Rheology of the brittle-plastic transition

Role of fabric and phyllosilicates

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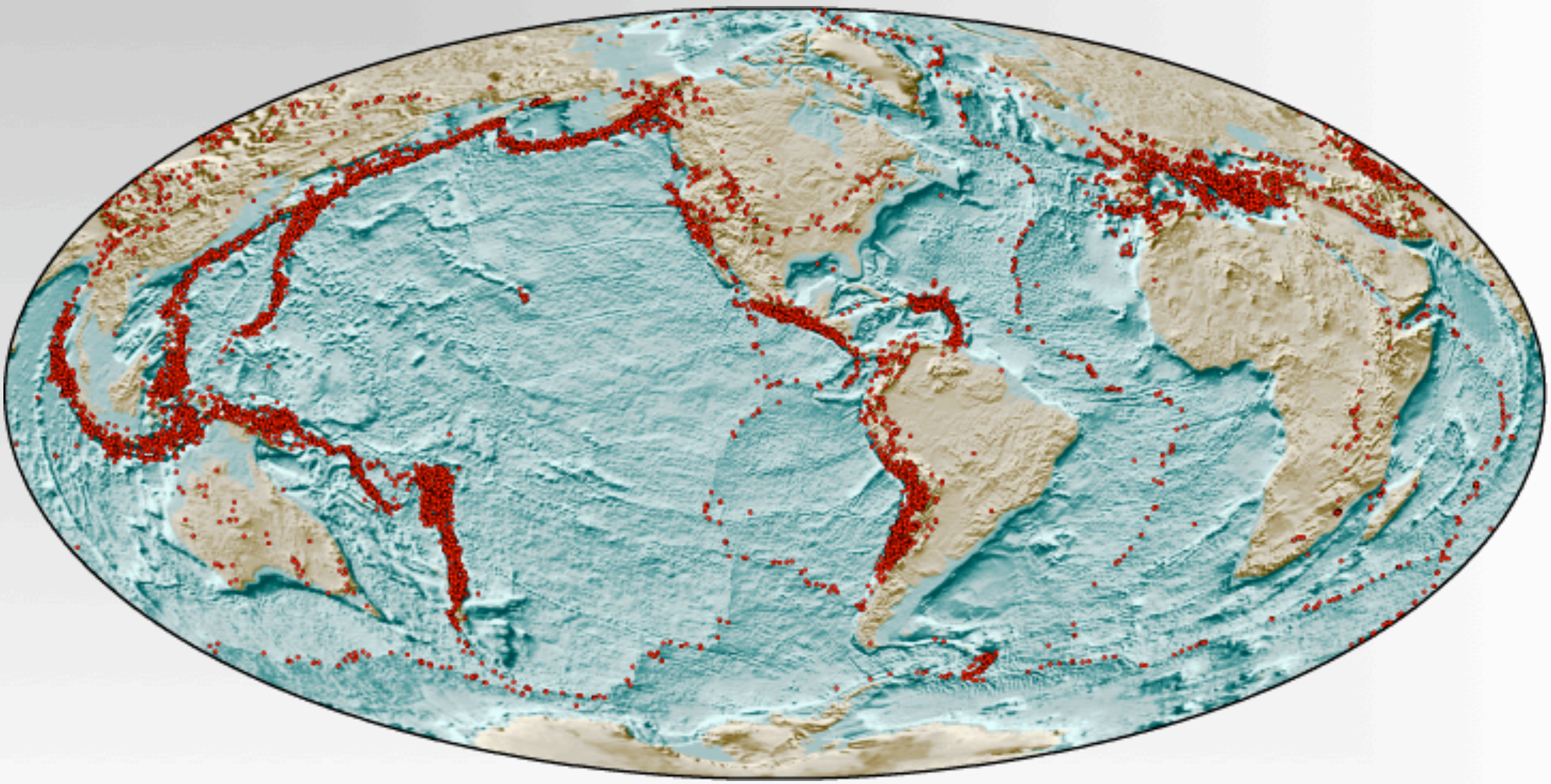
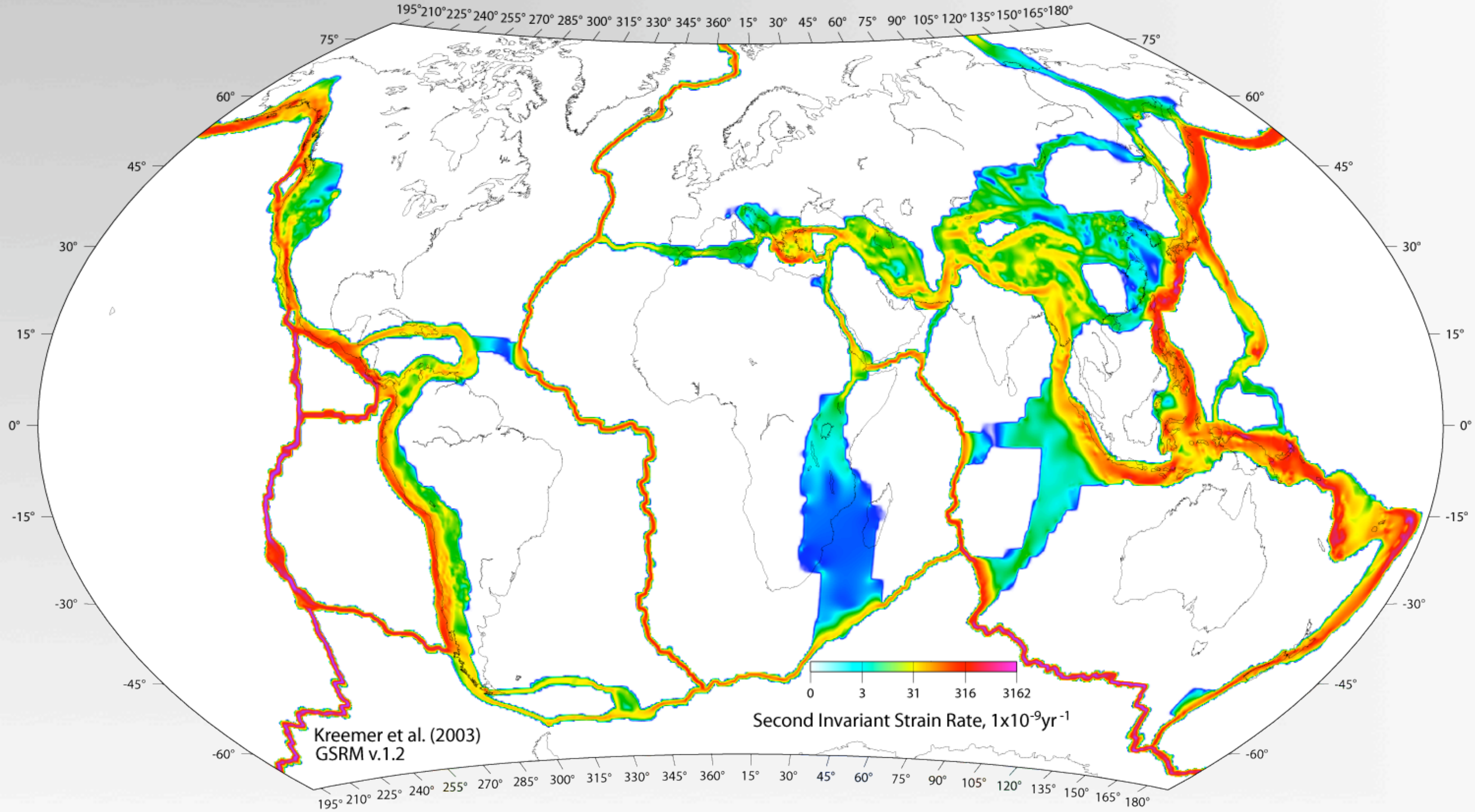
Global Seismicity



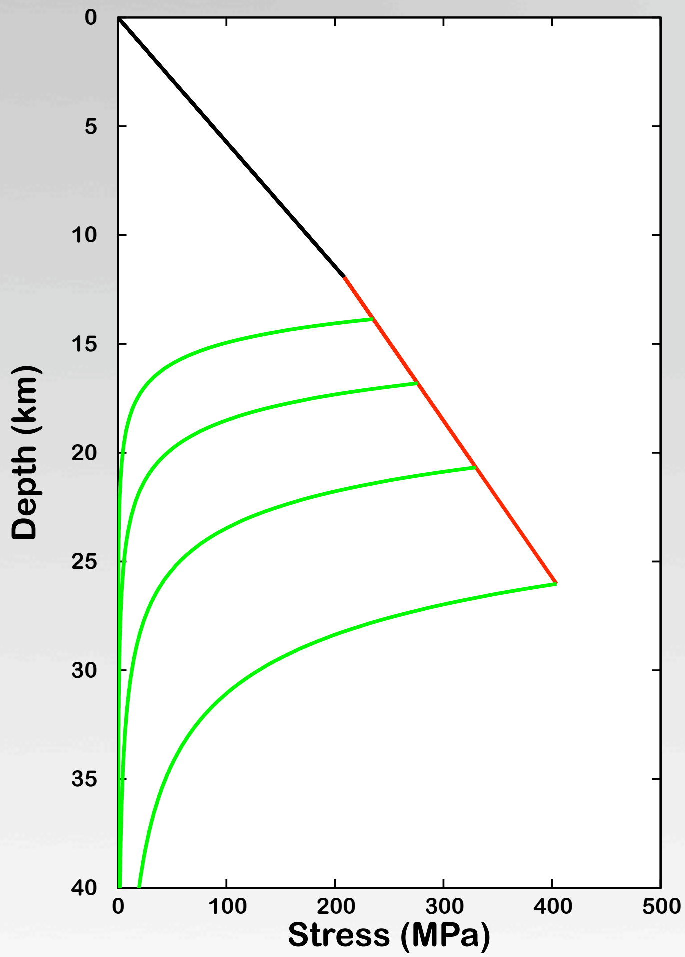
IRIS catalogue, M>2.0, 01-01-2006 to 01-10-2006

World Strain Rate Map



Kreemer et al., 2000, 2003

Brittle-Plastic transition



- Brittle law
  - Dominated by cracks
  - Strength increases with depth (Pressure effect)
- Plastic rheology
  - Intracrystalline deformation
  - Strength decreases with depth (Temperature effect)
  - Strain rate dependent

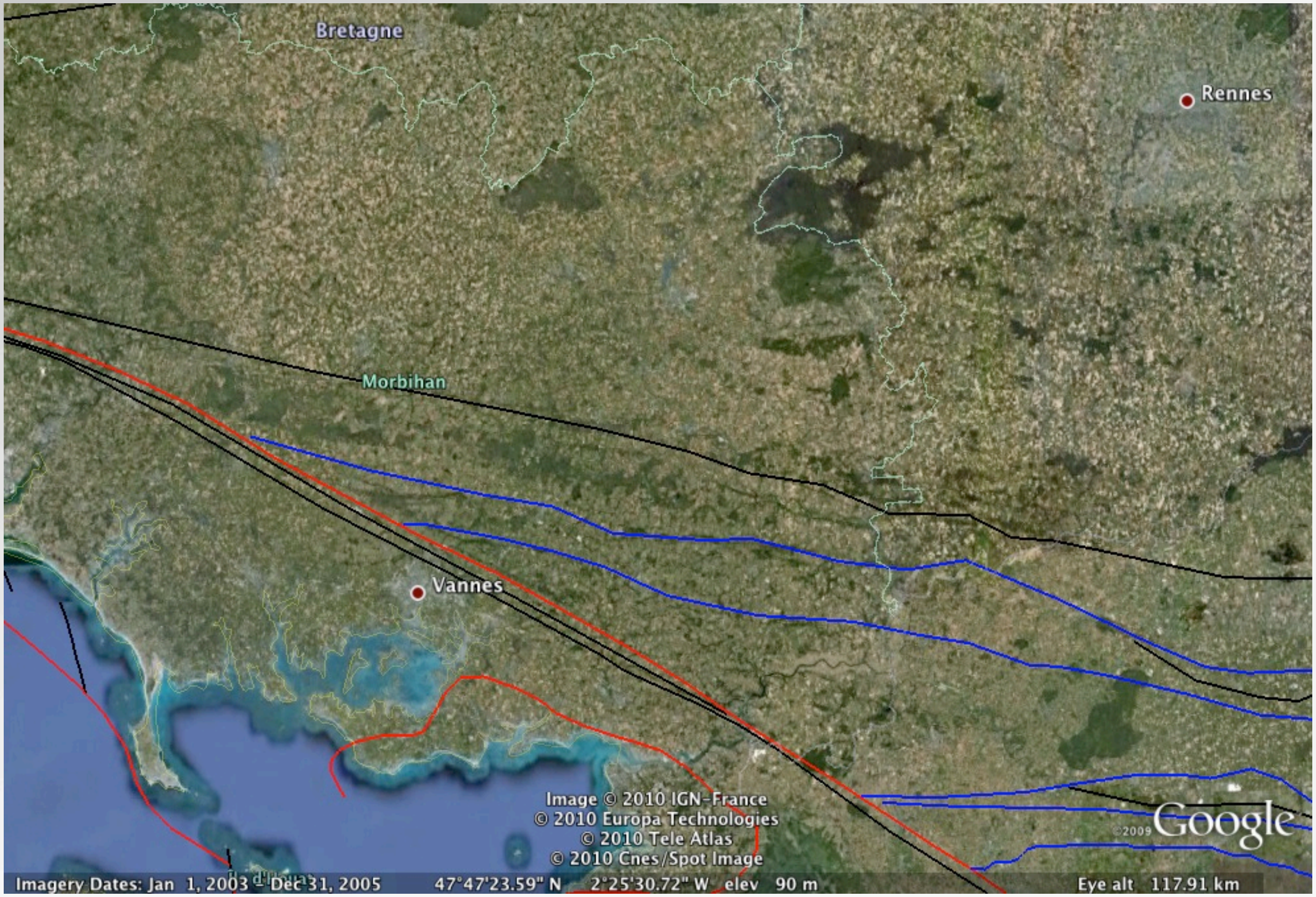
Brittle and plastic shear zones

Small brittle fault
Monterosa Massif, Italy

Shear zone in migmatite
Fosdick Mountains
West Antarctica (F. Korhonen)

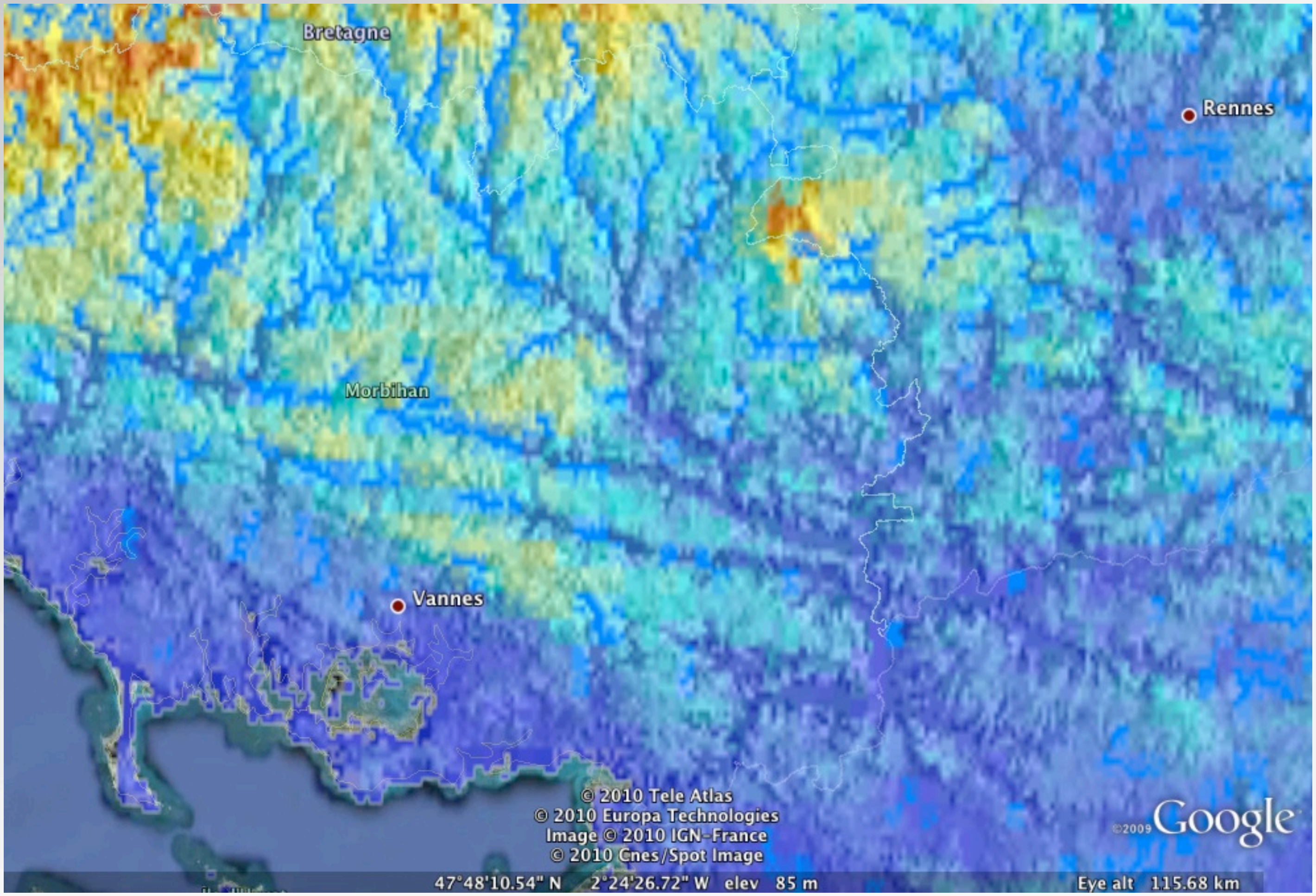
South Armorican …

South Armorican Shear Zone …



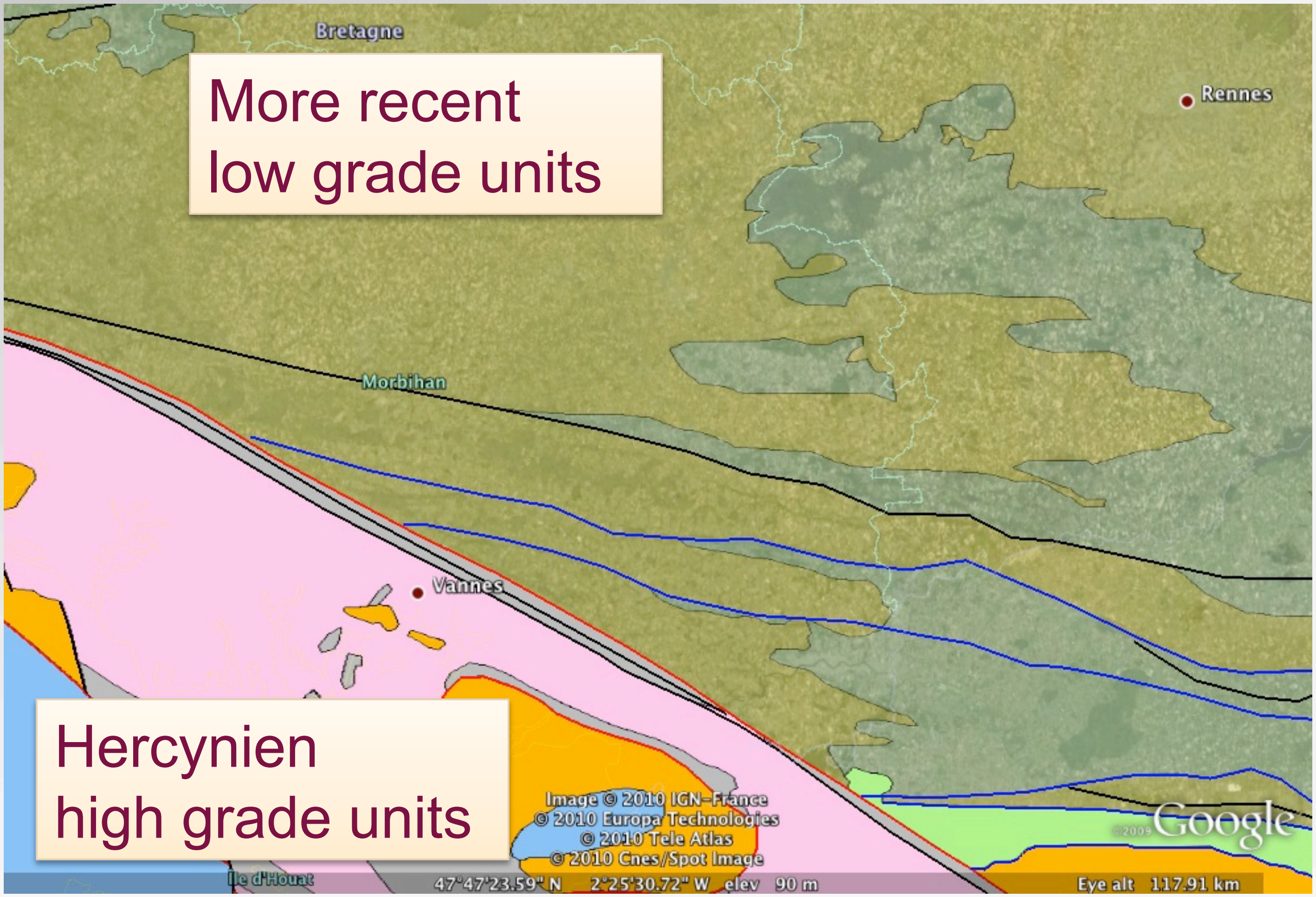
Google Earth KMZ from:
http://perso.univ-rennes1.fr/frederic.gueydan/Kit_MA.htm

South Armorican Shear Zone …



DTM and Google Earth KMZ from:
http://perso.univ-rennes1.fr/frederic.gueydan/Kit_MA.htm

… a lithospheric-scale structure



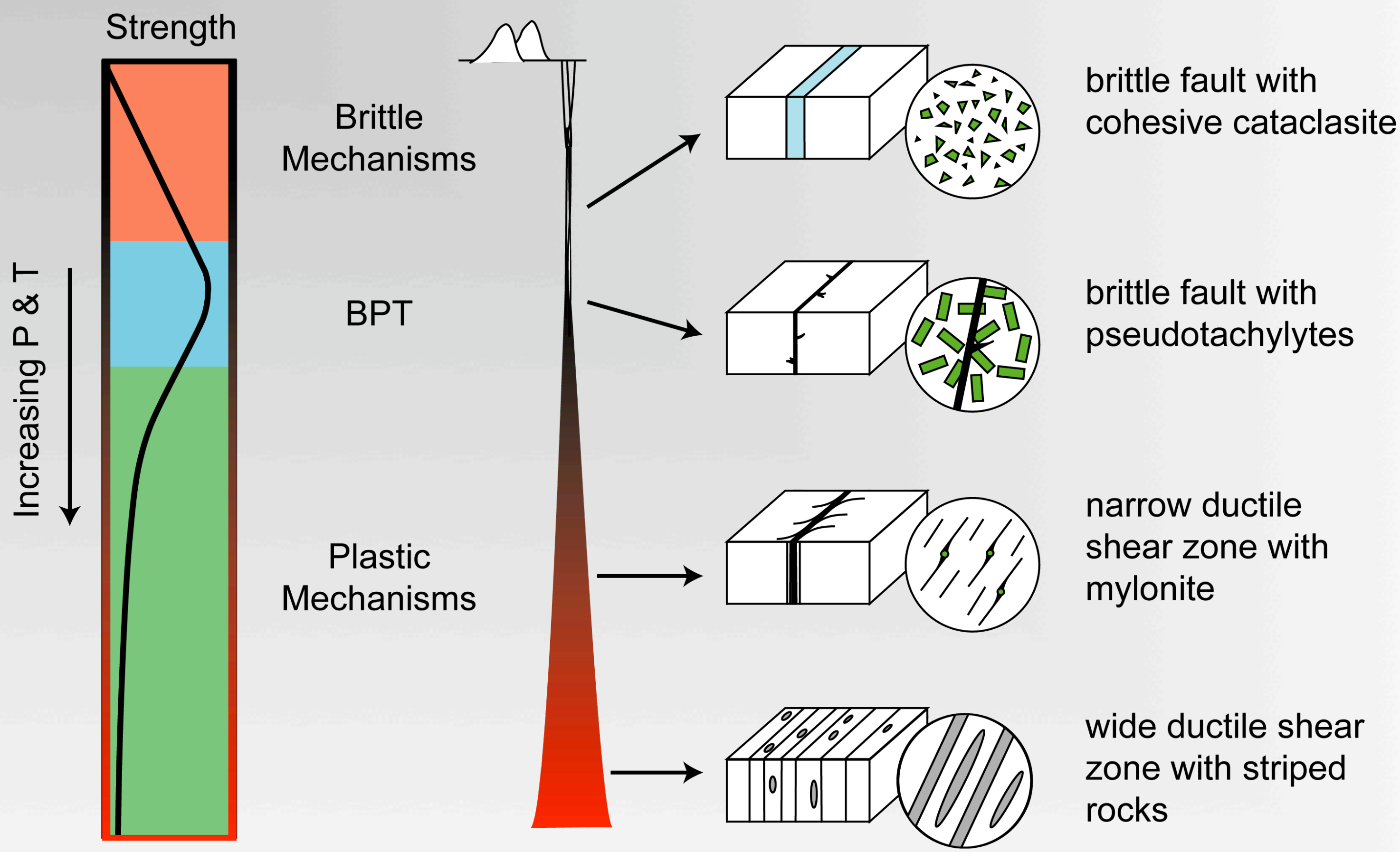
Google Earth KMZ from:
http://perso.univ-rennes1.fr/frederic.gueydan/Kit_MA.htm

Shear zone structure

- Requires change in state or environment
  - Temperature
  - Grain size
  - Interconnection of weak phase
  - Abundance of weak phase
- On Earth, weak phase is often hydrated
  - Mica, serpentine

L-S tectonites, South Armorican Shear Zone
F. Gueydan, personal communication, 2006

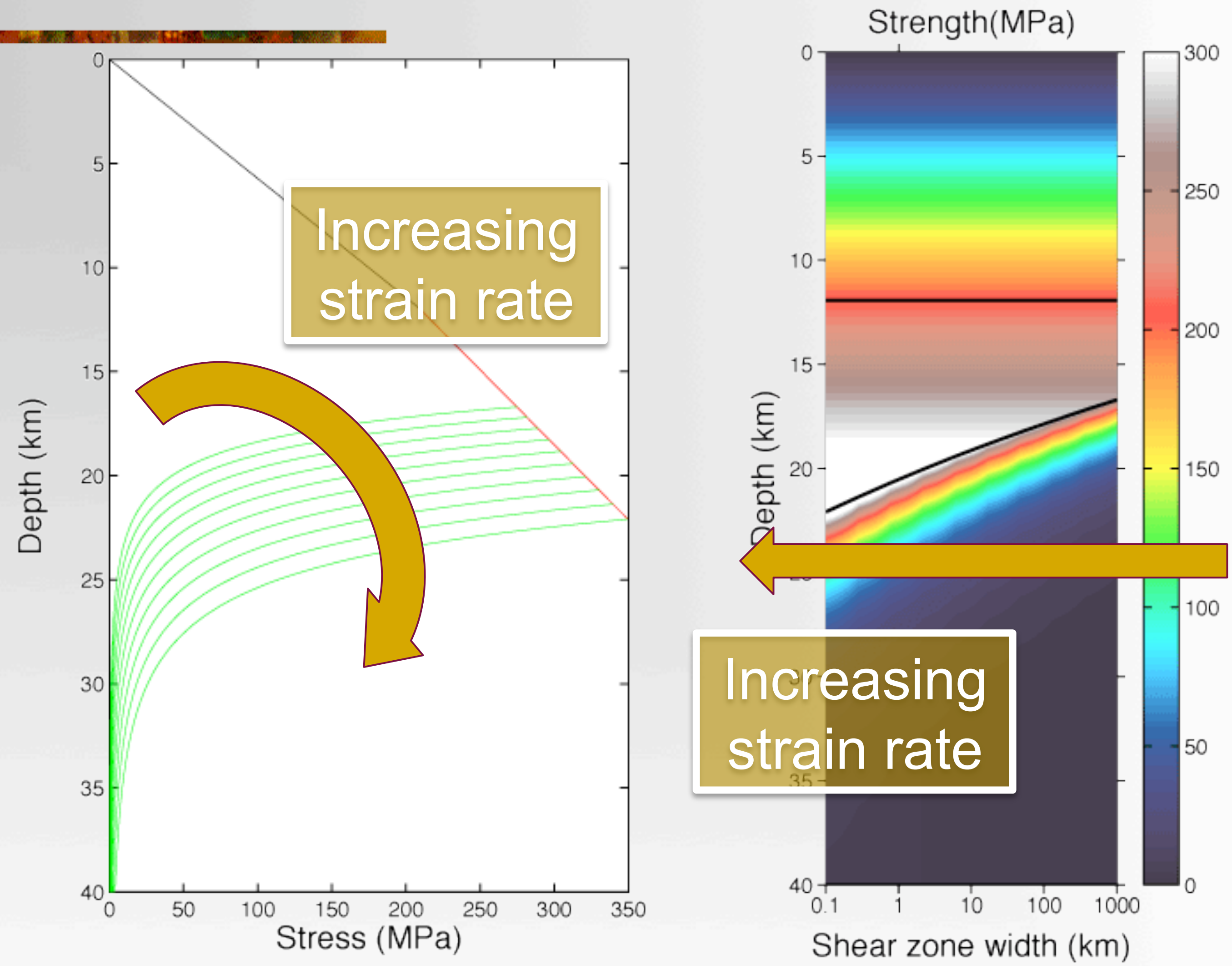
Shear zone profile



Modified from Passchier & Trouw 1998

Visualizing shear zone strength

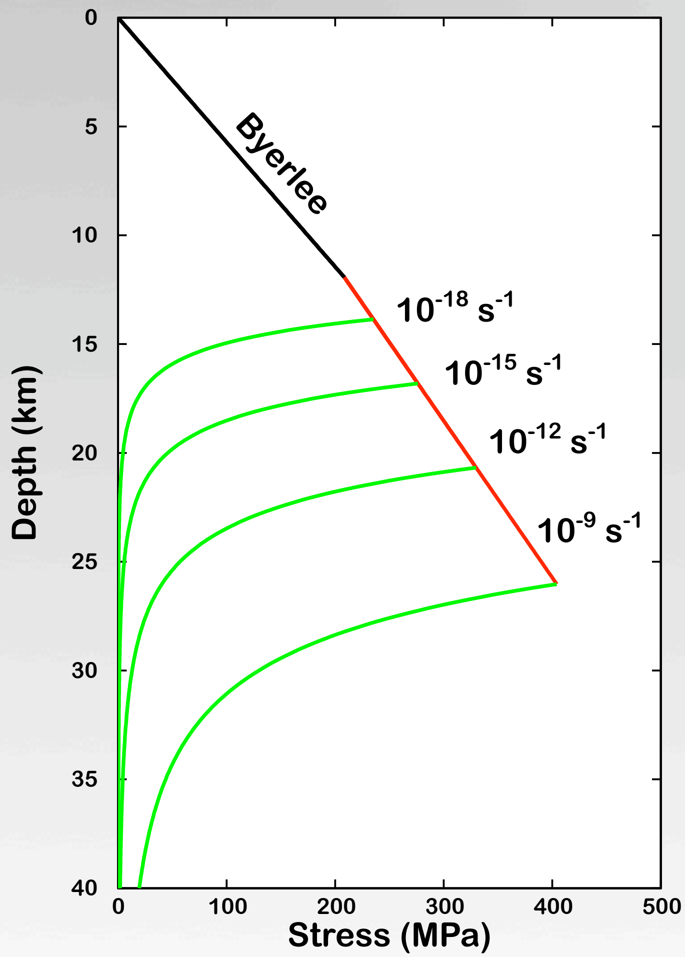
- Strength envelope
  - Impose strain rate
- Constant velocity strength map
  - Impose velocity across the shear zone
  - 35 mm/yr over 1km ⇔ $10^{-12}\ s^{-1}$



Strength profile

Strength Map

Standard strength envelope



- "Byerlee" friction

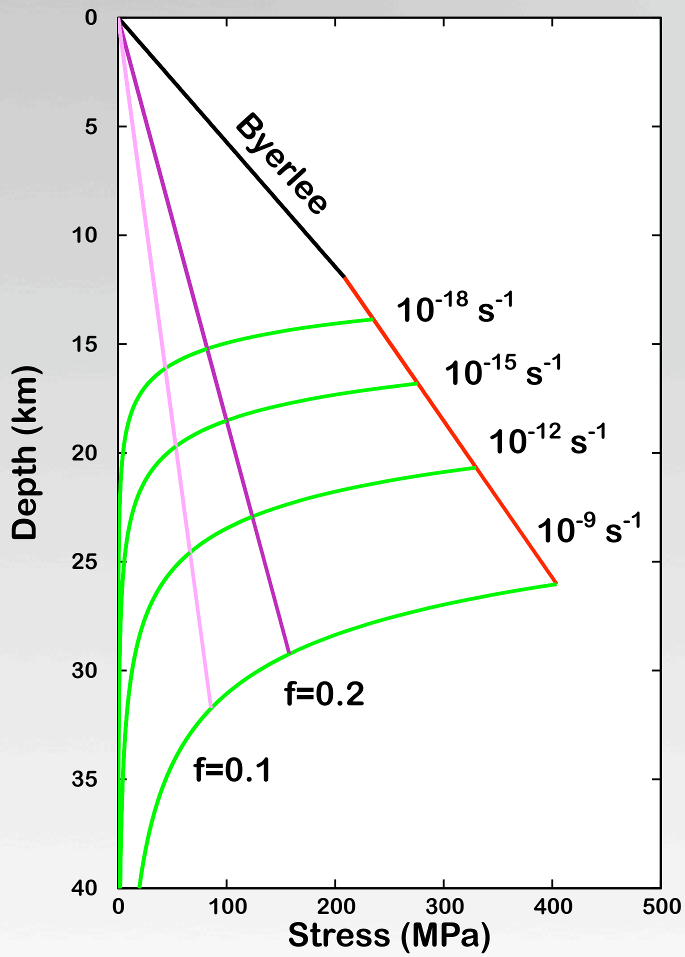
$$\tau = C + f\,\sigma_n$$

- Wet anorthite dislocation creep (Rybacki and Dresen 2000)

$$\sigma_{II} = A\,\sigma^n\,d^{-m}\,f^r_{H_2O}\,\exp\left(\frac{Q - PV}{RT}\right)$$

- Half space cooling, 30°/km at the surface, 1350°C at infinity

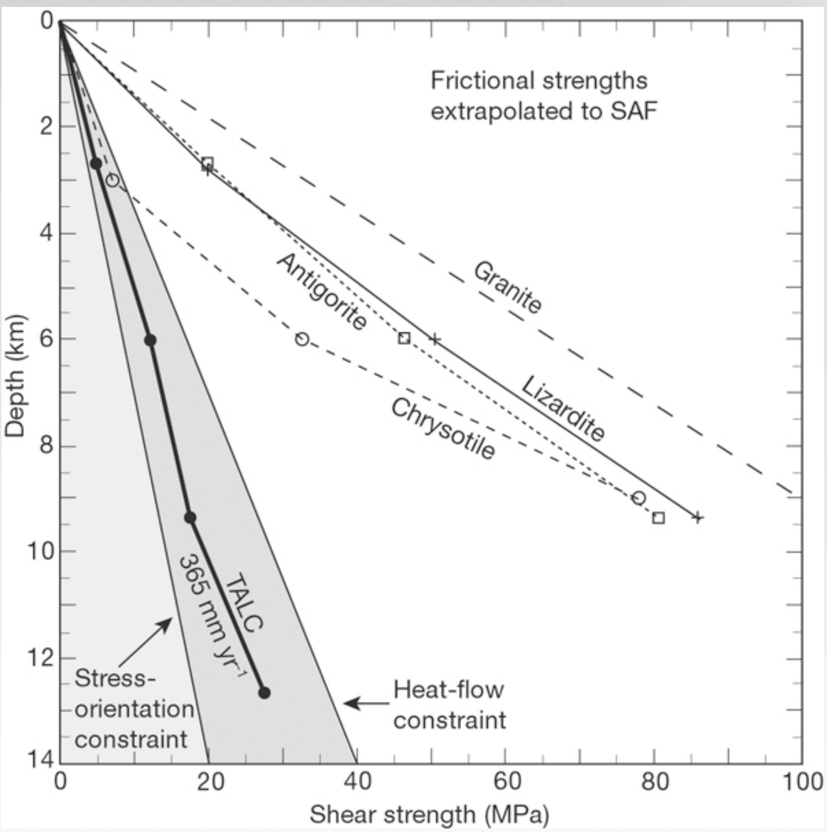
Reduced friction



- Intrinsically weak fault material
  - Talc @ SAFOD (Moore & Rymer, 2007)
- High pore fluid pressure
  - quasi lithostatic
- Dynamic effects
  - Near friction-less sliding at high speed (Di Toro et al., 2004, 2006)
  - Flash heating (Segall & Rice 2006; Rice, 2006)

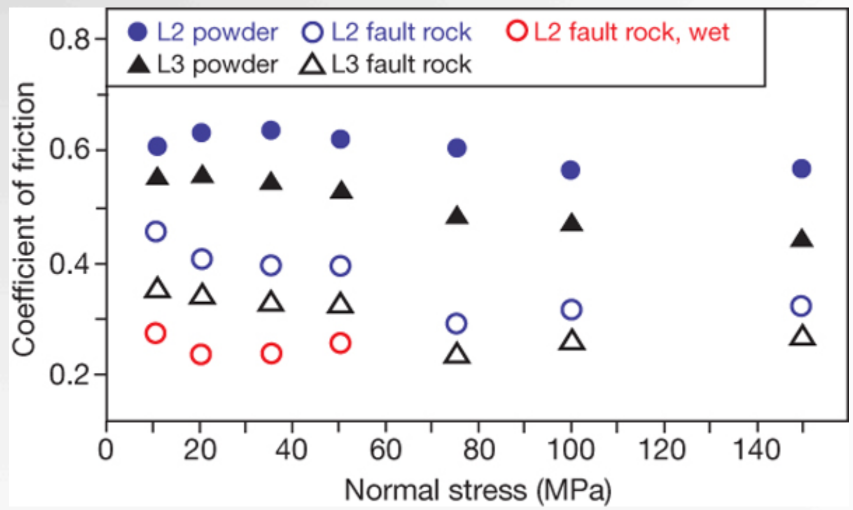
Natural fault samples

- Talc recovered from SAFOD
- Friction coefficient: 0.25



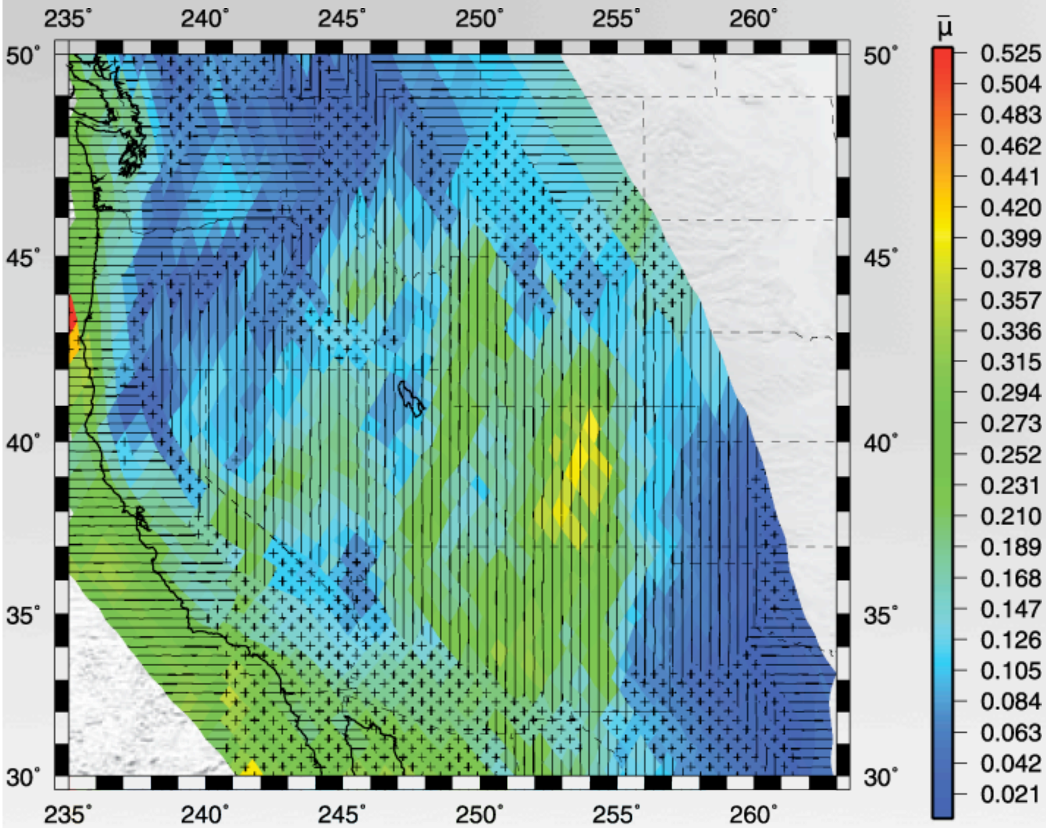
Moore and Rymer, 2007

- Frictional properties of fault rocks and powders made from them
- Fault weakness related to foliated fabric



Collettini et al., 2009

Geodynamic evidence for weak faults



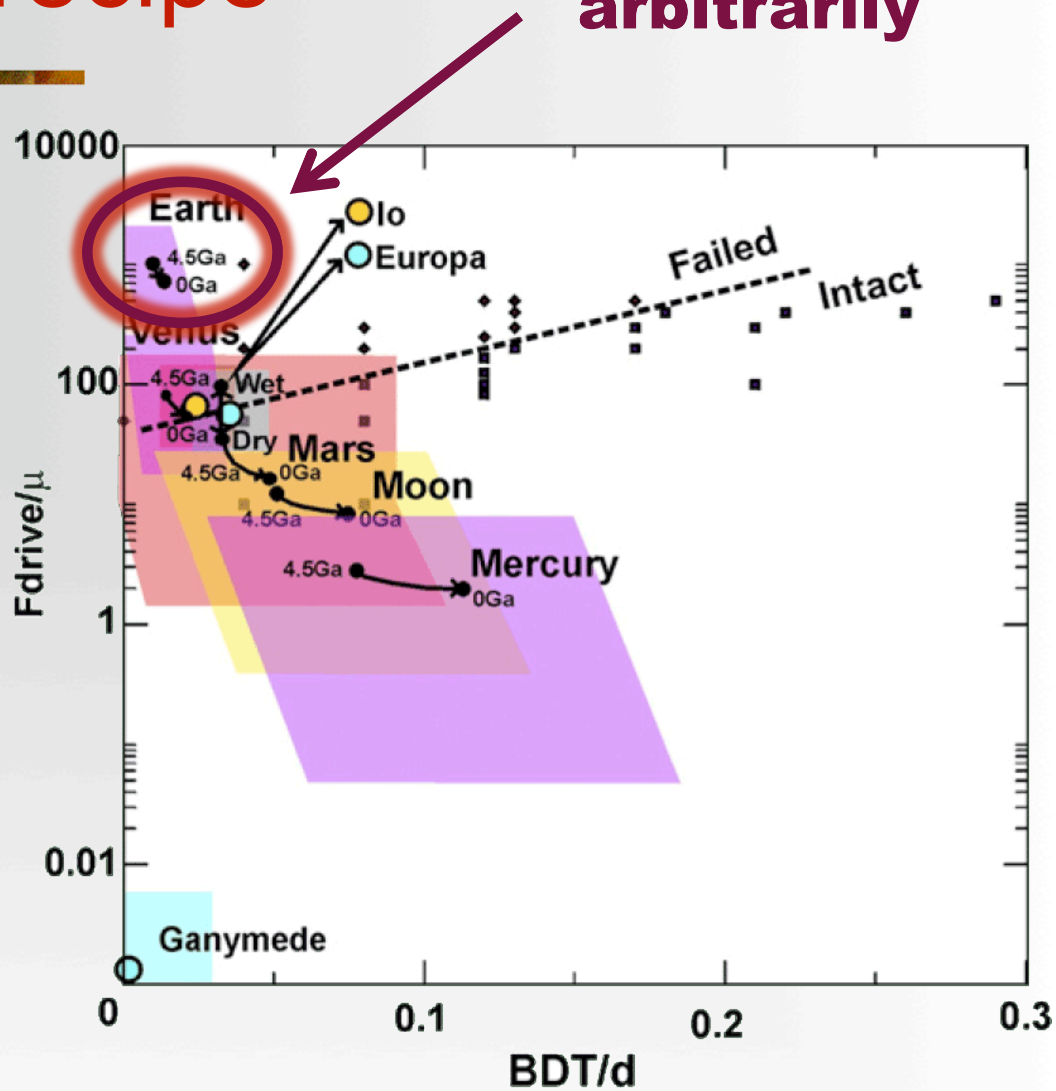
Flesch et al., 2007
Klein et al., 2009

- Geodynamic modeling of stress orientation and tectonic style
  - Klein et al., 2009
  - 20-40 MPa average viscosity, dominated by seismogenic depths
  - Coefficient of friction of 0.2 or less even with λ=0.7 (“wet” crust)
- Slip and stress inversions
  - Carena & Moder, 2010
  - Coefficient of friction between 0.05 and 0.2,

A plate tectonic recipe

- Vigorous convection
- Failure in the lithosphere
  - Yield strength <~3 MPa (Solomatov, 2004)
  - Effective coefficient of friction: 0.15 (O'Neill et al. 2007)

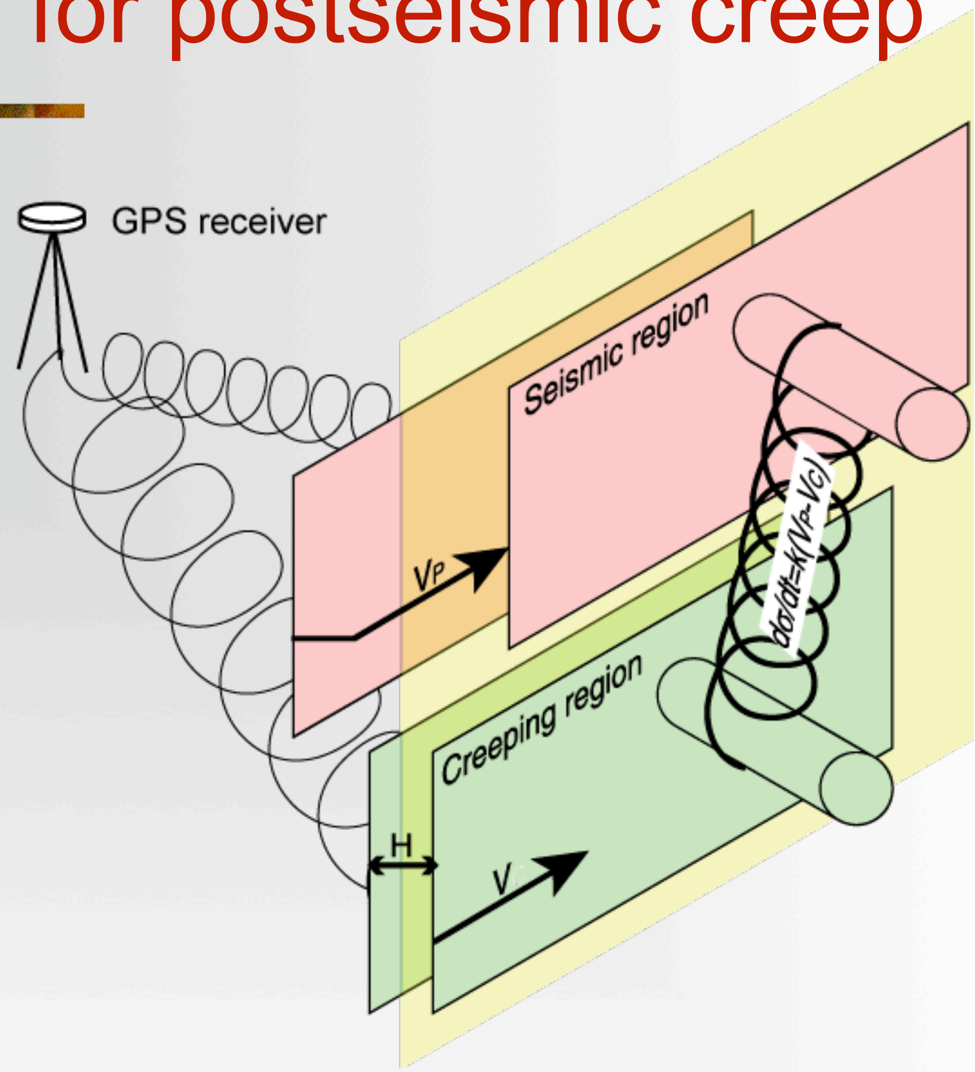
Weakened arbitrarily



O'Neill, Jellinek, and Lenardic, 2007

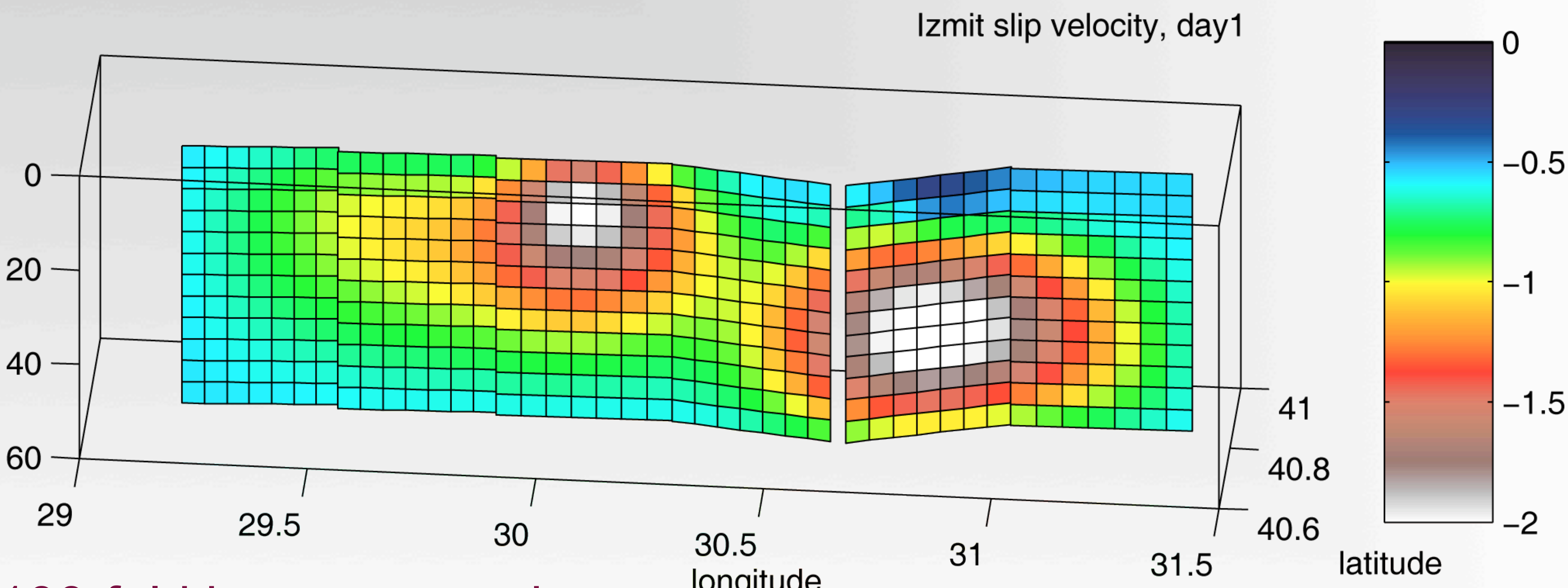
Conceptual model for postseismic creep

- Sudden motion on fault loads elastically nearby shear zone
- Shear zone accelerates
- When stress is released, shear zone decelerates



Change in shear zone velocity

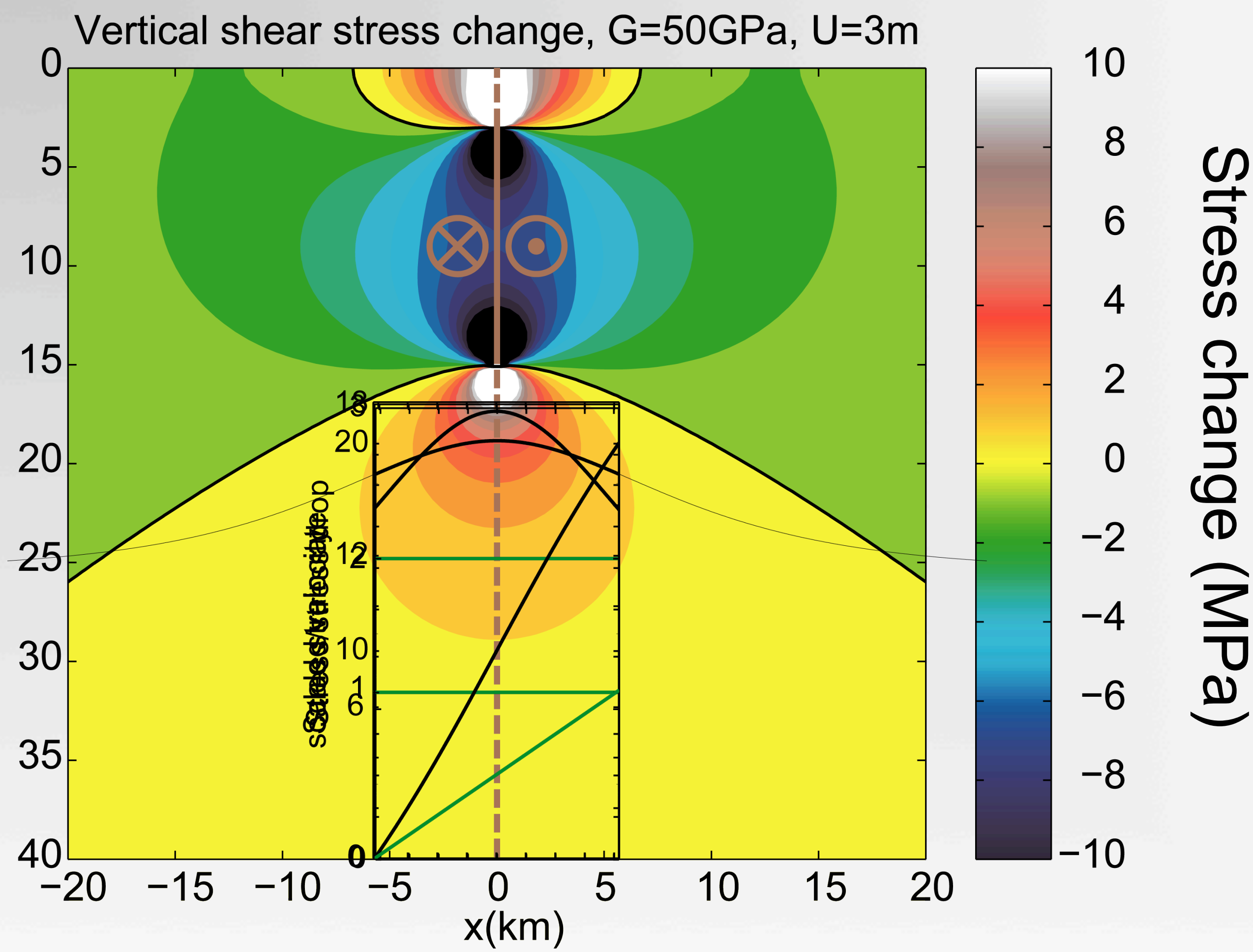
- North Anatolian Fault interseismic velocity: 25 mm/yr (McClusky et al., 2001)
- Post-Izmit slip rate: up to 2 m/yr



100-fold increase requires initial stress comparable to stress drop

Bürgmann et al., 2002

Transient velocity increase

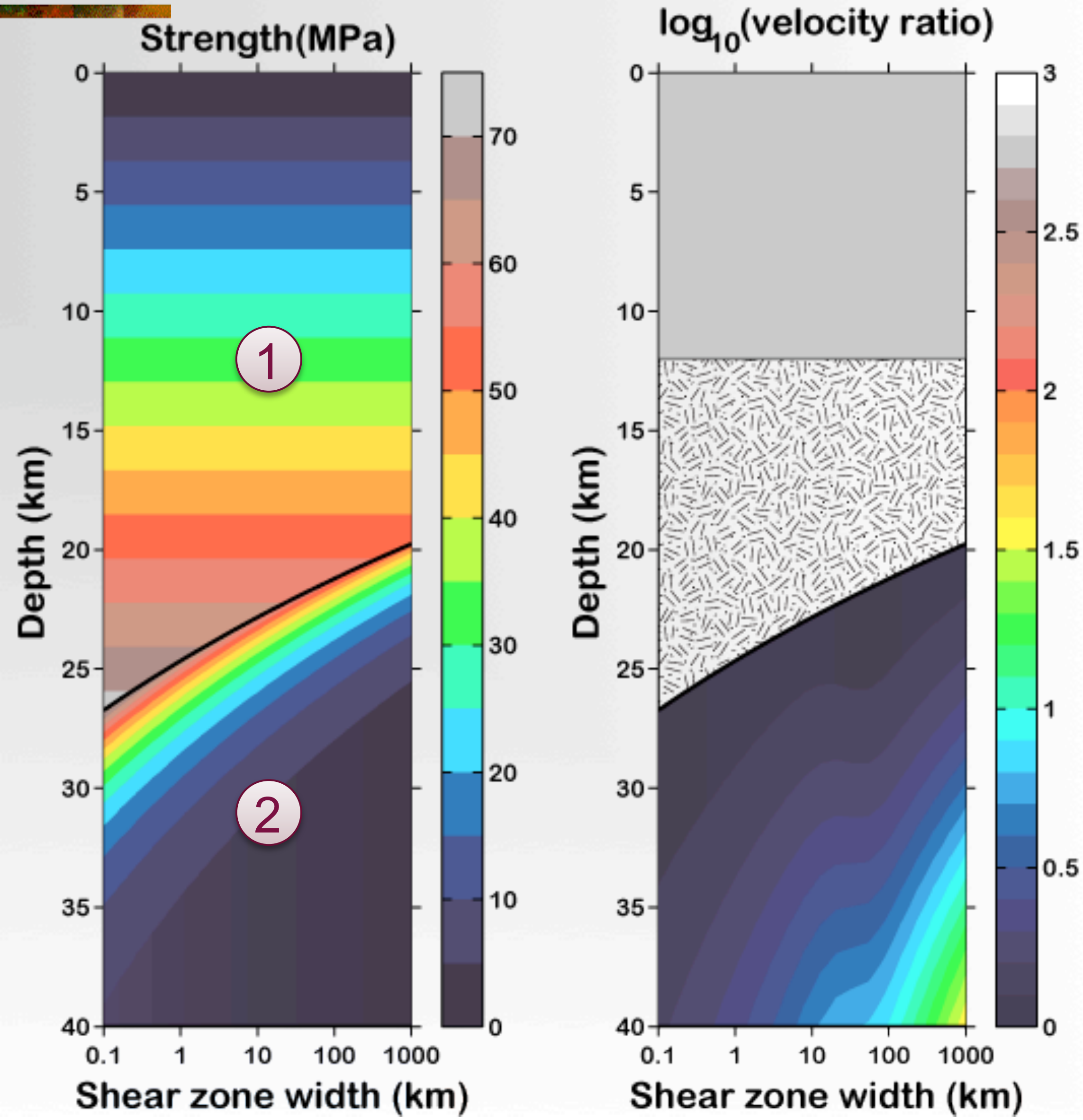


Feldspar dislocation creep

- Anorthite flow law (Rybacky and Dresen, 2000)
  - 0.07 wt% H_2O: “wet” conditions
  - Earthquake to 12 km depth, 5m slip
  - 30 K/km geotherm
- Shear zone is too strong: no response to earthquake

① Brittle (f=0.1)

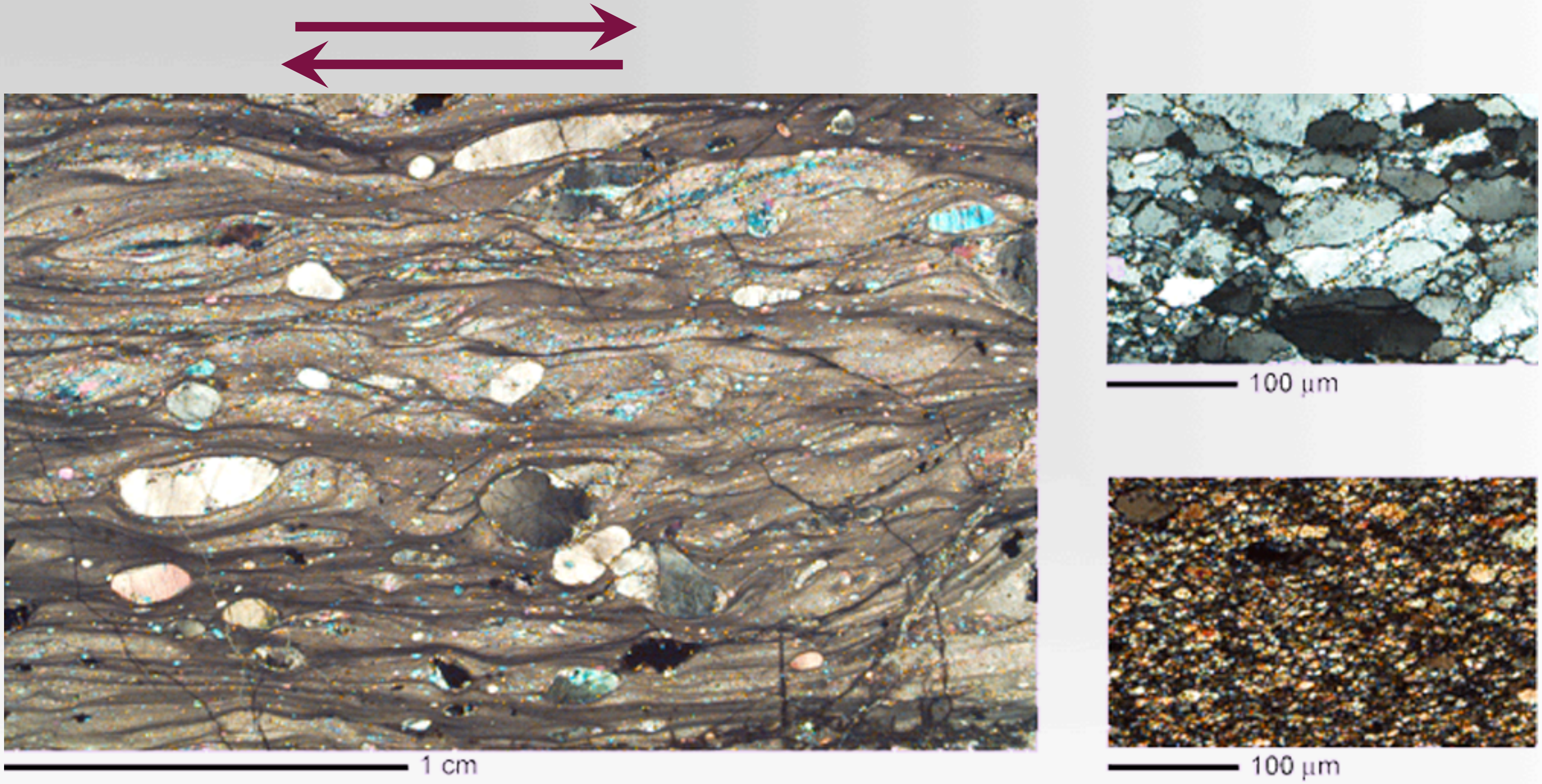
② Dislocation creep



Grain Size Reduction

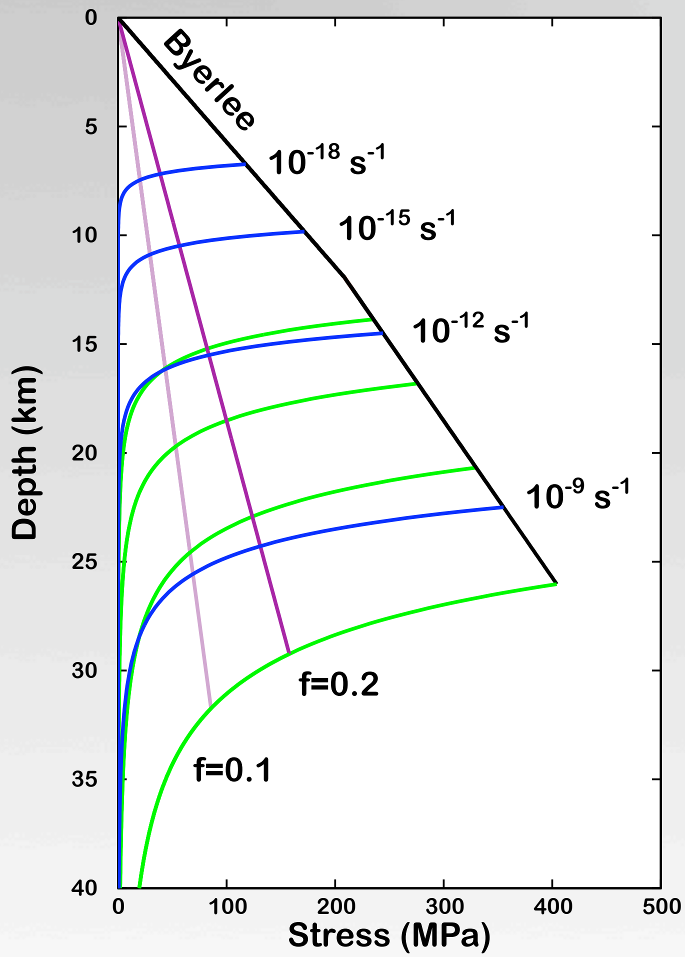
- Mylonite in oceanic peridotite, Shaka Fracture zone

Shear direction



Warren and Hirth, 2006

Grain size reduction



- Byerlee" friction
- Wet anorthite rheology (Rybacki and Dresen 2000)
  - Dislocation creep
  - Diffusion creep 10 microns grain size
- Surface geotherm 30°/km
- Strain rate 10^{-9} to 10^{-18} s^{-1}

Feldspar dislocation creep

- Anorthite flow law (Rybacky and Dresen, 2000)
  - 0.07 wt% H_2O: “wet” conditions
  - Earthquake to 12 km depth, 5m slip
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① Brittle (f=0.1)

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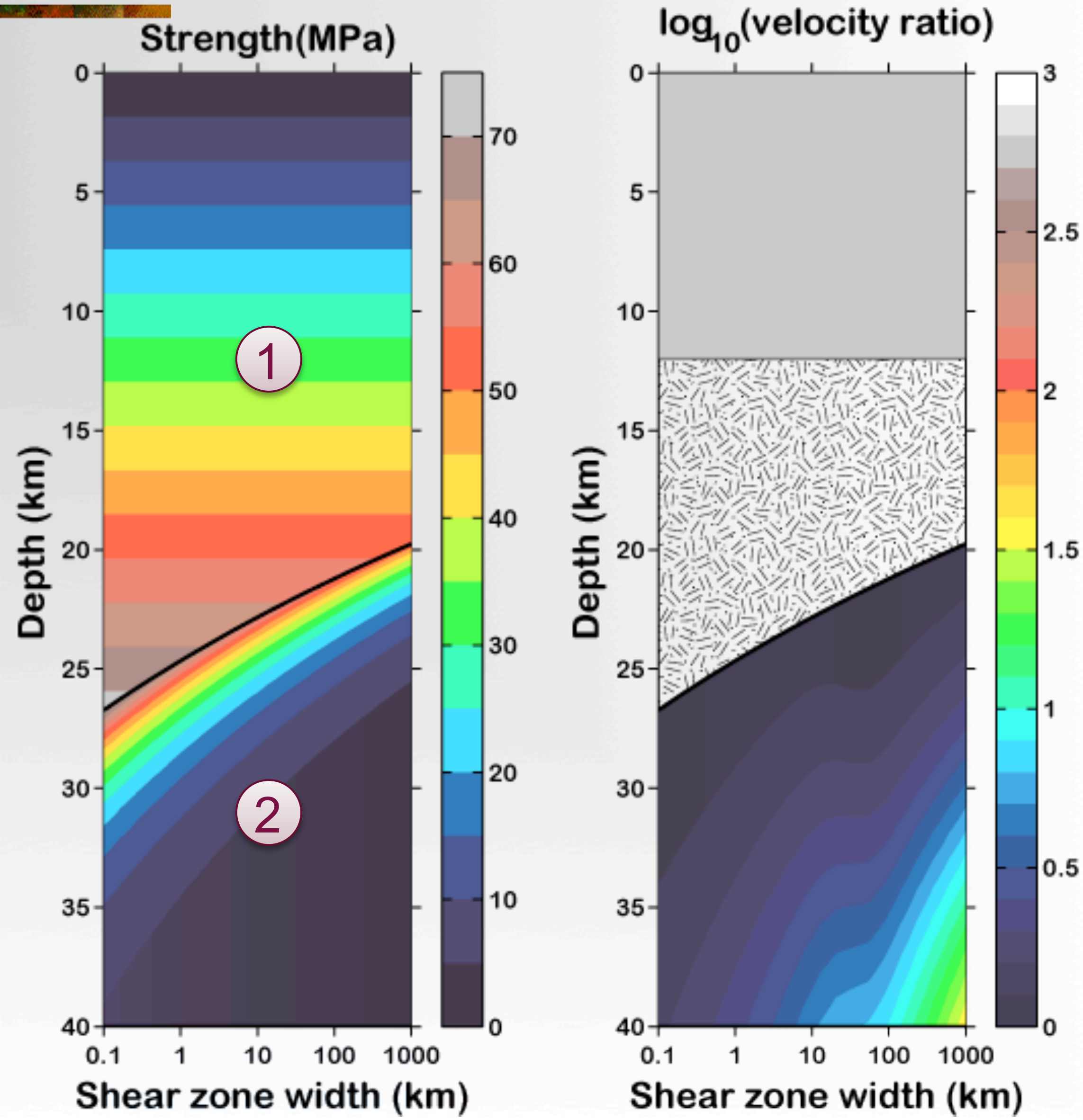
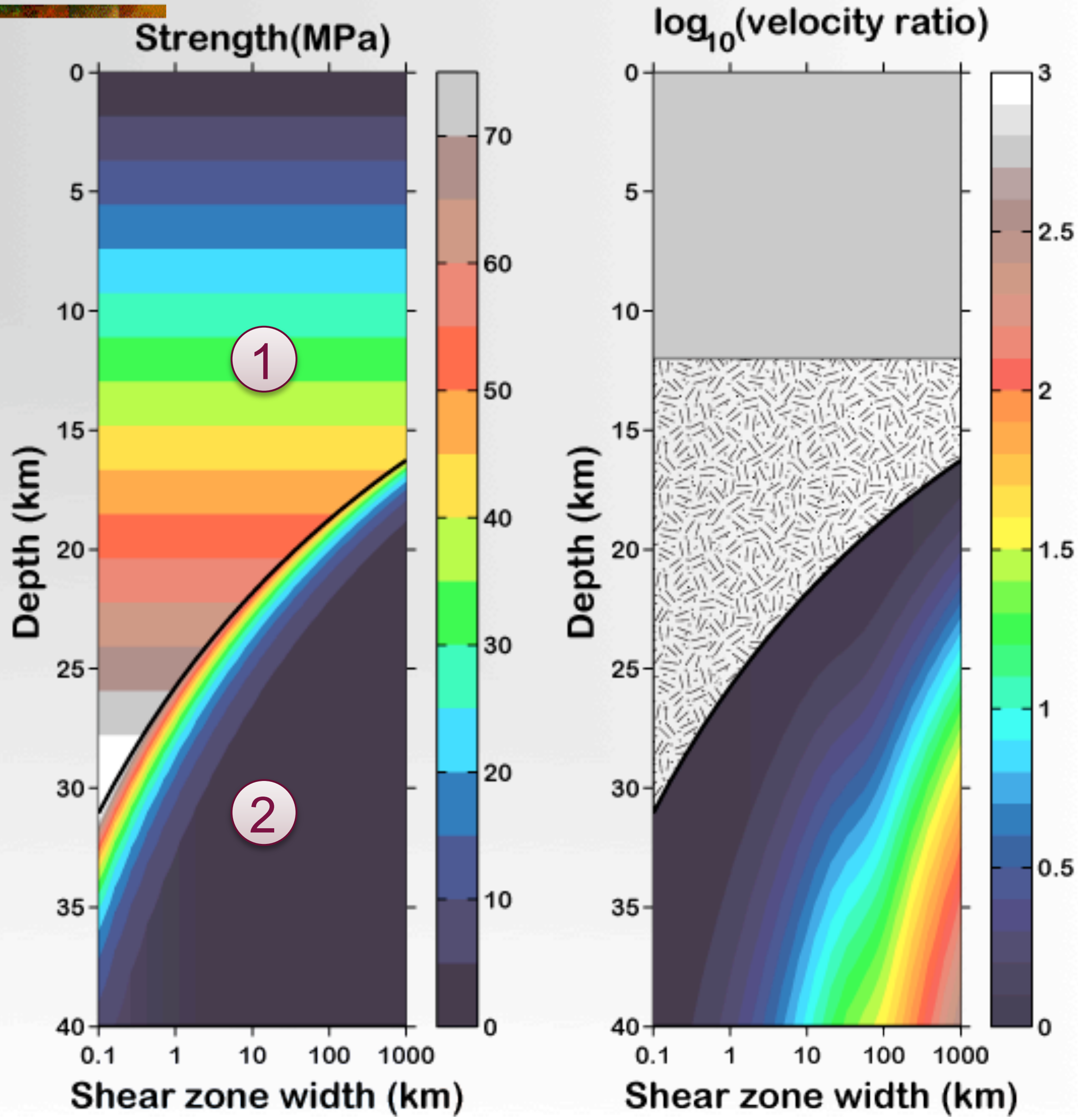


Feldspar (100 μm grain size)

- Anorthite flow law (Rybacky and Dresen, 2000)
  - 0.07 wt% H_2O: “wet” conditions
  - Earthquake to 12 km depth, 5m slip
  - 30 K/km geotherm
- Shear zone is still too strong

① Brittle (f=0.1)

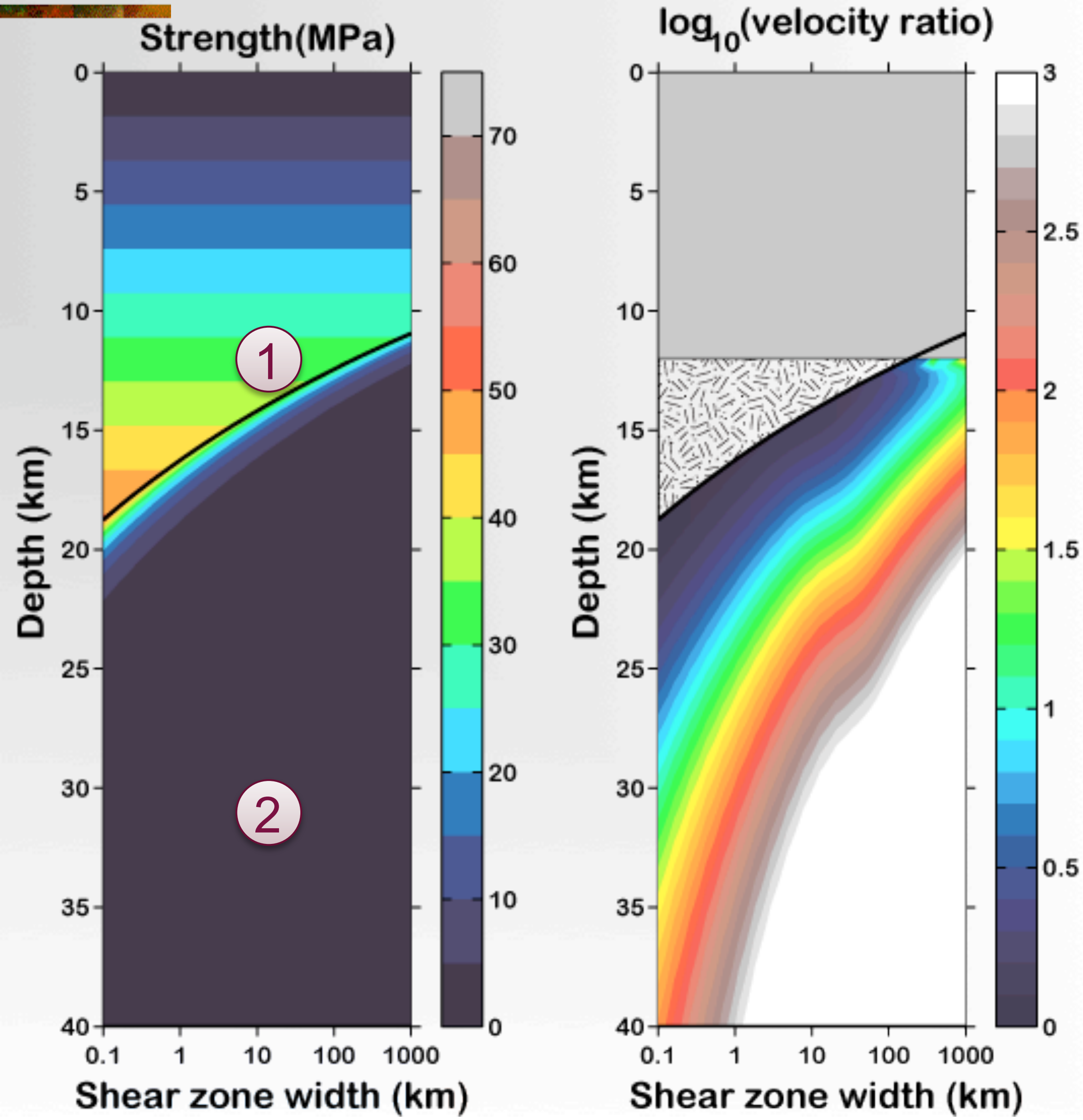
② Diffusion creep



Feldspar (10 µm grain size)

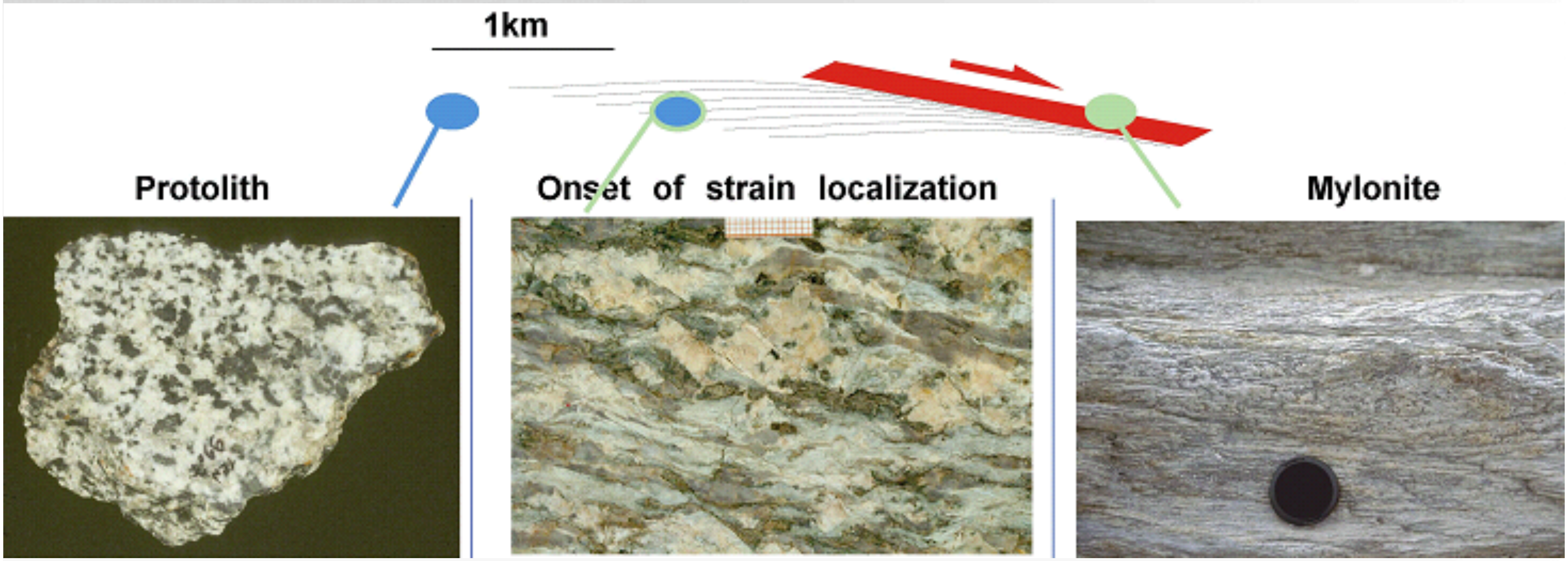
- Anorthite flow law (Rybacky and Dresen, 2000)
  - 0.07 wt% H_2O: "wet" conditions
  - Earthquake to 12 km depth, 5m slip
  - 30 K/km geotherm
- Deep postseismic creep in wide shear zones only

1. Brittle (f=0.1)
2. Diffusion creep



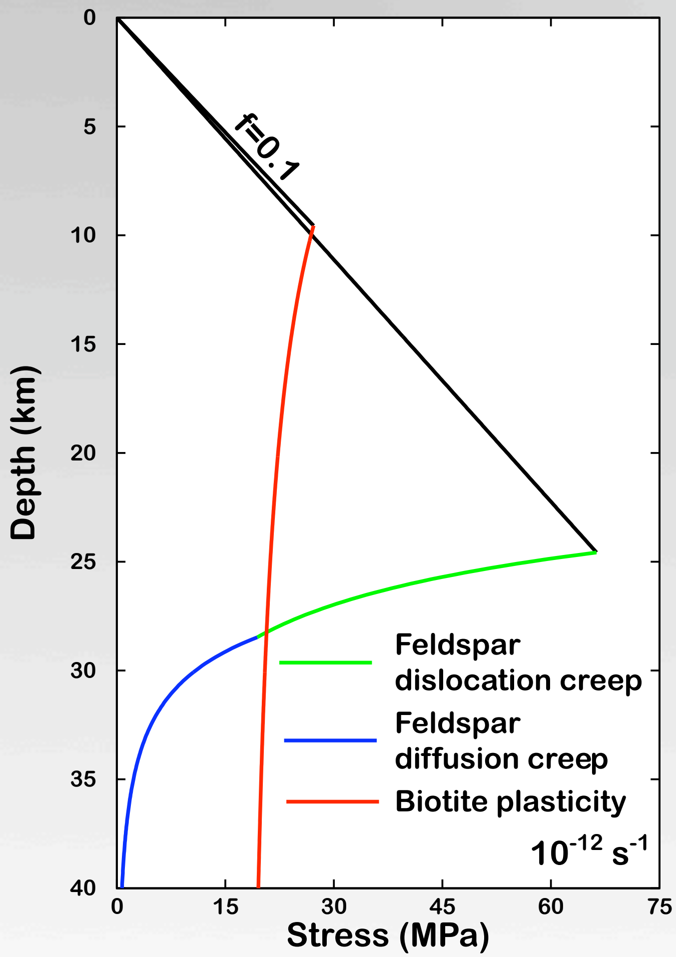
Fabric development and metamorphism

- Tenda Massif, Corsica (granitoid)
- Initial localization: fracturing of Feldspar
- Mylonite development: Feldspar-to-mica reaction



Gueydan et al., JGR, 2003

Mica rheology



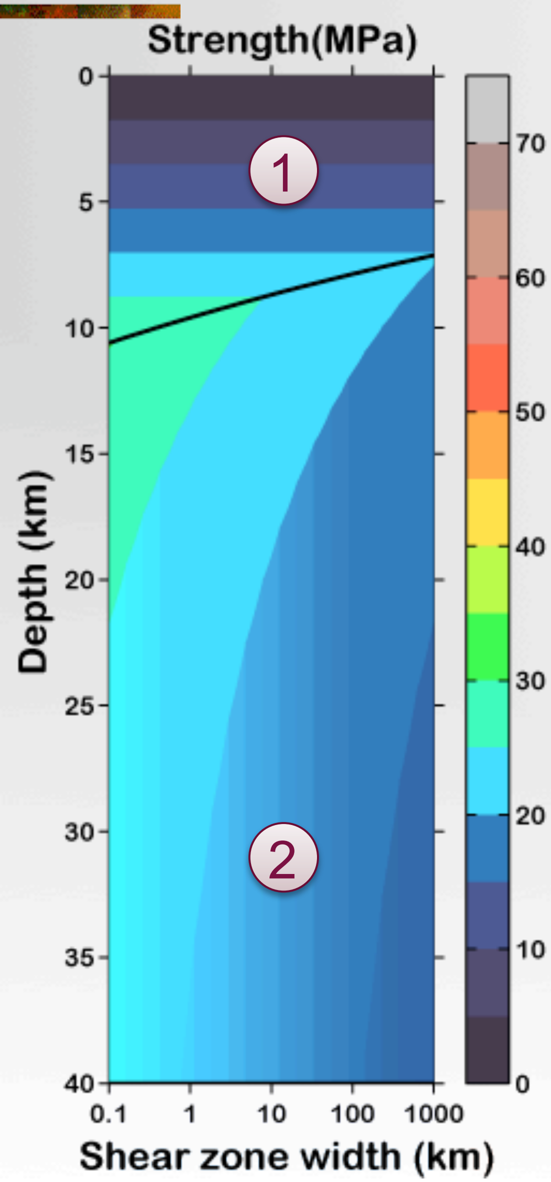
- Kronenberg, 1990
- Biotite aggregate
  - Low activation energy
  - High stress exponent
  - Power law may not be the most appropriate rheology

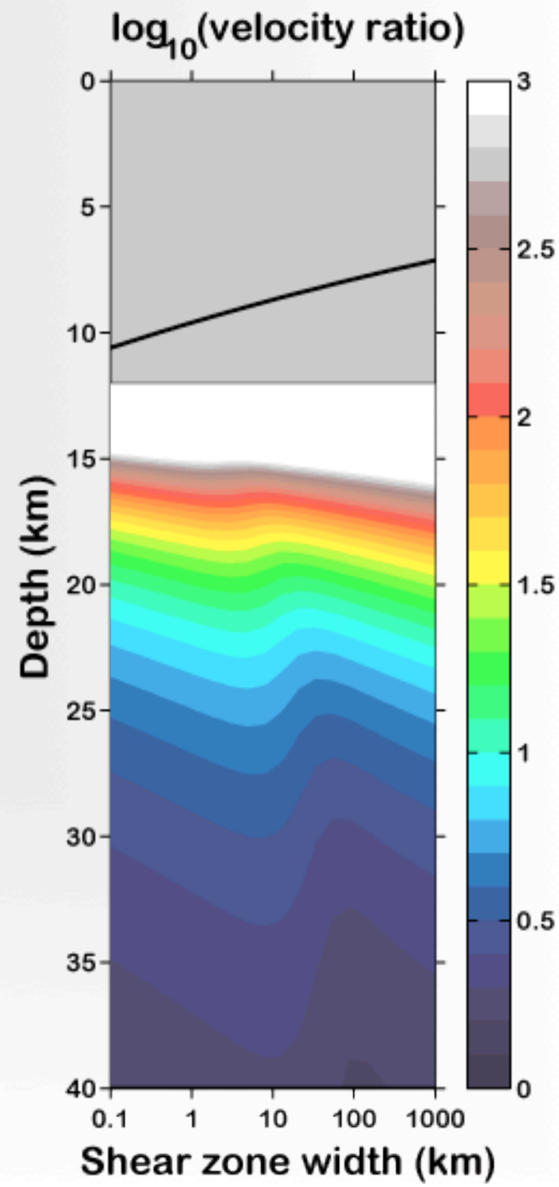
Biotite shear zone

- Biotite flow law (Kronenberg, 1990)
  - Highly nonlinear
  - Little temperature dependence
- Shallow postseismic creep
- Mica acts as strength control

① Brittle (f=0.1)

② Biotite dislocation creep



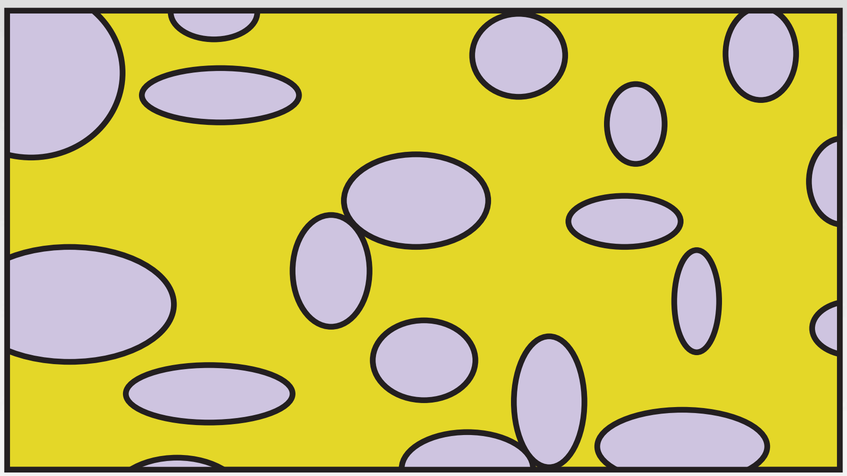


End-member mixture models

Constant strain rate

Appropriate of well-mixed aggregate, with strain incompatibility

Protolith

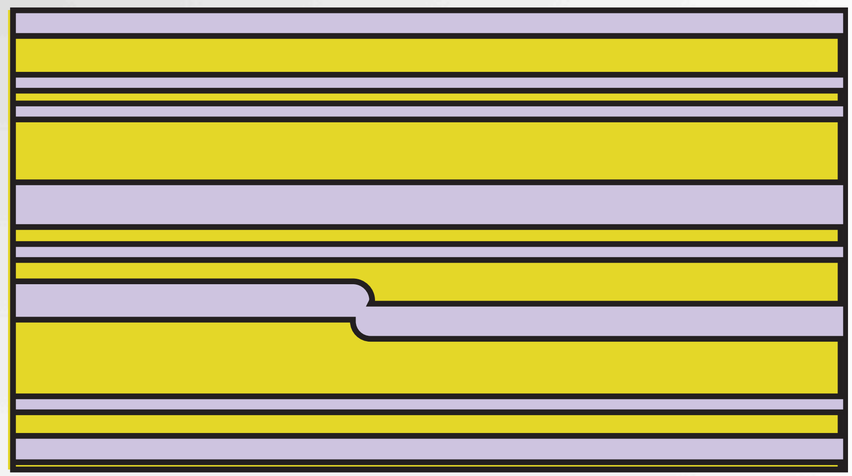


$$\sigma_d = (1 - C)\left(\dot{\varepsilon}/A_a\right)^{n_a} + C\left(\dot{\varepsilon}/A_b\right)^{n_b}$$

Constant stress

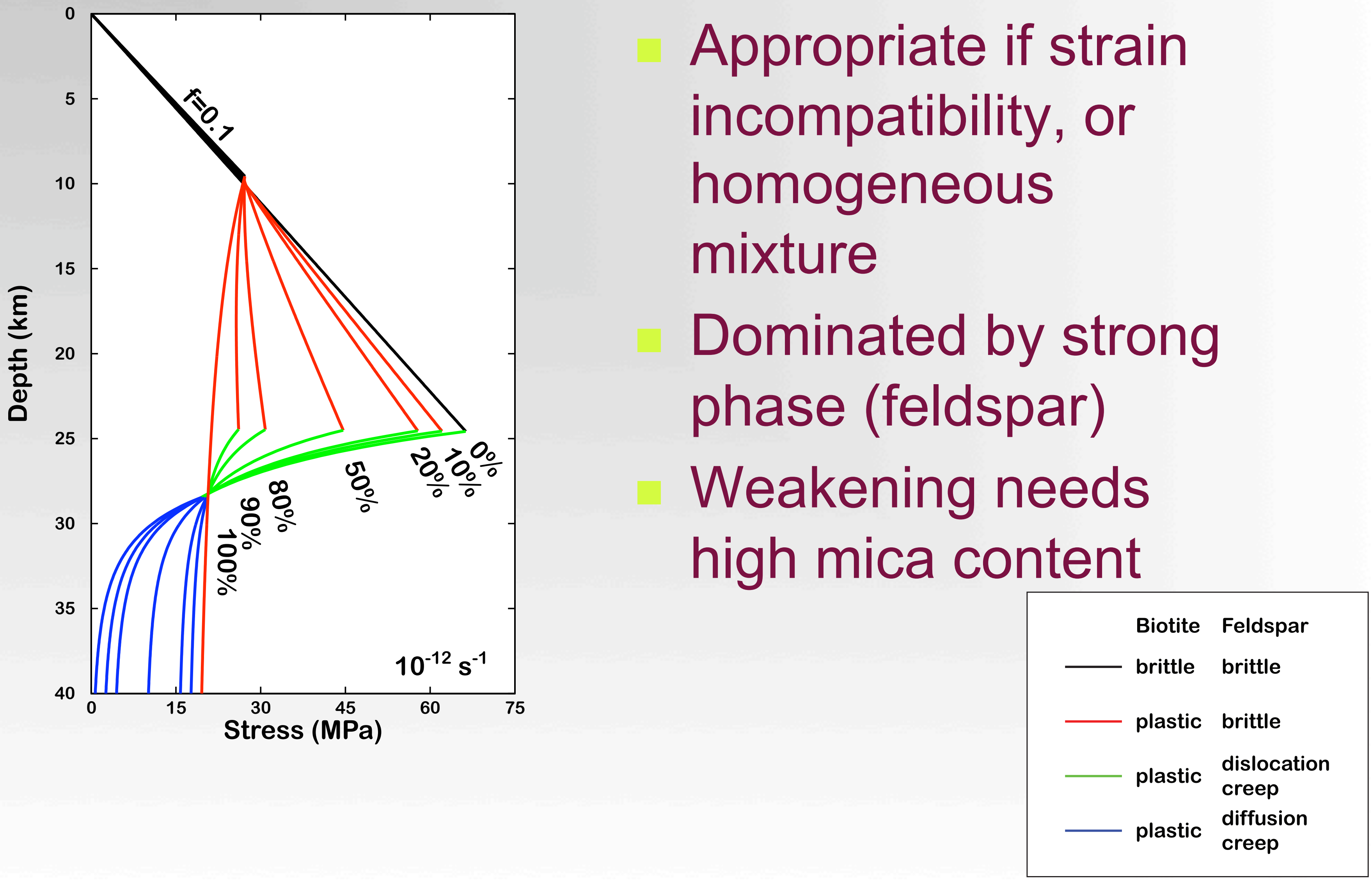
Appropriate for layered fabric, with phase separation

Shear zone



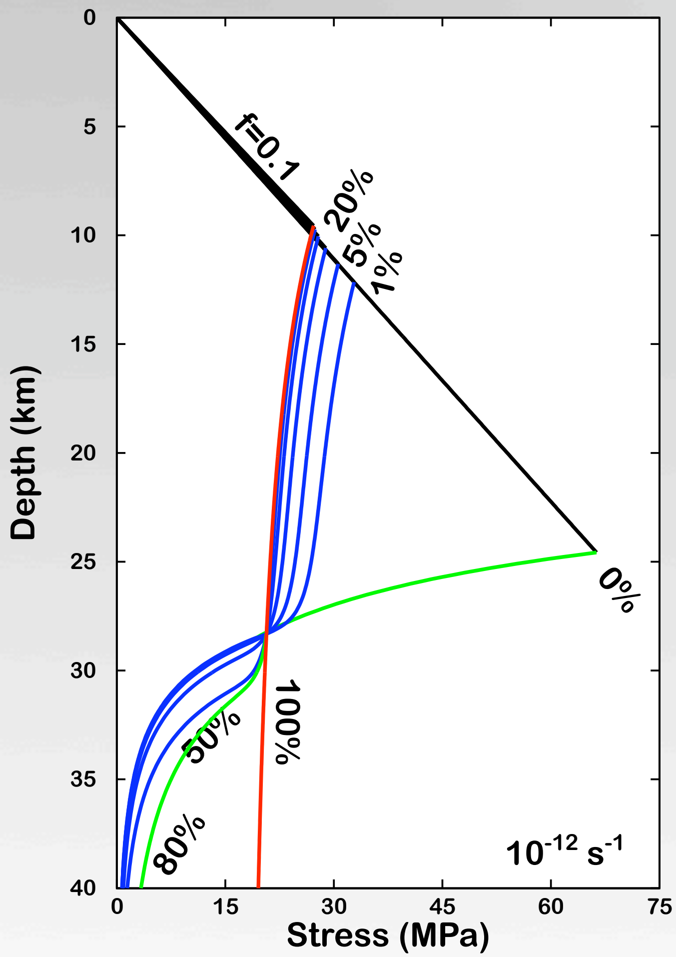
$$\dot{\varepsilon} = (1 - C)A_a\sigma_c^{\ n_a} + CA_b\sigma_c^{\ n_b}$$

Mixing model: constant strain rate

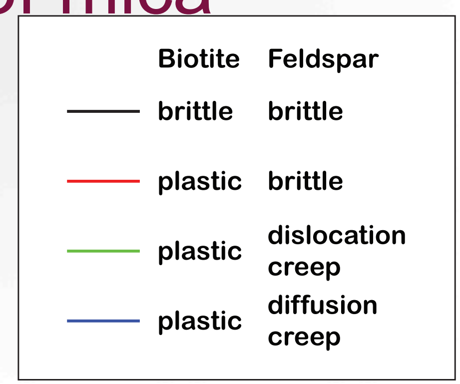


- Appropriate if strain incompatibility, or homogeneous mixture
- Dominated by strong phase (feldspar)
- Weakening needs high mica content

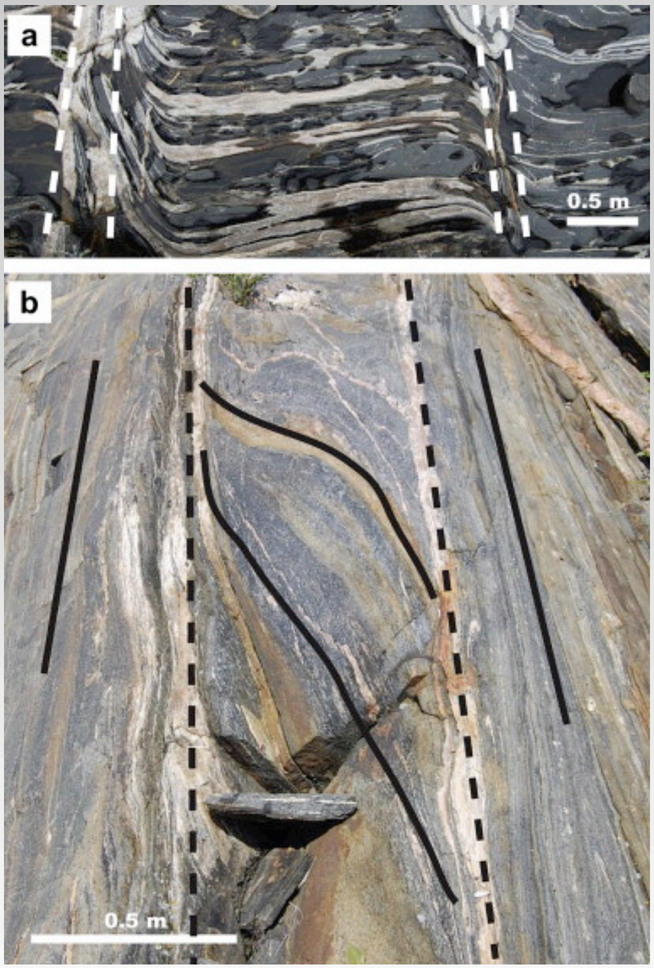
Mixing model: constant stress

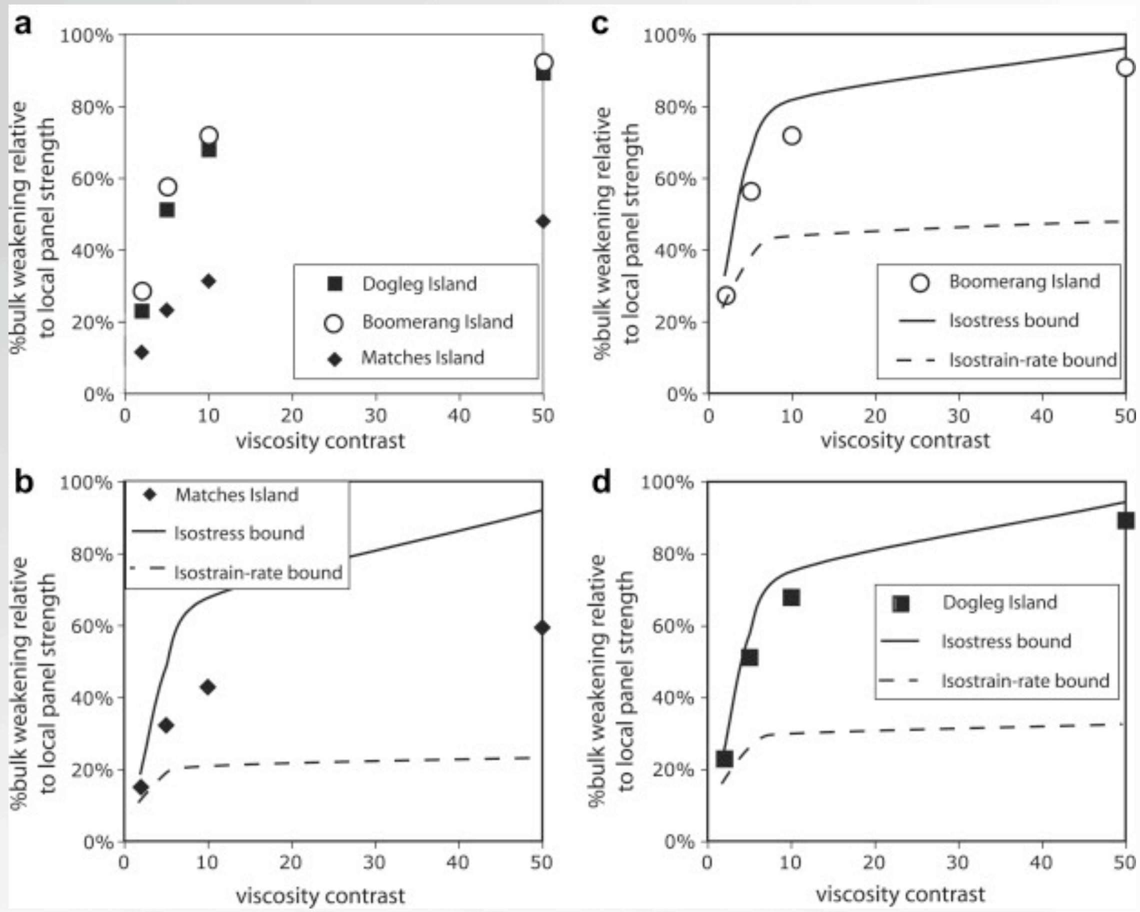


- Appropriate if phase separation, layering
- Dominated by weak phase
- Weakening even for small amounts of
- Almost insensitive to the amount of mica



Strength contrast in shear zones



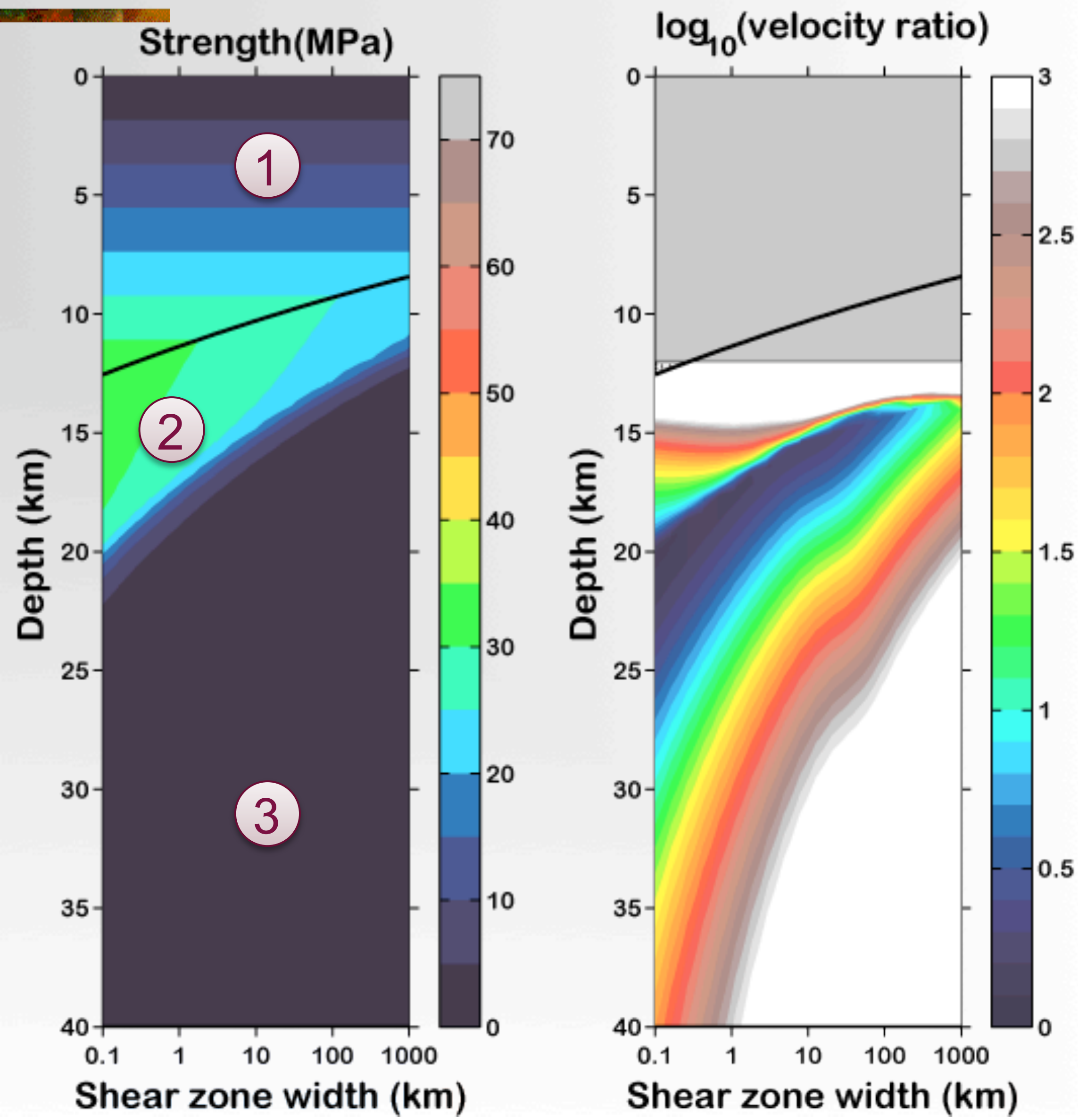


Gerby et al., 2010

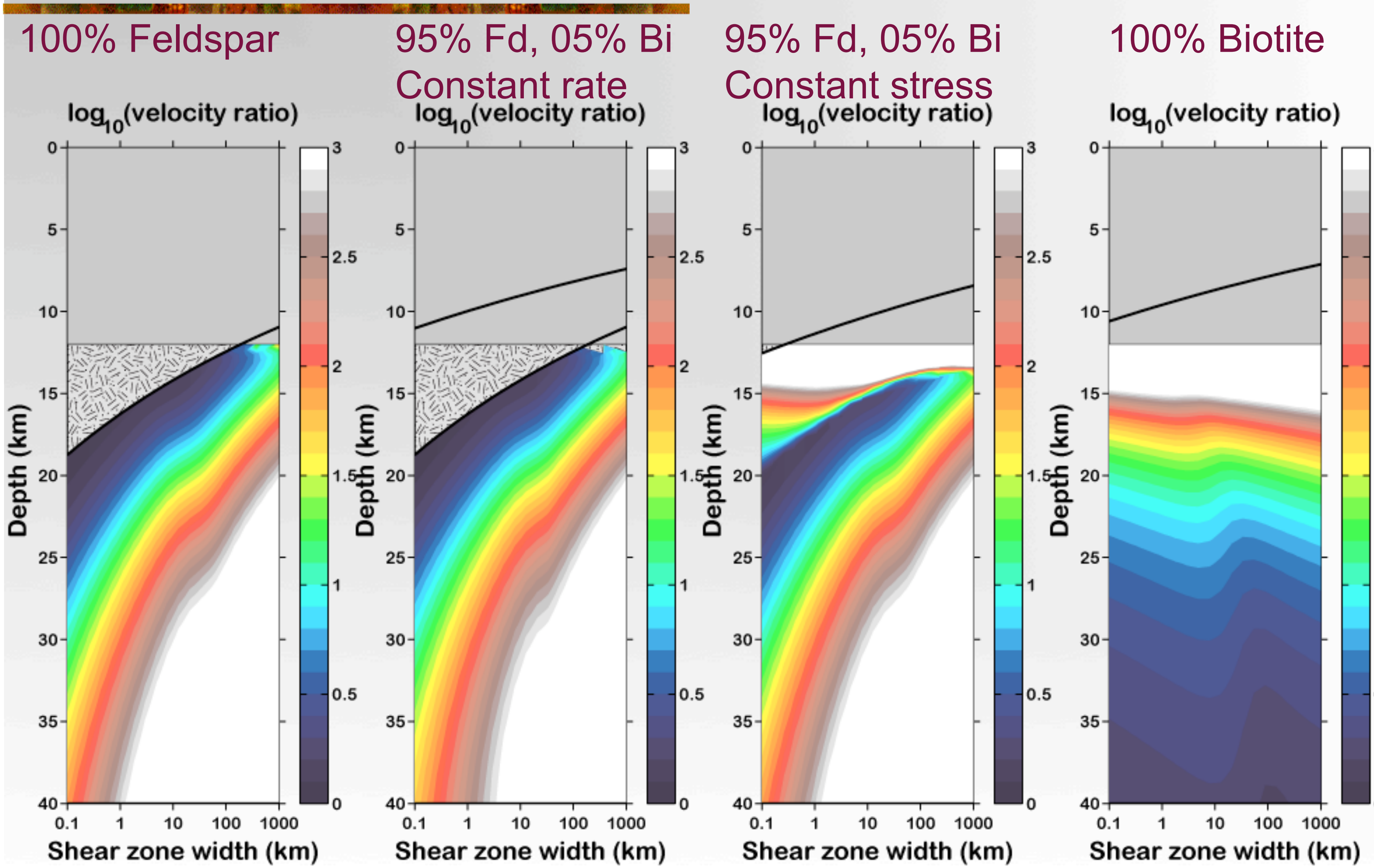
Biotite/feldspar foliated shear zone

- 95 % feldspar (10 μm grain size) and 5% biotite
- Perfect foliation
- Two-level response
  - Near BPT: biotite control
  - At depth: Grain size reduction

1. Brittle (f=0.1)
2. Biotite-dominated plastic creep
3. Feldspar-dominated plastic creep



Effect of fabric (10μm grain size)



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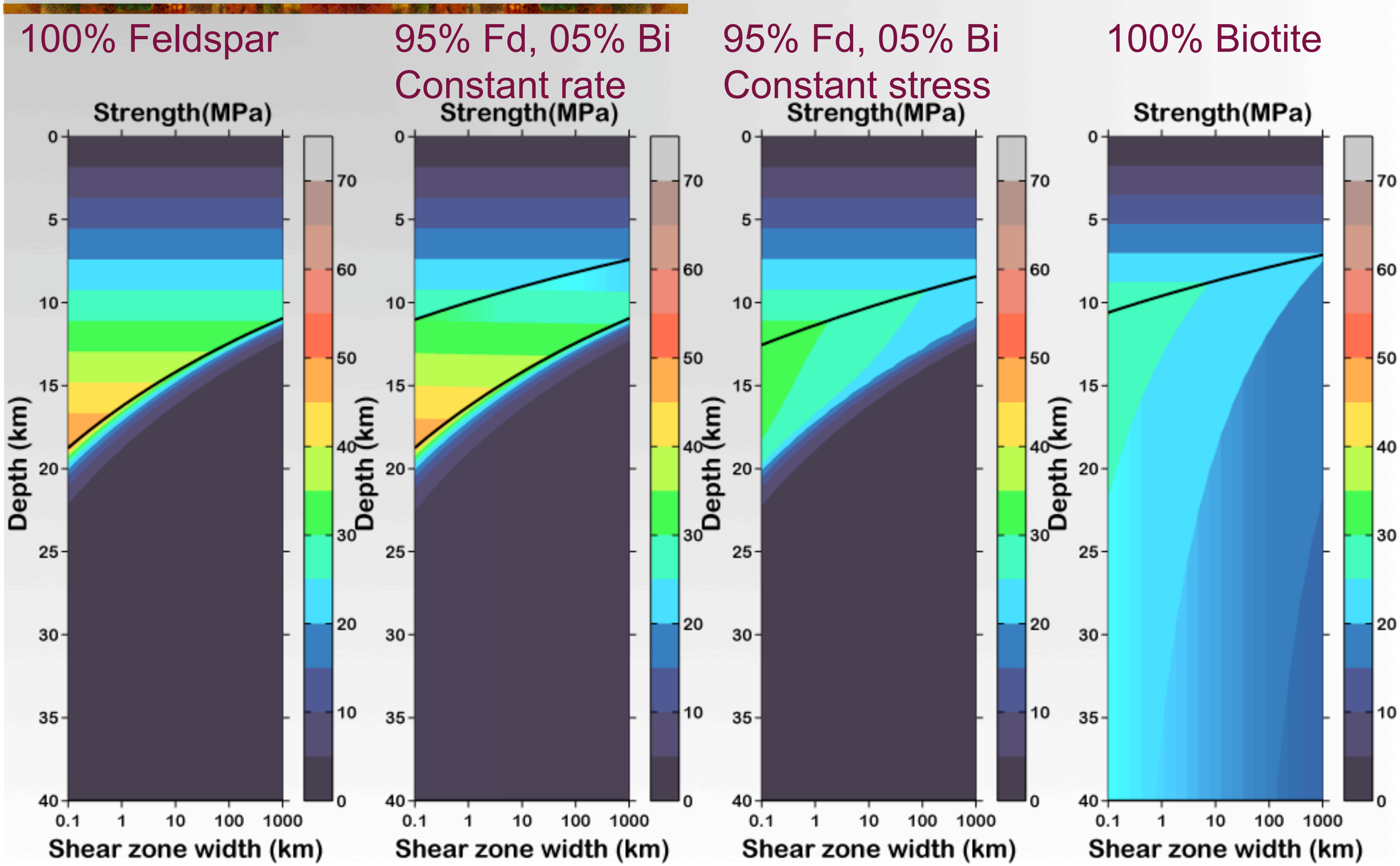
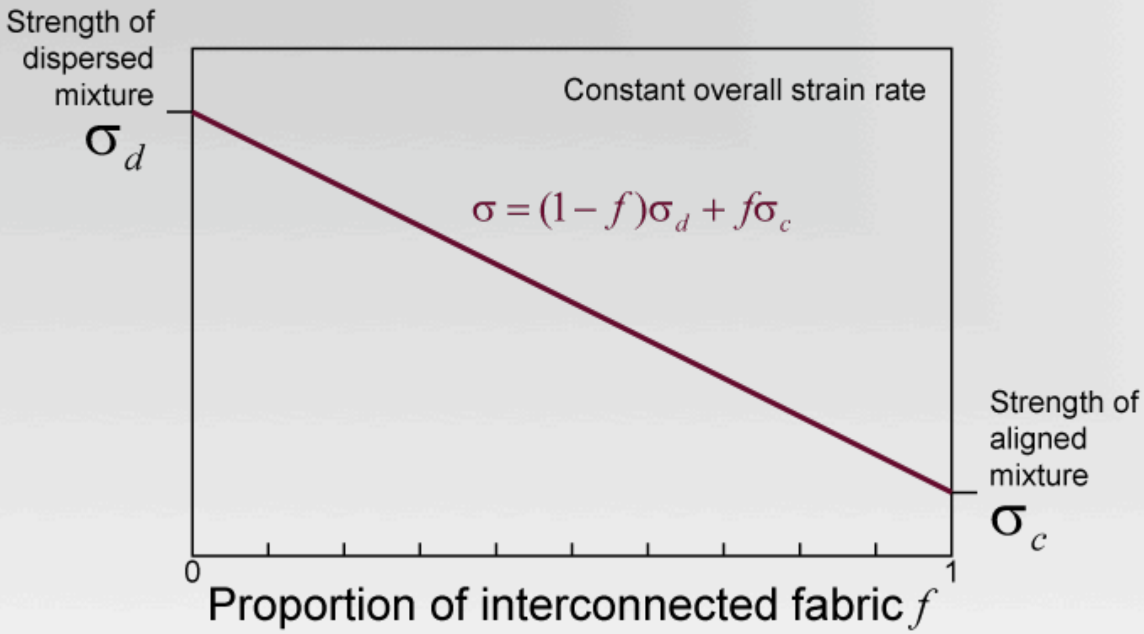
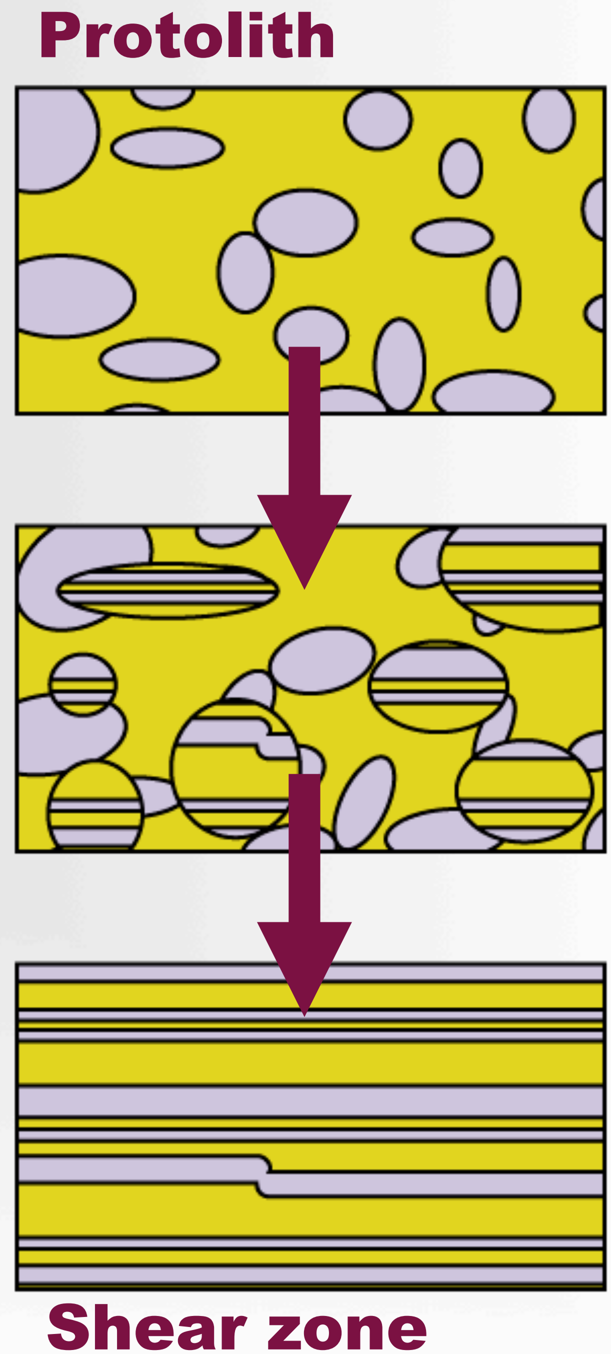


Mixture Model



Interconnected: $\dot{\varepsilon} = (1-C)A_a\sigma_c^{\,n_a} + CA_b\sigma_c^{\,n_b}$

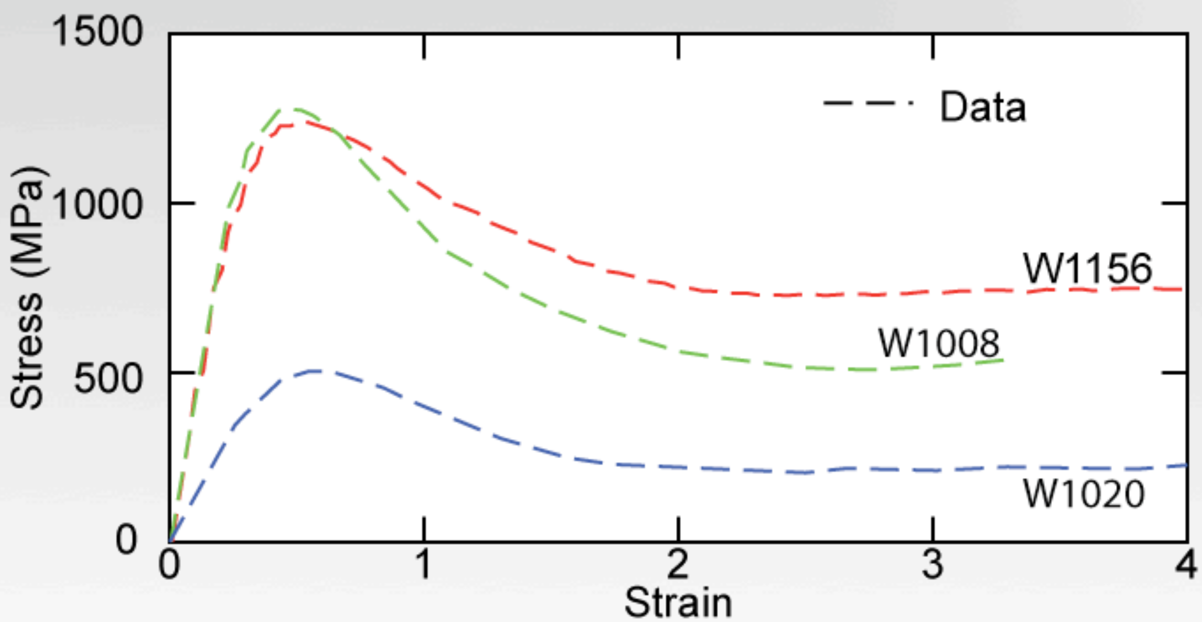
Dispersed: $\sigma_d = (1-C)\left(\dot{\varepsilon}/A_a\right)^{n_a} + C\left(\dot{\varepsilon}/A_b\right)^{n_b}$

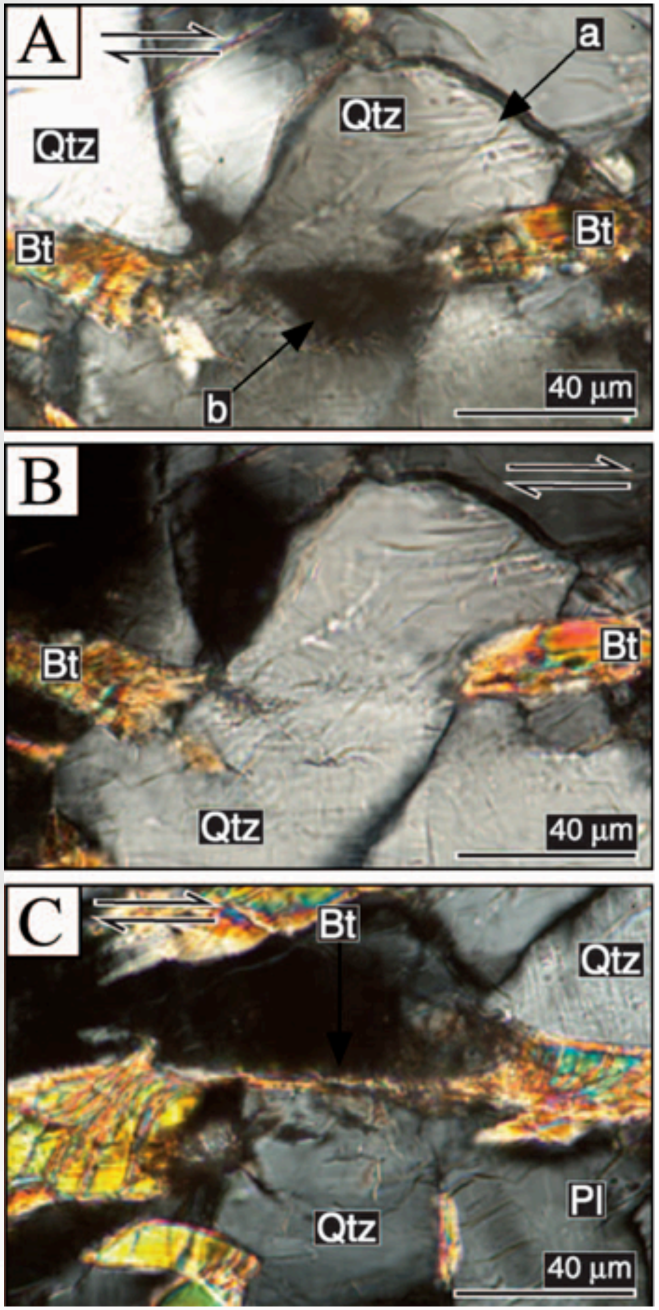


Montési, GRL, 2007

Foliation Development

- Lab experiments on Gneiss Minuti
- Cracking of quartz and feldspar grains between biotite





Holyoke and Tullis, 2006

Fabric evolution

- Two-level mixing rheology

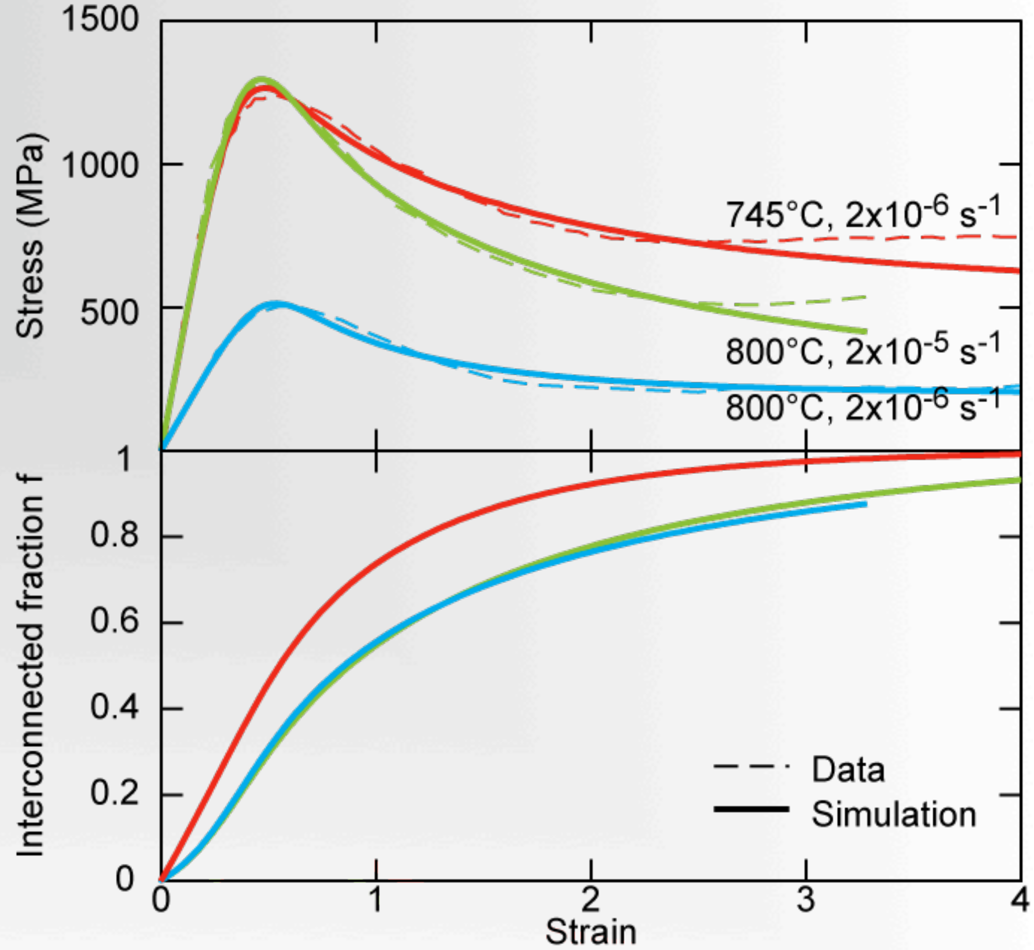
$$\sigma = (1-f)\sigma_d + f\sigma_c$$

- Elastic loading

$$d\sigma/dt = KH(\varepsilon_p - \dot{\varepsilon}_s)$$

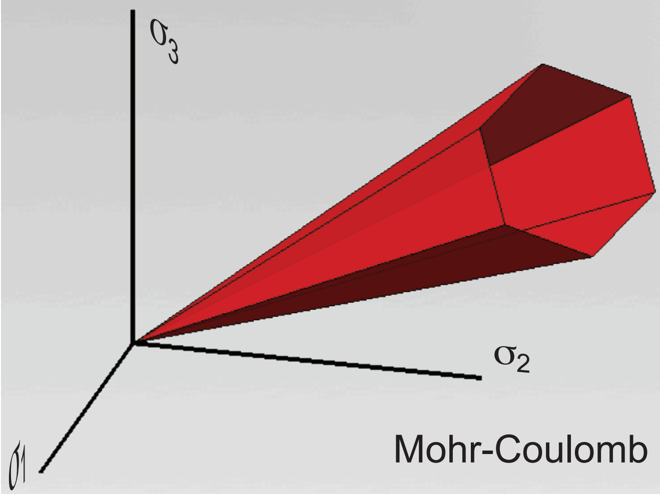
- Connection rate linked to probability of failure

$$\frac{df}{d\varepsilon} = R(1-f)\frac{1}{2}\left[1+\mathrm{erf}\left(\frac{\sigma-\sigma_y}{\chi\sqrt{2}}\right)\right]$$

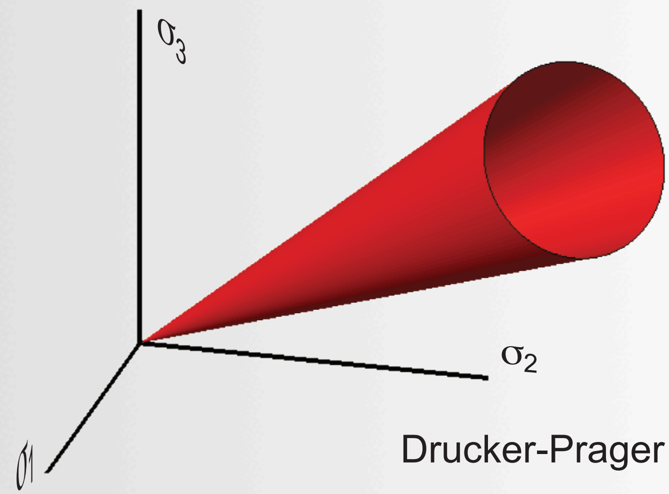


Montési, GRL, 2007

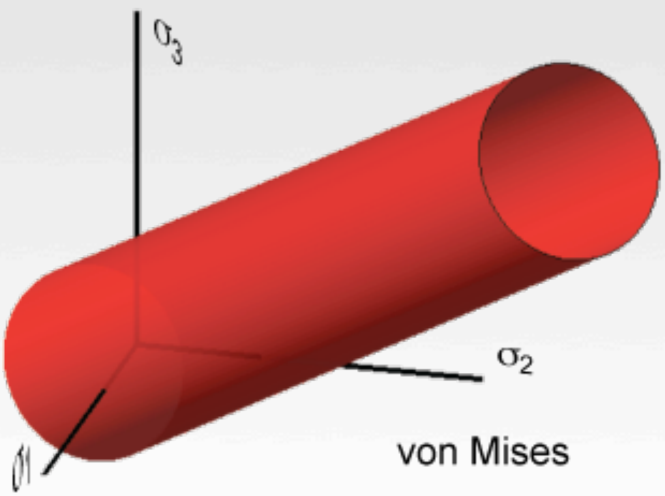
Yield surfaces



Fault surfaces

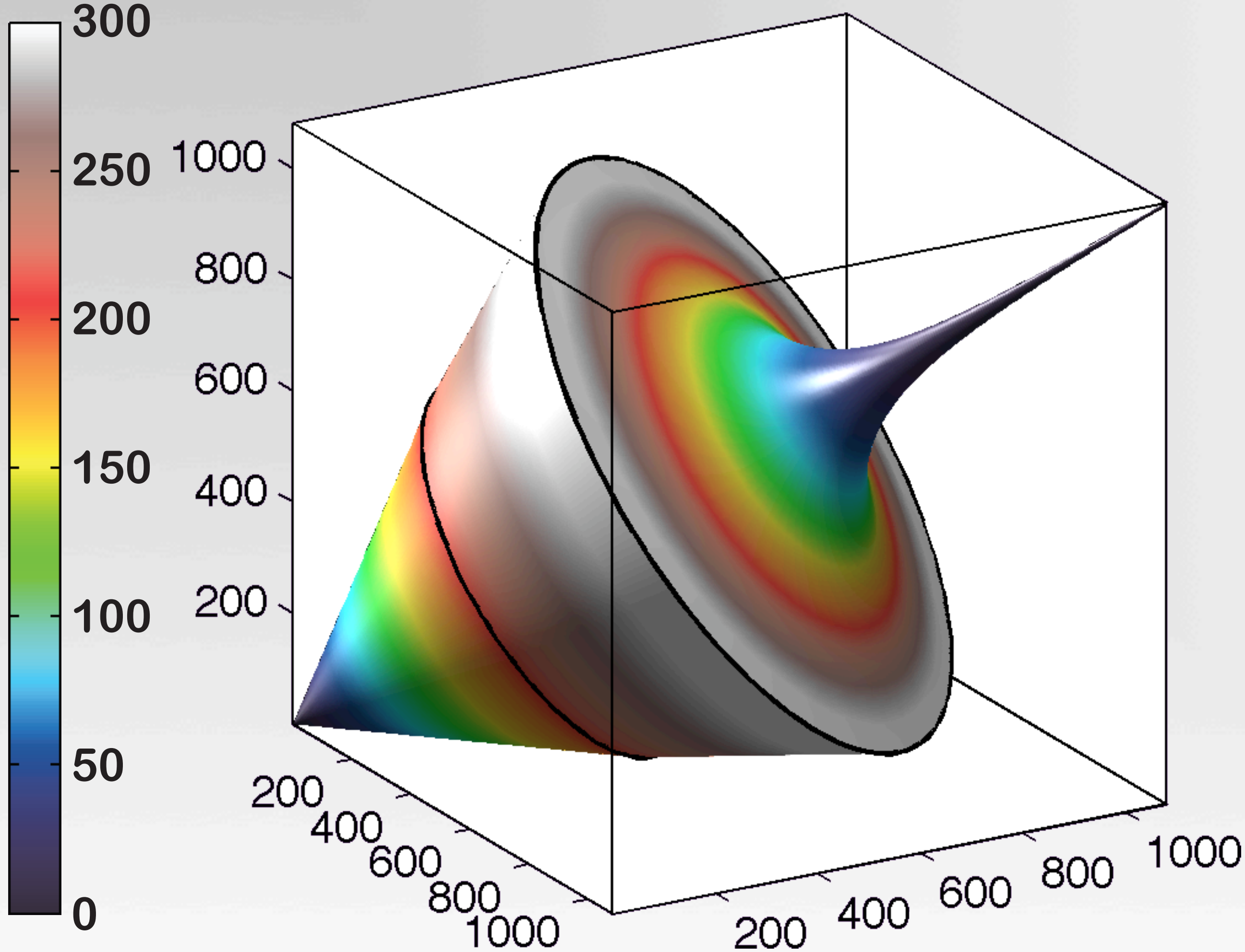


Fault continuum (in PyLith)



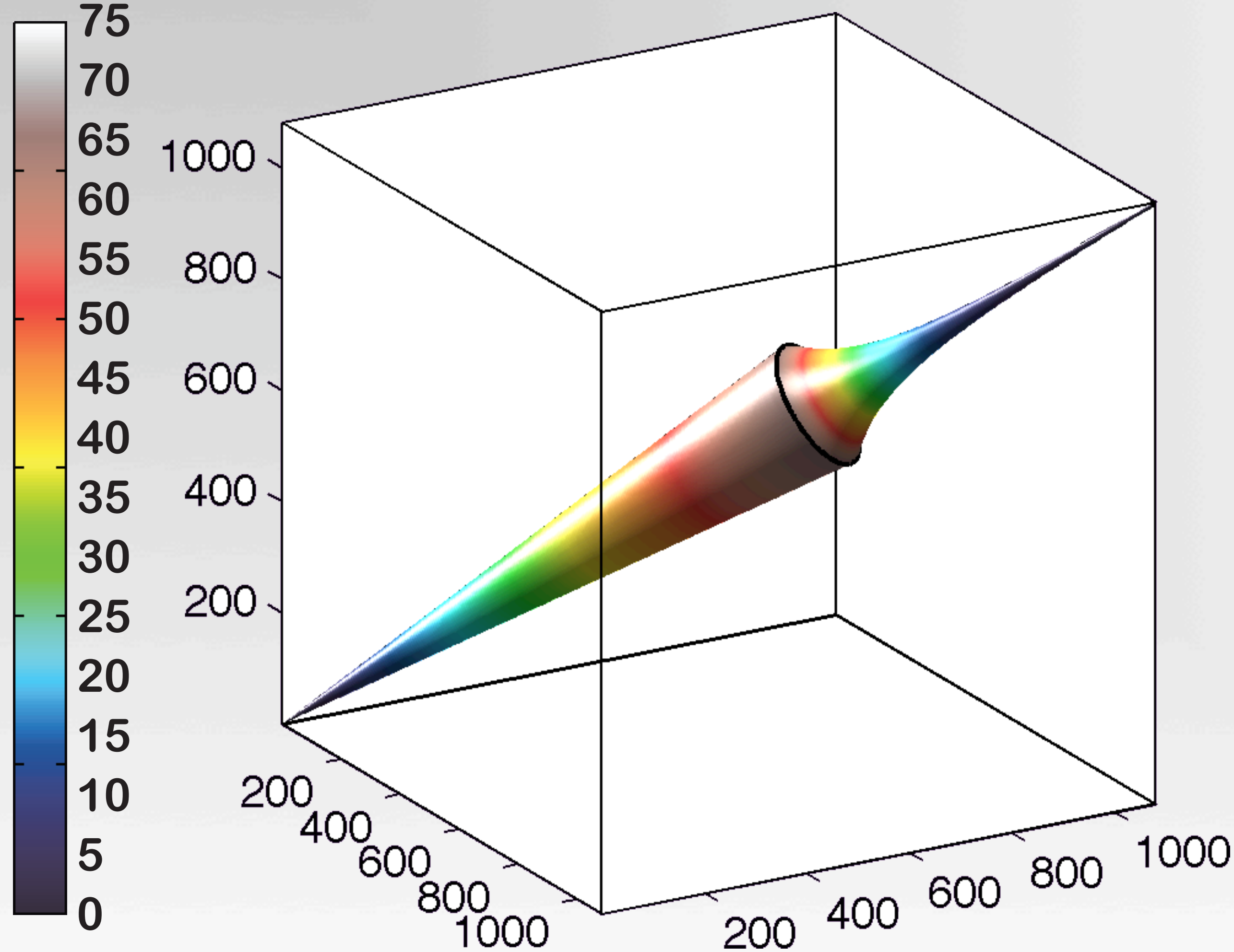
For plasticity
(depends on Temperature, environment, strain rate)

3D yield envelope (standard)



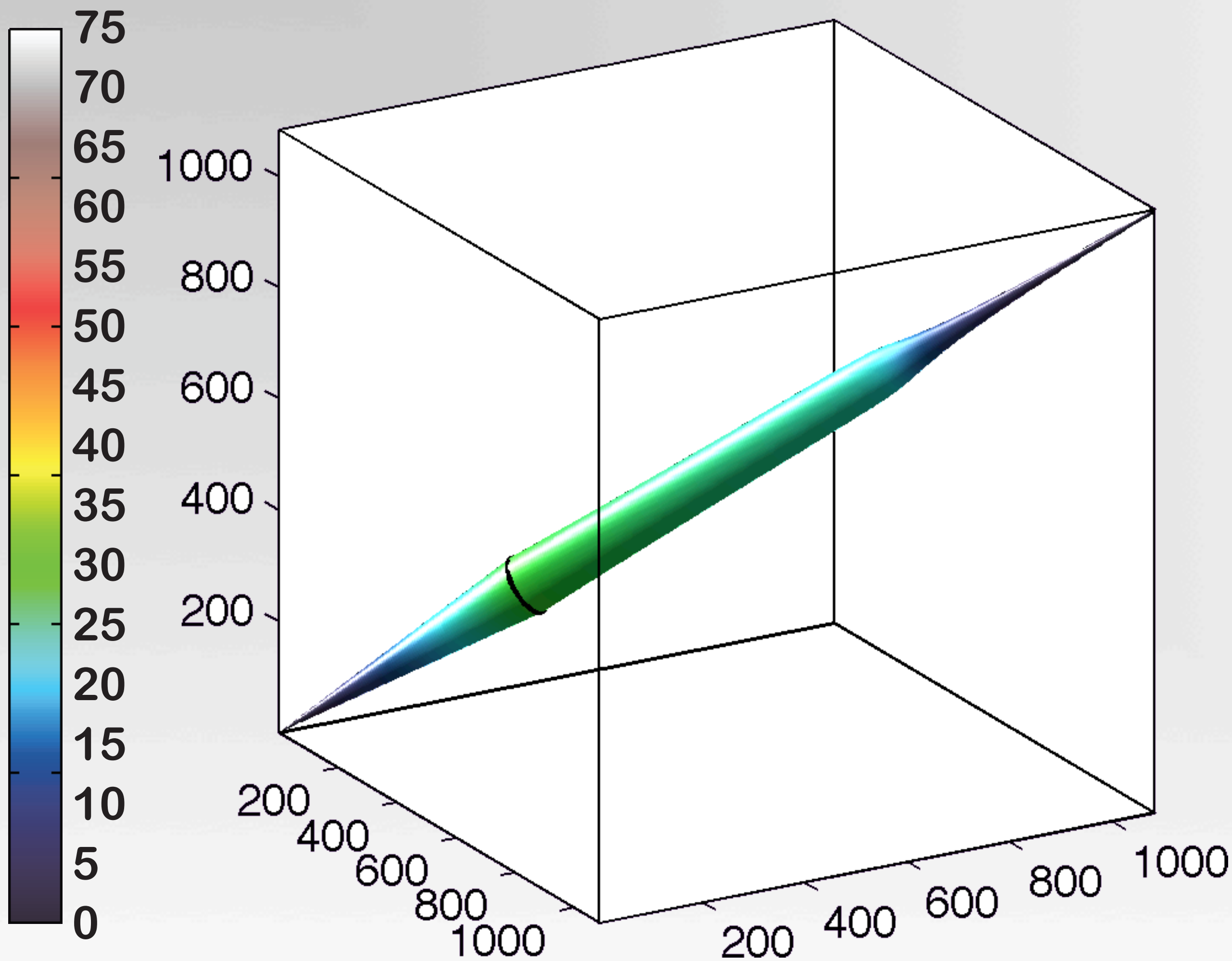
- Byerlee's law
- Feldspar dislocation creep

3D yield envelope (reduced friction)



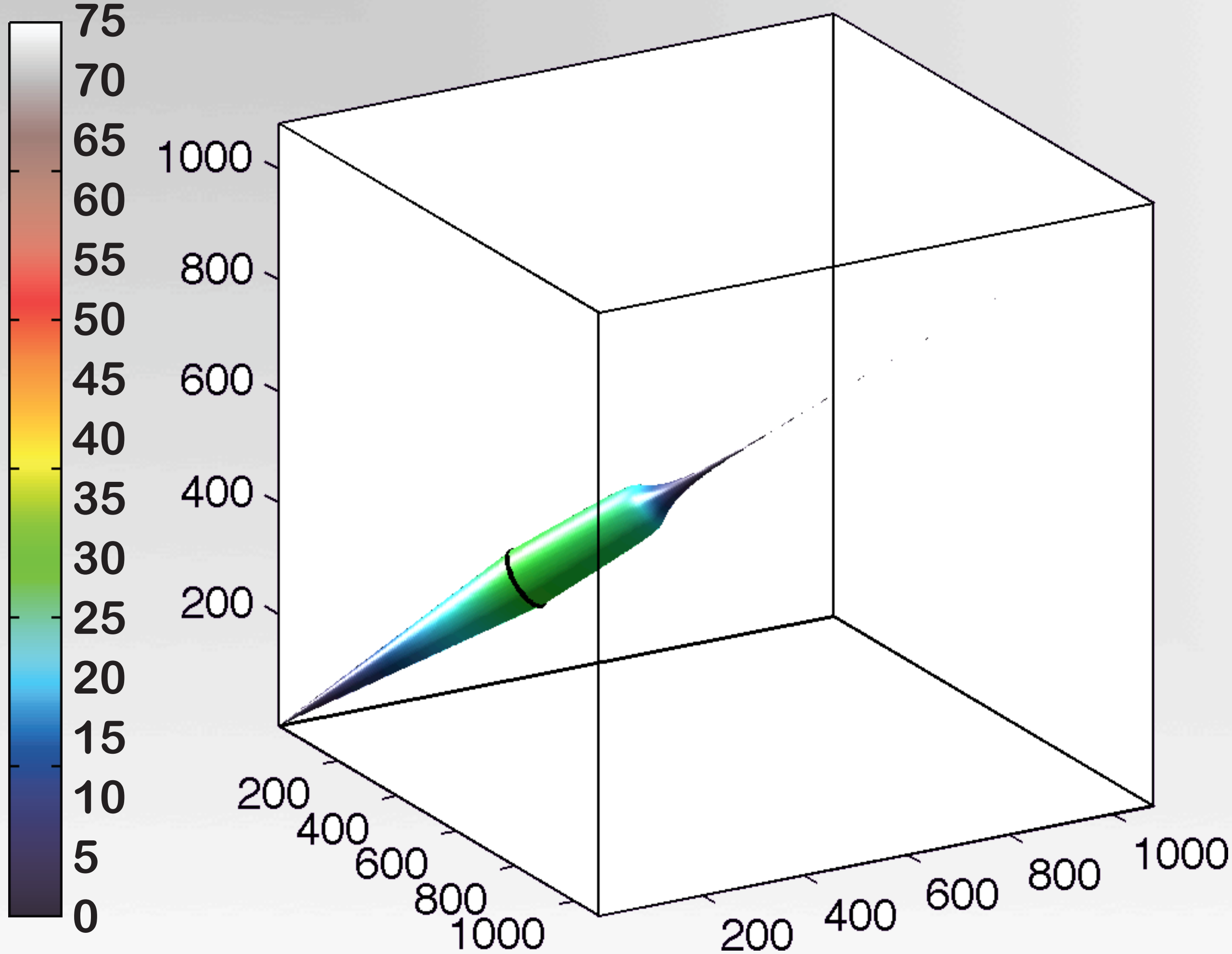
- Friction with f=0.1
- Feldspar dislocation creep

3D yield envelope (include mica)



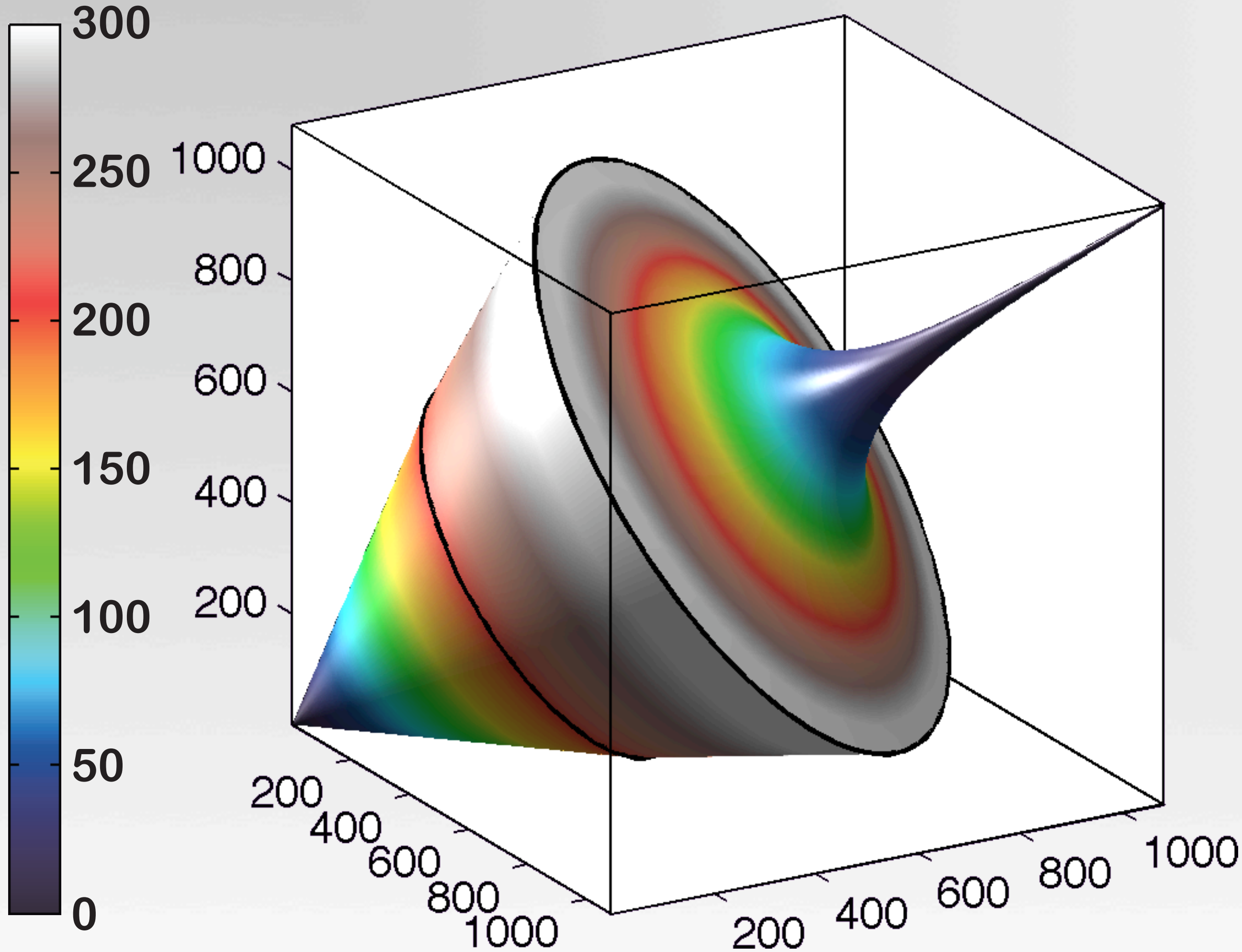
- Friction with f=0.1
- 95% Feldspar dislocation creep
- 5% Biotite
- Constant stress mixing

3D yield envelope (reduce grain size)



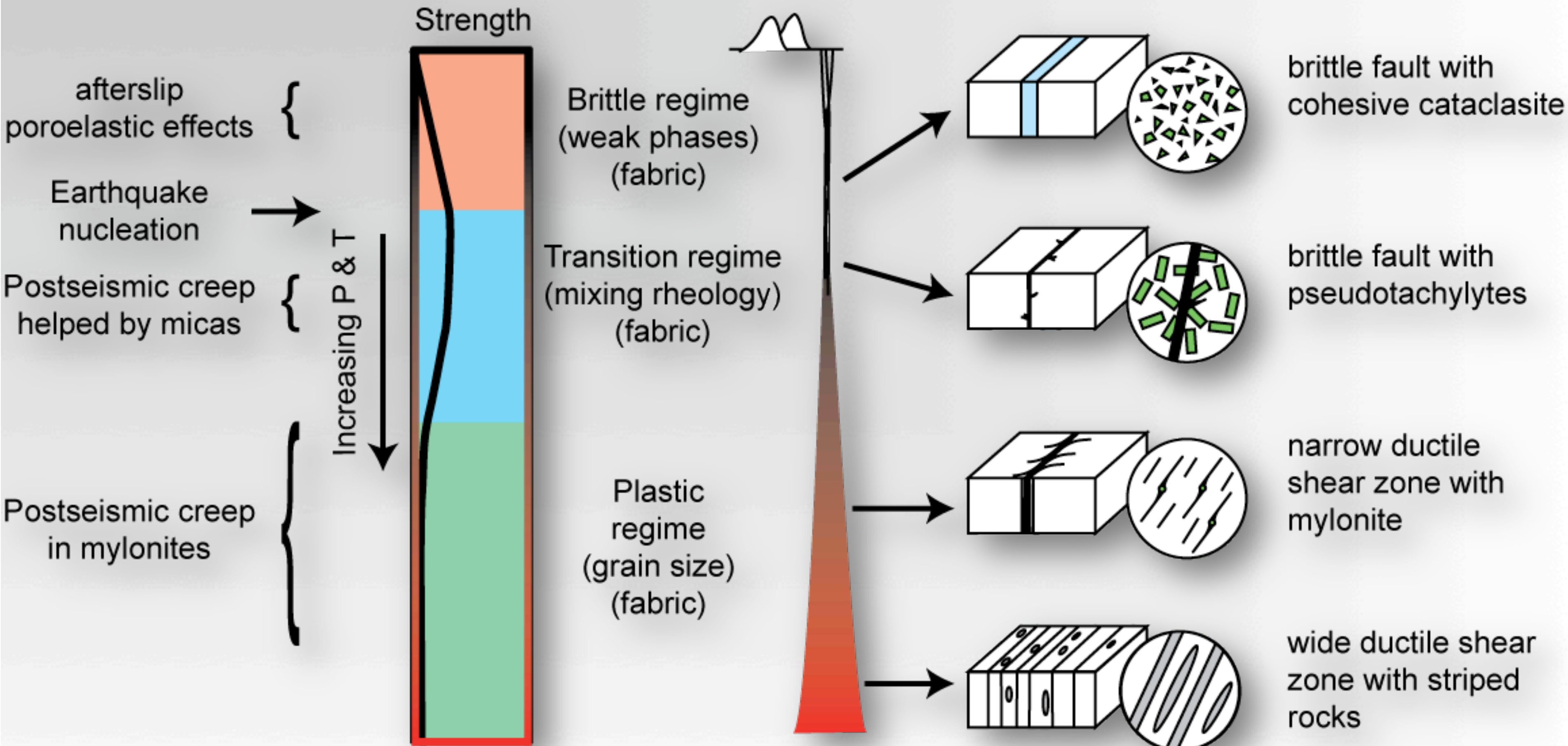
- Friction with f=0.1
- 95% Feldspar diffusion and dislocation creep with 10μm grain size
- 5% Biotite
- Constant stress mixing

3D yield envelope (standard)



- Byerlee's law
- Feldspar dislocation creep

A weaker view of the crust…



Modified from Passchier & Trouw 1998