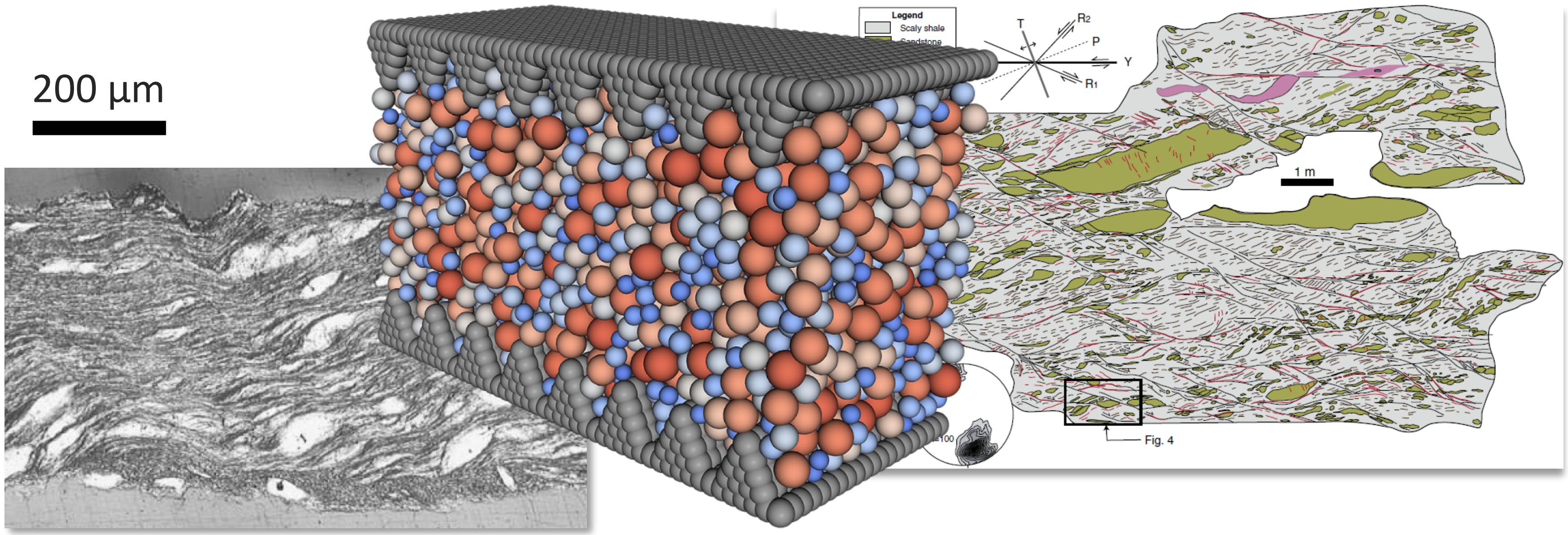
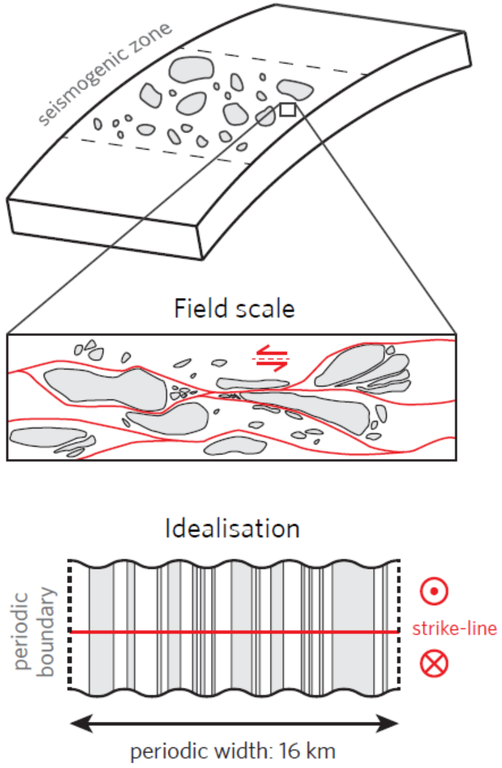




A micro-scale perspective on a km-scale problem

Microphysically based modelling of friction and earthquakes

Dieterich (1972)

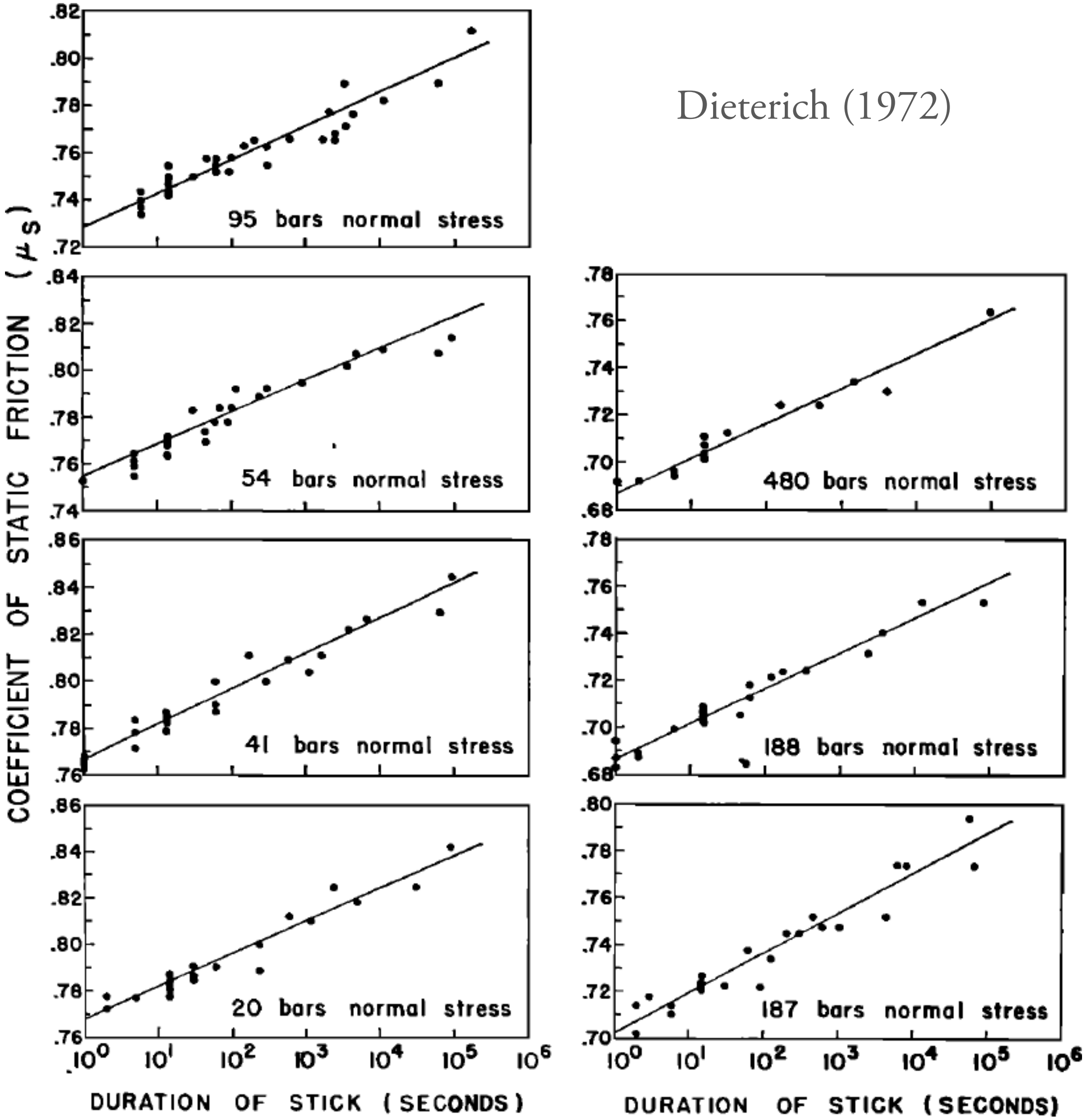
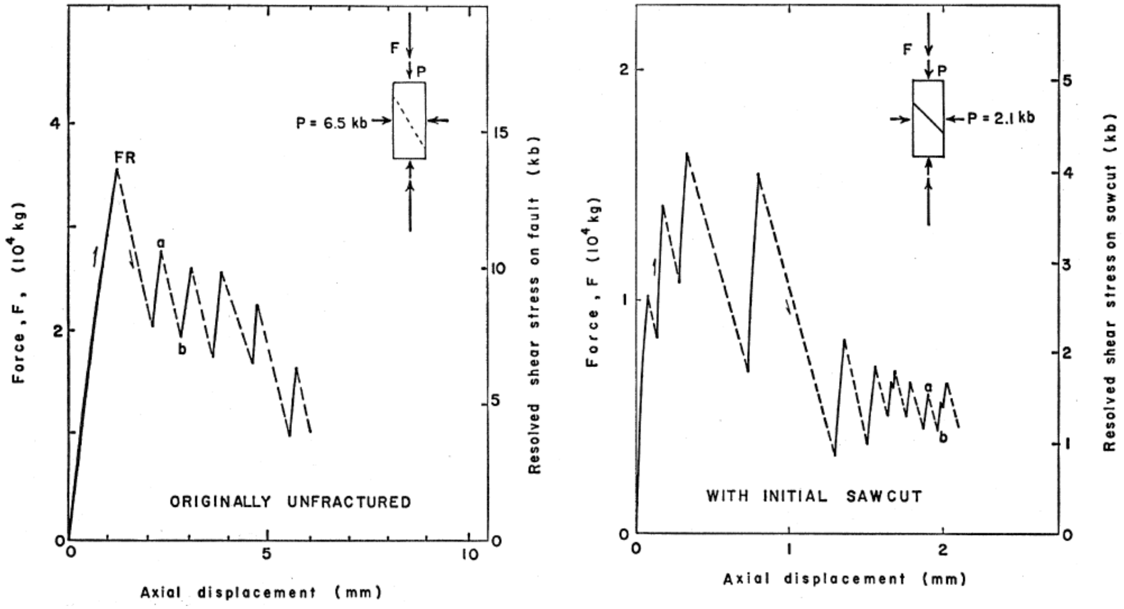
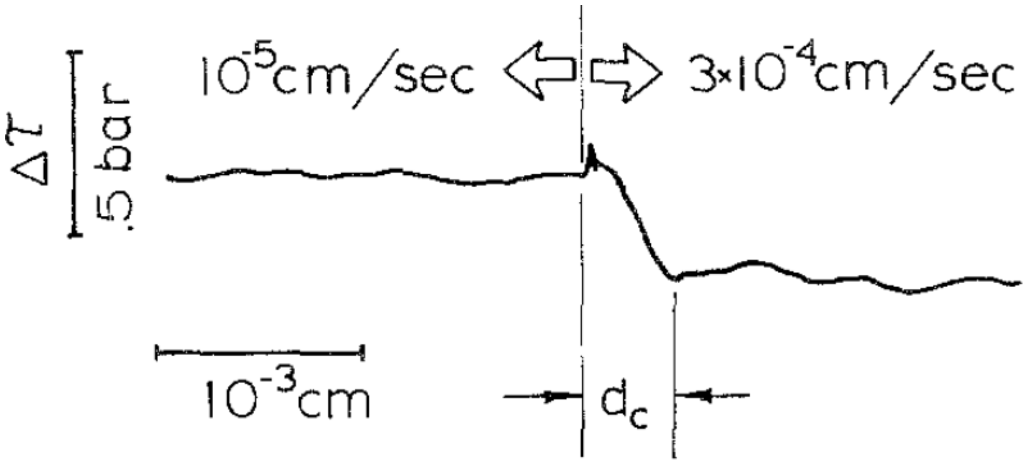


Fig. 2. Time dependence of the coefficient of static friction μ_s for sandstone.

Brace & Byerlee (1966)





Dieterich (1978)

Pageoph, Vol. 116 (1978), Birkhäuser Verlag, Basel

Time-Dependent Friction and the Mechanics of Stick-Slip

By JAMES H. DIETERICH[1])

---

stress was then rapidly increased to the critical level required to produce slip. The results satisfy the empirical law:

$$\mu = \mu_0 + A \log (Bt + 1) \tag{2}$$

where t is the time of contact, and A, B and μ_0 are constants. Note that relationship

---

are then replaced with new and consequently weaker points. This model then implies a velocity-dependence of friction since the effective lifetime, T, of a point of contact is inversely proportional to slip velocity, V:

$$T = \frac{d_c}{V} = \frac{\gamma h}{V} \tag{5}$$

Hence, if t, the time of stationary contact in equation (2) is replaced with T, the average lifetime of a population of contacts at a steady velocity:

$$\mu = \mu_0 + A \log \left(\frac{Bd_c}{V} + 1 \right) \tag{6}$$

or

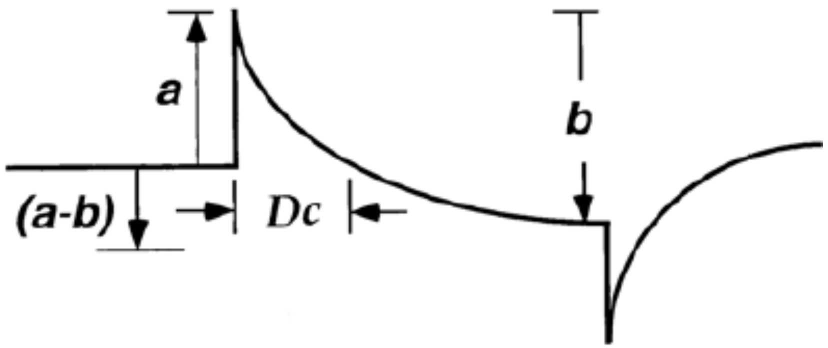
$$\mu = \mu_0 + A \log \left(\frac{B\gamma h}{V} + 1 \right) \tag{7}$$

Rate & State Friction

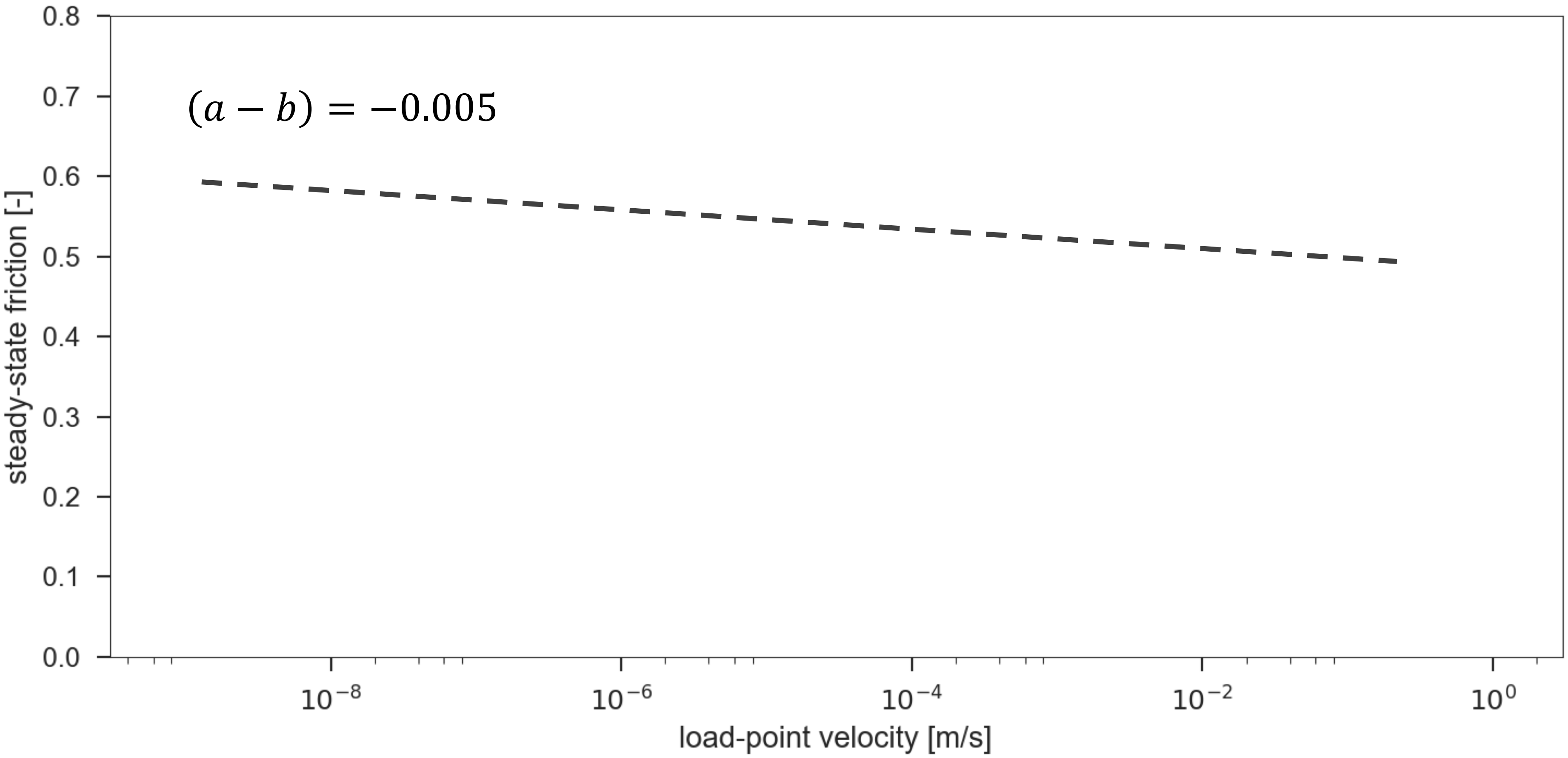
$$\mu(V,\theta) = \mu^* + a\ln\left(\frac{V}{V^*}\right) + b\ln\left(\frac{V^*\theta}{D_c}\right)$$

$$\frac{d\theta}{dt} = f(\theta, V, \ldots)$$

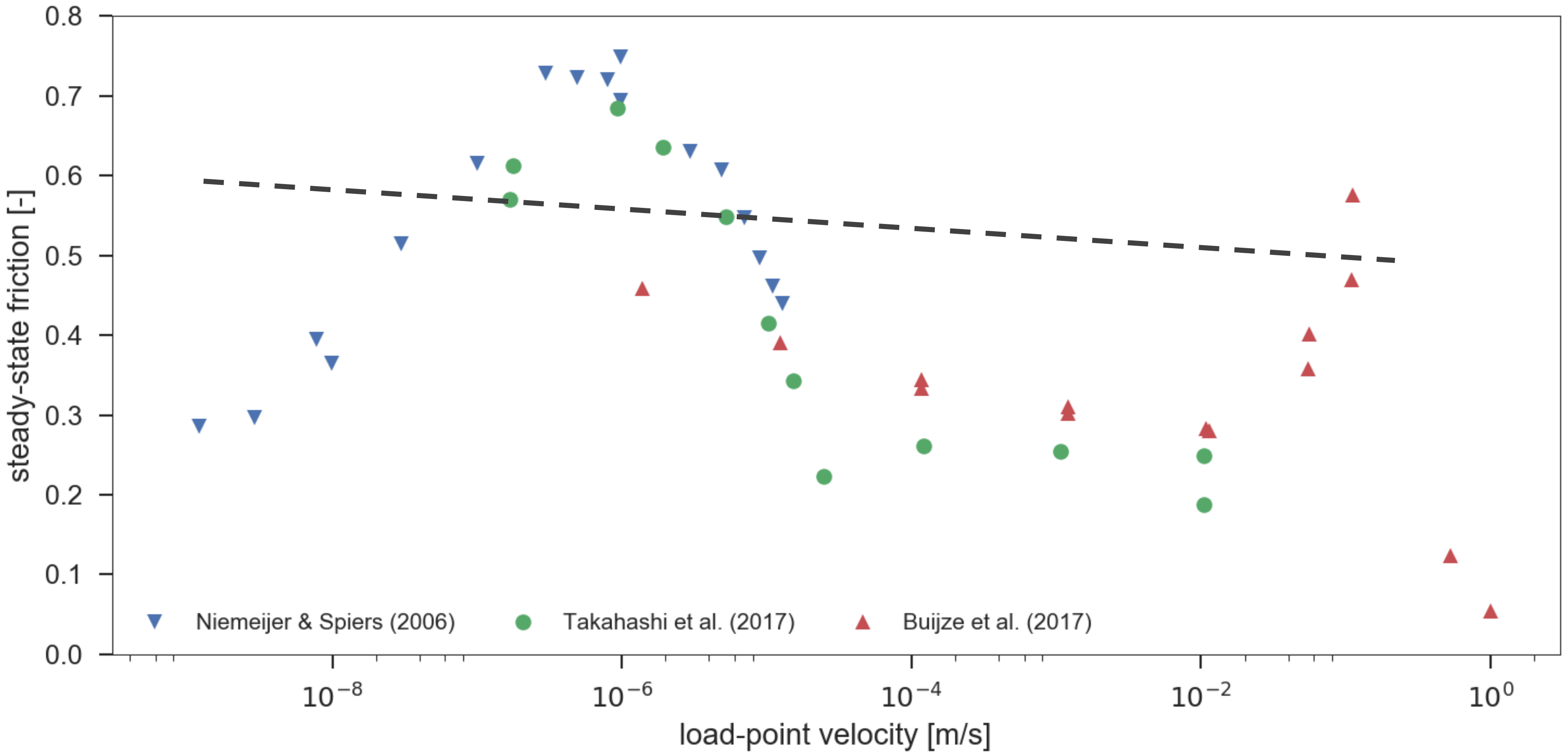
Scholz (2002)



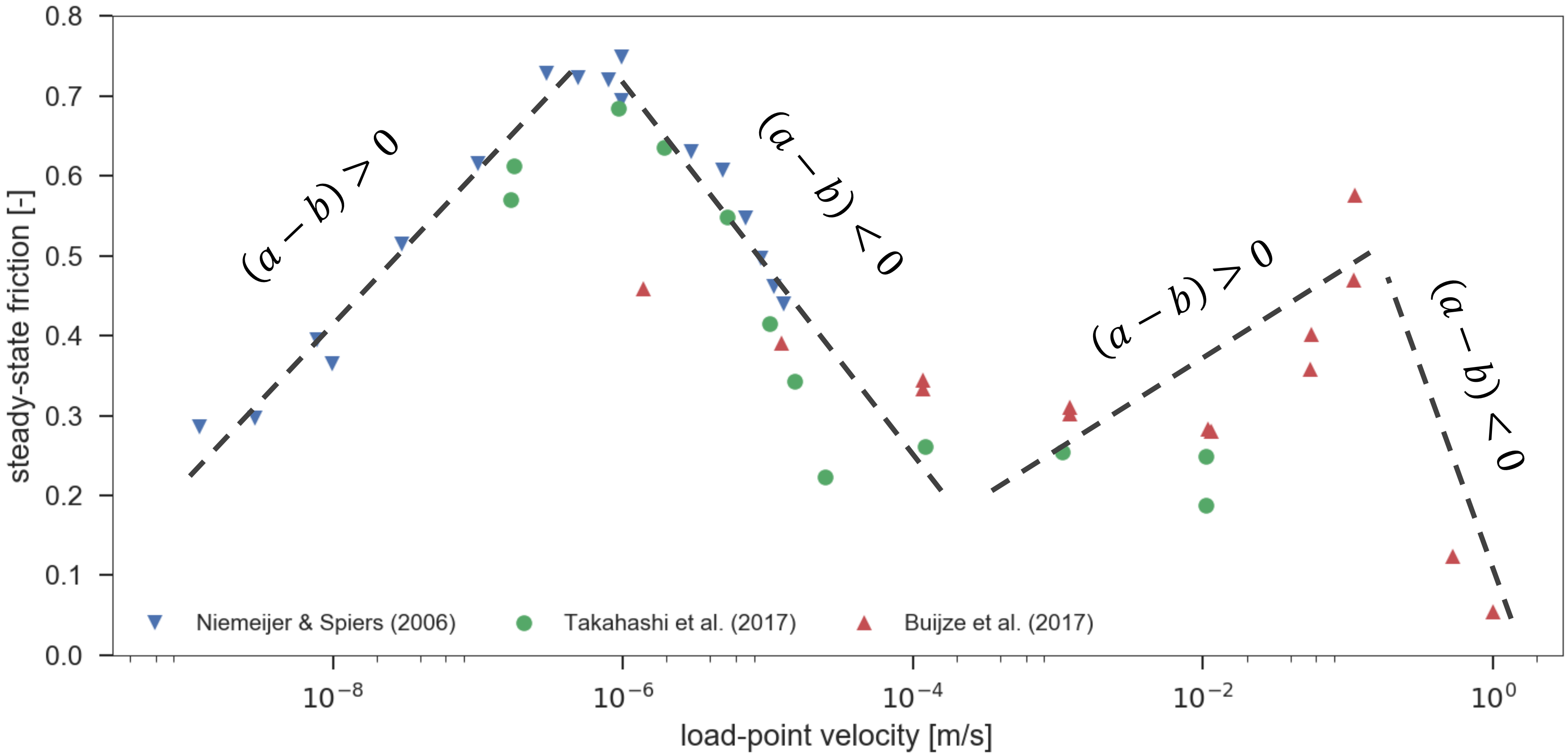
$$\mu_{ss} = \mu^{*} + (a - b)\ln\left(\frac{V}{V^{*}}\right)$$



$$\mu_{ss} = \mu^* + (a - b)\ln\left(\frac{V}{V^*}\right)$$



$$\mu_{ss} = \mu^* + (a - b) \ln\left(\frac{V}{V^*}\right)$$



Quick summary

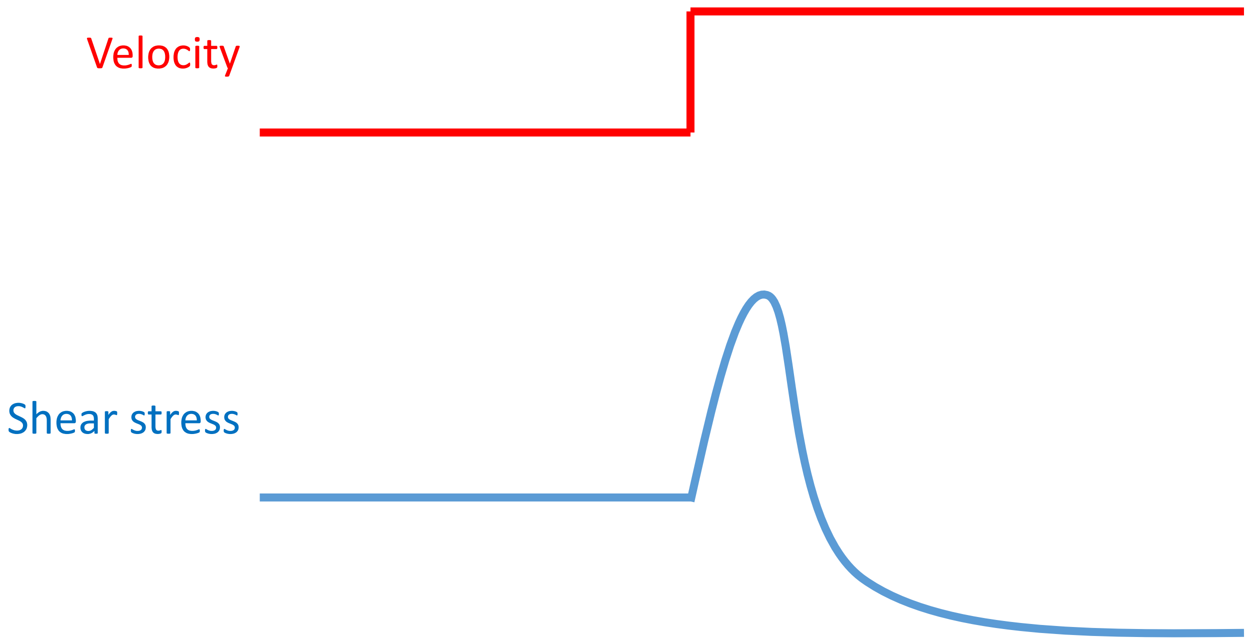
- Modelling and analysis relies on rate-and-state friction
- RSF is empirical formulation => problem for extrapolation
- We need models based on physical principles

Coming up…

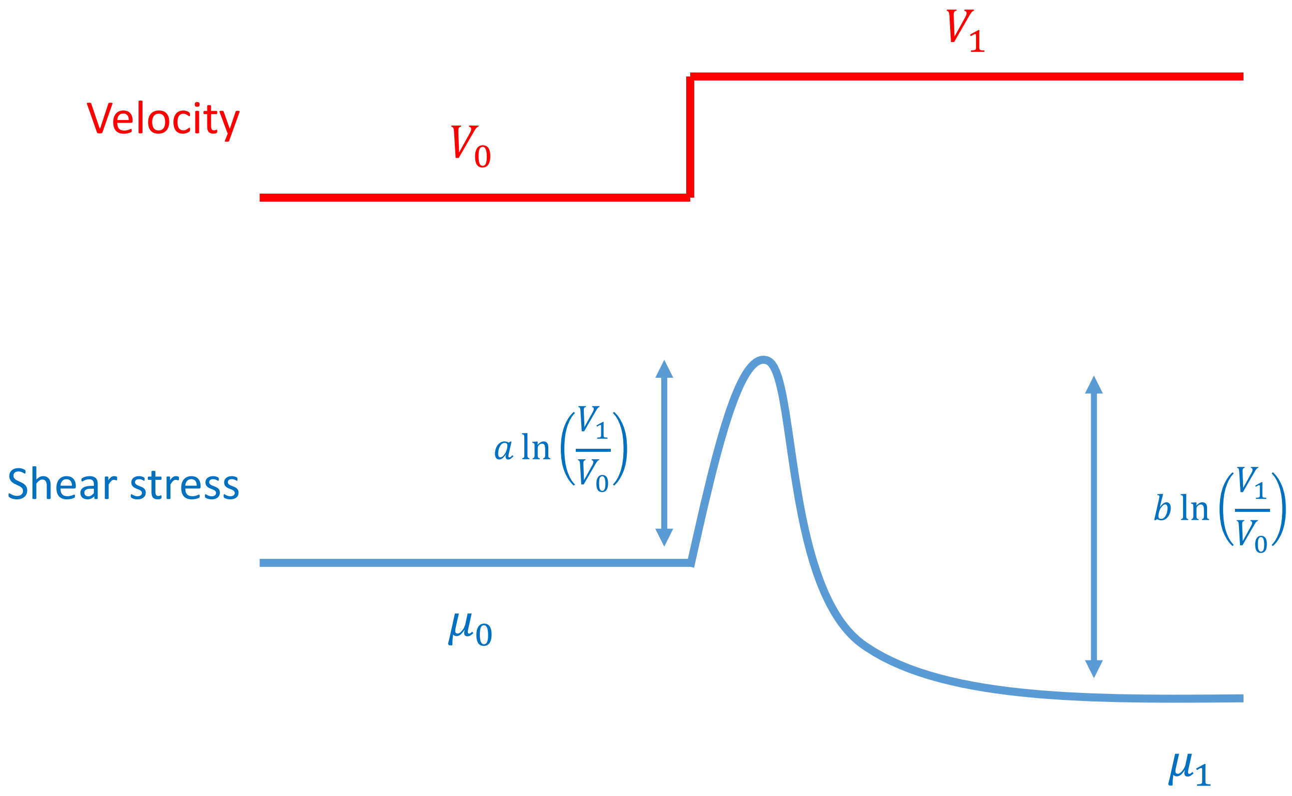
1. Lab observations of fault friction, micro-scale processes
2. Basic concepts behind microphysical models
3. Applications in seismic cycle modelling

Part 1:
Lab observations

Velocity-step tests



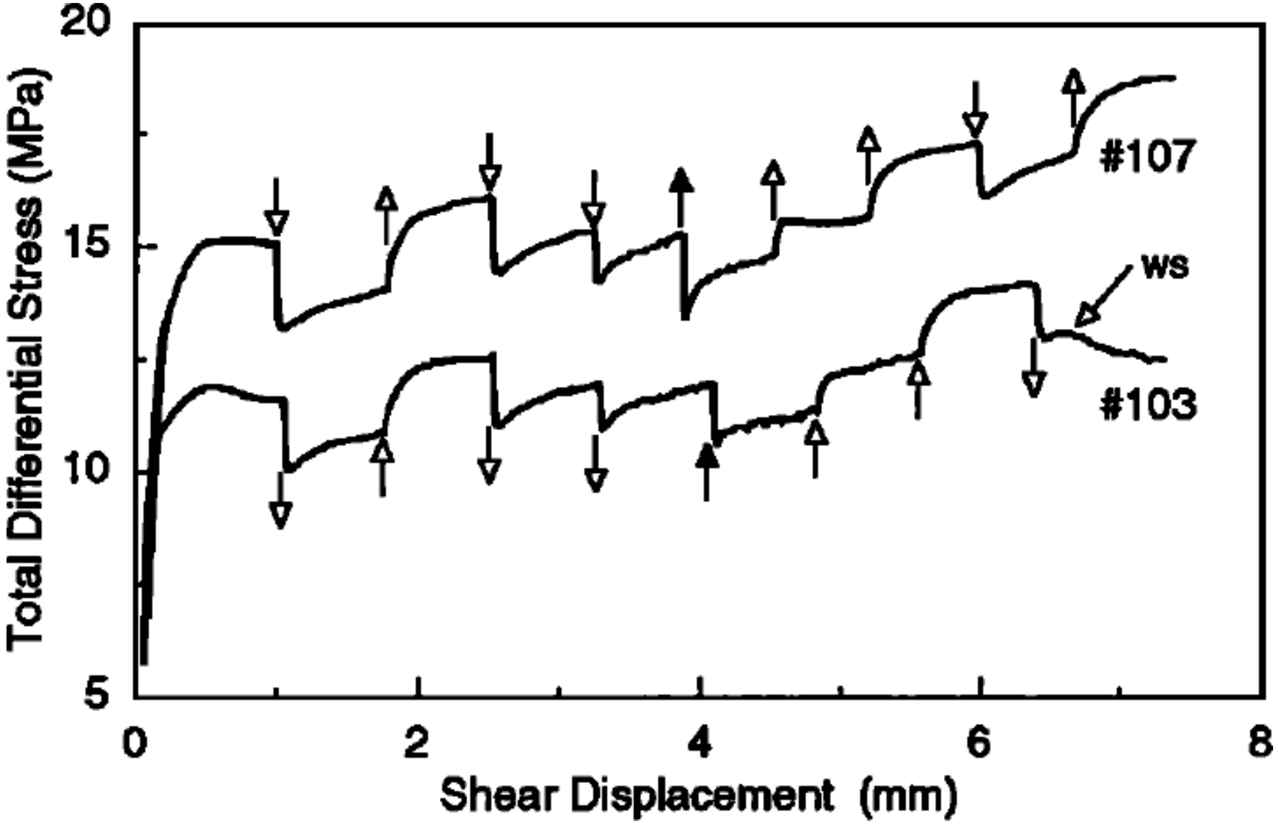
Velocity-step tests



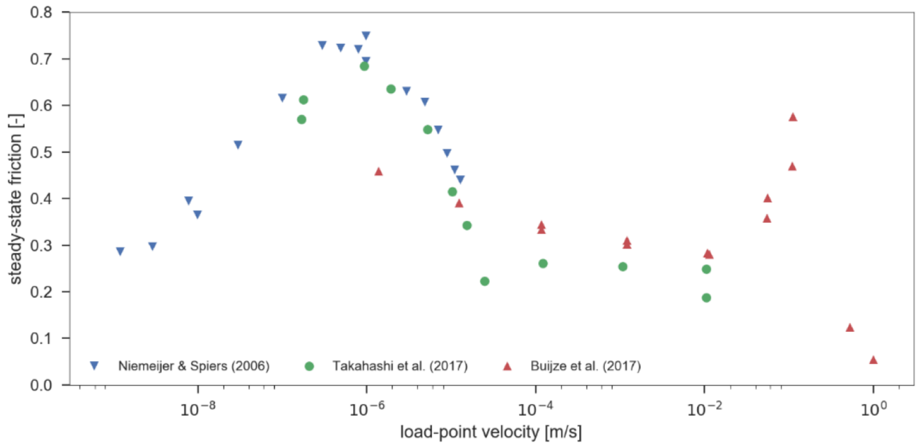
$$\Delta\mu = (a - b)\ln\left(\frac{V_1}{V_0}\right)$$

Velocity-step tests

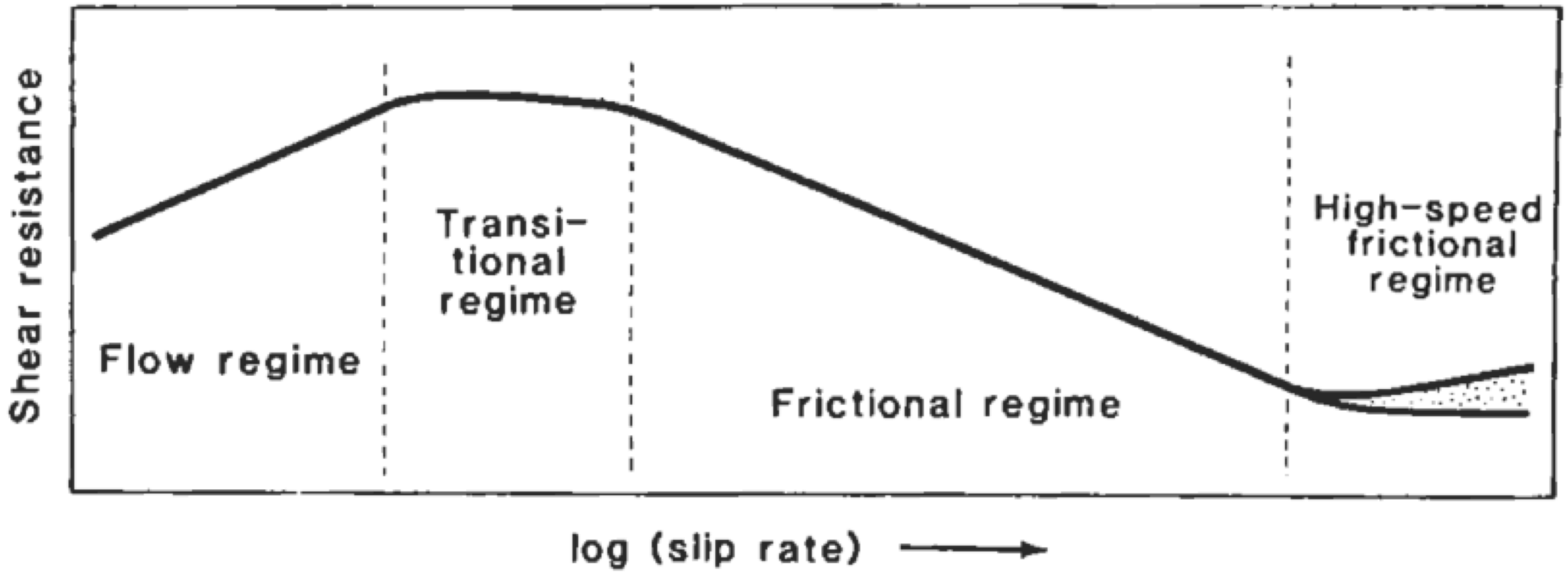
Chester (1994)



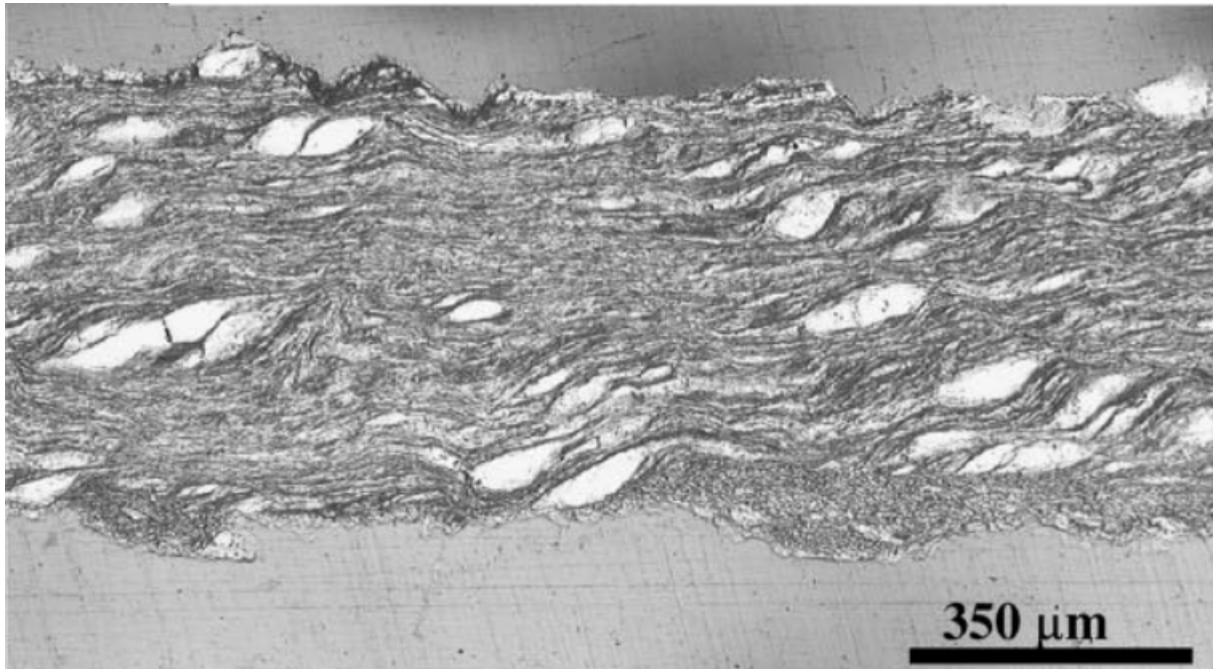
Microstructures



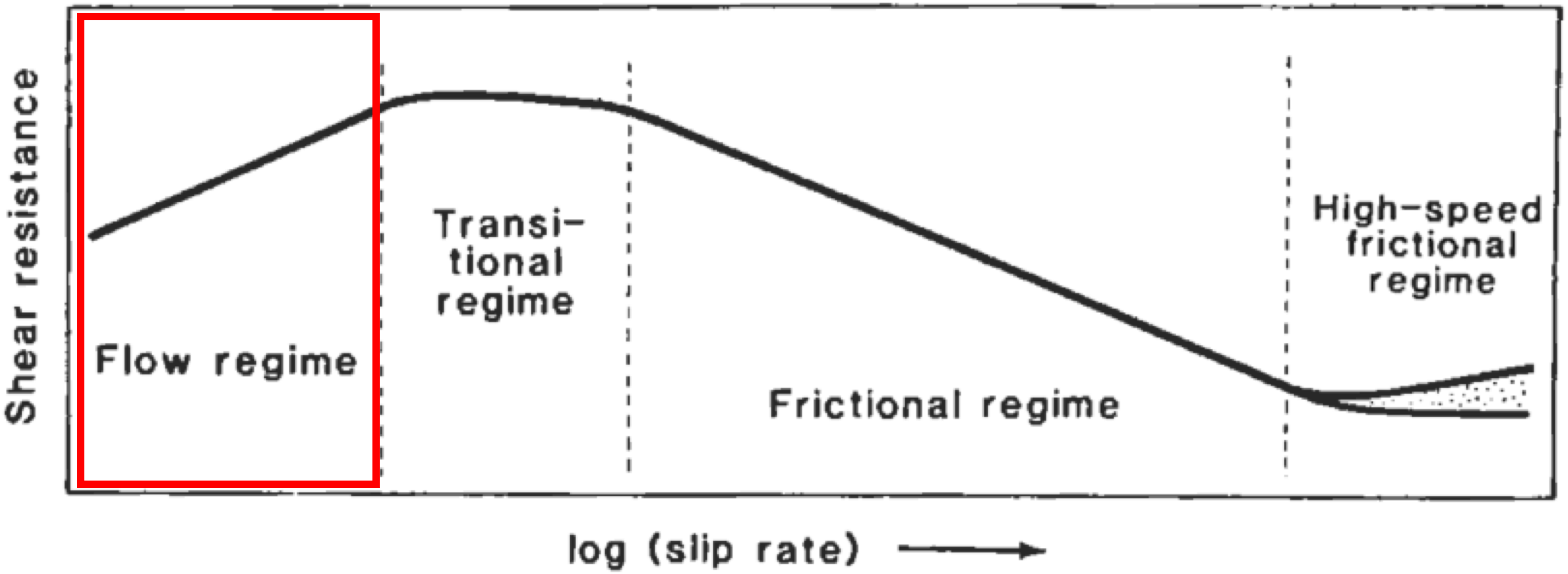
Shimamoto (1986)

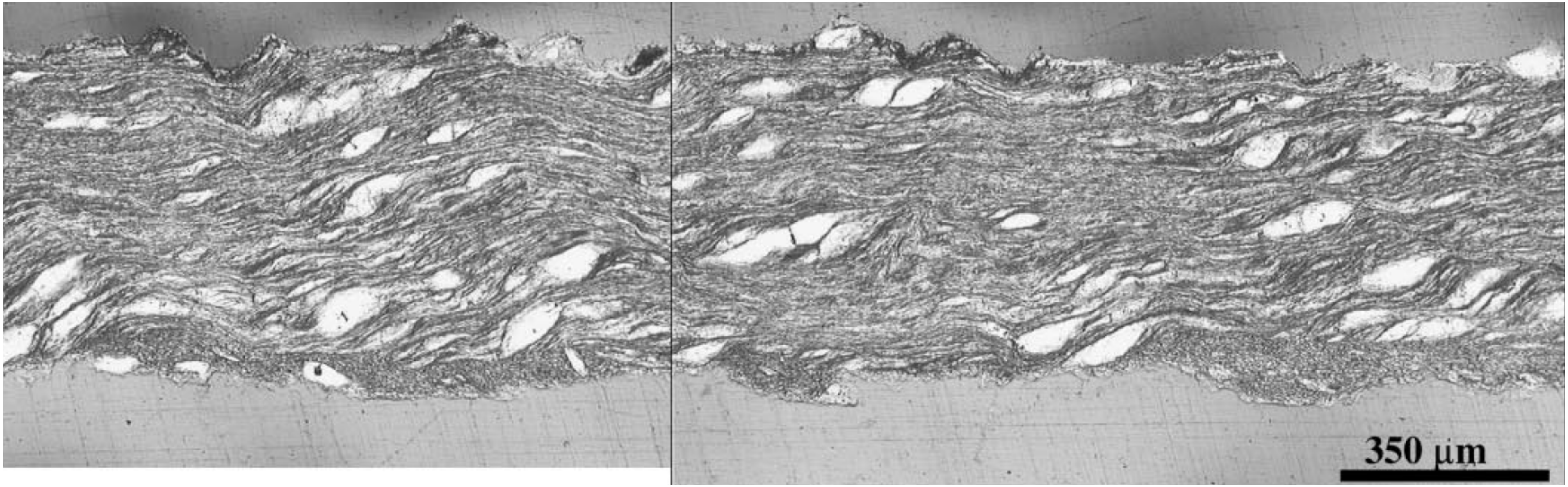


Microstructures

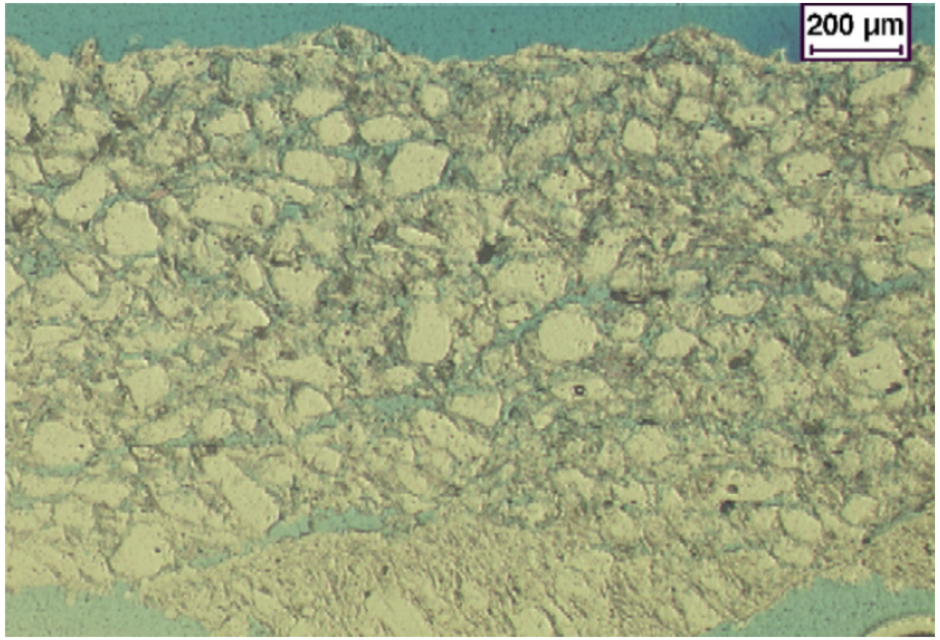


Bos *et al.* (2000)

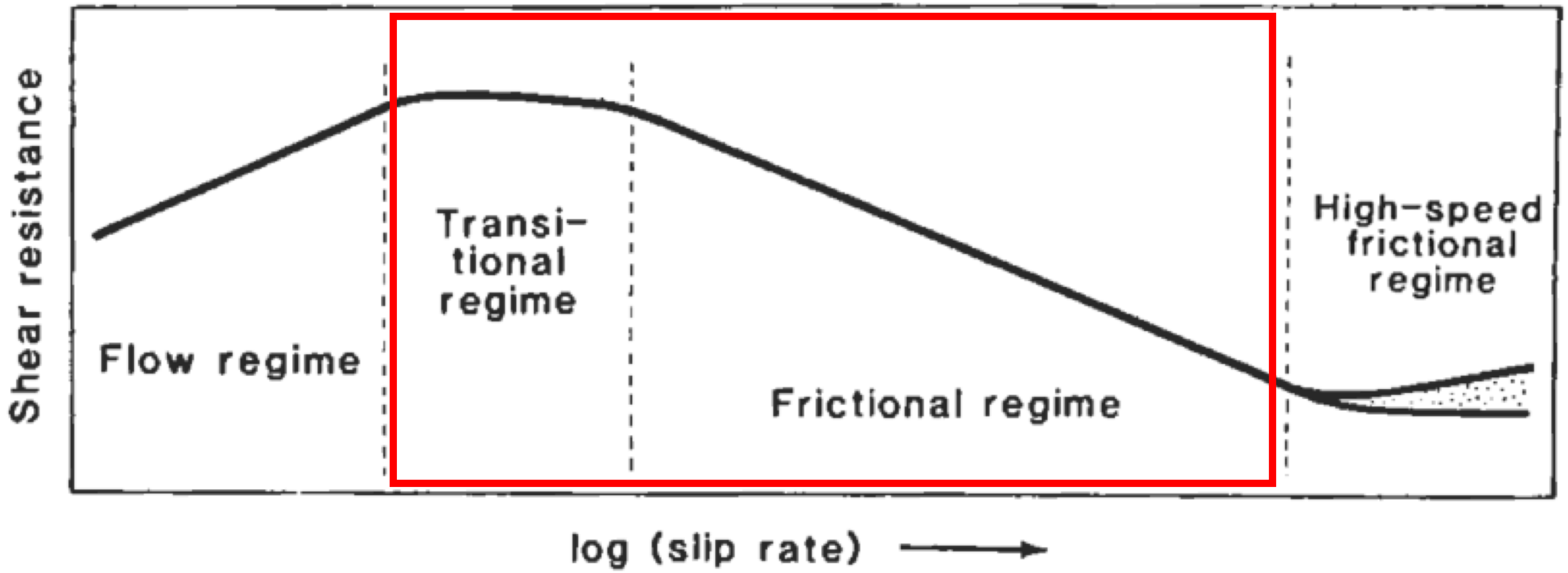


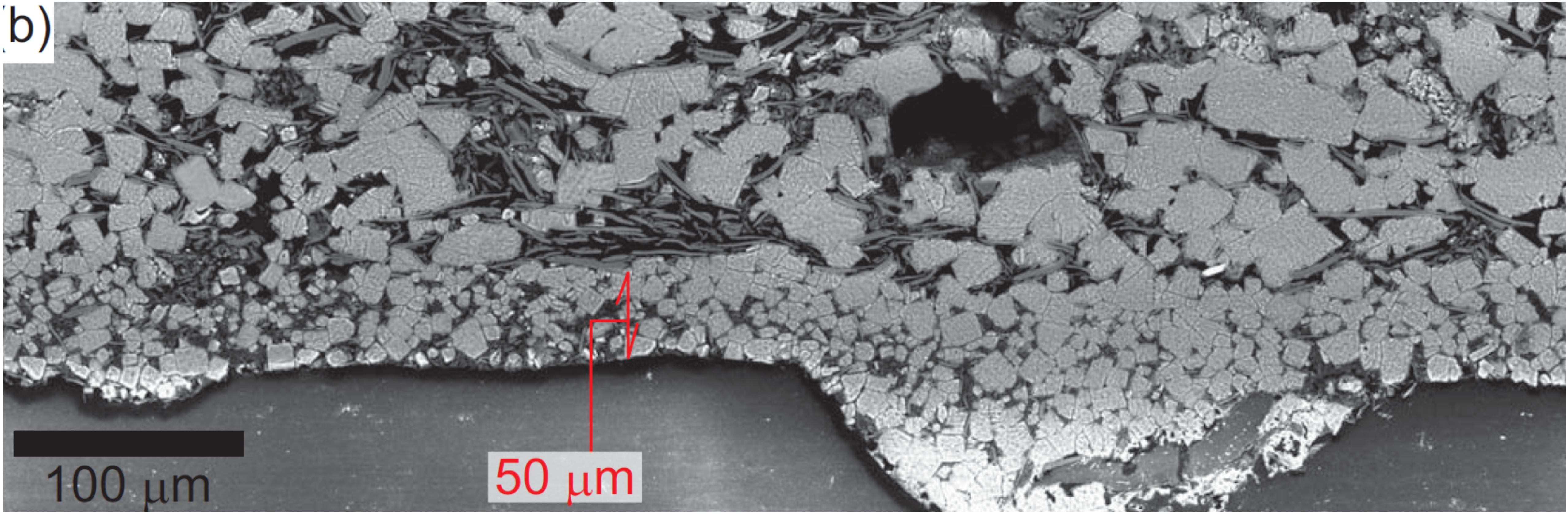

350 µm

Microstructures

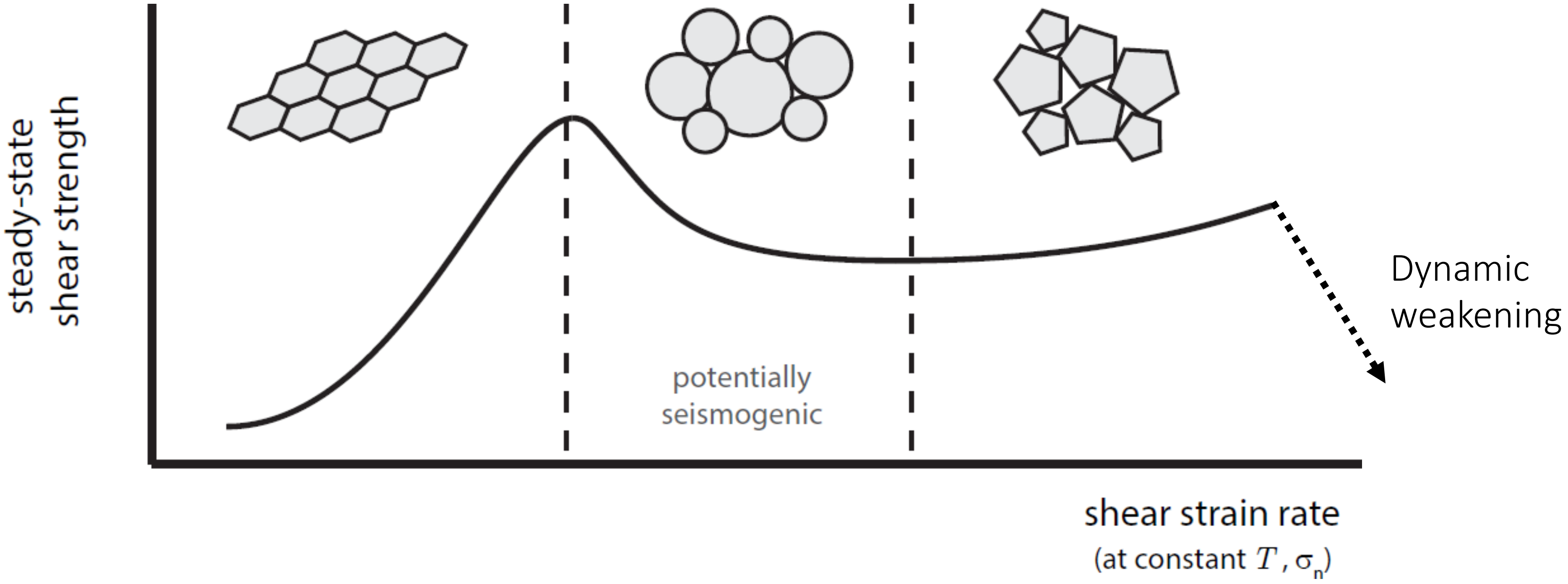


Niemeijer & Spiers (2007)



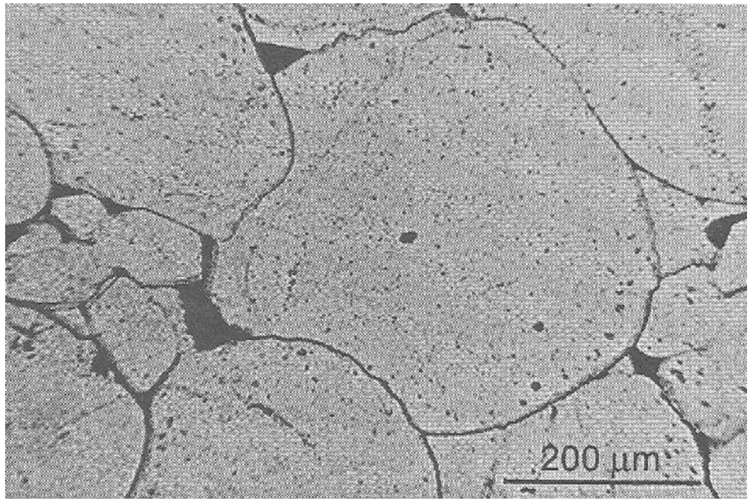

b)
100 µm
50 µm

Microstructures

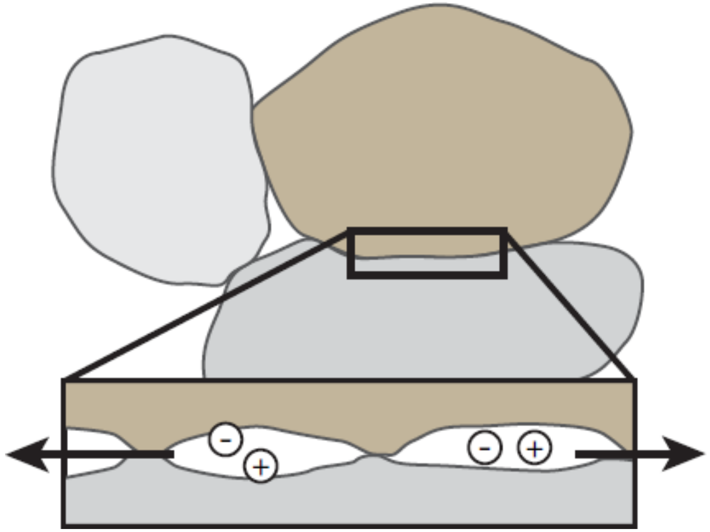


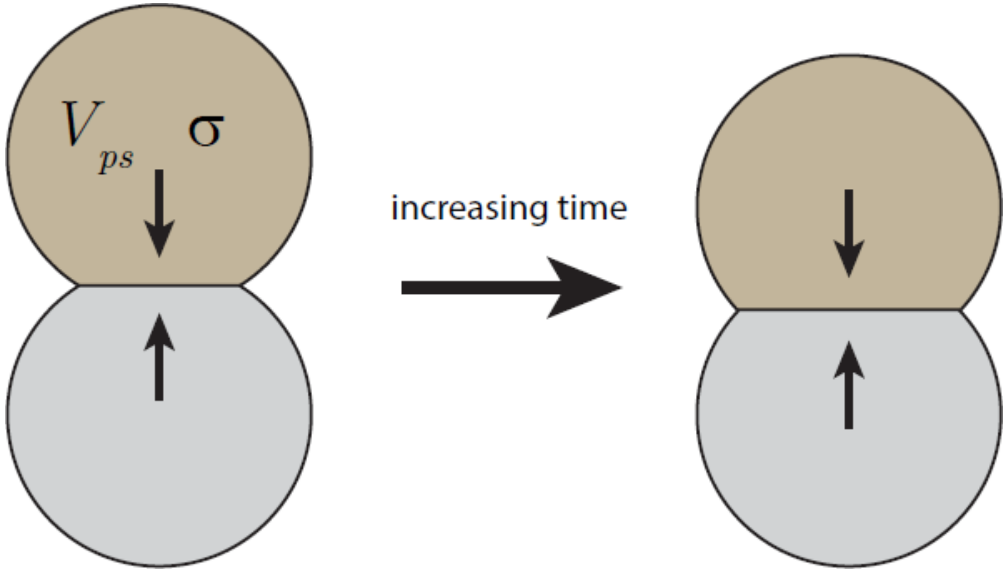
Micro-scale processes

Pressure solution



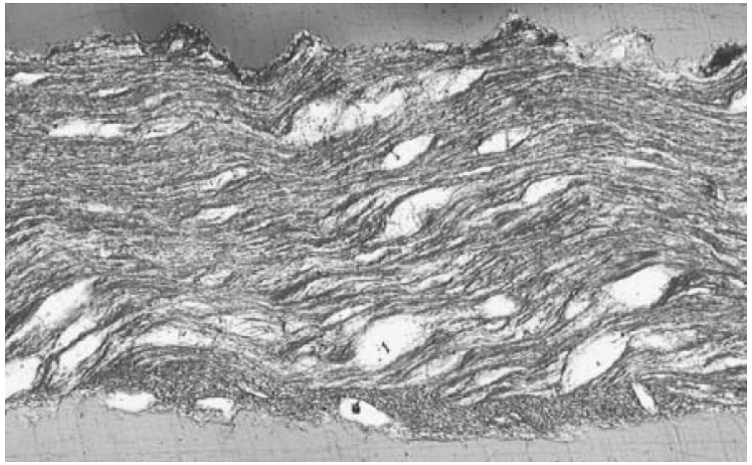
Barker & Kopp (1991)



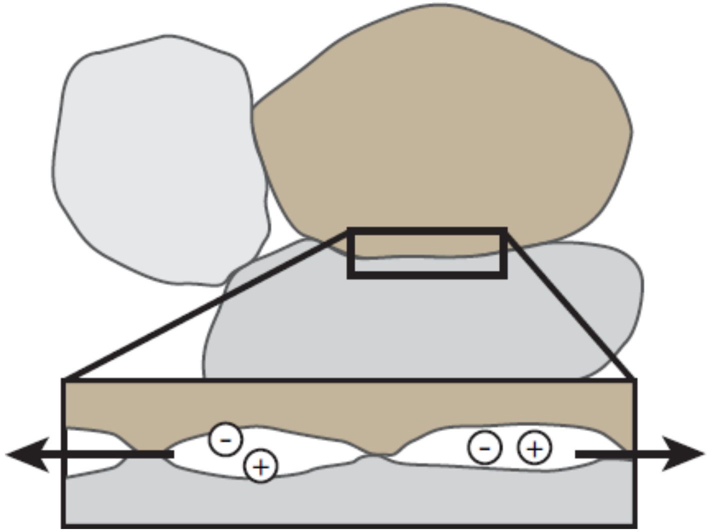


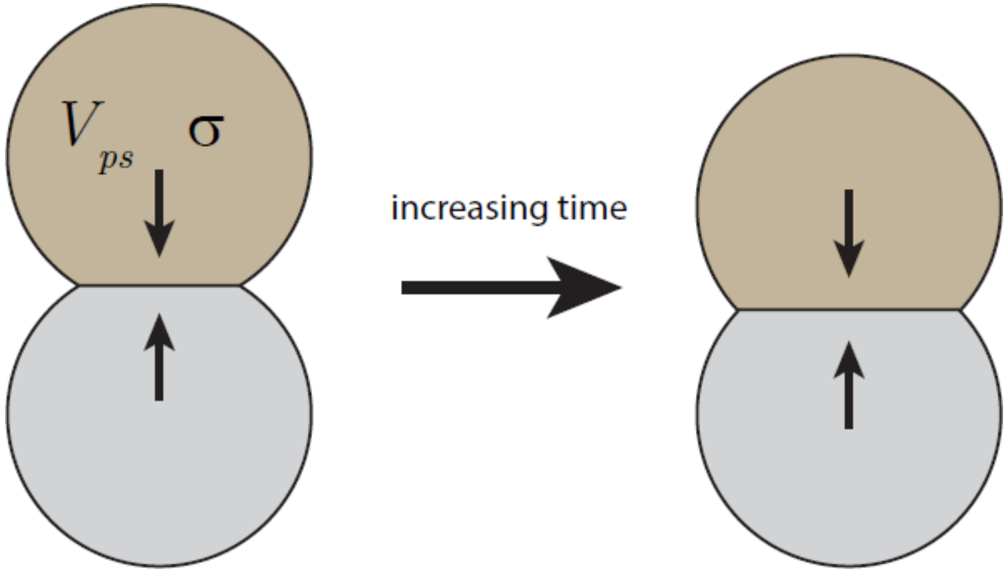
Micro-scale processes

Pressure solution

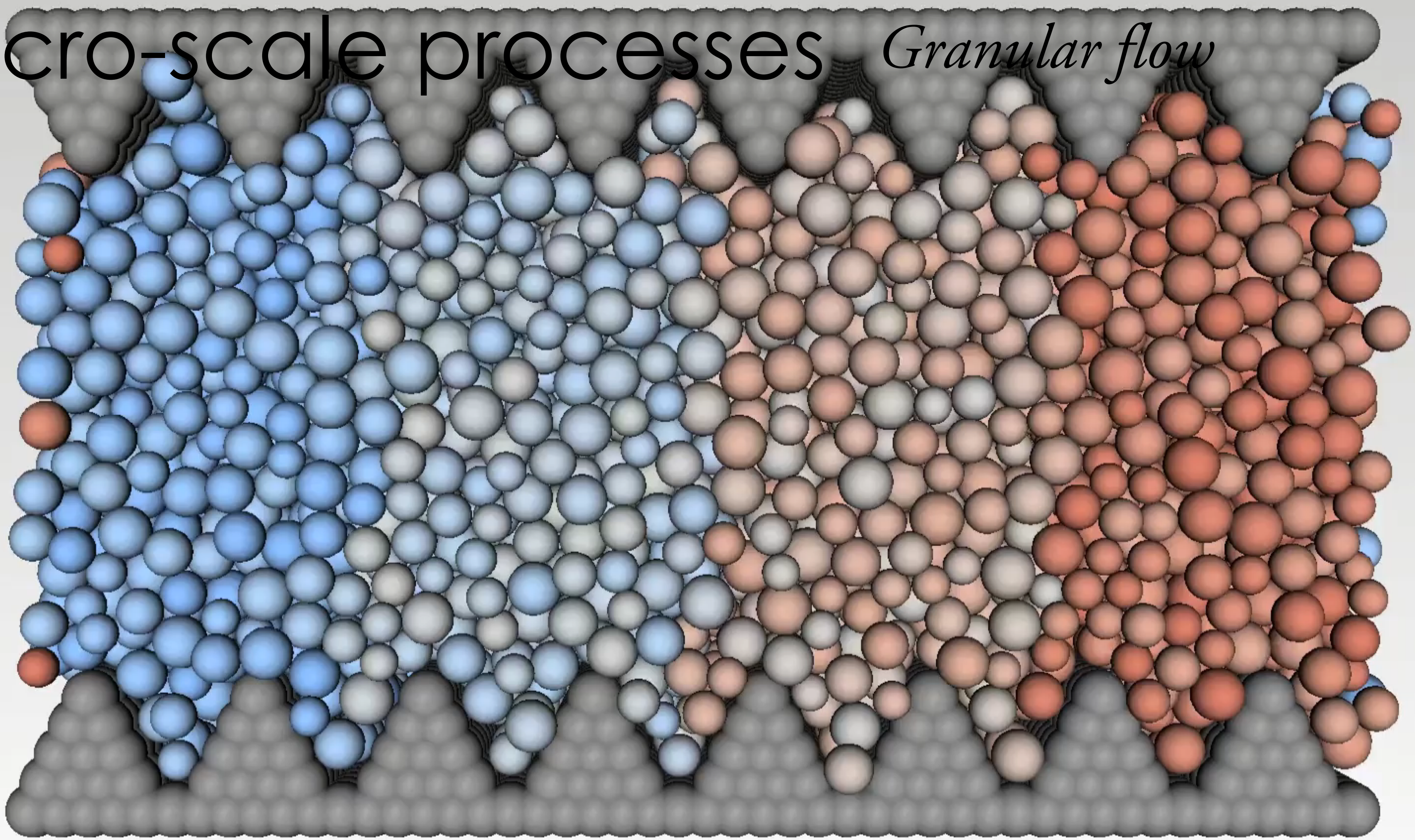


Bos *et al.* (2000)





Micro-scale processes *Granular flow*



Recap Part 1

- Velocity dependence of friction is not a constant
- Several deformation regimes
- Microstructural changes between deformation regimes
- At least 2 micro-scale processes

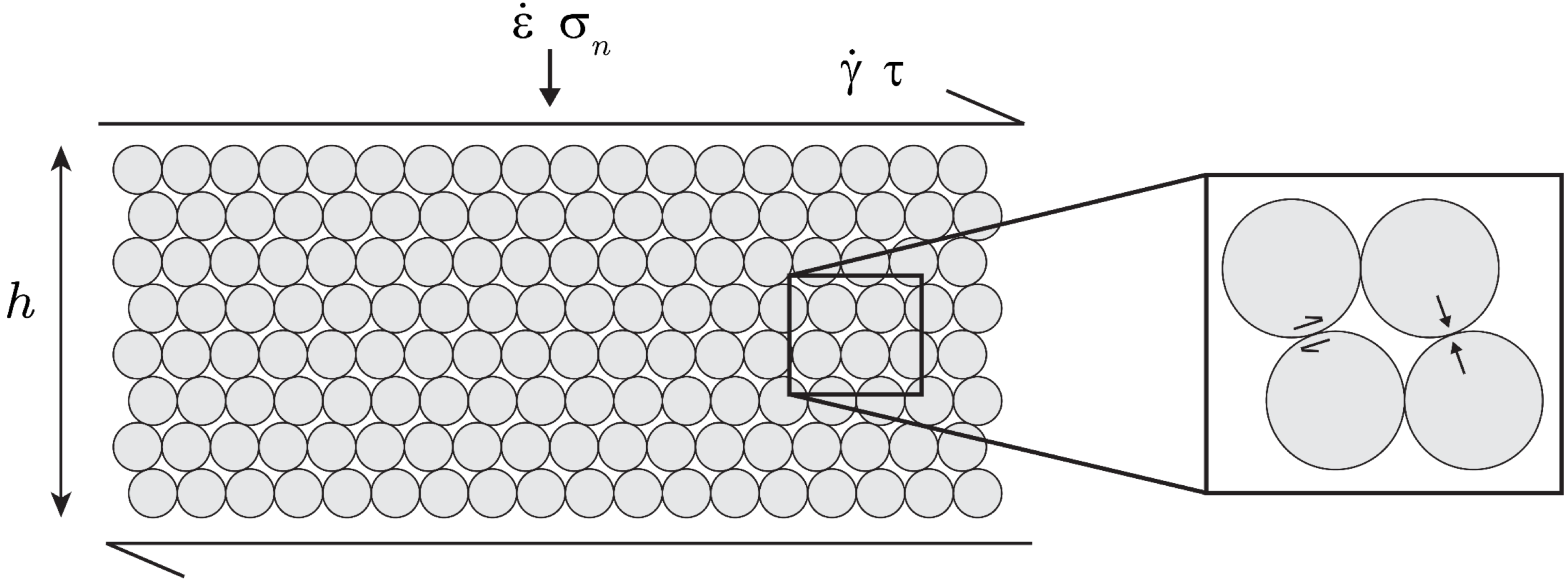
Part 2:
Microphysical models

Basic ingredients

1. Pressure solution => Time-dependent compaction
2. Granular flow => Slip-dependent dilatation
3. Microstructure => Porosity
4. Boundary conditions => Constant σ_n, V_{lp}

Model geometry (CNS model)

Niemeijer & Spiers (2007)
Chen & Spiers (2016)



Model equations

Main ODE

$$\frac{d\tau}{dt} = k\left(V_{lp} - h\left[\dot{\gamma}_{ps} + \dot{\gamma}_{gr}\right]\right)$$

$$\frac{d\varphi}{dt} = -(1-\varphi)\left(\dot{\varepsilon}_{ps} + \dot{\varepsilon}_{gr}\right)$$

Pressure solution:

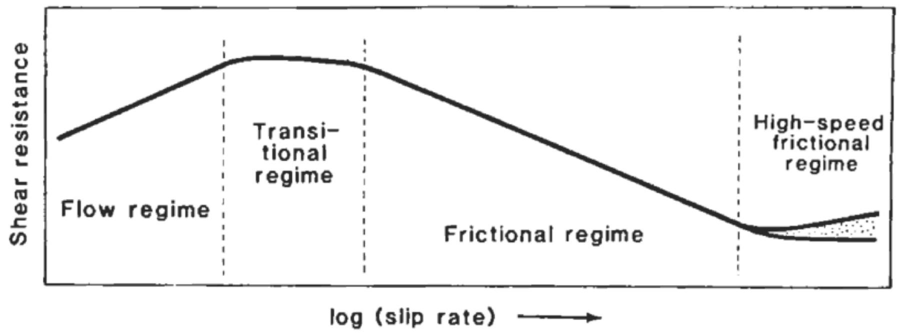
$$\dot{\gamma}_{ps} = Z\tau f(\varphi) \qquad \dot{\varepsilon}_{ps} = Z\sigma f(\varphi)$$

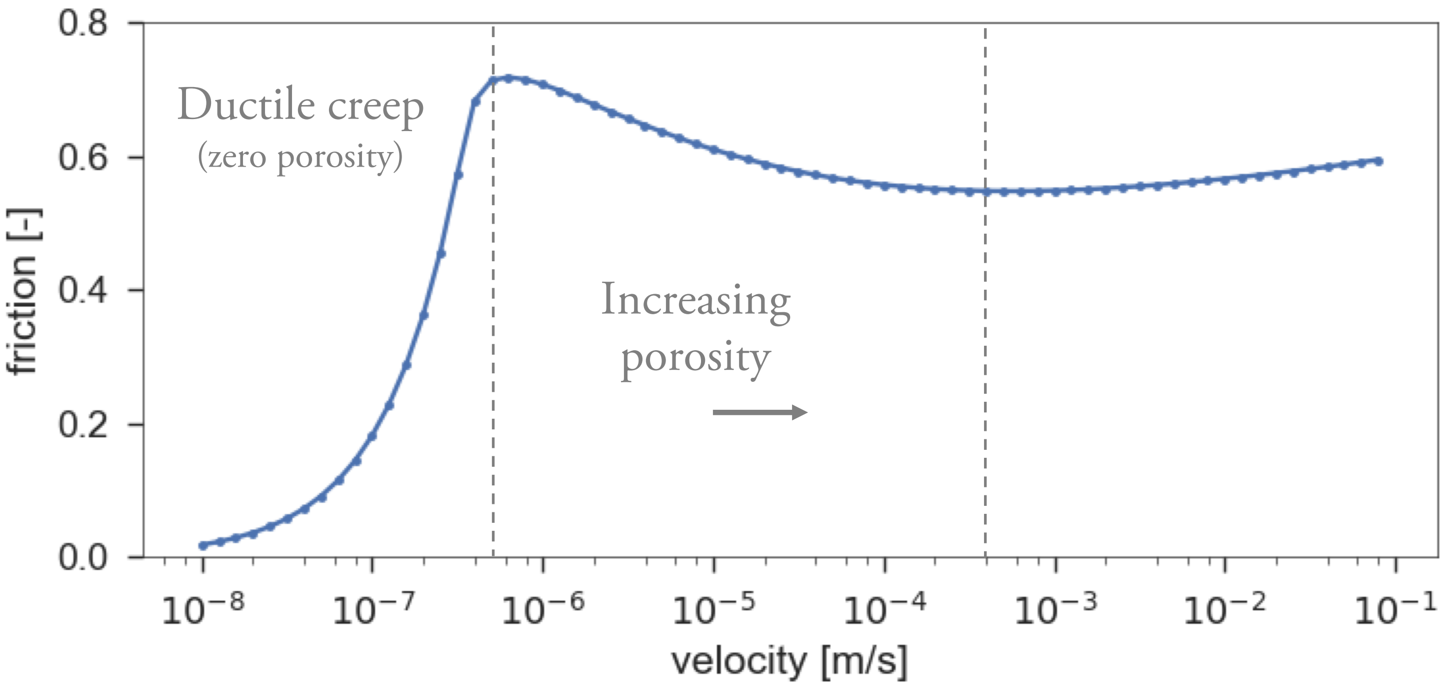
Granular flow:

$$\dot{\gamma}_{gr} = \dot{\gamma}_{gr}^{*} \exp\left(\frac{\tau[1-\mu^{*}\tan\psi] - \sigma[\mu^{*} + \tan\psi]}{\tilde{a}[\sigma + \tau\tan\psi]}\right)$$

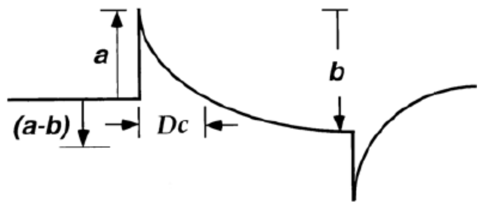
$$\dot{\varepsilon}_{gr} = -\tan\psi\,\dot{\gamma}_{gr}$$

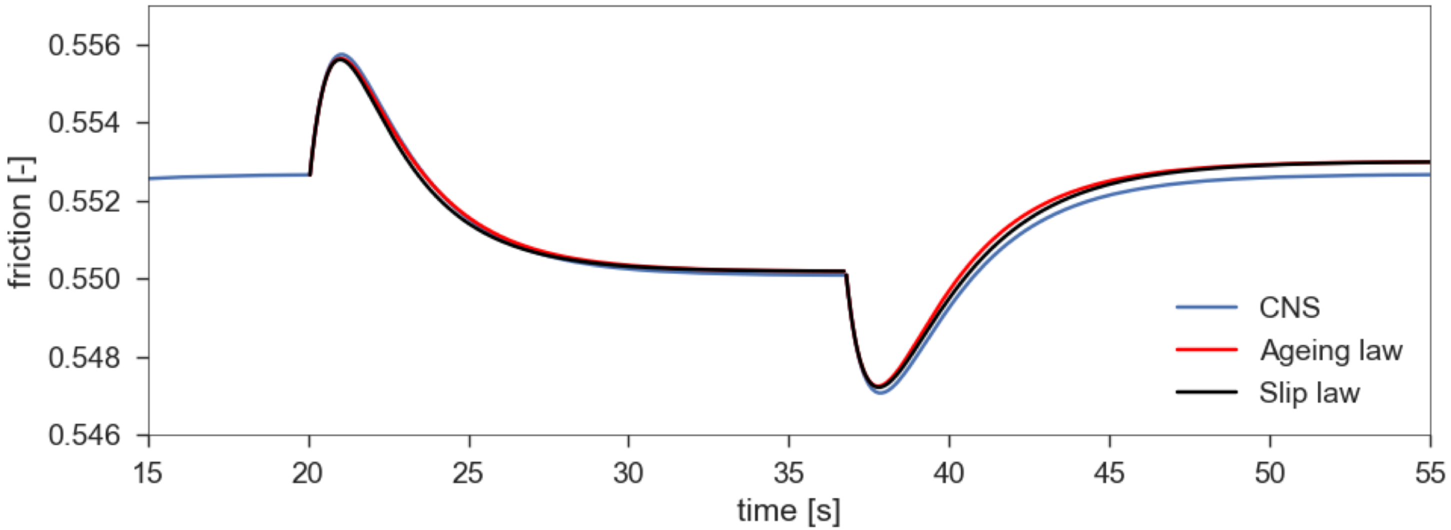
Steady-state behaviour





Transient behaviour





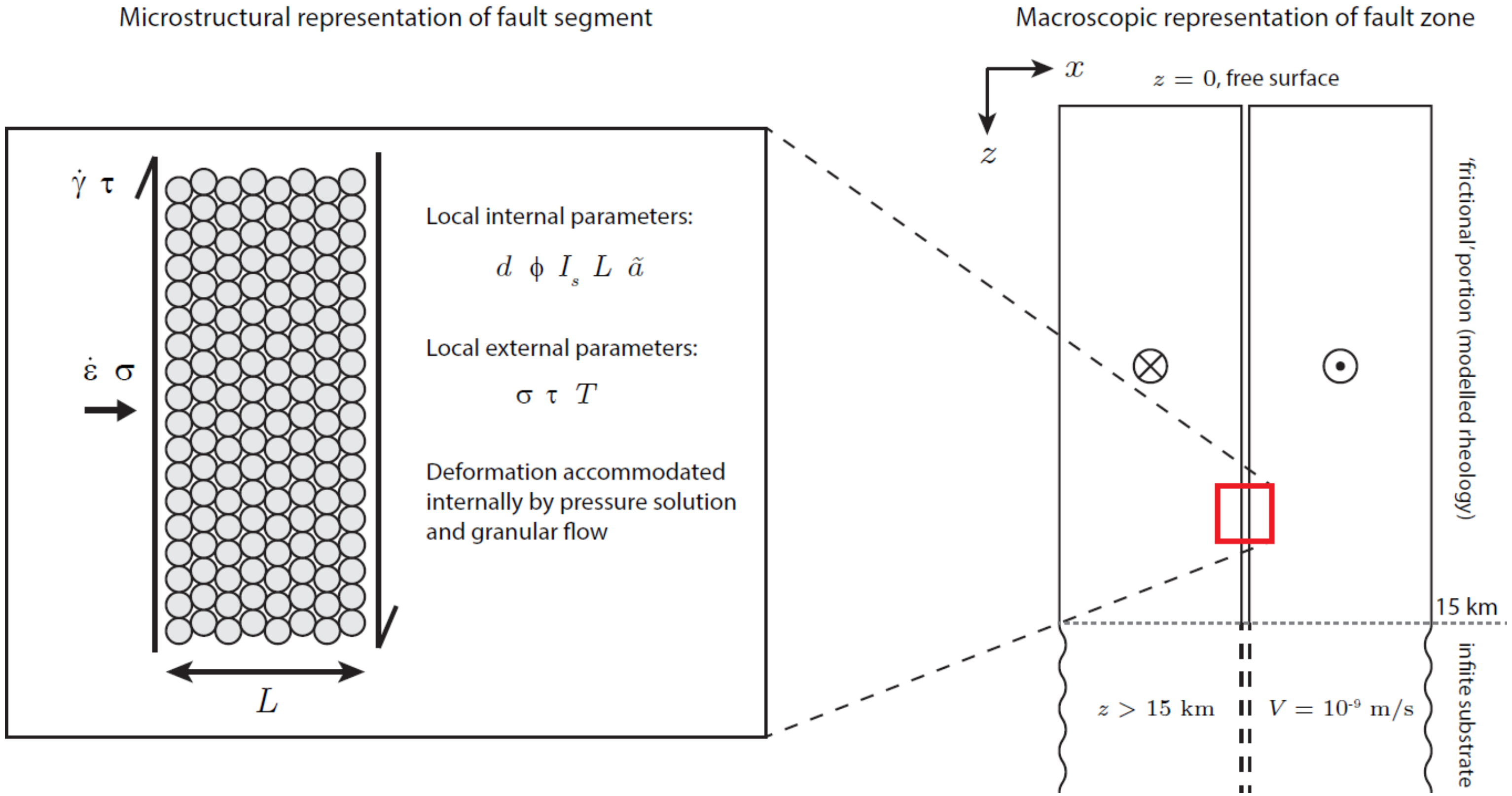
Recap Part 2

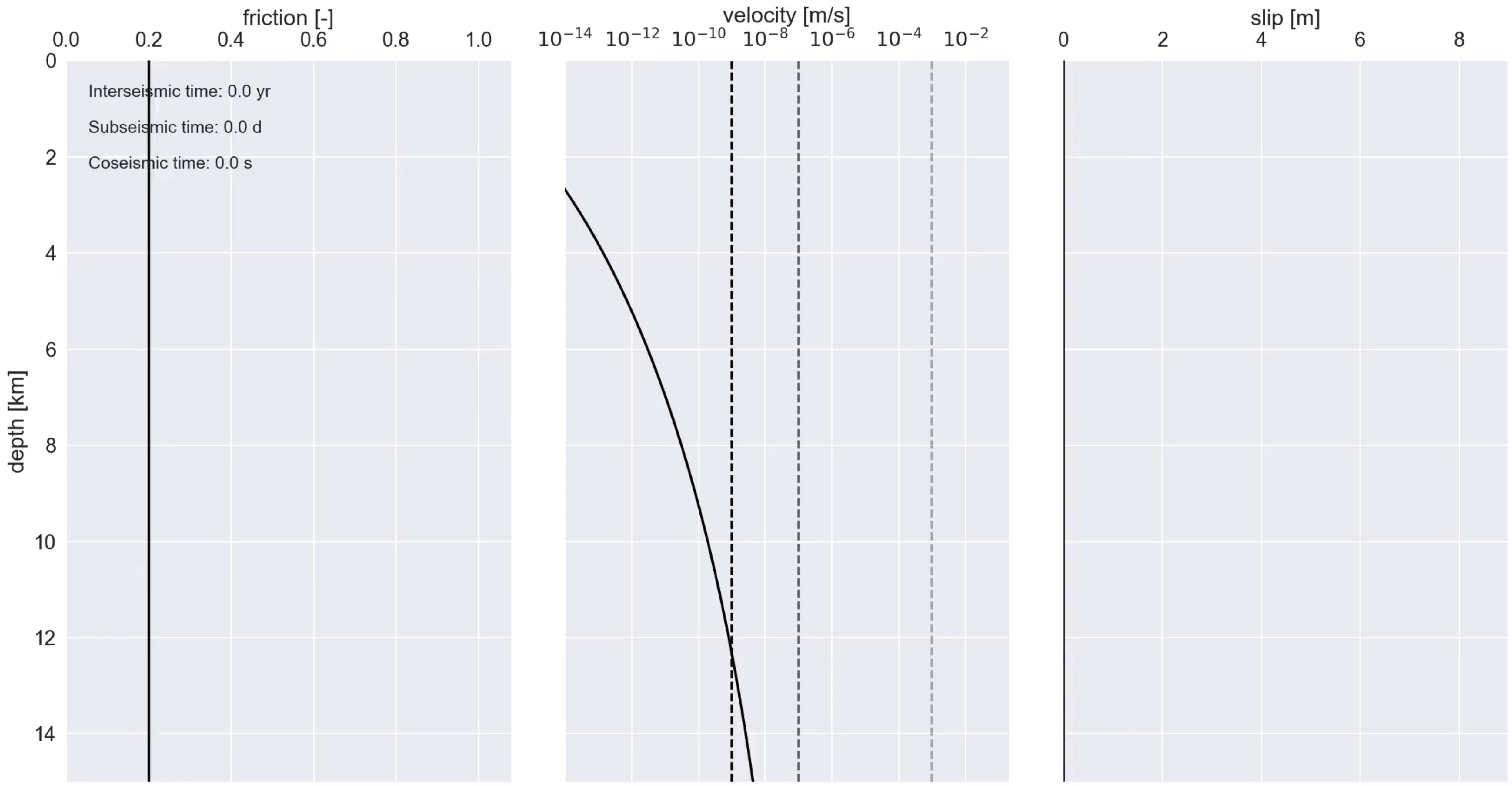
- Quantified micro-scale processes
- Incorporated constitutive relations into spring-block model
- Steady-state and transient frictional behaviour = OK
- Microphysical model explains lab results

Part 3:
Seismic cycle modelling

Skipping 6 orders

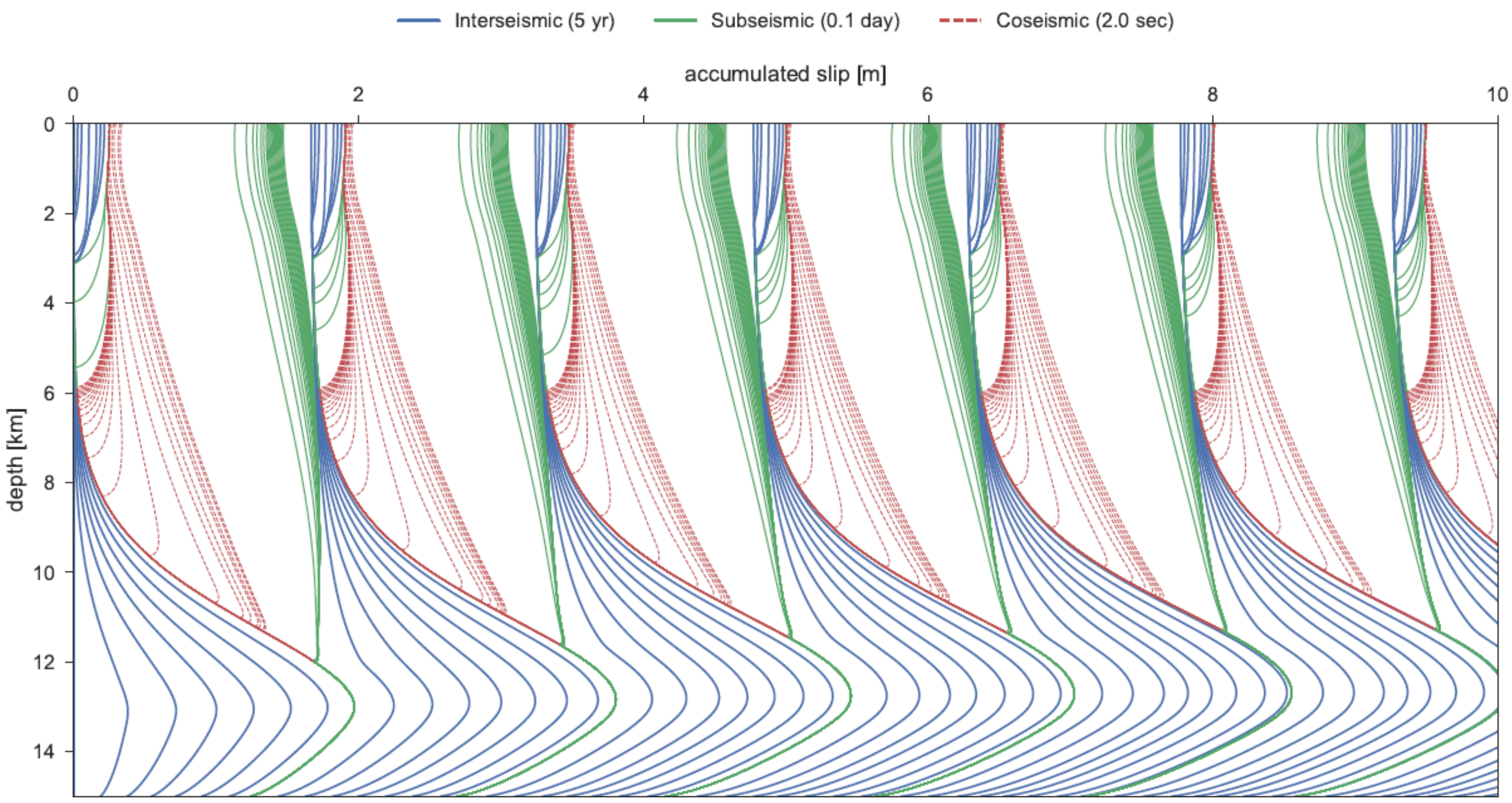
github.com/ydluo/qdyn





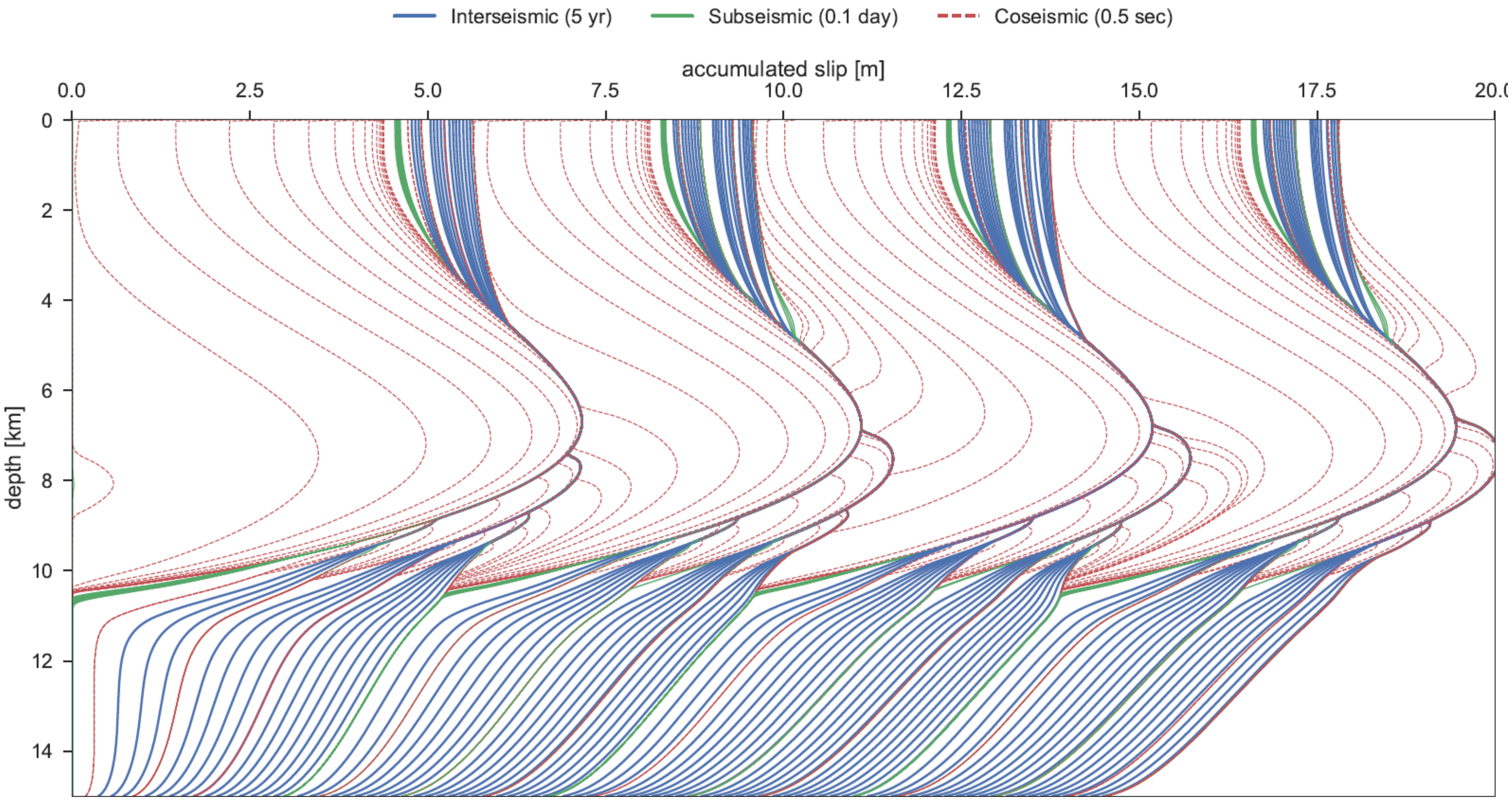
friction [-]
0.0
0.2
0.4
0.6
0.8
1.0
velocity [m/s]
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
slip [m]
0
2
4
6
8
depth [km]
0
2
4
6
8
10
12
14
Interseismic time: 0.0 yr
Subseismic time: 0.0 d
Coseismic time: 0.0 s

Earthquakes!

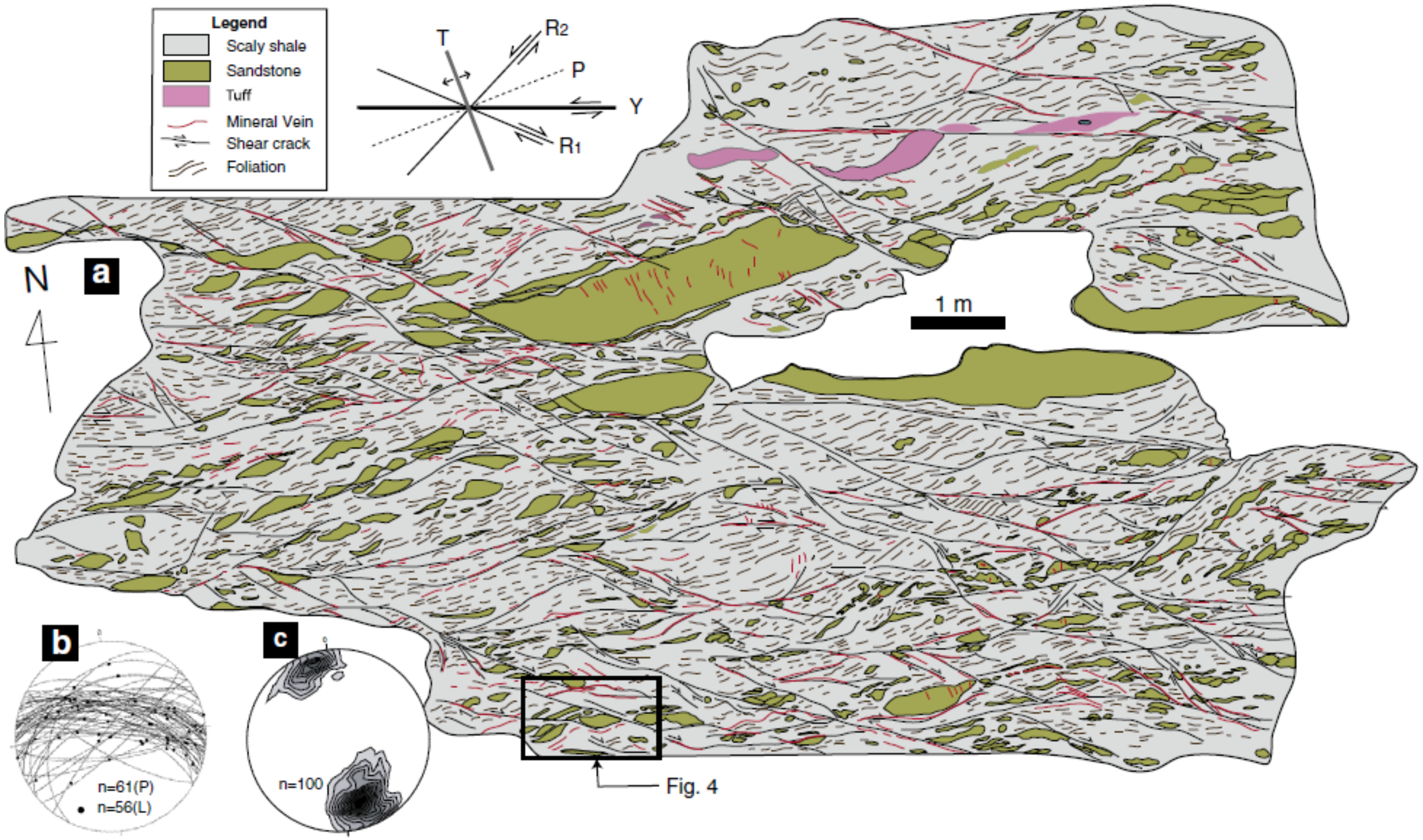


Earthquakes!

See: Van den Ende, Chen, Ampuero, Niemeijer (2018, Tectonophysics)



Into the field

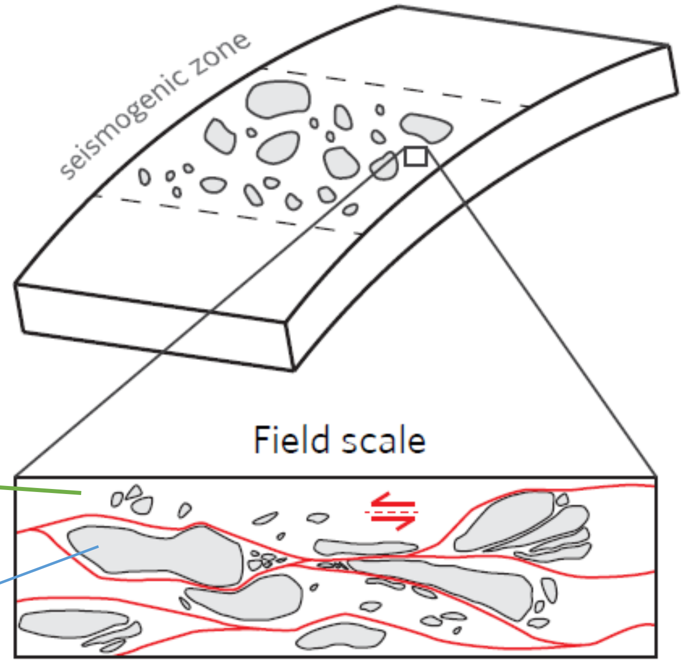


Faulkner *et al.* (2003)
Fagereng (2011a,b)
Kimura *et al.* (2012)
and others…

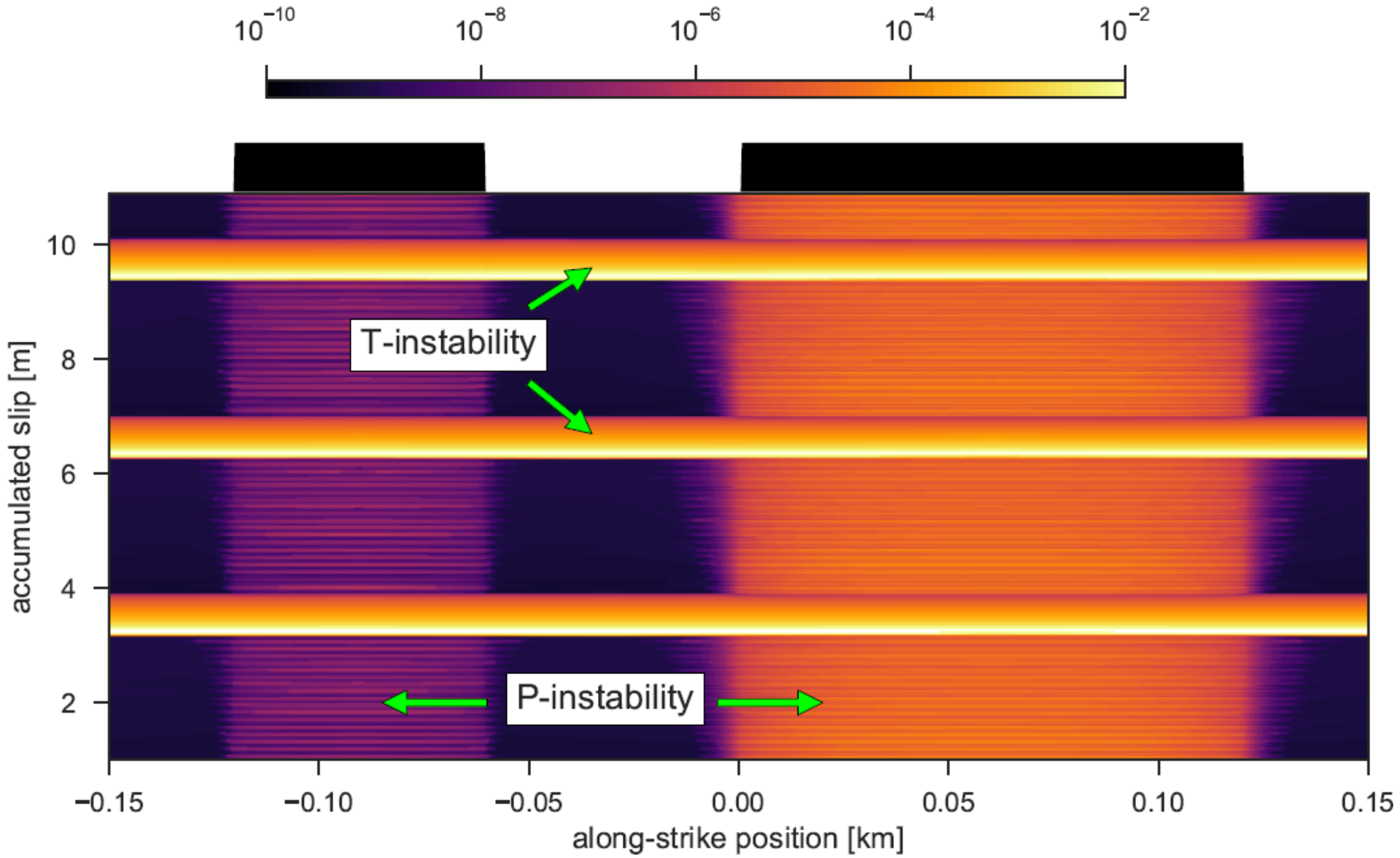
Back to safety…

Matrix: "fast" pressure solution

Asperities: "slow" pressure solution

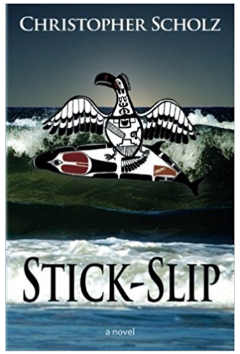


Earthquakes!



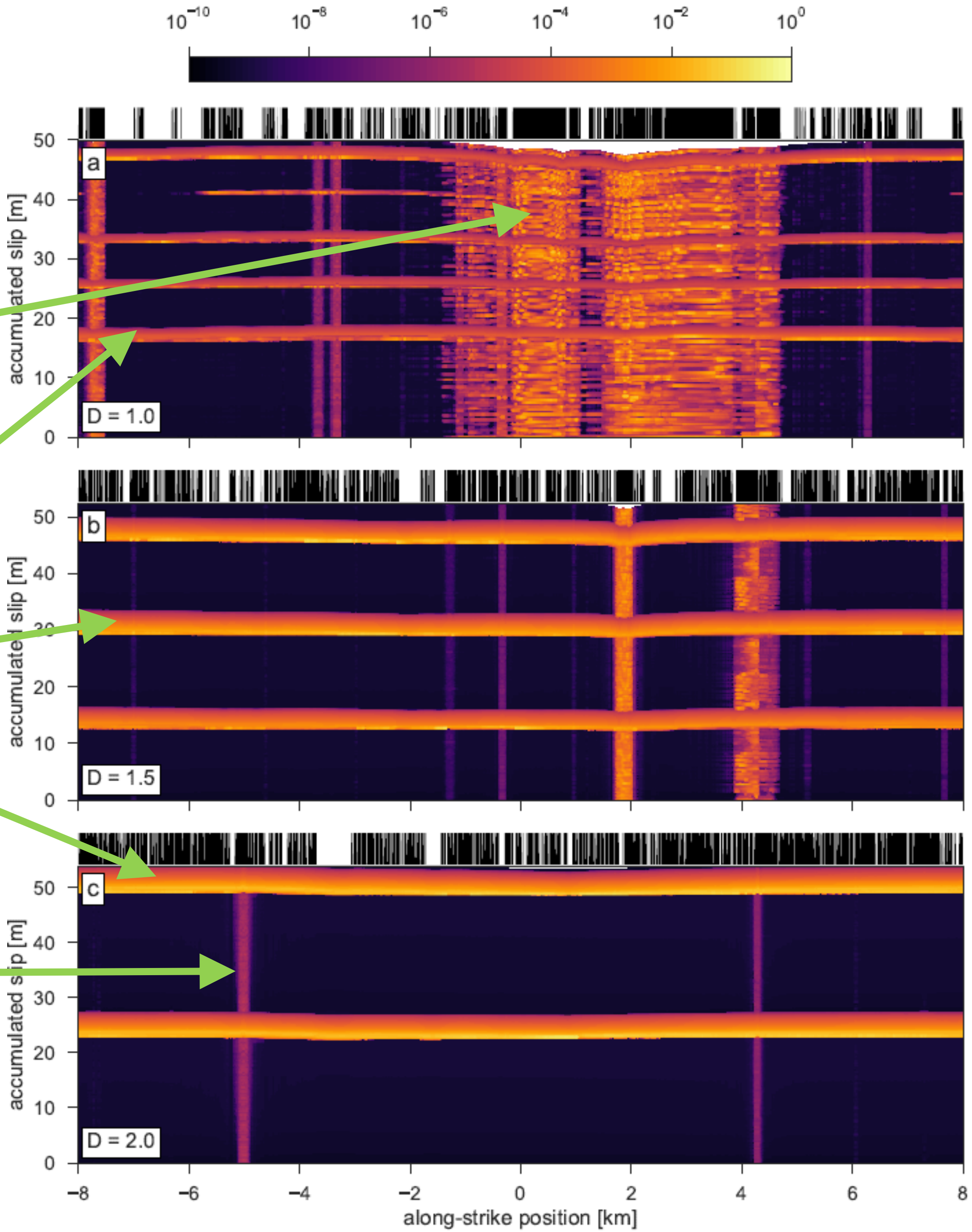
Earthquakes!

"Regular" earthquakes ($M_w < 6$)

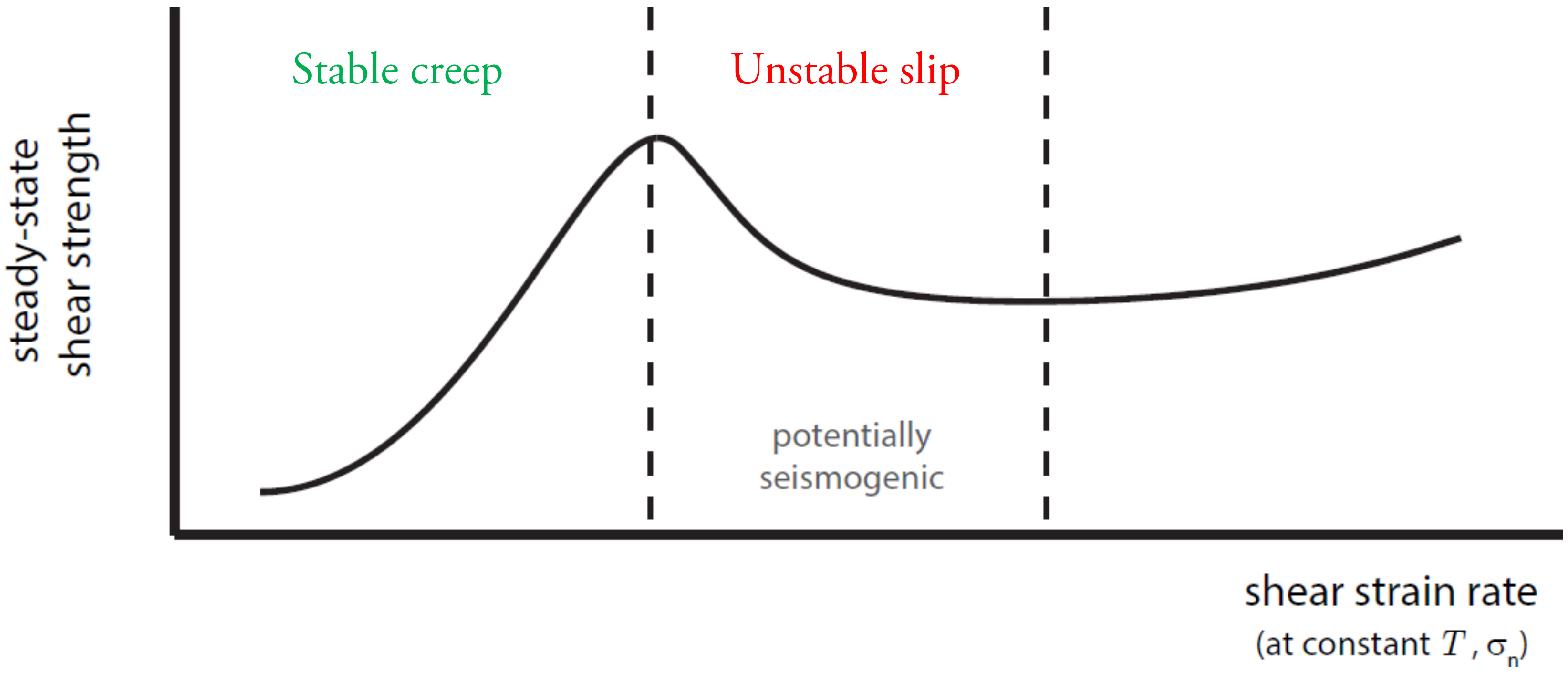


"Anomalous" earthquakes

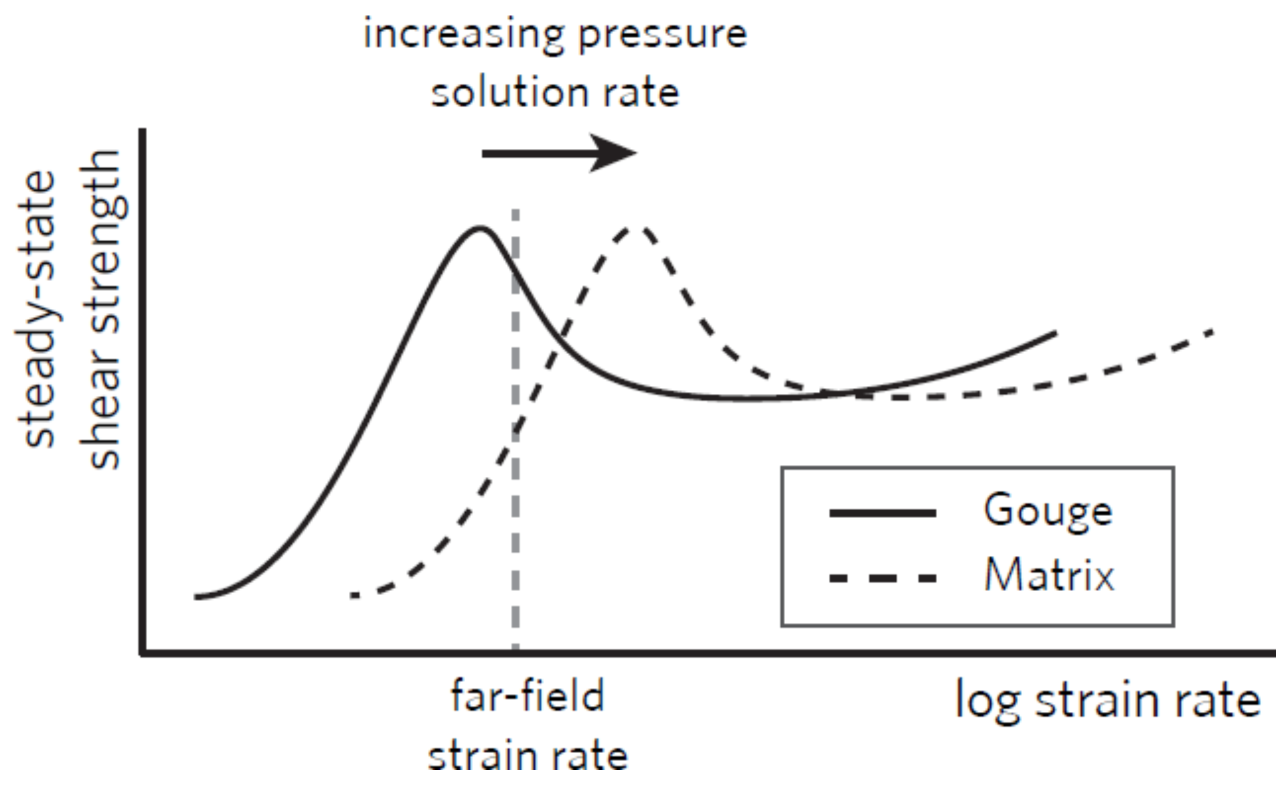
Slow slip events



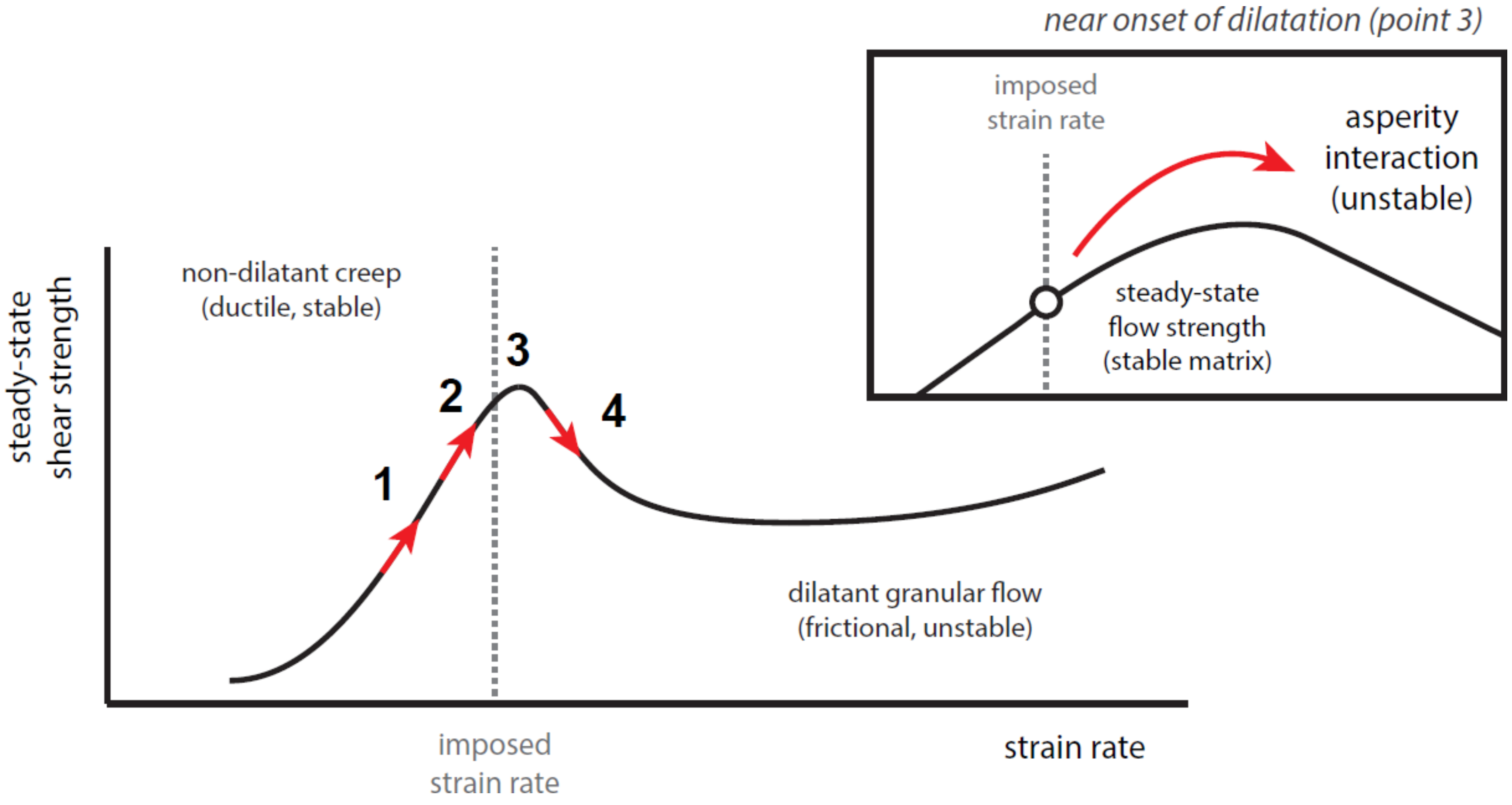
Why anomalous earthquakes?



Why anomalous earthquakes?



Why anomalous earthquakes?



Recap Part 3

- Interplay between pressure solution and granular flow gives earthquakes
- Variations in pressure solution kinetics leads to complex slip behaviour
- Massive instability facilitated by flow-to-friction transition

Perspectives

1. Microphysically-based (numerical) modelling offers new avenues for studying earthquake and slow slip mechanics
2. Incorporating micro-scale processes and physical principles facilitates collaboration between experimental- and field geologists, and modellers
3. Far future: earthquake hazard assessment and forecasting based on physical/chemical considerations