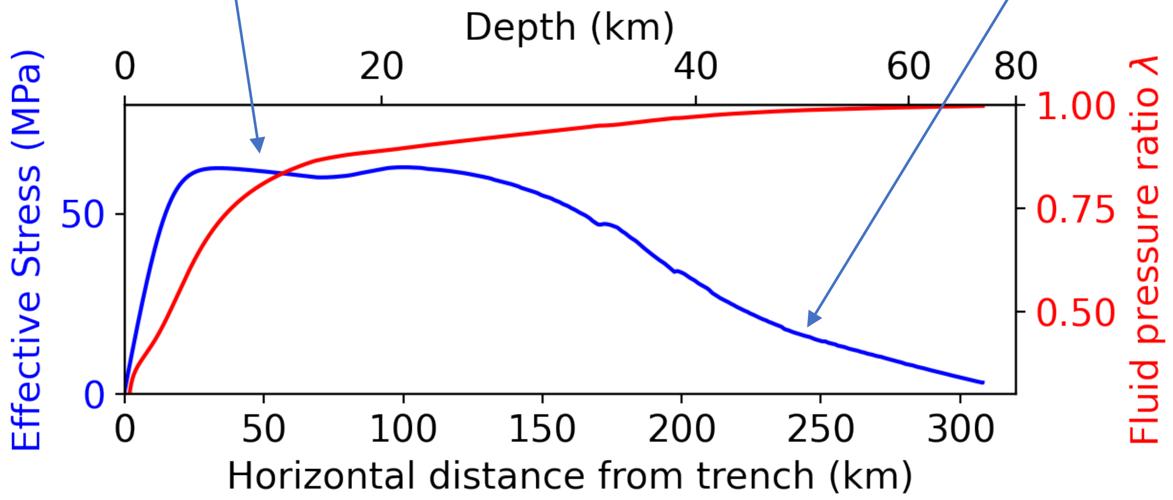
Effective stress decreases with depth below the frictional-viscous transition

Nearly uniform effective stress

$$\sigma' \sim \sigma_0 \ln\left(\frac{k_{max} w_f \Delta\rho g \sin\theta}{\eta_f \chi H V_{pl}}\right)$$

Decrease due to healing

$$\sigma' \sim \frac{\eta_s V_{pl}}{f w_v}$$



Frictional earthquake cycle models for slow slip assume even more rapid drop of effective stress at ETS regions

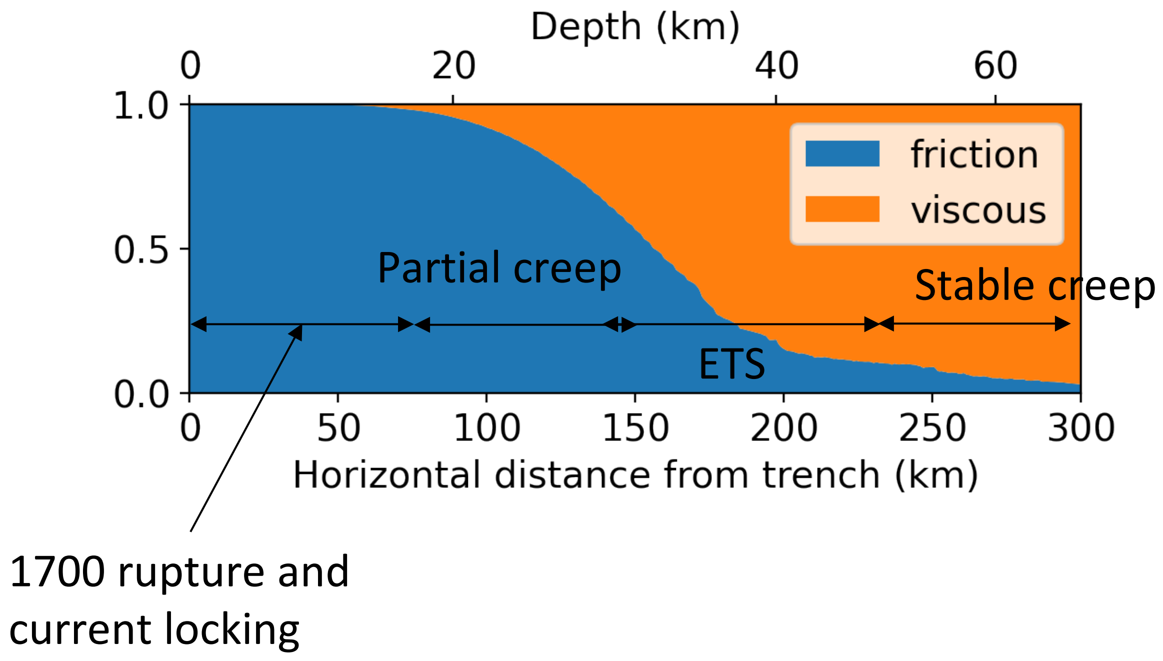
Li & Liu, 2016

Frictional viscous transition is gradual and monotonic

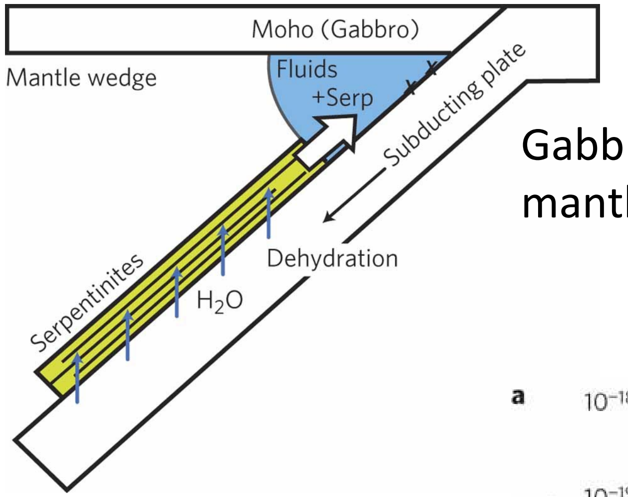
Viscous flow sets in at 15 km depth, but the transition complete around at 60 km depth. ETS corresponds to a region where 20-30% of deformation is viscous

Gao & Wang (2017) argued that the transition is not monotonic. The gap between the seismogenic zone and ETS zone is more viscous

Can we reproduce non-monotonic transition in our framework?

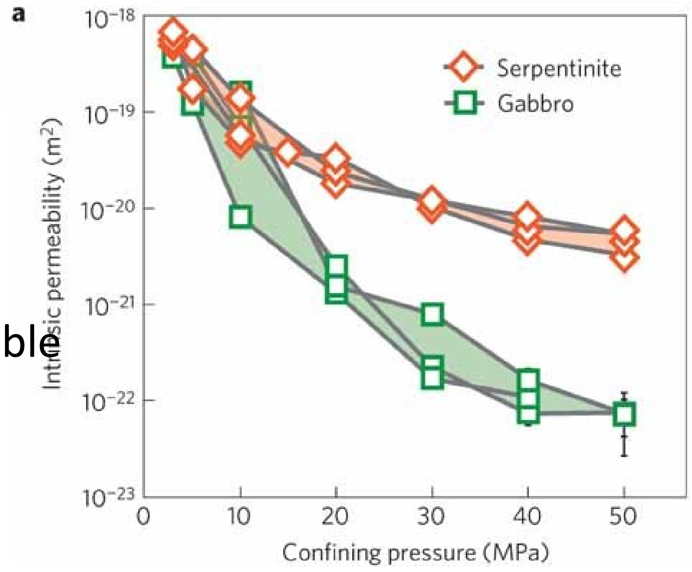


Permeability contrast from lithology

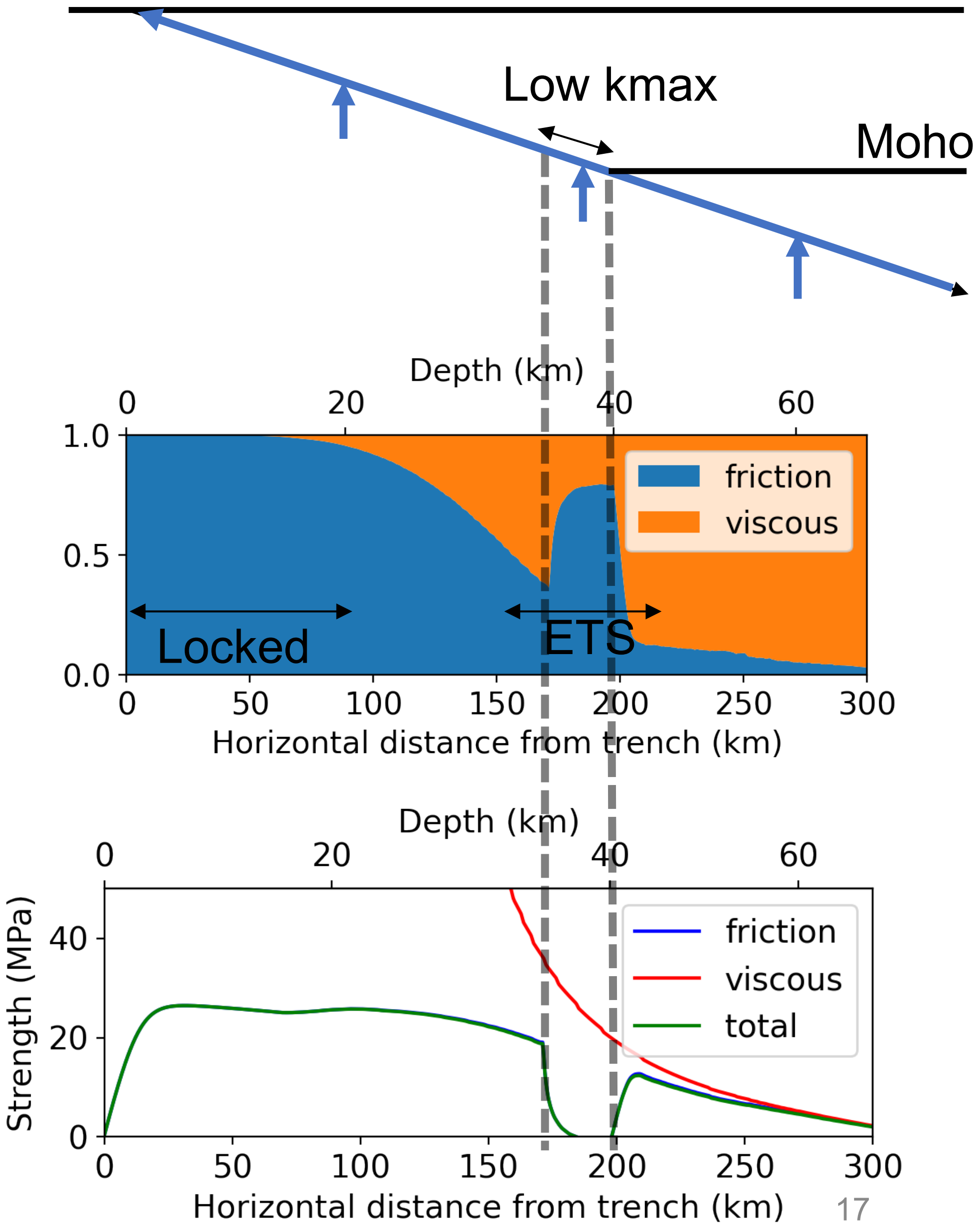


Gabbro above the serpentinized mantle wedge corner

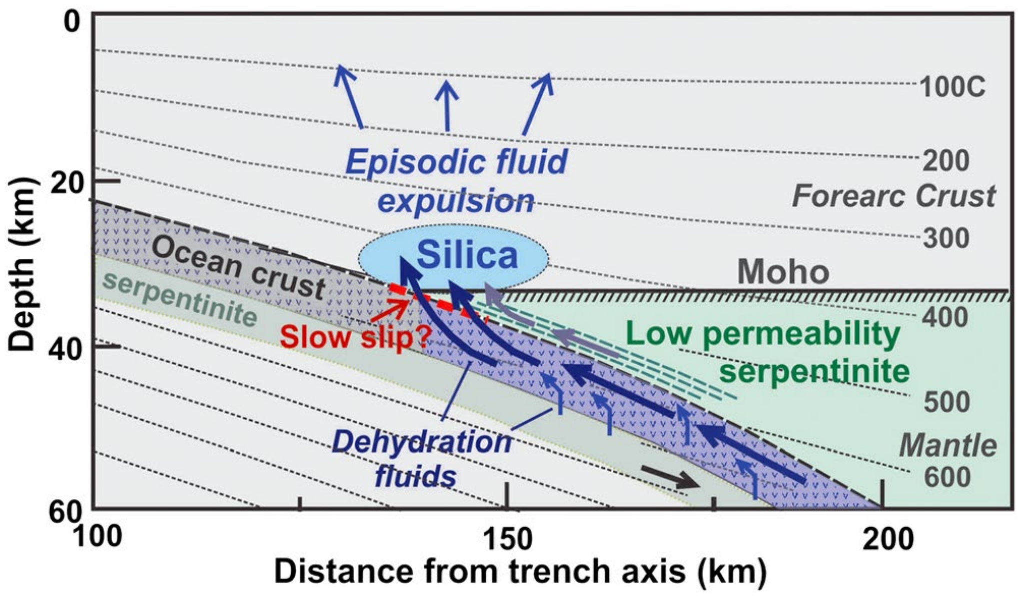
Serpentinite is more permeable than gabbro for a given effective stress



Katayama et al. 2012



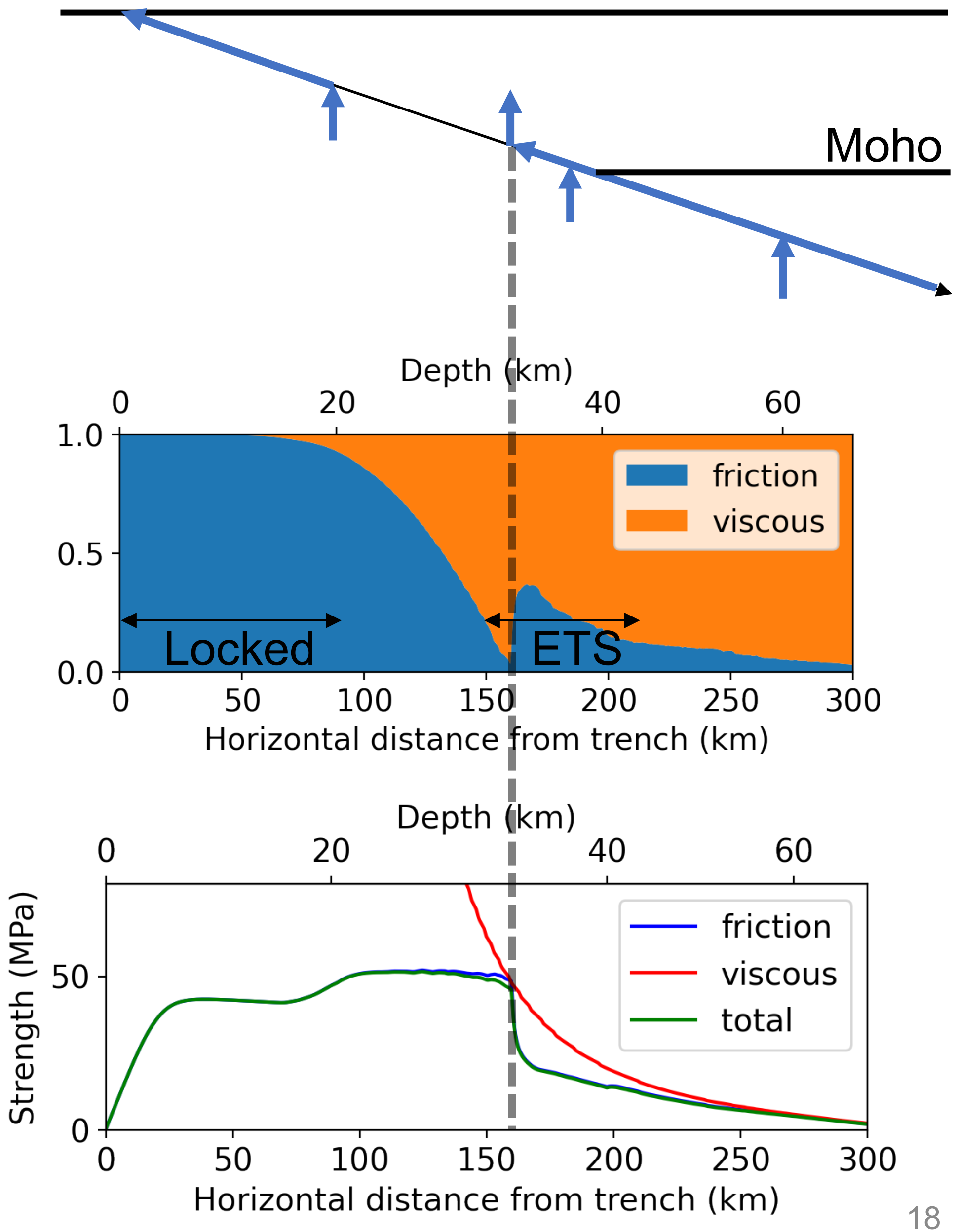
Draining from upper plate



Hyndman et al. (2015)

Similar idea by Gao and Wang (2017)

High fluid pressure by impermeable overriding plate by serpentinization



Summary

- The stress profile and partition of deformation along the Cascadia megathrust is calculated using fluid production from dehydration reactions of oceanic crust.
- The effective stress in the seismogenic zone is almost uniform value and a function of fluid production and transport properties
- The effective stress and hence frictional strength decrease with depth below the seismogenic zone.
- Fluid loss at the mantle wedge corner or locally low permeability produce non-monotonic frictional viscous transition, potentially explaining the gap in Cascadia

See also Wenqiang Zhang's poster for seismic cycle simulations using the stress profile calculated in this work

Zhang, Ozawa, Dunham (Poster)

Earthquake cycle simulation in the Cascadia subduction zone

Relaxing the assumption of impermeable overriding plate

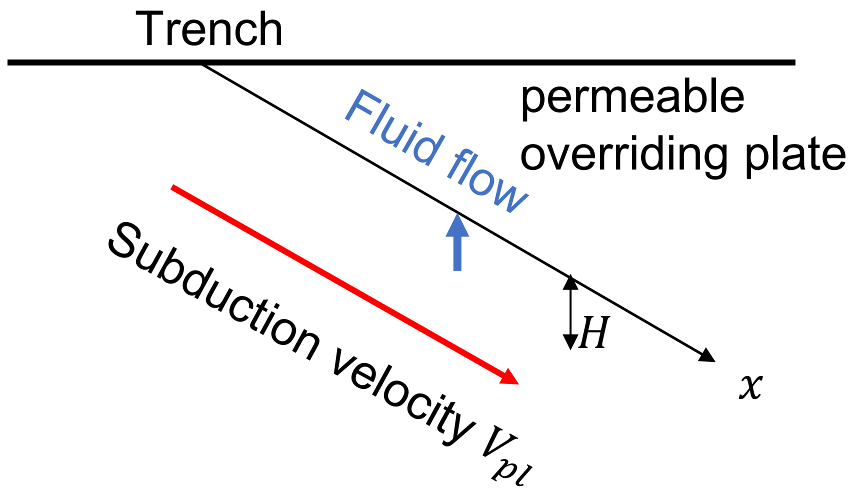
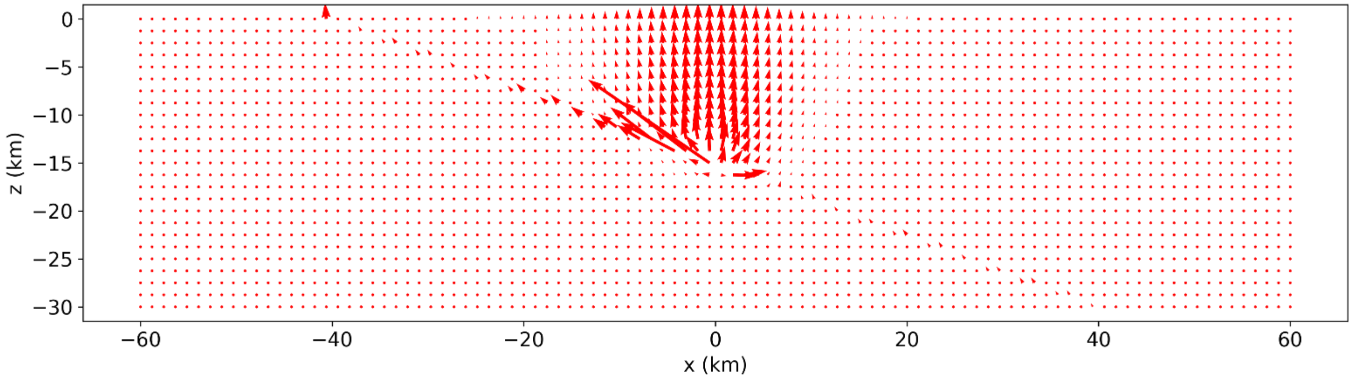
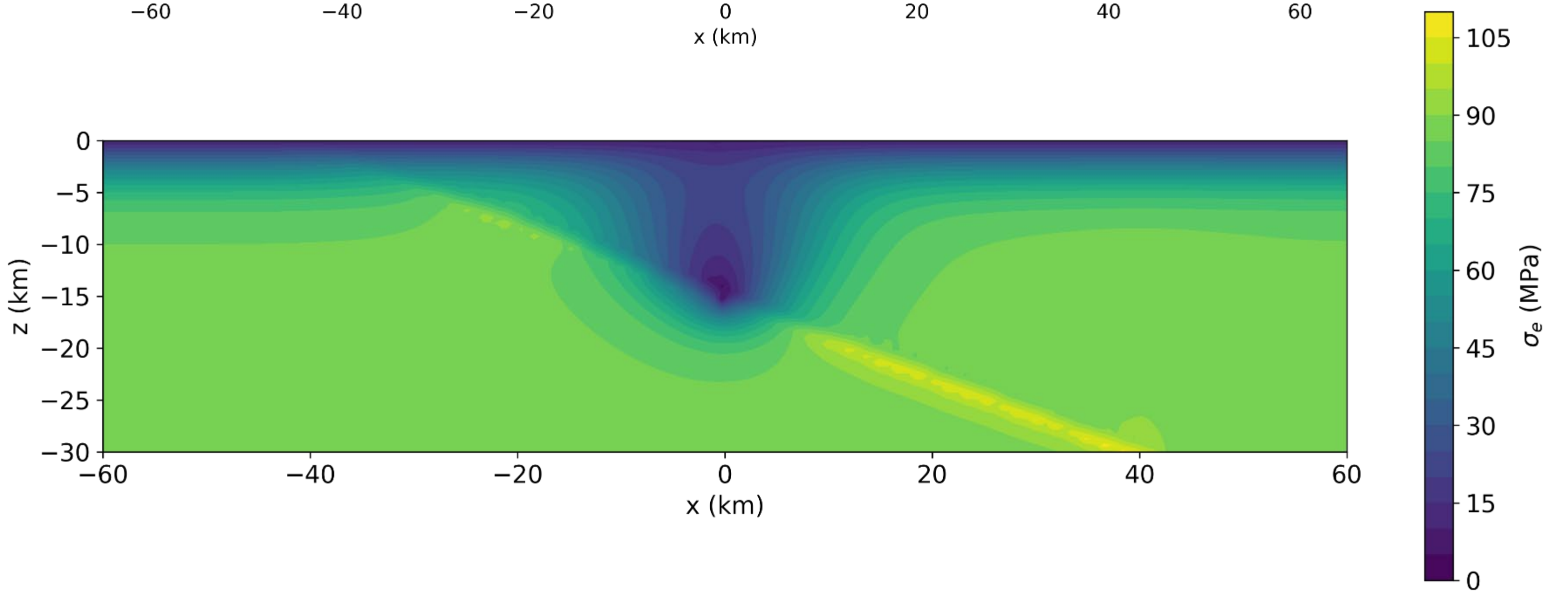


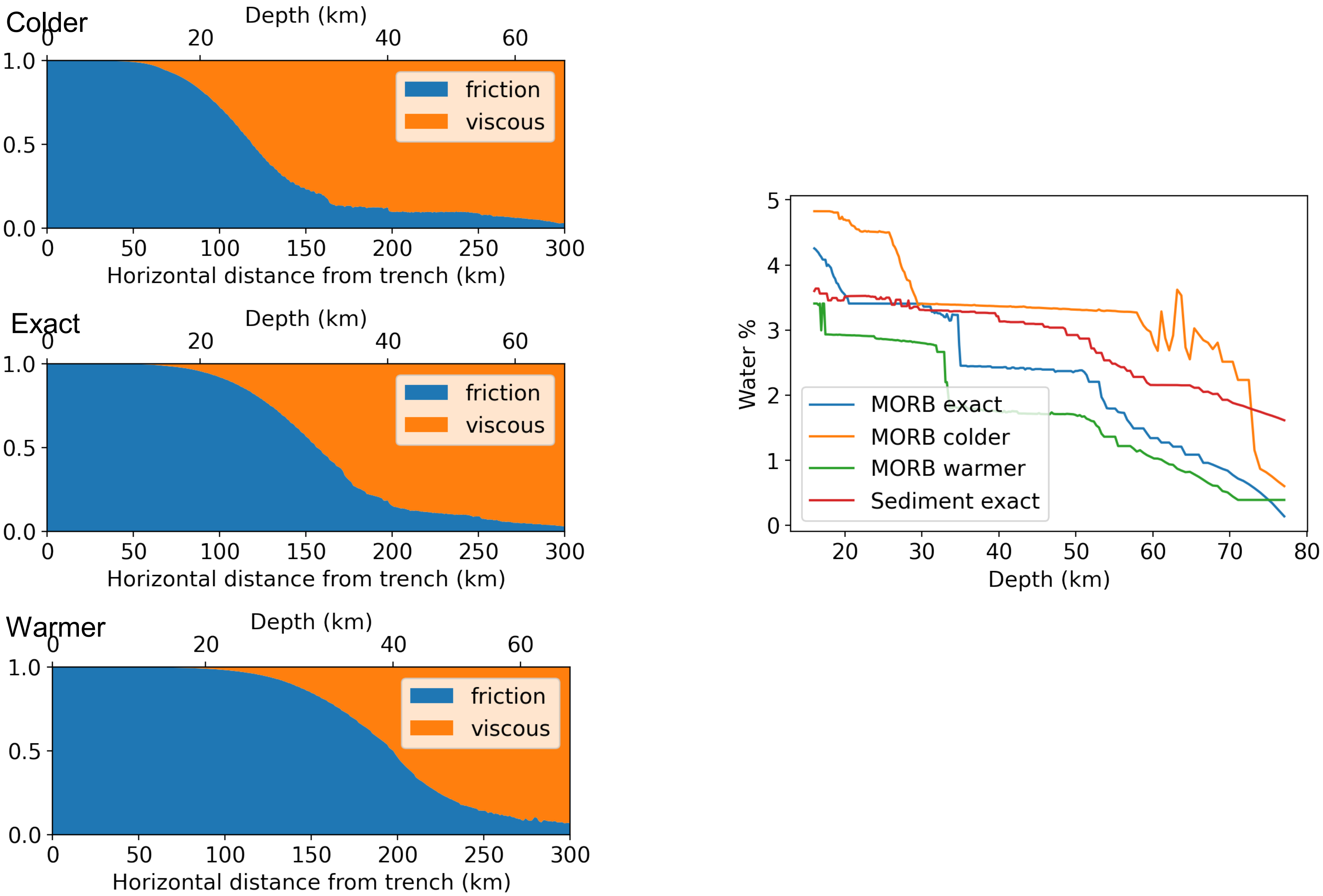
Plate interface is 10 x more permeable than surrounding rock

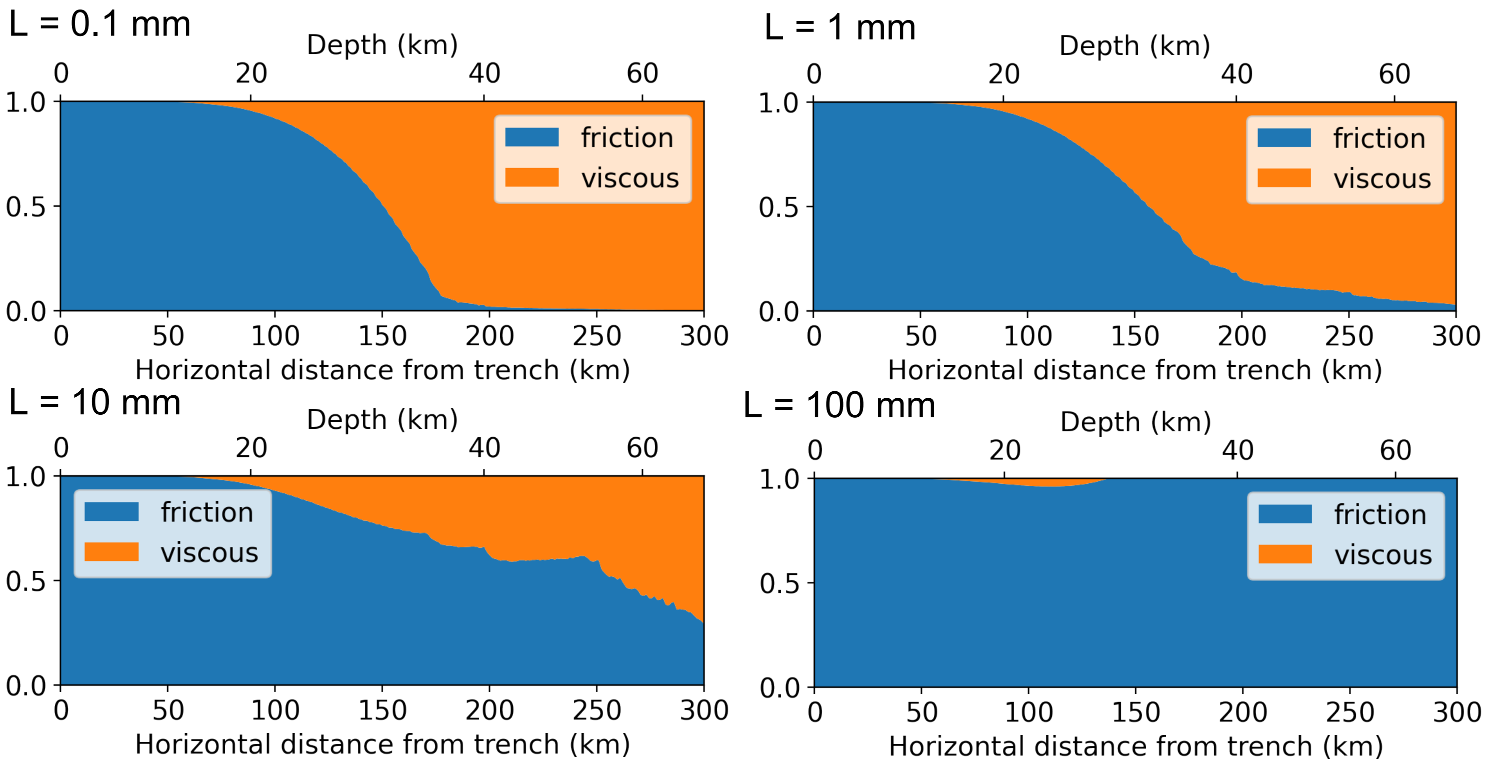


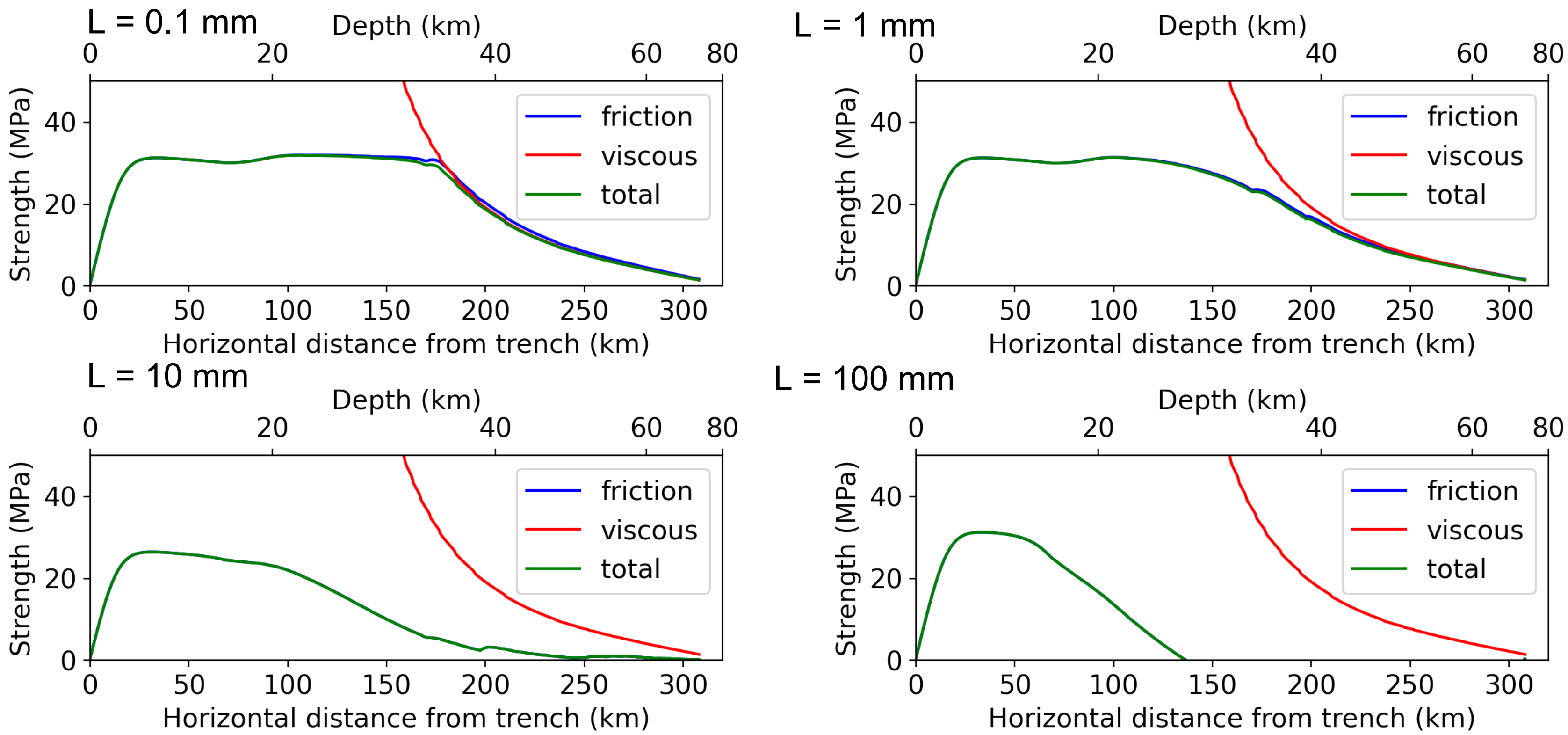


- Fluids want to move vertical owing to buoyancy
- There still exists updip flow due to the high permeability
- Broad low effective stress region above the fluid source

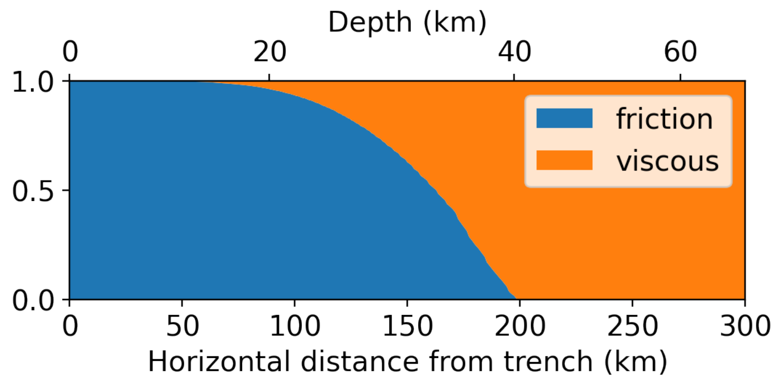
Fluid pressure, porosity → seismic velocity, resistivity, geochemical signature

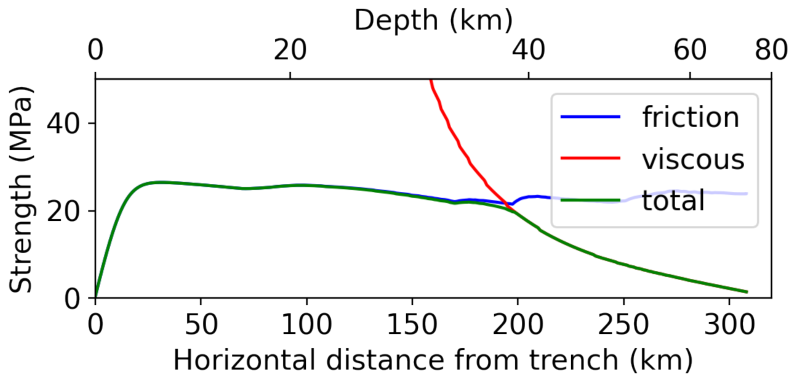

Colder
Depth (km)
0
20
40
60
1.0
0.5
0.0
friction
viscous
0
50
100
150
200
250
300
Horizontal distance from trench (km)
Exact
Depth (km)
0
20
40
60
1.0
0.5
0.0
friction
viscous
0
50
100
150
200
250
300
Horizontal distance from trench (km)
Warmer
Depth (km)
0
20
40
60
1.0
0.5
0.0
friction
viscous
0
50
100
150
200
250
300
Horizontal distance from trench (km)
Water %
5
4
3
2
1
0
MORB exact
MORB colder
MORB warmer
Sediment exact
20
30
40
50
60
70
80
Depth (km)


L = 0.1 mm
Depth (km)
0
20
40
60
1.0
0.5
0.0
friction
viscous
0
50
100
150
200
250
300
Horizontal distance from trench (km)
L = 1 mm
Depth (km)
0
20
40
60
1.0
0.5
0.0
friction
viscous
0
50
100
150
200
250
300
Horizontal distance from trench (km)
L = 10 mm
Depth (km)
0
20
40
60
1.0
0.5
0.0
friction
viscous
0
50
100
150
200
250
300
Horizontal distance from trench (km)
L = 100 mm
Depth (km)
0
20
40
60
1.0
0.5
0.0
friction
viscous
0
50
100
150
200
250
300
Horizontal distance from trench (km)

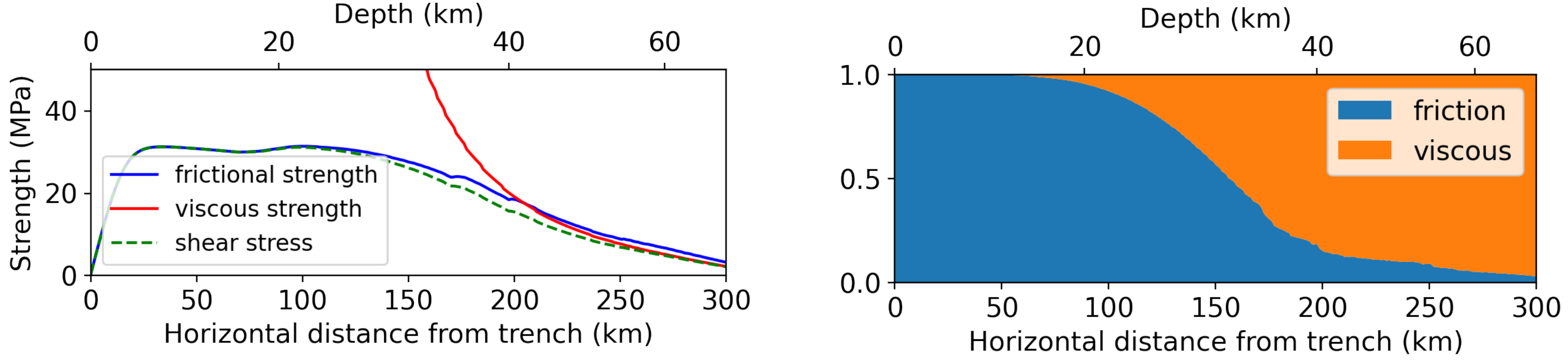

L = 0.1 mm
L = 1 mm
L = 10 mm
L = 100 mm
Depth (km)
0
20
40
60
80
Strength (MPa)
Horizontal distance from trench (km)
0
50
100
150
200
250
300
friction
viscous
total

If permeability enhancement is caused by V instead of Vslip



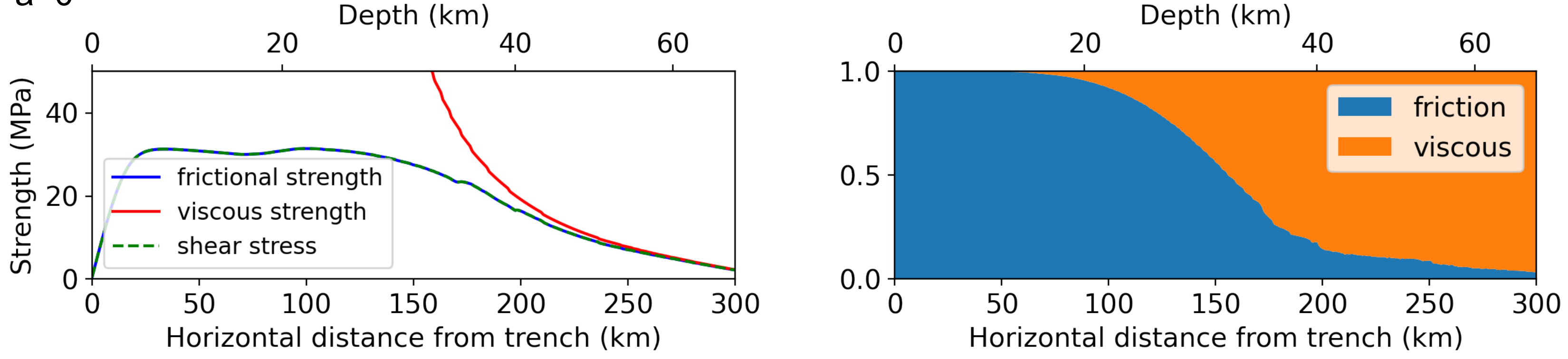


a=0.05



Depth (km)
0
20
40
60
Strength (MPa)
0
20
40
frictional strength
viscous strength
shear stress
0
50
100
150
200
250
300
Horizontal distance from trench (km)
Depth (km)
0
20
40
60
1.0
0.5
0.0
friction
viscous
0
50
100
150
200
250
300
Horizontal distance from trench (km)

a=0



Depth (km)
0
20
40
60
Strength (MPa)
0
20
40
frictional strength
viscous strength
shear stress
0
50
100
150
200
250
300
Horizontal distance from trench (km)
Depth (km)
0
20
40
60
1.0
0.5
0.0
friction
viscous
0
50
100
150
200
250
300
Horizontal distance from trench (km)