Models Bridging Subduction and Earthquake Dynamics Show Fault Strength as a Strain-average Quantity

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Aim

- **What strength / friction values are appropriate across various scales?**

  - Geodynamic modelers interested in simulating subduction and plate tectonics: $\boldsymbol{\mu_{eff,static} < \sim 0.05}$

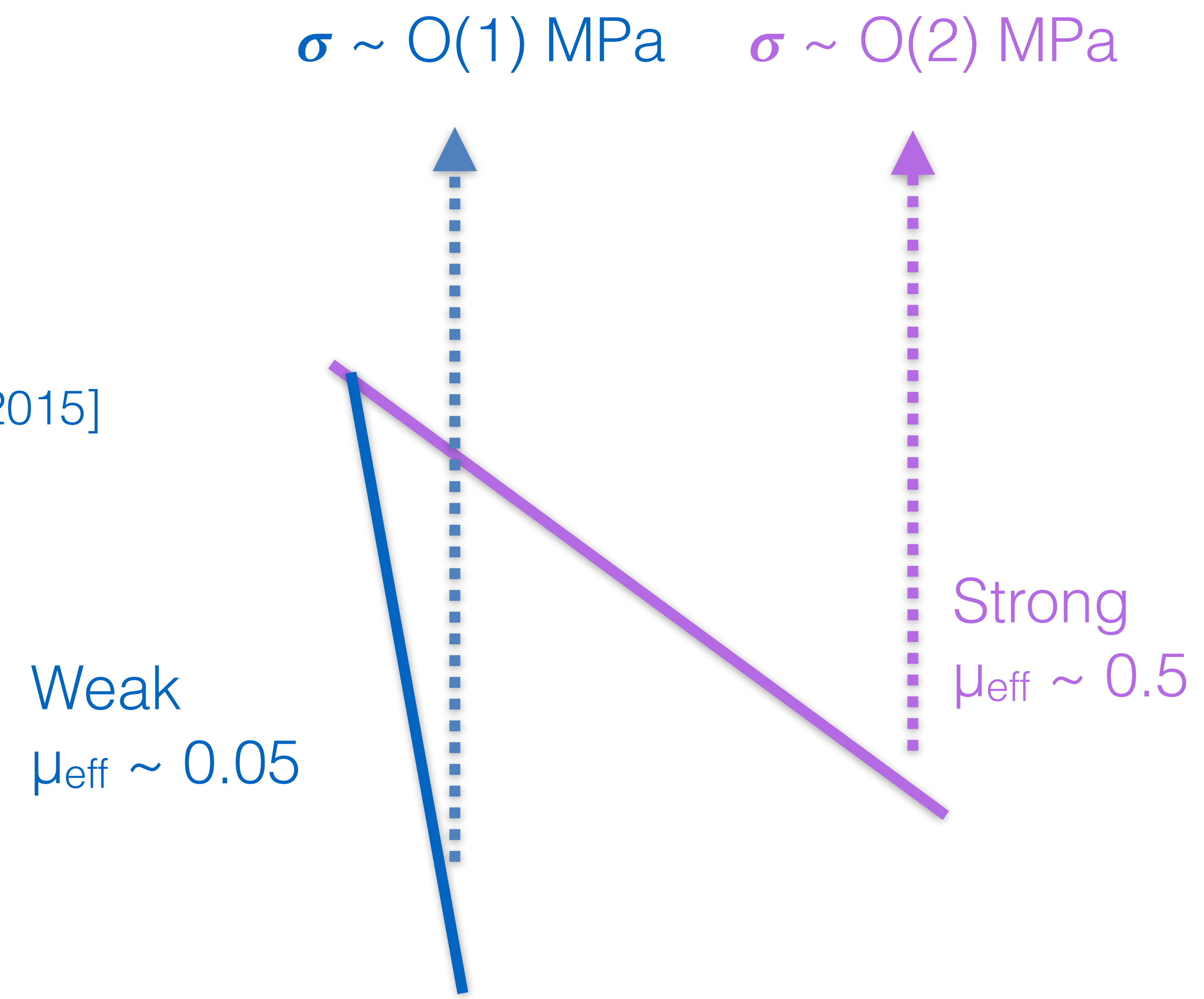
  - Earthquake modelers interested in frictional sliding typically use Byerlee's friction (μ ~ 0.6-0.85): $\boldsymbol{\mu_{eff,static} > \sim 0.5}$

$$\mu_{eff} = 1 - \frac{Pf}{P} = 1 - \lambda$$

- Are these results as far apart as they seem? I show that
  - » Recent cross-scale and earthquake models converge perspectives
  - » Analytical considerations constrained by observations and laboratory experiments suggest $\boldsymbol{\mu_{eff,char}}$ is about **0.02 - 0.3**

Long-standing debate: How weak or strong? Why?

- Absent local heat flow anomaly
  [e.g., Lachenbruch and Sass, 1992]
- Stress field rotation & z-indep. stress drop
  [e.g., Hardebeck, 2015]
- Differential stress estimates
  [e.g., Seno, 2009]
- Sustain subduction in models
  [e.g., Zhong et al., 1998; Duarte et al., 2015]
- …



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Data: Behr & Platt, EPSL, 2011

- Laboratory experiments
  (e.g., Byerlee, 1978)
- In-situ stress measurements
  (e.g., Brody et al., 1997)
- Dip orientation of earthquakes on (re-activated) faults
  (e.g., Sibson and Xie, 1998)
- Sustain mountains
- …

I. Revisit arguments

- Absent local heat flow anomaly
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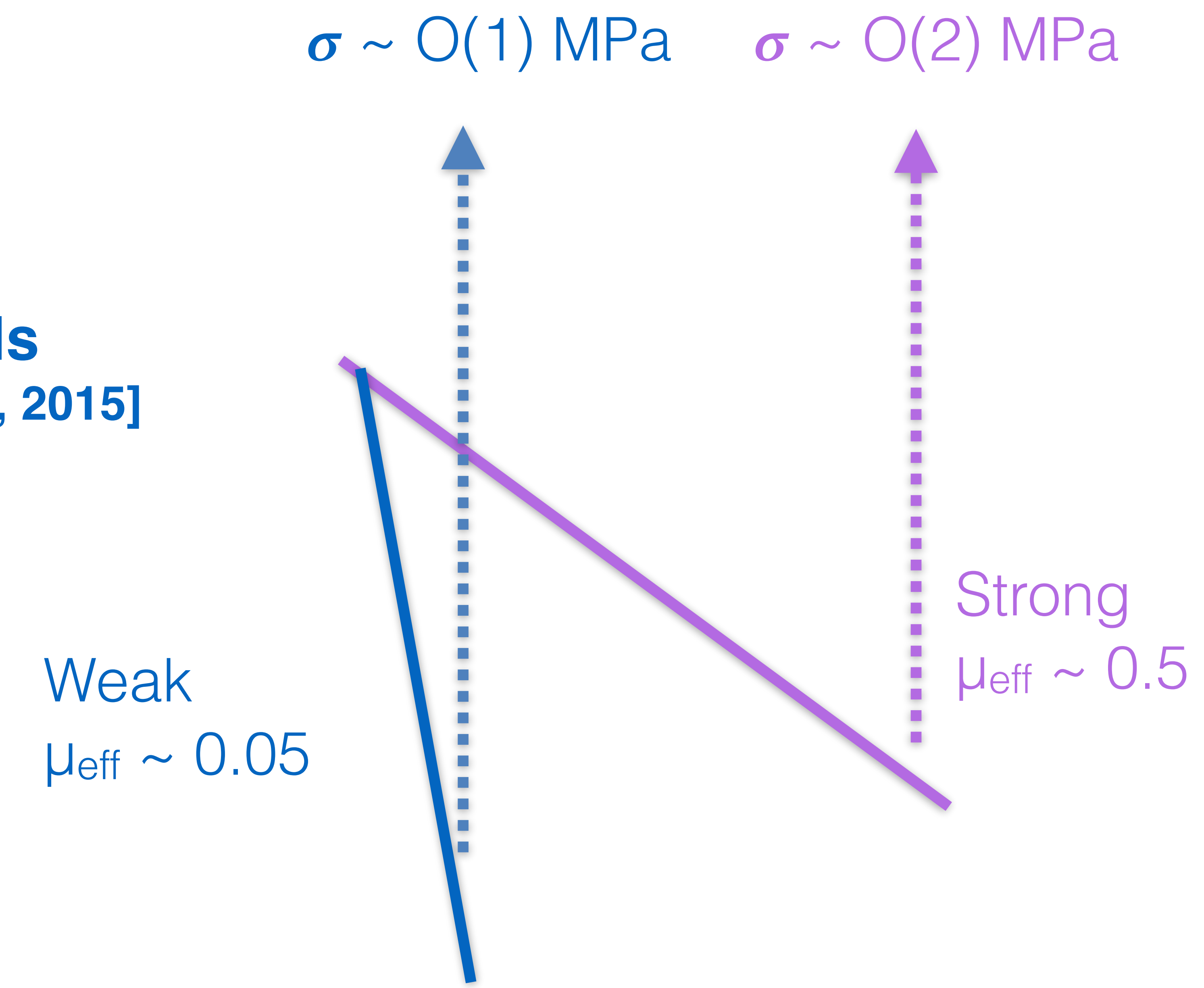

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- **Laboratory experiments**
  (e.g., Byerlee, 1978)
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- Dip orientation of earthquakes on (re-activated) faults
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- **Sustain mountains**
- …

II. Estimate what mechanisms are most important

- Absent local heat flow anomaly
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- What weakening mechanism is most important?
  - High pore fluid pressures
  - Low static friction
  - Large dynamic earthquake weakening

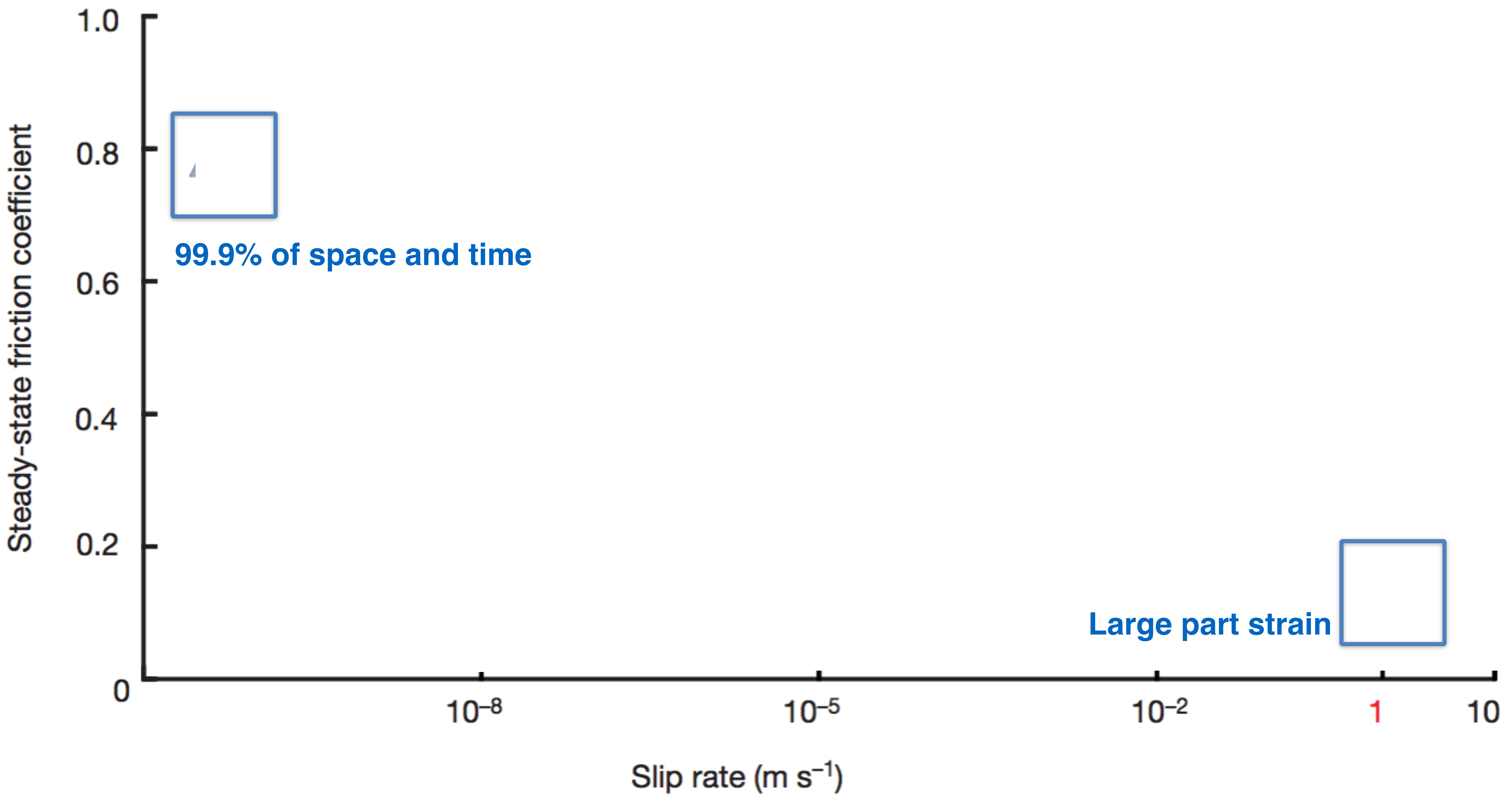
Rocks are almost always strong, but not at coseismic slip rates where most strain occurs

- High-speed lab experiments reveal enhanced dynamic weakening [e.g., Di Toro et al., Nature, 2011]
  - Low slip rates μ_{eff} ~ 0.7
  - High coseismic slip rates μ_{eff} ~ 0.15

} dynamic weakening γ ~ 0.79 $\gamma = 1 - \frac{\mu_d}{\mu_s}$

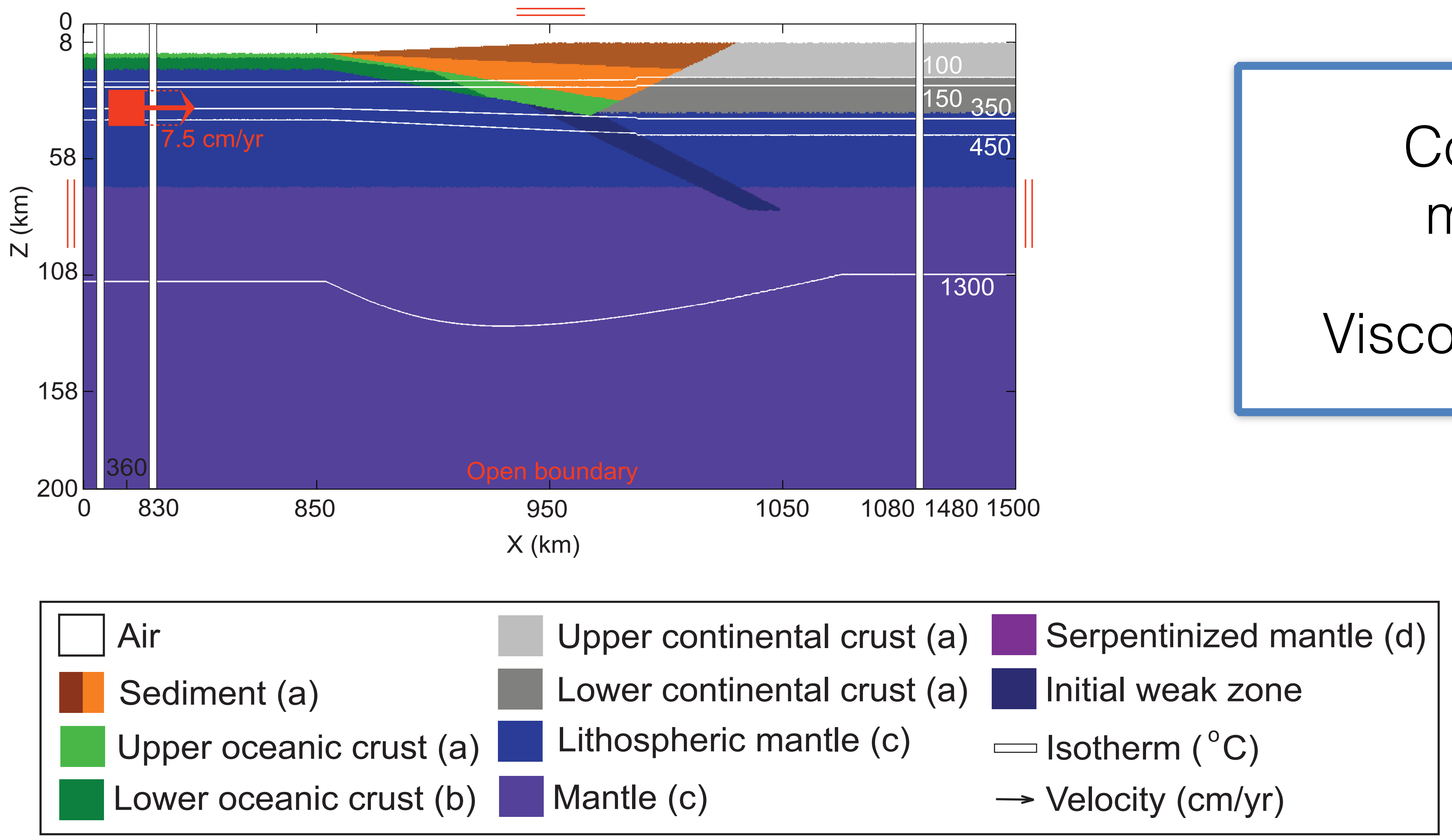
Static friction

Dynamic friction



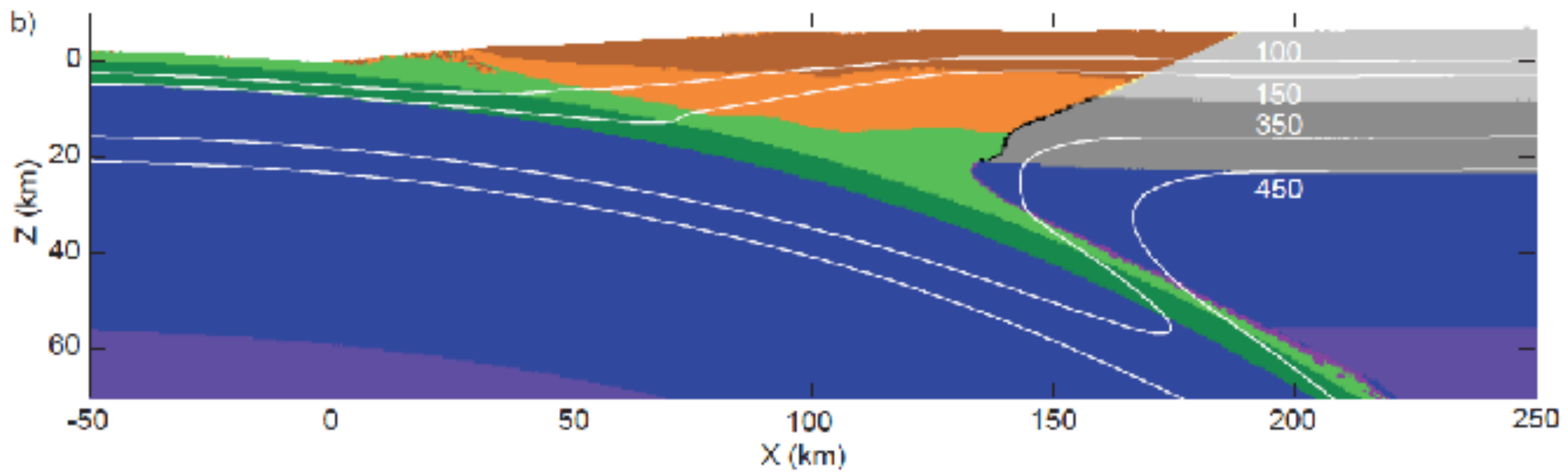
Di Toro et al., Nature, 2011

- Included dynamic weakening in geodynamic models [Seismo-Thermo-Mechanical; STM; van Dinther et al., 2013a,b]



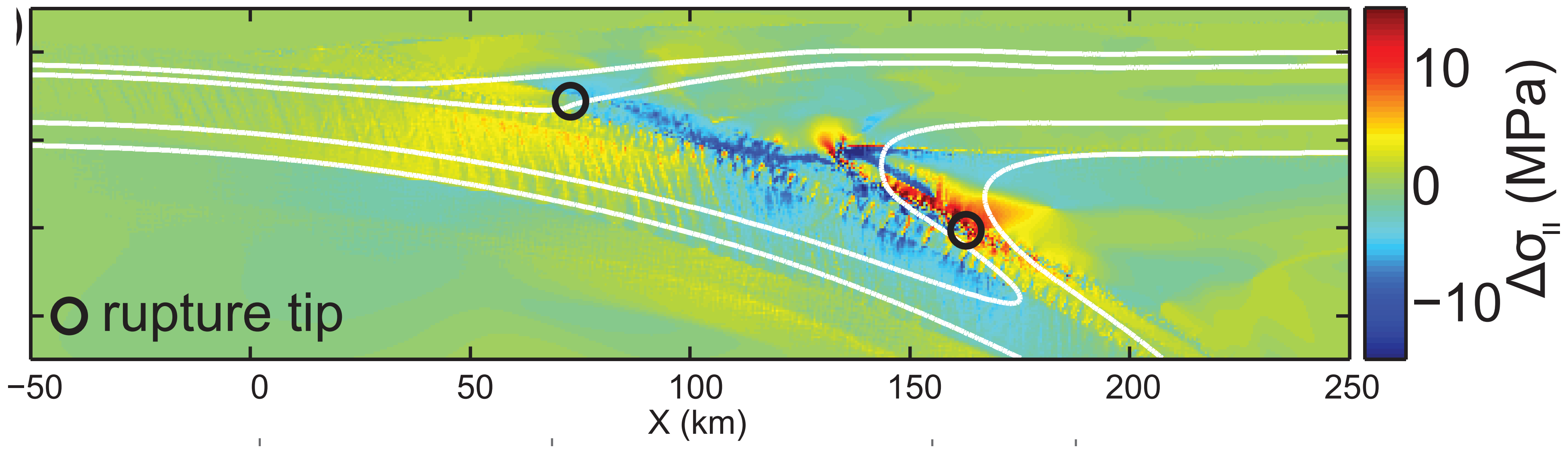
Conservation of mass, momentum and heat

Visco-elasto-plastic rheology



>> Spontaneous state and geometry
e.g., stress, temperature, viscosity, fluid distribution

Small time steps
+ rate-dep. friction
+ inertia

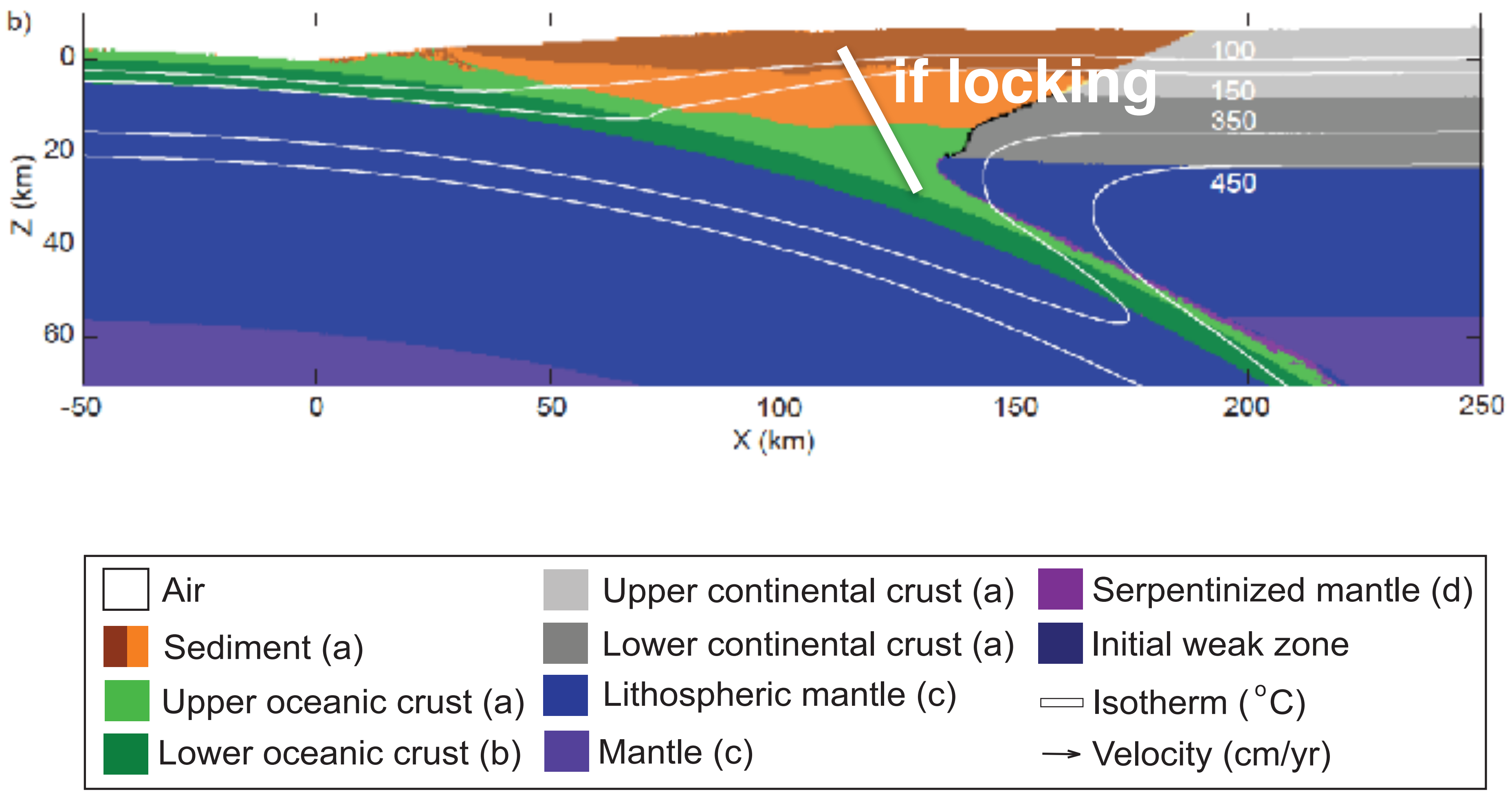


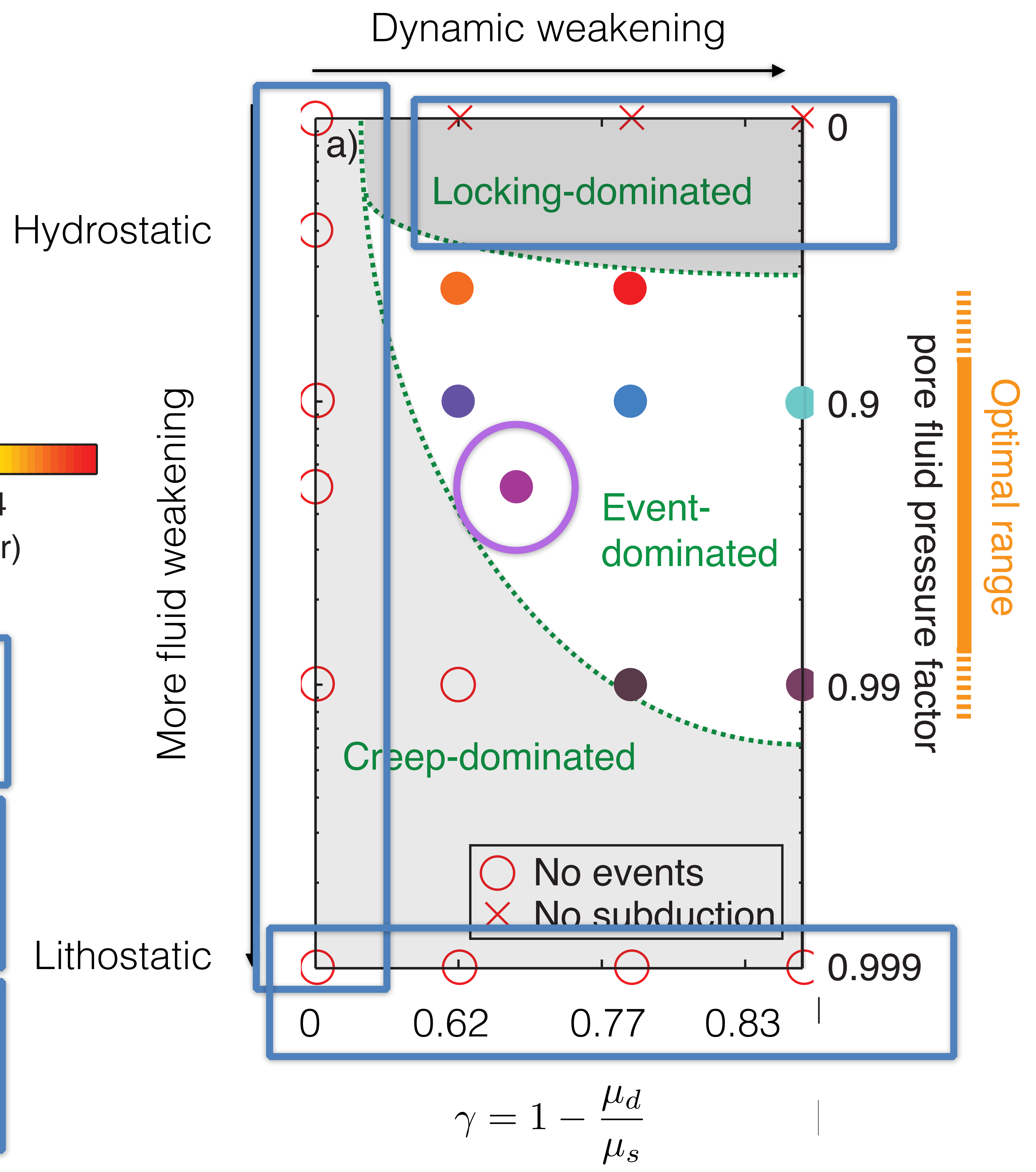
>> Spontaneous rupture nucleation, propagation and arrest

TM: Gerya and Yuen, PEPI, 2007; STM: van Dinther et al., 2013a,b, 2014

Need fluid and dynamic weakening in cross-scale models

- For subduction, mountain building, and reasonable earthquake characteristics need **~0.005 < $\mu_{eff,\ static}$ < ~0.125**



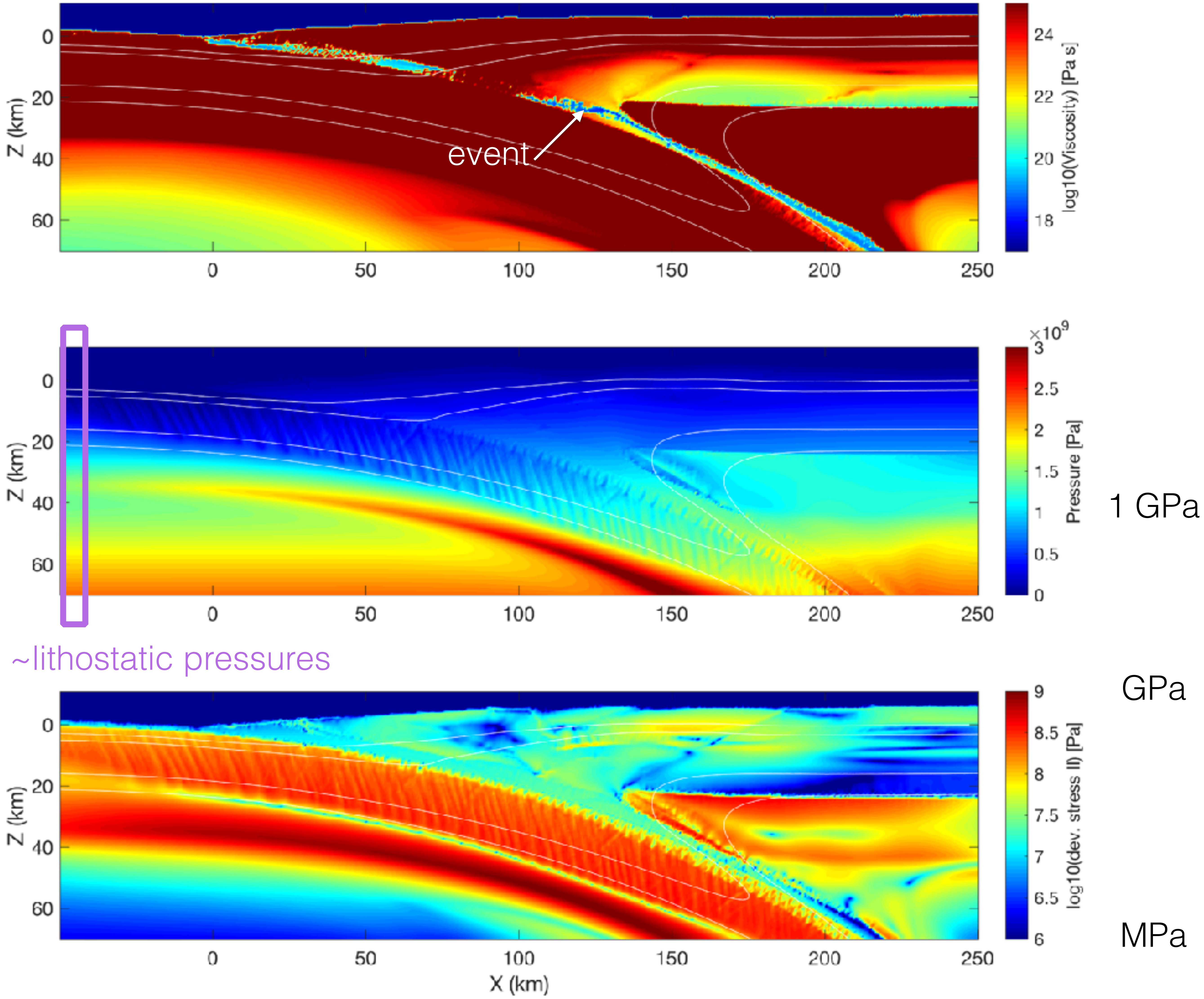


✕	Need fluid weakening to allow for subduction along shallow megathrust
○	But not too much! Still need interseismic locking to build stresses to generate events
○	Need dynamic weakening to generate events

van Dinther et al., JGR, 2013b

Very weak @ very limited space or time does not mean weak throughout

- Temporarily weak (~10 MPa min.) and continuously overpressurized megathrust does not mean weak throughout lithosphere!
- Could still build mountains



max. megathrust σ'$_{II}$ ~ 40 MPa,
but elsewhere still almost GPa

$\mu_{eff, static} = 0.05$

Long-term fault strength as a strain-average quantity

» Rocks are “always” strong, but weak during dynamic slip, where most strain occurs → How do we account for that in long-term models?

- Consider friction as a strain-average quantity:

- Time-integrated mechanical energy dissipation

For equations I refer to van Dinther, in prep.

>> Derive constraints from observations and laboratory experiments

Long-term fault strength as a strain-average quantity

» Rocks are "always" strong, but weak during dynamic slip, where most strain occurs ➝ How do we account for that in long-term models?

- Consider friction as a strain-average quantity, since
- Time-integrated mechanical energy dissipation

$$H = \int \sigma_{ij(d)} \dot{\varepsilon}_{ij(d)} dt + \int \sigma_{ij(s)} \dot{\varepsilon}_{ij(s)} dt$$

- Mechanical consistency of energy and strain for unresolved **d**ynamics requires

$$\sigma_{II(c)} = \frac{\varepsilon_{II(d)}}{\varepsilon_{II(d)} + \varepsilon_{II(s)}} \sigma_{II(d)} + \frac{\varepsilon_{II(s)}}{\varepsilon_{II(d)} + \varepsilon_{II(s)}} \sigma_{II(s)}$$

- With stress limited by strength (parameters) and

seismic coupling $\chi = \frac{M_0^{\Sigma}}{M_{0e}}$ pore fluid pressure ratio $\lambda = \frac{P_f}{P}$ dynamic weakening $\gamma = 1 - \frac{\mu_d}{\mu_s}$

- Long-term average, effective friction is strain-averaged as

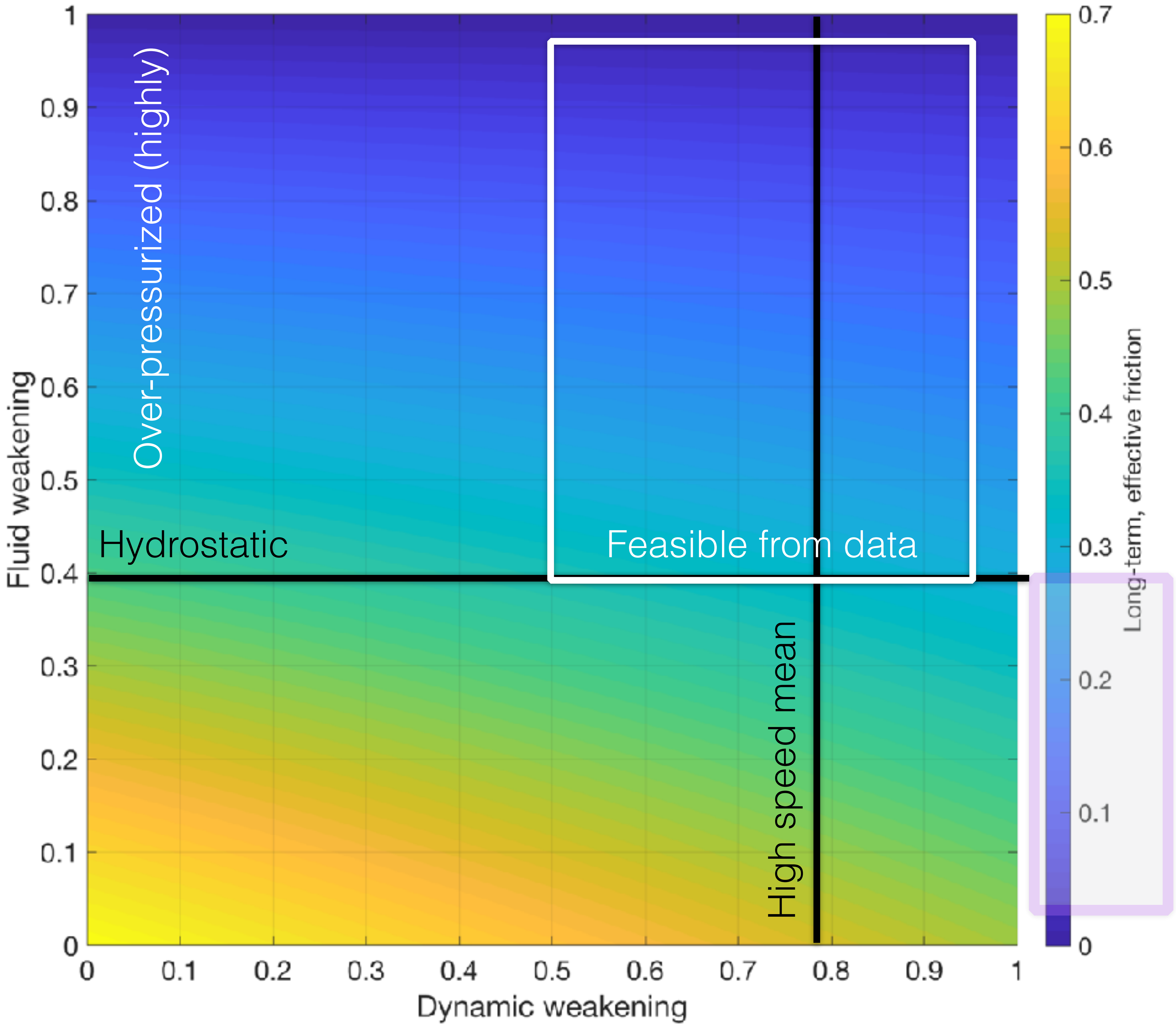
$$\mu_{eff(c)} = \chi(1-\lambda)(1-\gamma)\mu_{(s)} + (1-\chi)(1-\lambda)\mu_{(s)}$$

>> Derive constraints from observations and laboratory experiments

Energy dissipation for dike intrusion: Gerya et al., Nature, 2015

Long-term, effective friction for pore fluid pressure vs. dynamic weakening

$$\lambda = \frac{P_f}{P}$$



$$\gamma = 1 - \frac{\mu_d}{\mu_s}$$

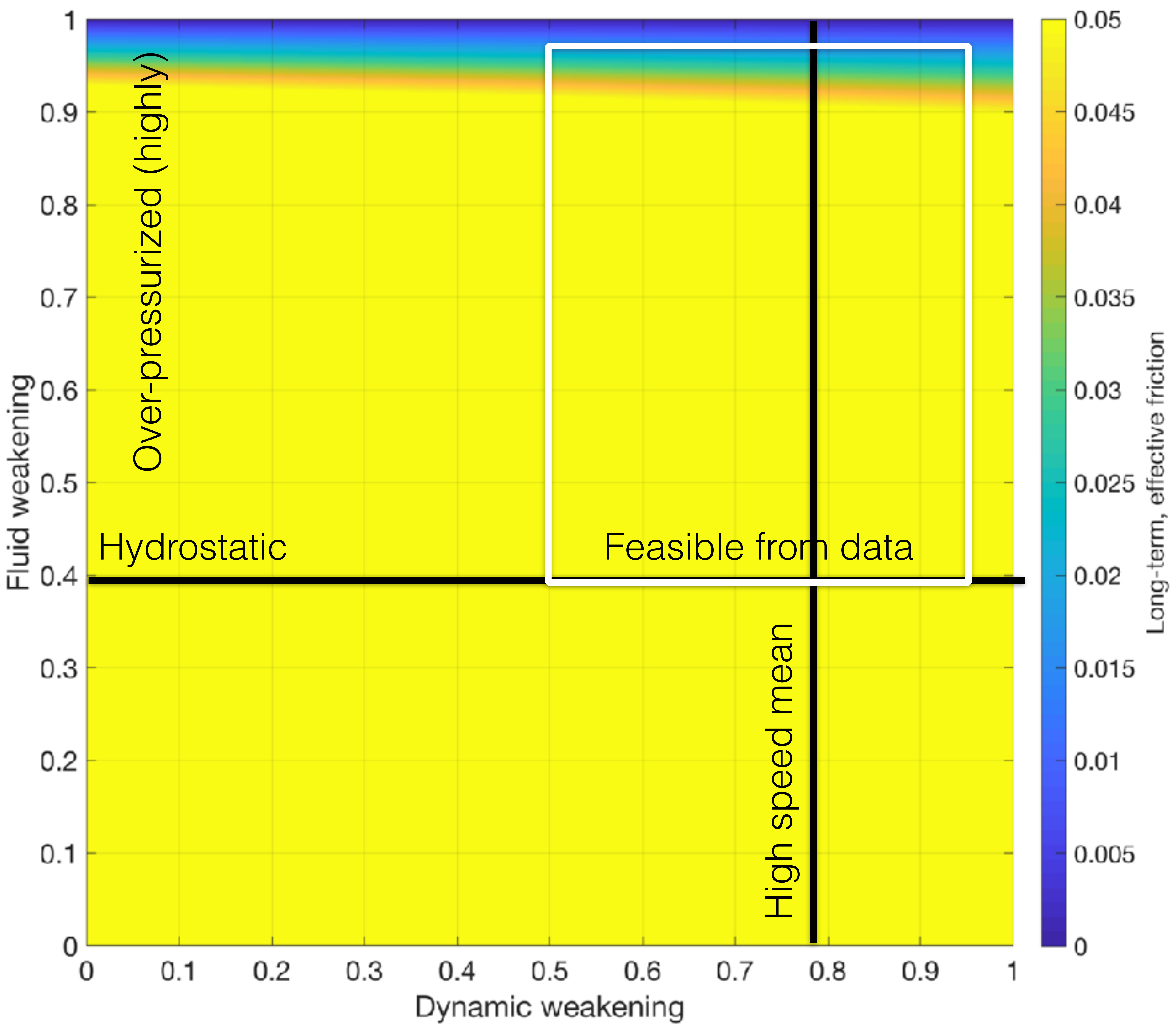
Feasible long-term friction values from data: ~ 0.02 - ~0.3

- Best guess:
- μ_s = 0.7 [e.g., DiToro et al., Nature, 2011]
- χ = 0.3 [e.g, McCaffrey, BSSA,1997]

What do we need for long-term weak faults ($\mu_{eff,c}$ < 0.05)?

- What is needed for subduction to occur in geodynamic models? (i.e., $\mu_{eff,c}$ < 0.05; e.g., Zhong et al., 1998; Buiter et al., 2001; Sobolev & Babeyko, 2005; Duarte et al., 2015)

» Dynamic weakening can bring pore fluid pressures in more acceptable range, but still **requires largely over-pressurized megathrust**



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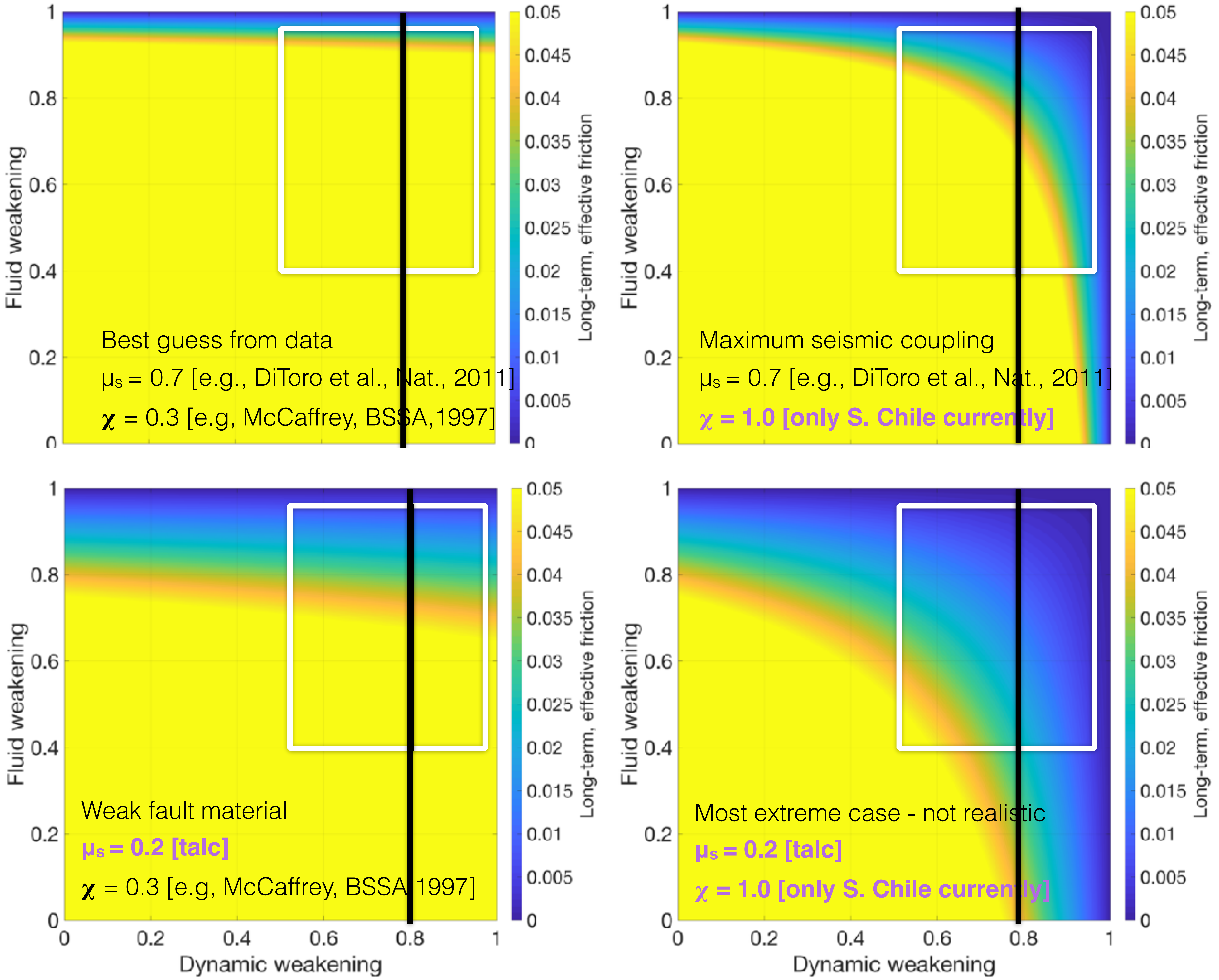

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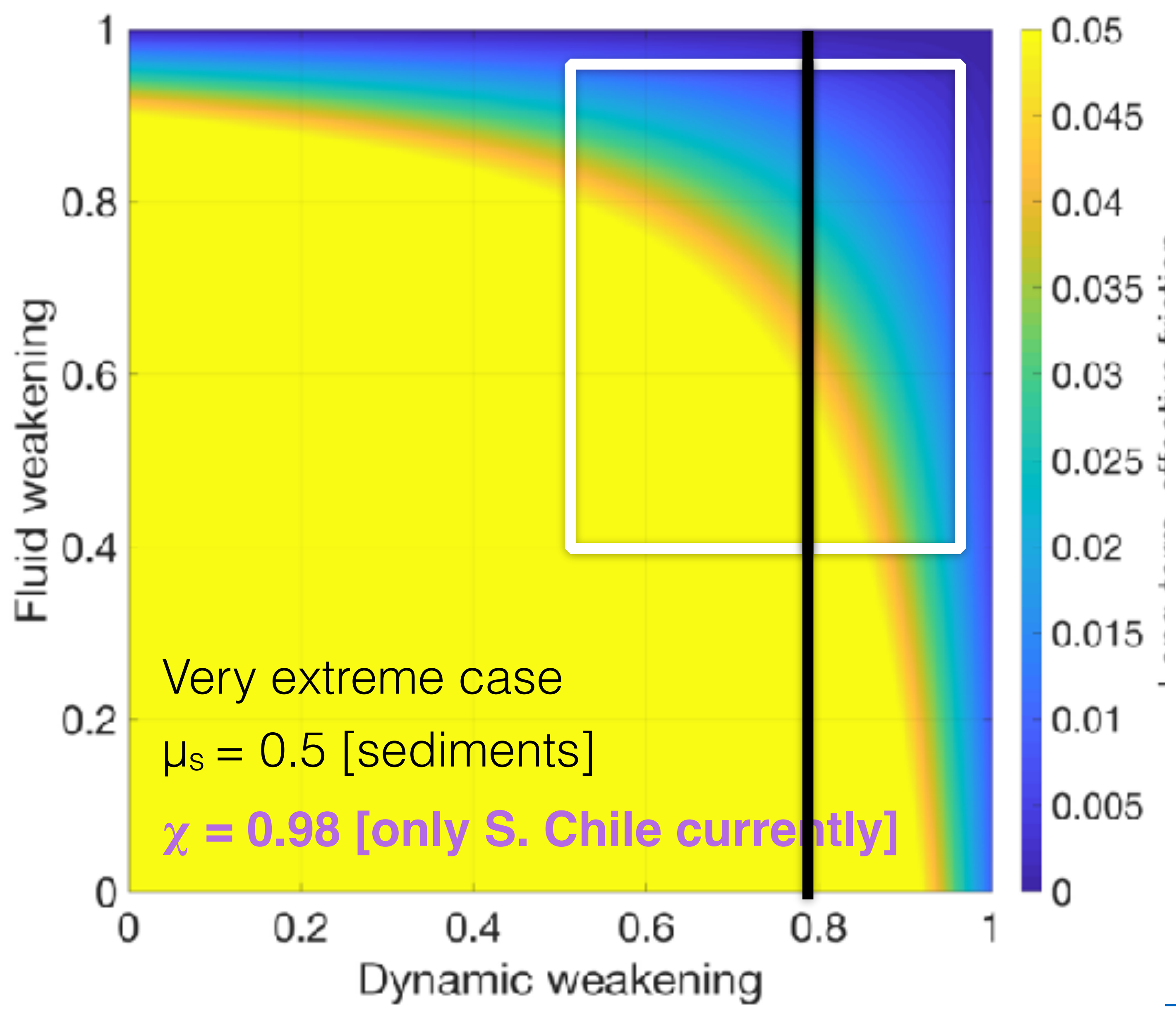


highly over-pressurized faults

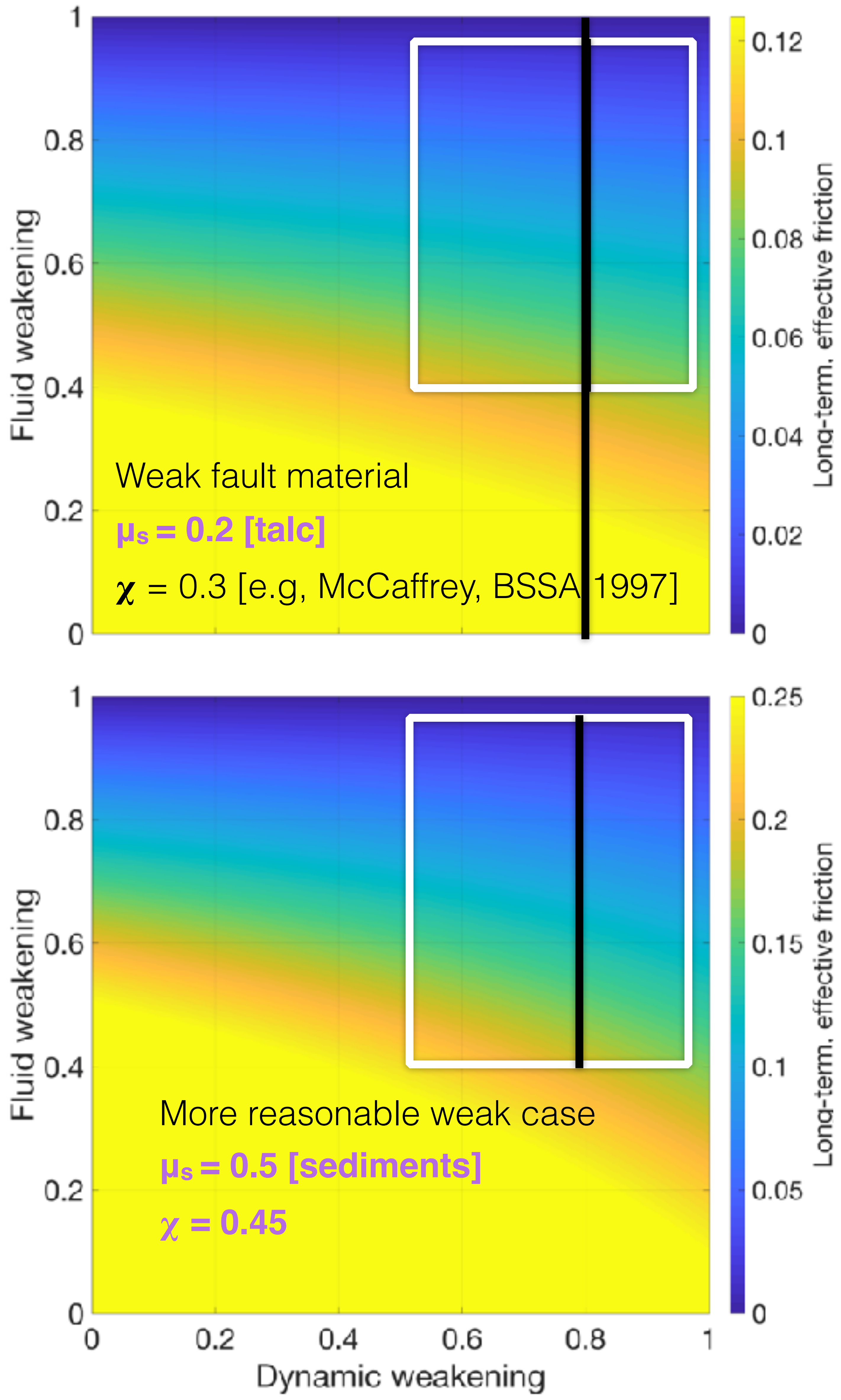
~~**unless full seismic coupling**~~

(or a different weakening mechanism is missing)

(or long-term models incorrect)

Alternatively avoid fluid over-pressurized megathrusts through higher $\mu_{eff,c}$

» IF subduction with realistic characteristics can occur in long-term geodynamic models for



$\mu_{eff,c}$ ~ 0.1 for statically very weak megathrust (too weak)

$\mu_{eff,c}$ ~ 0.2-0.3 for weak, but potentially reasonable megathrust

» **I have not seen this**

Relative effectiveness of weakening mechanisms

» Most effective way to remove highly over-pressurized faults remains reducing static friction (not earthquake slip)

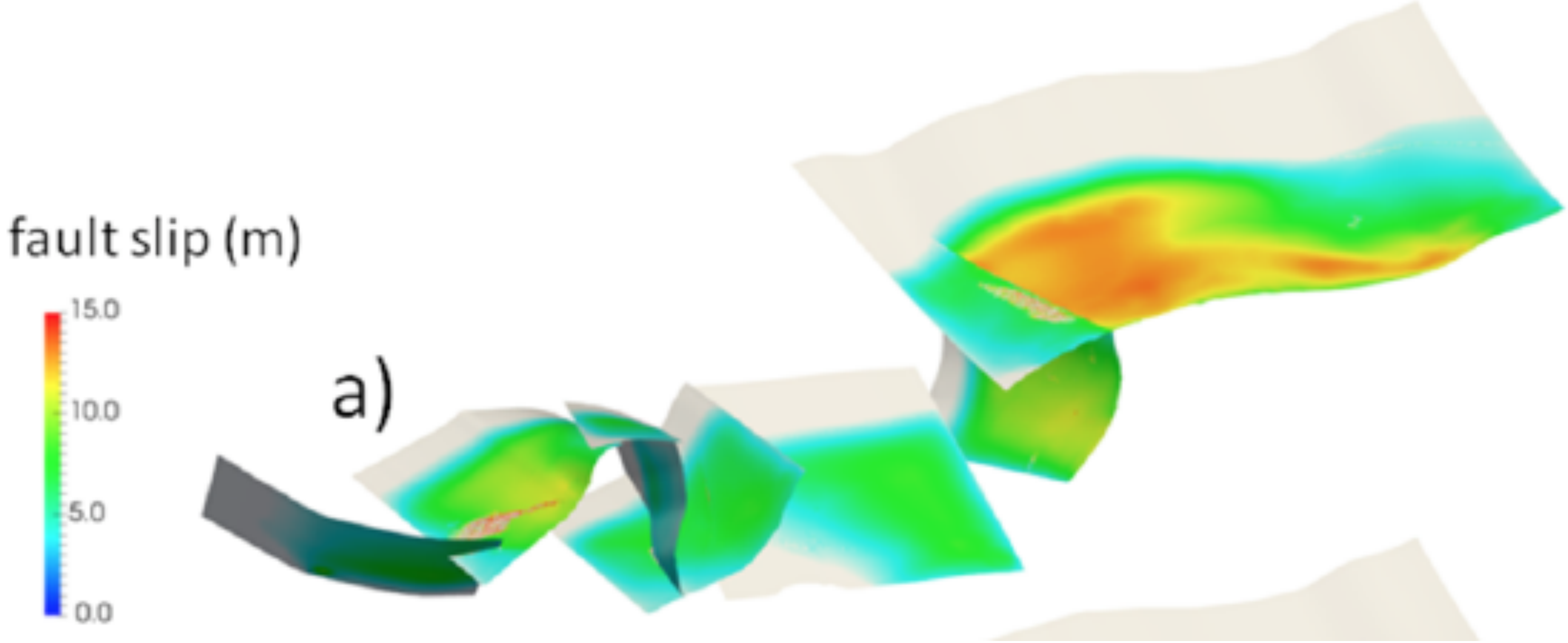
Double	**Reduces $\mu_{eff\ (char)}$ at reference values by**	**Reduces $\mu_{eff\ (char)}$ at full seismic coupling by**
1. pore fluid pressure	67%	
2. static friction	50%	
3. seismic coupling	47%	
4. friction drop	20%	50%

Apparently weak faults also work better for dynamic earthquake ruptures (DR)

- Lab-observed large strength drops allowed in slip/rate-weakening DR models through distinctly increased pore fluid pressures

  - 2016 M7.8 KAIKOURA earthquake only jumps for large fluid pressures (λ ~0.66)

$$\Delta\tau \sim (\mu_s - \mu_d)(1 - \lambda)$$

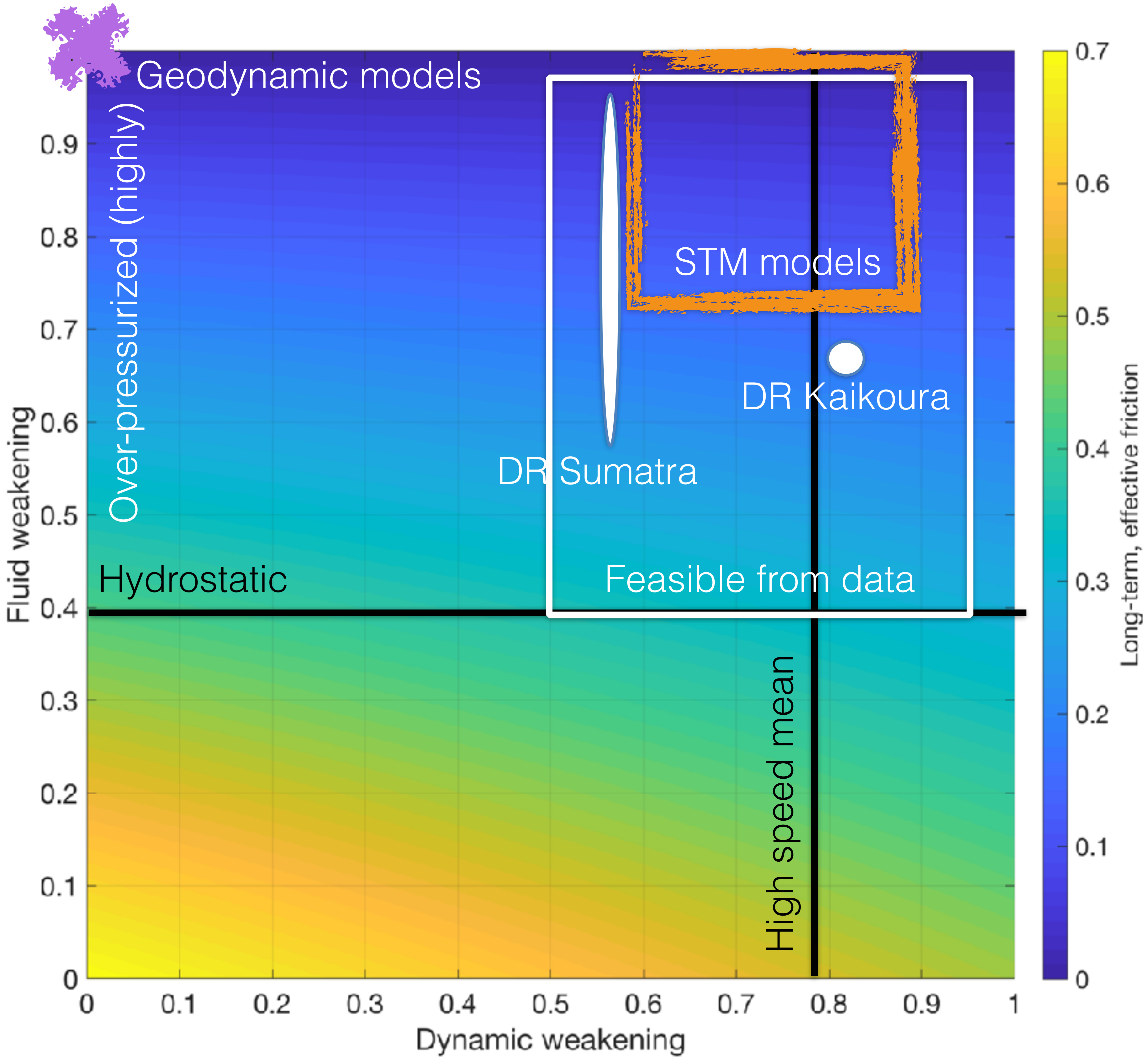


Ulrich et al., Nat. Comm., 2019
Strongly rate-dep. friction, γ ~ 0.8

» Strain occurs around μ_{eff} <= 0.1

Models across scales support weak(er) megathrusts

» Recent modeling results show that long- and short-term results are not so far apart as they seem



DR Sumatra: Madden et al., AGU, 2018

Feasible long-term friction values from models:
$\mu_{eff,c}$ ~ 0.02 - ~0.20

- Best guess:
- μ_s = 0.7 [e.g., DiToro et al., Nature, 2011]
- χ = 0.3 [e.g, McCaffrey, BSSA,1997]

Conclusions

- Models at, and across, all time scales support (somewhat) weak megathrusts
  - » **$\mu_{eff,c}$ ~ 0.02 to 0.2**

- Long-term strength is a strain-average quantity
  - Described by pore fluid pressure ratio, static friction, seismic coupling, and dynamic friction

- Analytical considerations constrained by data and laboratory experiments support (somewhat) weak megathrusts
  - » **$\mu_{eff,c}$ ~ 0.02 to 0.3**
  - Megathrusts are mainly weak due to distinctly to highly over-pressurized pore fluids
  - » Geodynamic models not resolving earthquake dynamics are within their right within **bold** range (and can justify choice)