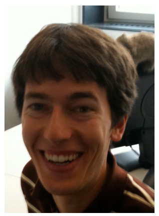
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Modeling strain localization:

which processes result in efficient localization?

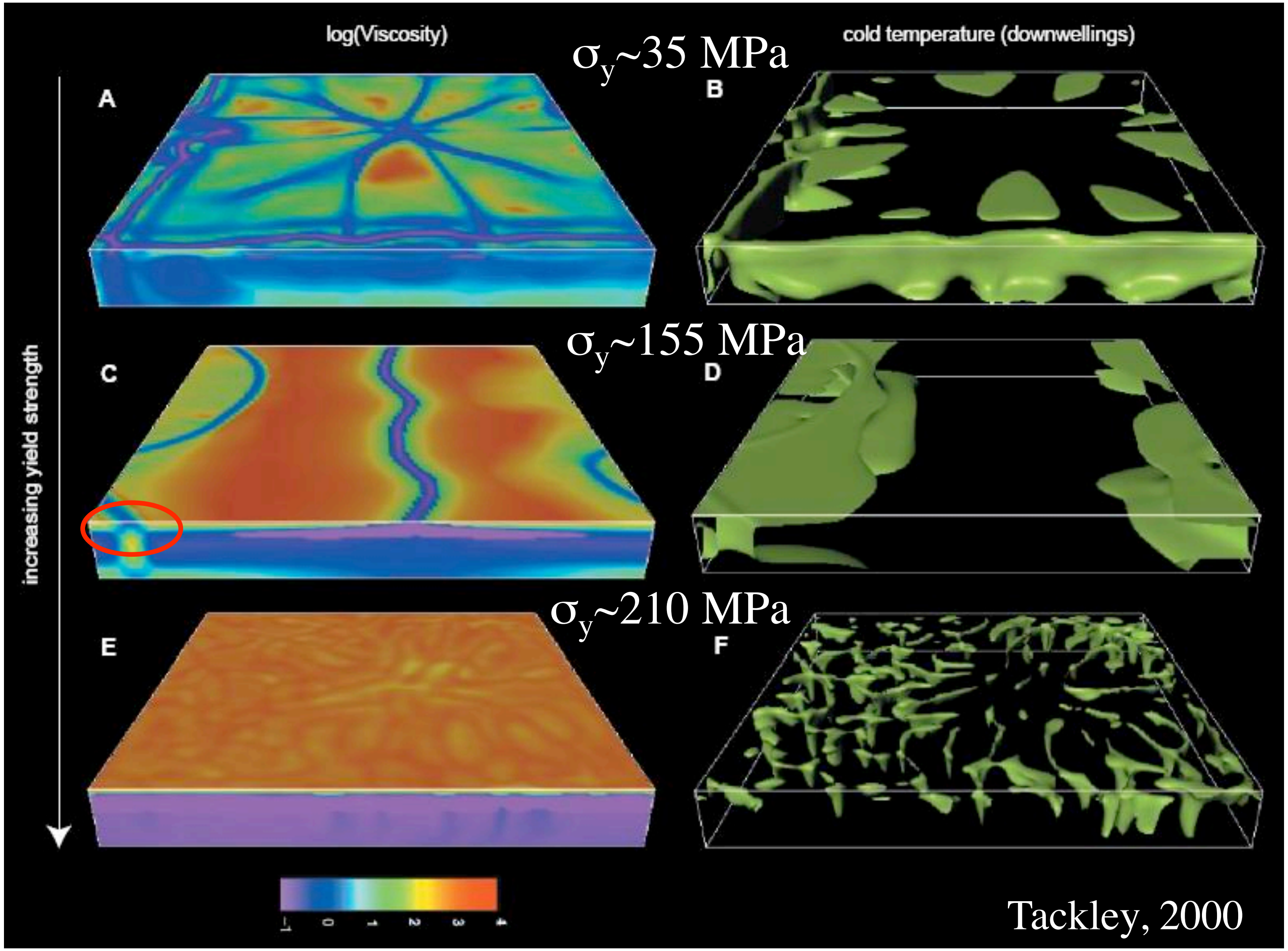
Boris Kaus



Fabio Crameri, Stefan Schmalholz, Marcel Thielmann

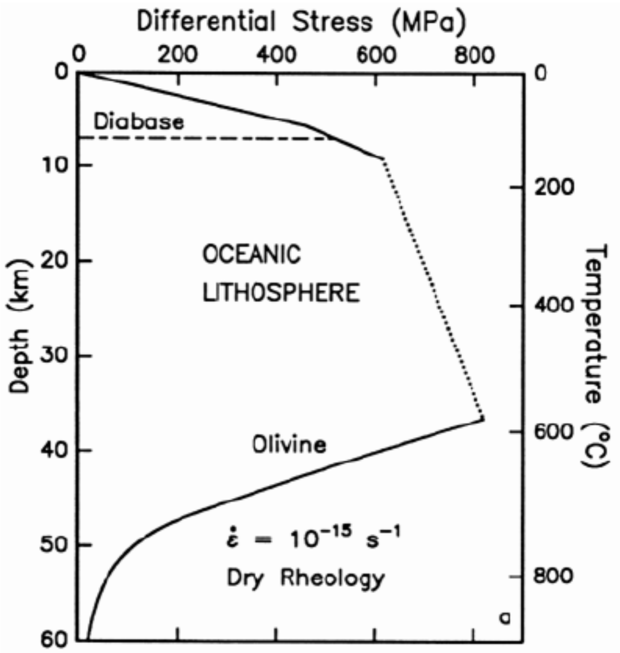
ETH Zurich, Switzerland

The problem



- Why is there plate tectonics on Earth?

Numerical modelling of shear localization



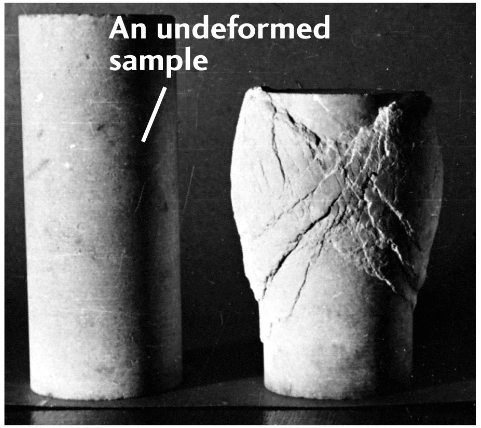
Kohlstedt et al. 1995

Oceanic lithosphere

1) Brittle regime

2) Semi-brittle regime

Brittle deformation



(a) (b)

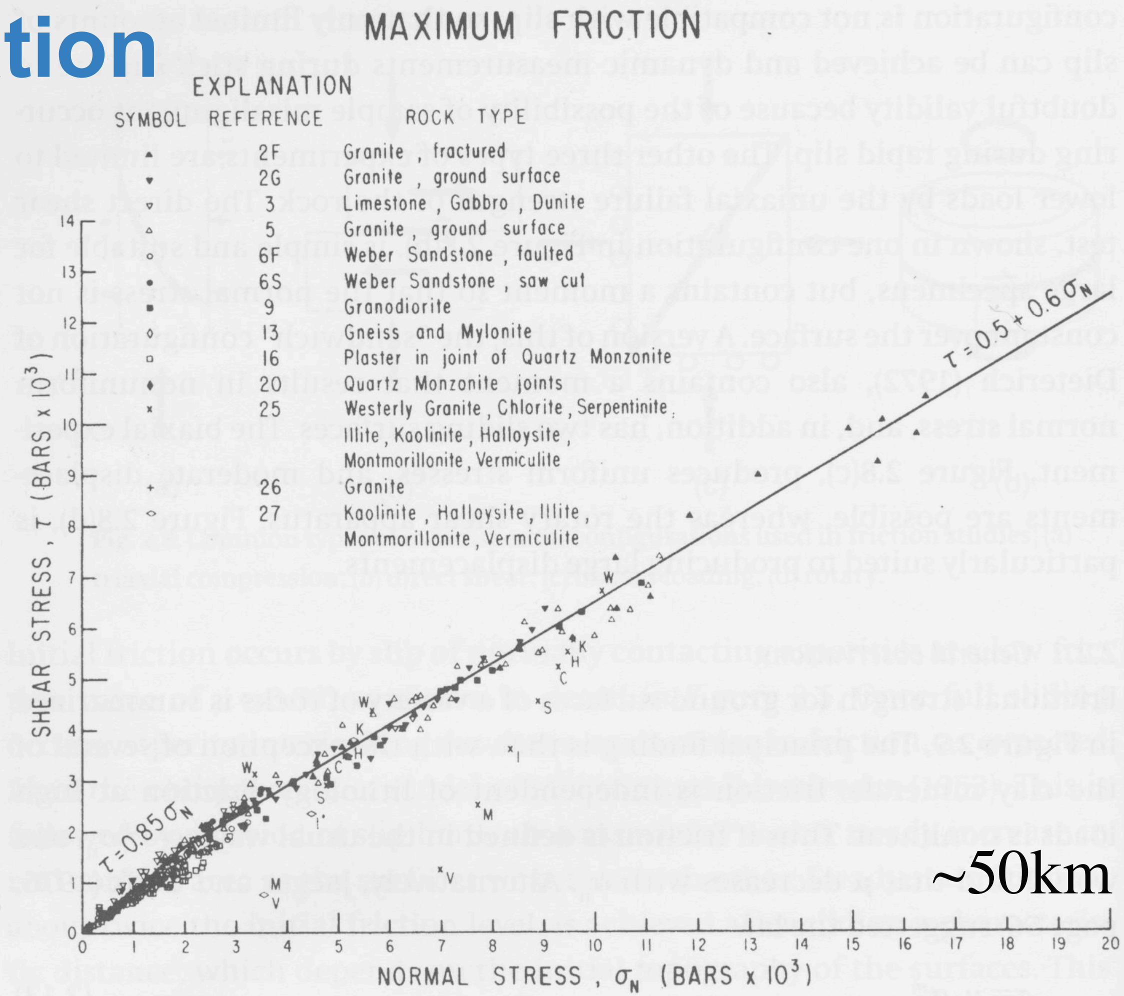
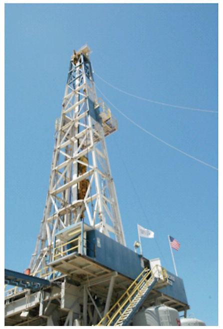
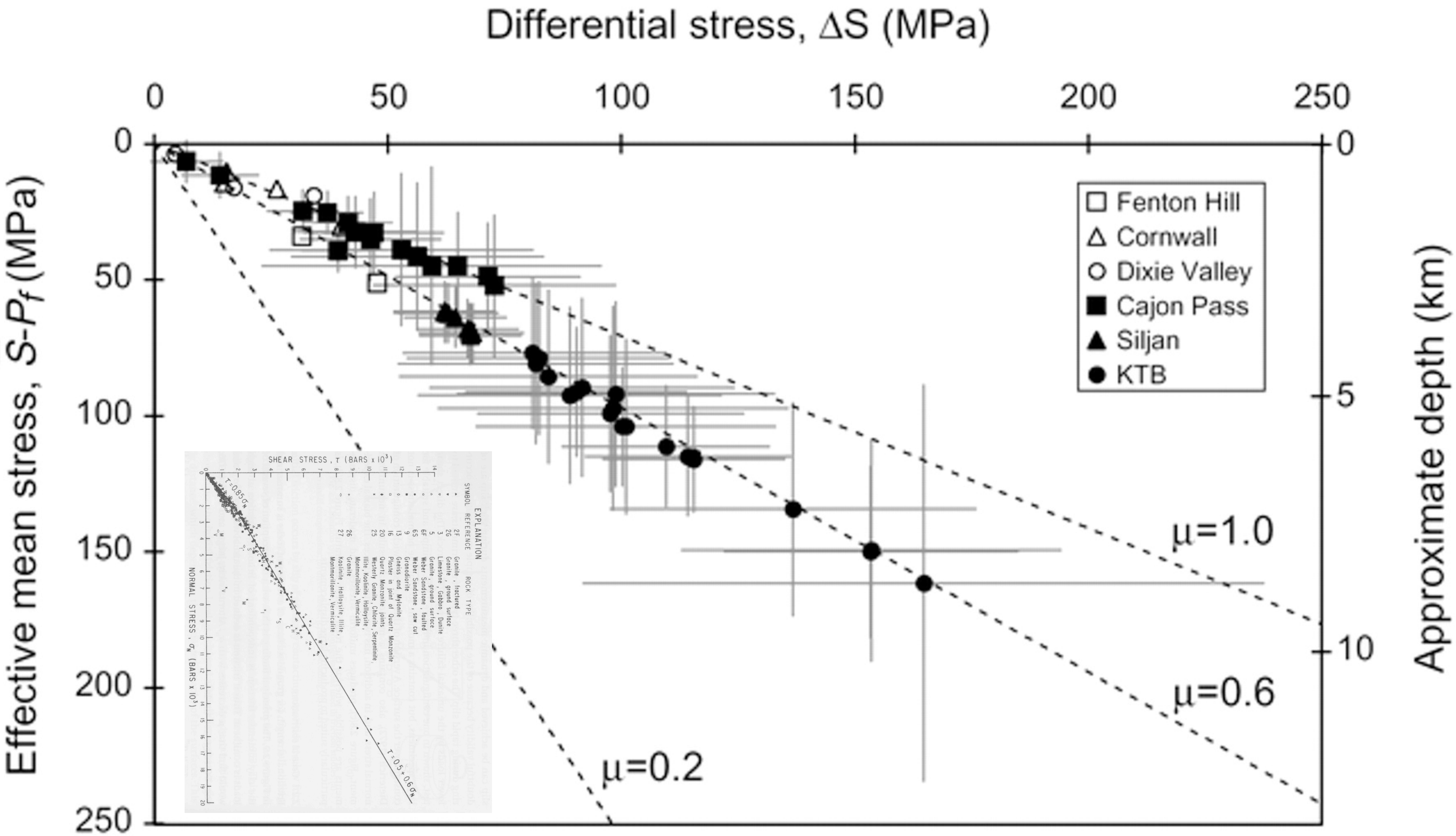


Fig. 2.9. Frictional strength for a wide variety of rocks plotted as a function of normal load. The lettered data points refer to clay minerals as indicated in the key. (From Byerlee, 1978.)

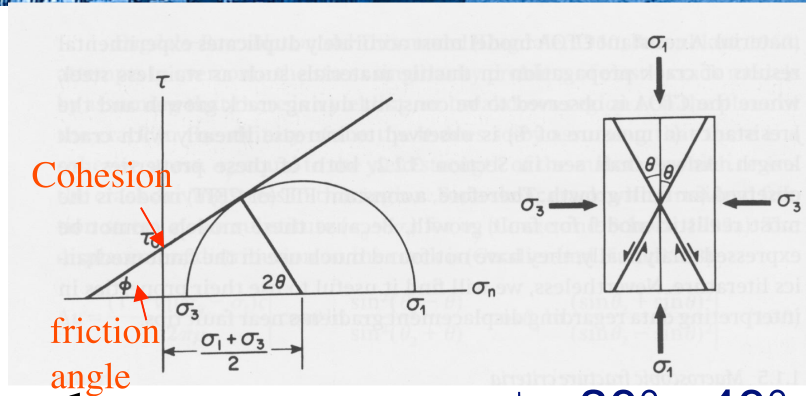
Byerlee's law & stress in the crust





Townend J, Zoback M D Geology 2000;28:399-402

Mohr-Coulomb plasticity



- Yield stress $\tau = \mu\sigma_n + C = \tan(\phi)\sigma_n + C$
- Plastic flow potential $\sigma_1 - \sigma_3 = 2\sin(\psi)\sigma_n$
- 3 parameters:

  friction angle ϕ, cohesion c, dilation angle ψ

  Rocks: $\psi \ll \phi$ (non-associated plasticity).

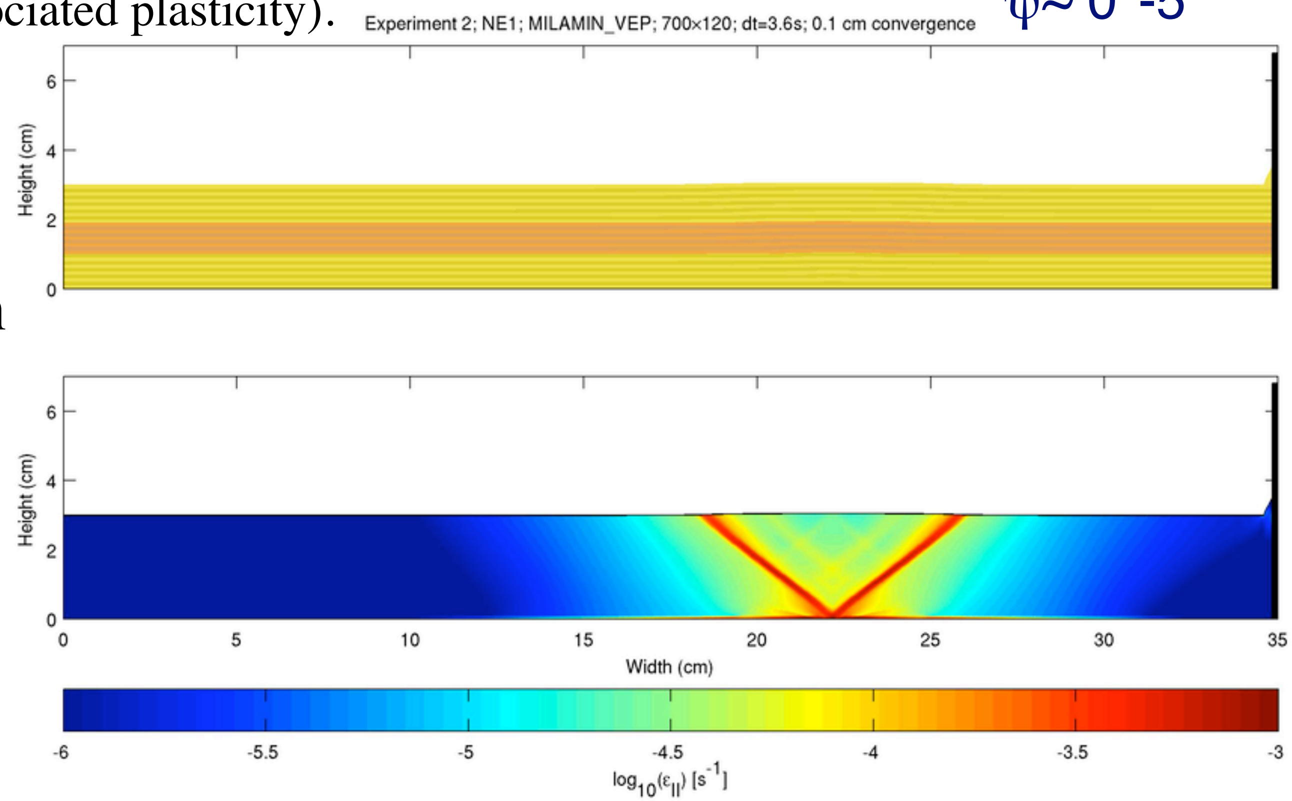
$\phi \sim 30° - 40°$

$\psi \sim 0°-5°$

$\phi>0$: Localization

$\phi=0$: poor localization

you need to add additional weakening



Some open questions

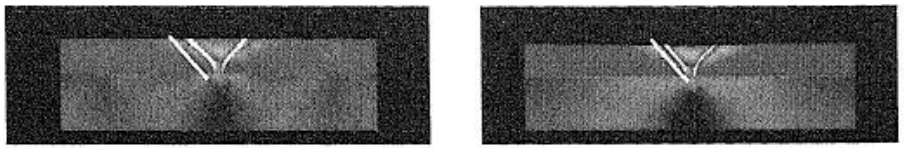
- What controls shear band angle?
- Length scale (mesh-sensitivity)

Theory

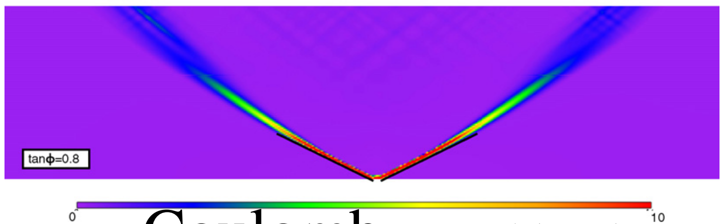
e.g. Vermeer, 1990; Lemiale et al (2008):

- Coulomb $45°+/-\phi/2$ (30°)
- Roscoe $45°+/-\psi/2$ (45°)
- Intermediate $45°+/-(\psi+\phi)/4$ (37.5°)

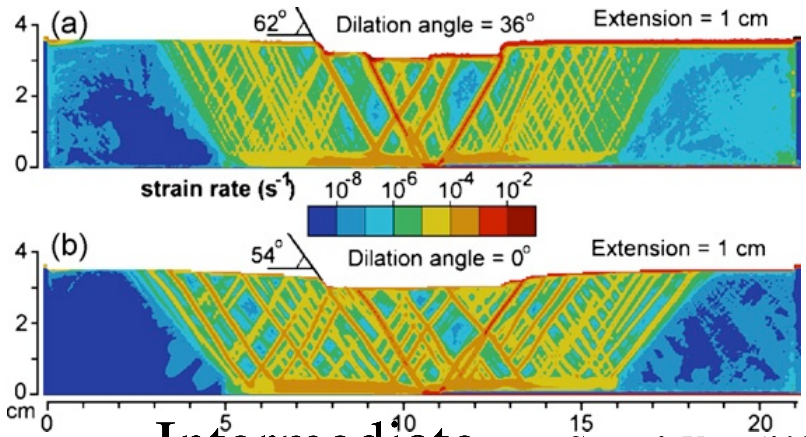
Everything inbetween possible!
And observed in sand.



Roscoe Moresi et al. (2007)

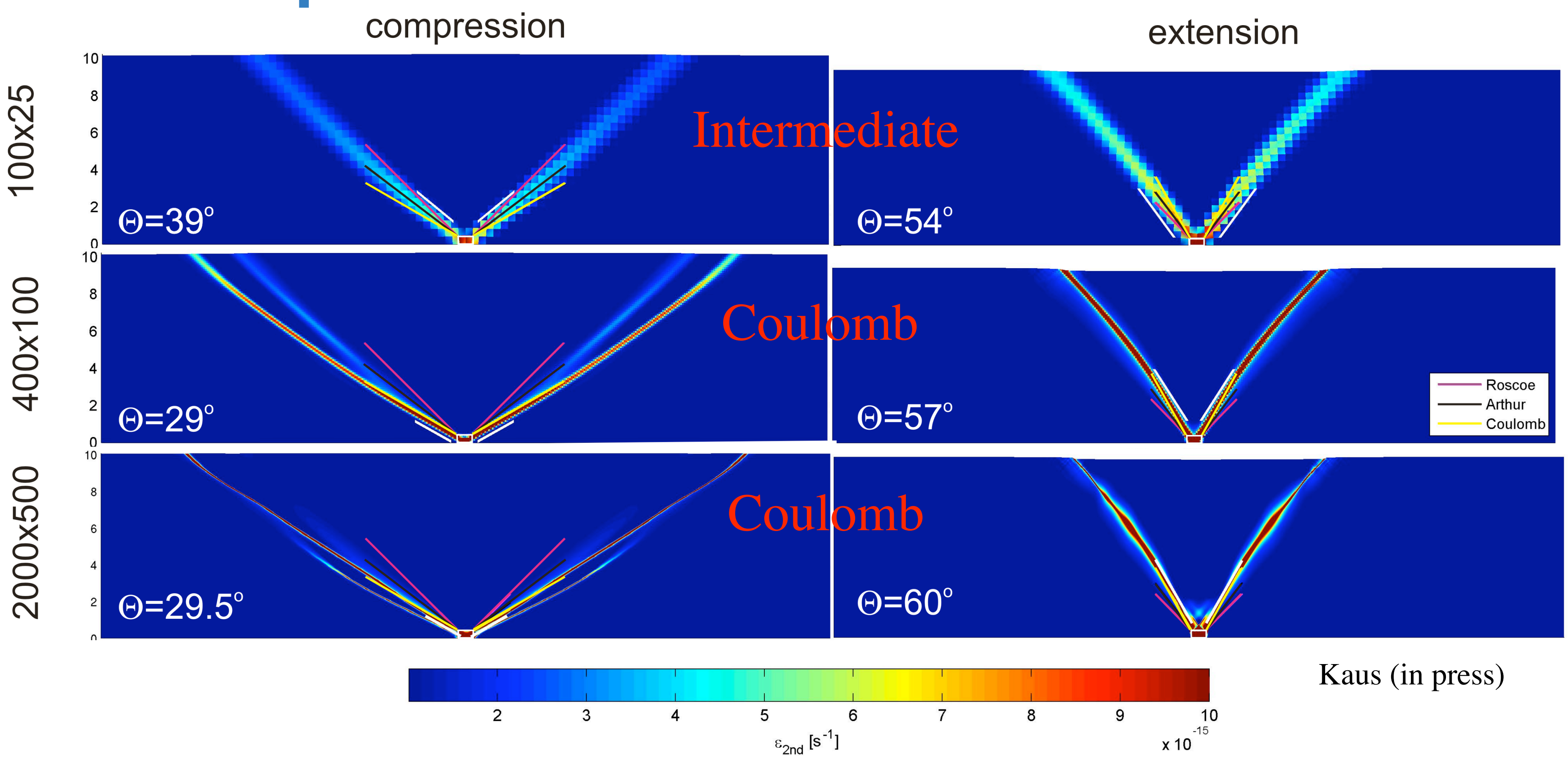


Coulomb Lemiale et al. (2008)



Intermediate Gerya & Yuen (2007)

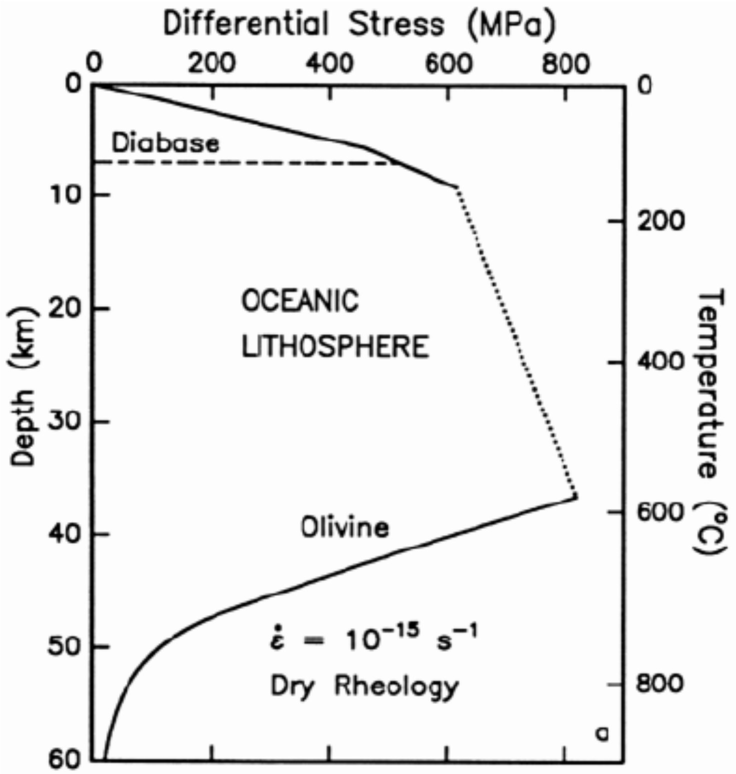
Some possible answers



Kaus (in press)

- Angle depends how well heterogeneities are resolved numerically.
- Questions remain regarding internal length scales of plasticity

Numerical modelling of shear localization

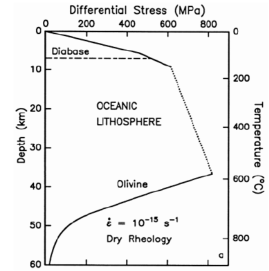


1) Brittle regime

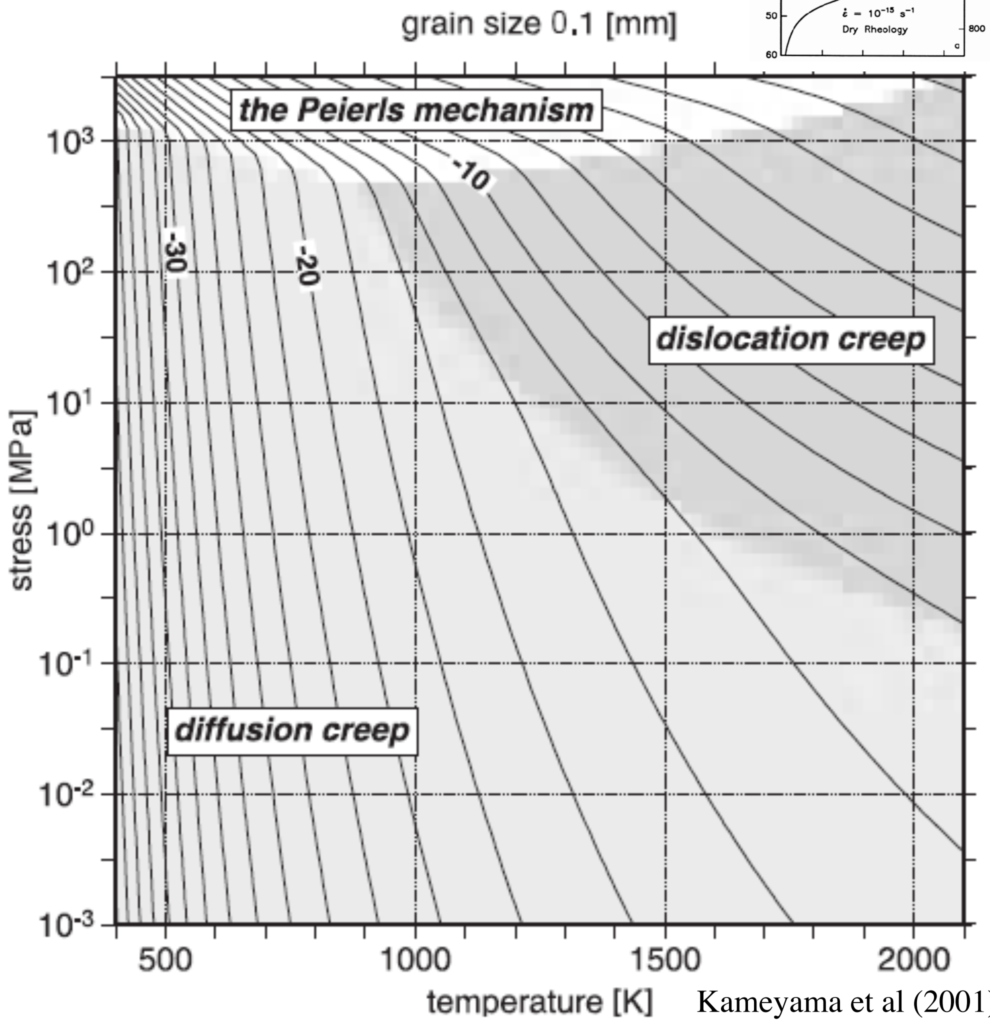
- “Easy” to generate localized deformation.
- No additional weakening mechanisms required.

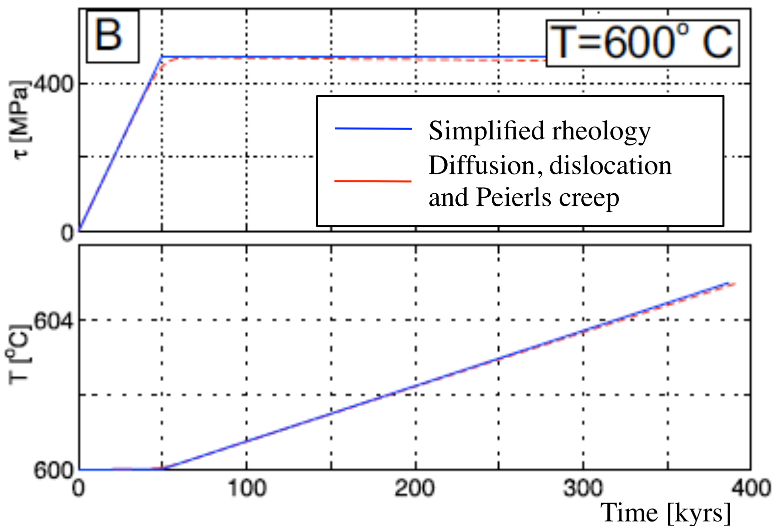
2) Semi-brittle regime

Low temperature plasticity



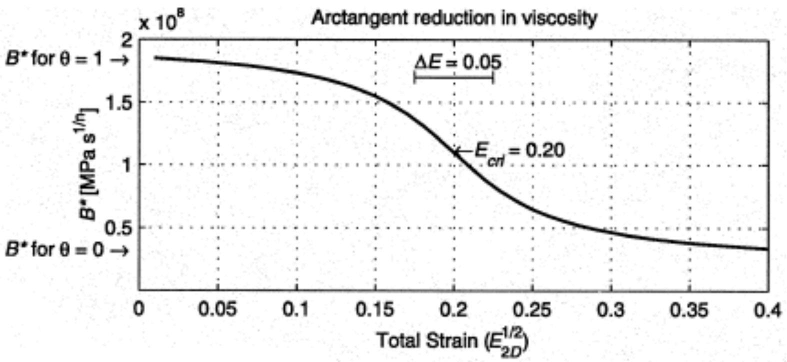
- Few experiments only.
- Mechanically like Mohr-Coulomb with ϕ=0º.
- Additional weakening mechanism required to produce localization.

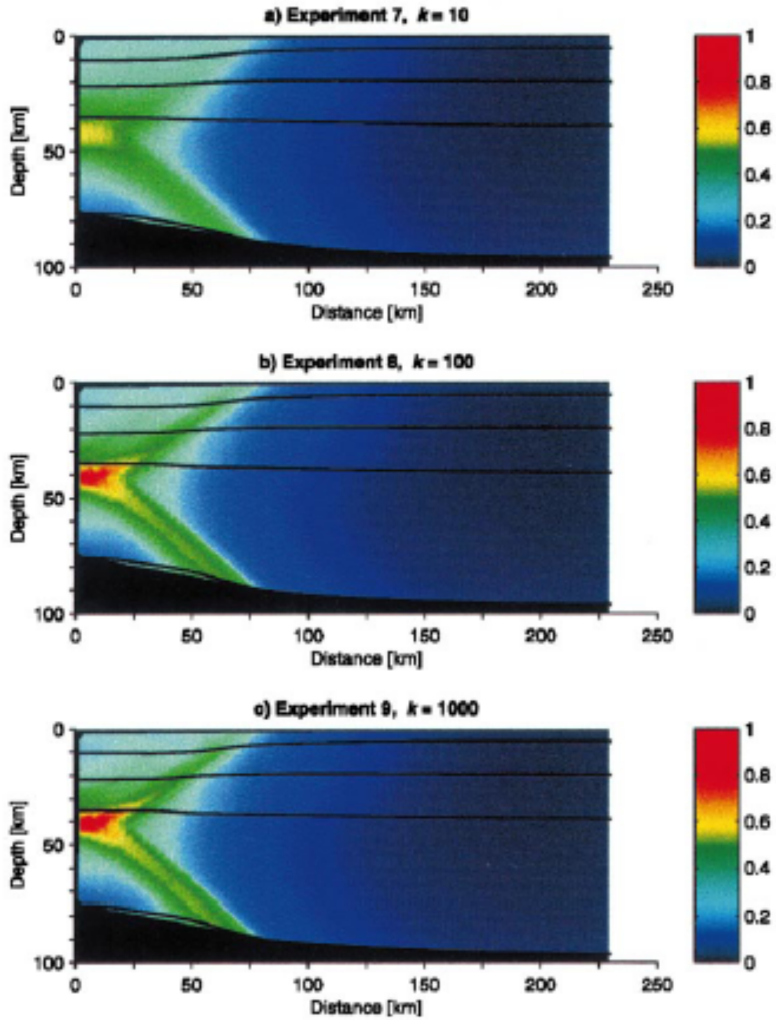




Kameyama et al (2001)

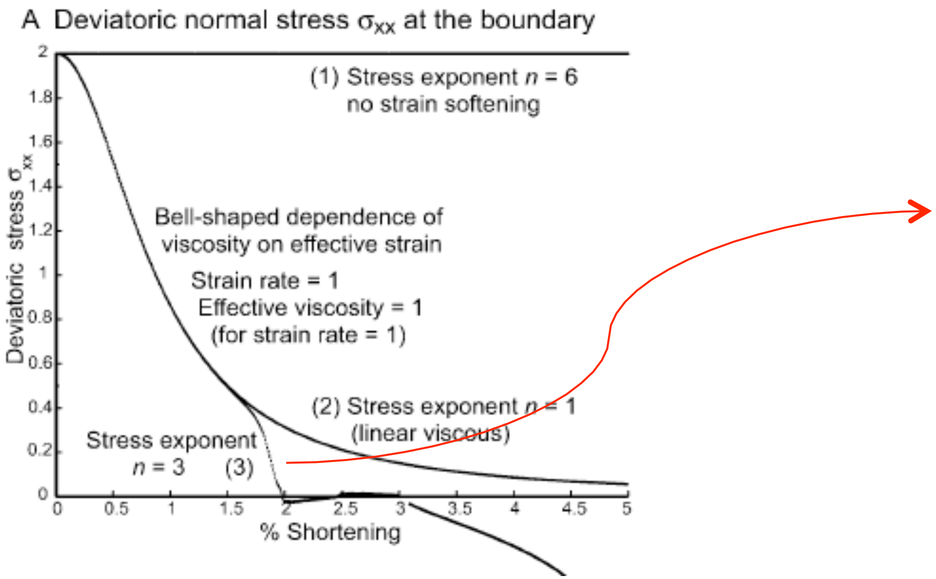
Ad-hoc weakening models



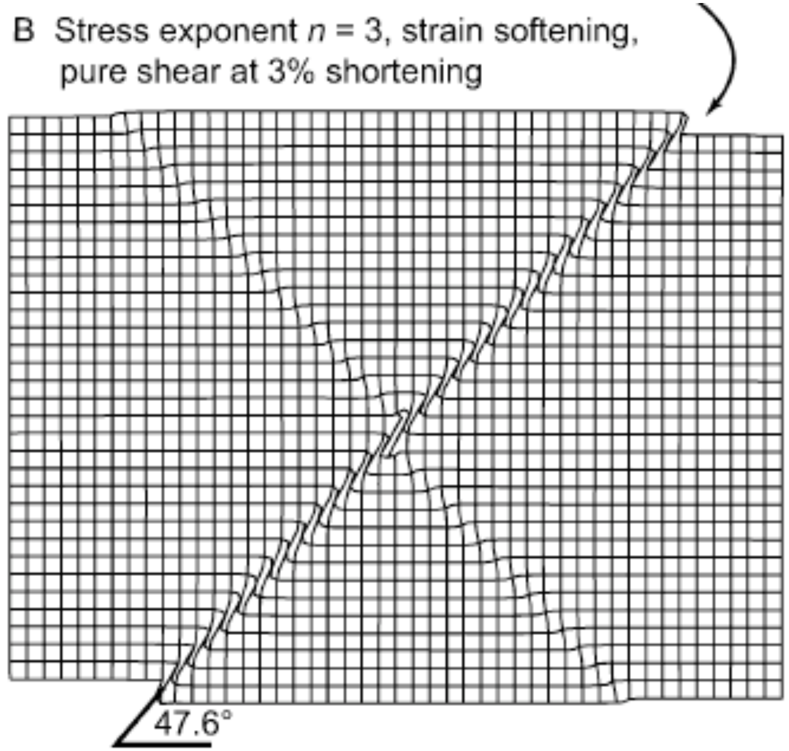


Frederiksen & Braun, EPSL 2001

Weakening & powerlaw rheology



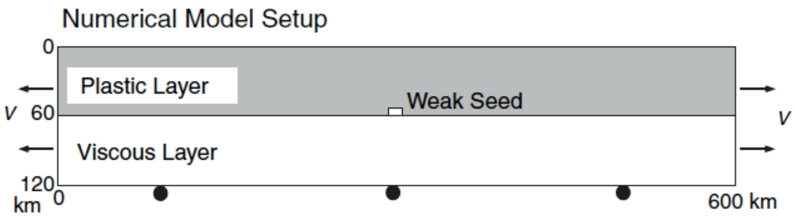
$$\eta = \eta_0 \dot{\varepsilon}_{II}^{\frac{1}{n}-1} \exp\left(\frac{E}{nRT}\right)$$

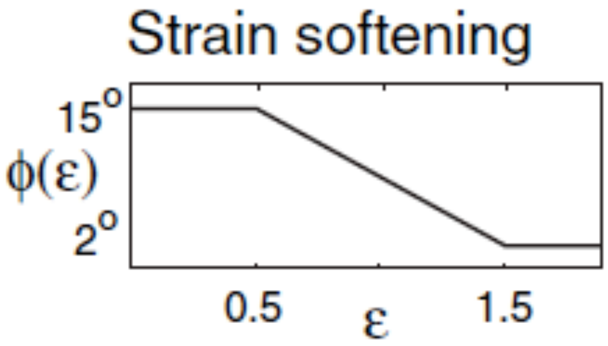


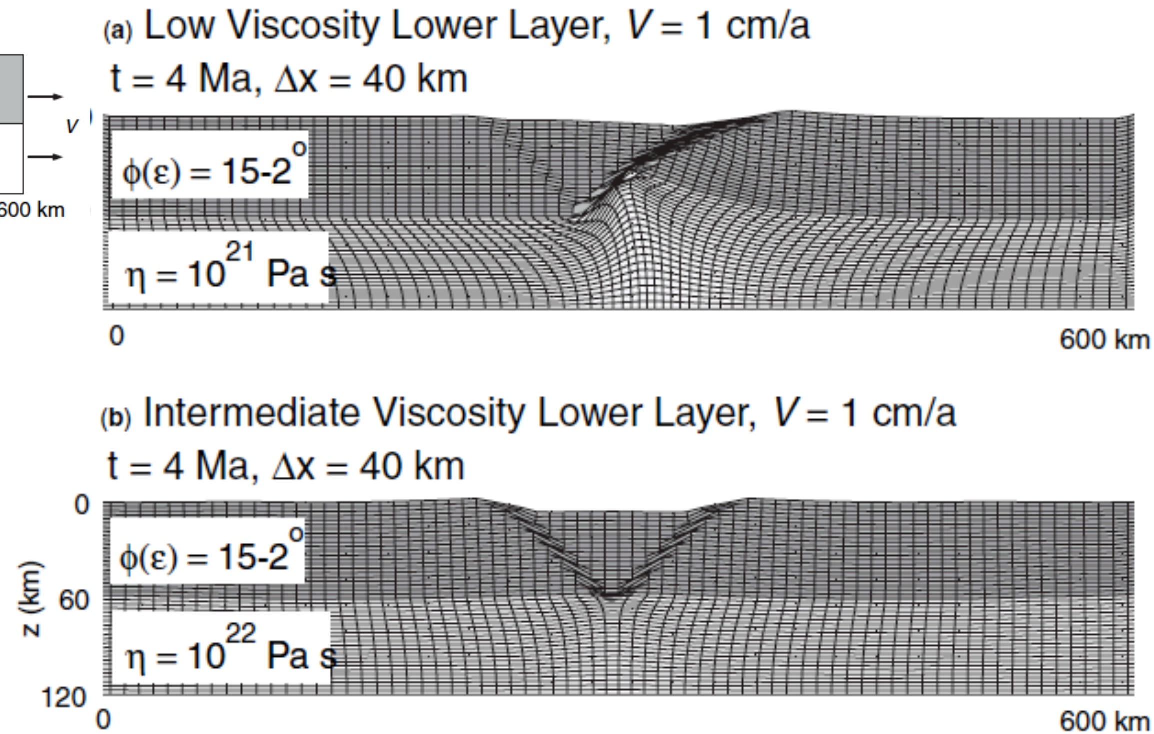
Mancktelow, Geology (2006)

- You need strain softening & powerlaw rheology to localize deformation.

Asymmetric vs. symmetric rifting







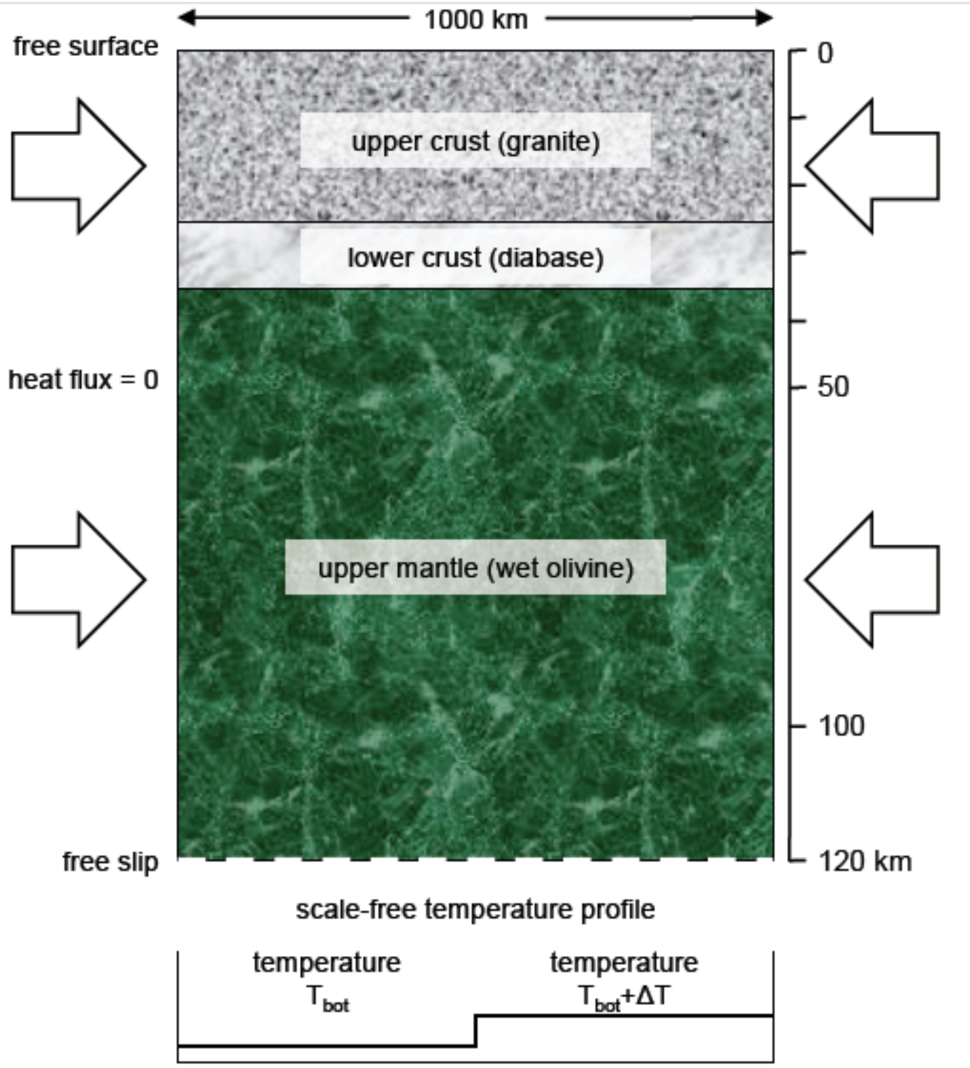
- Strain weakening of friction angle or viscosity.
- Asymmetric or symmetric rifting
- Developed analytical theory, which explains the results (minimum viscous dissipation)

Huismans & Beaumont, Geology (2002), JGR (2003), JGR (2005)

Candidates for weakening mechanisms

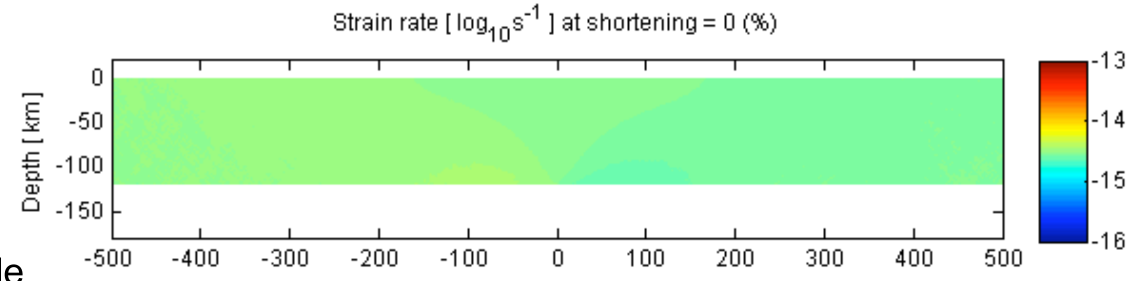
- Grain size evolution
  - e.g. Braun et al. (1999), Montesi & Hirth (2003), Ricard & Bercovici (2009), Rozel and Ricard (subm.)
- Olivine crystal anisotropy
  - e.g. Tommasi et al. (2009)
- Grain boundary sliding
  - e.g. Hirth & Kohlstedt (2003), Precigout & Gueydan (2009)
- Anisotropy development in a two-phase system
  - e.g. Montesi (2007), Dabrowski (2008).
- Two-phase damage rheology
  - e.g., Bercovici et al. (2002), Bercovici & Ricard (2005). Ricard & Bercovici (2009), Landuyt et al (2008,2009)
- Shear-heating
  - e.g., Yuen & Schubert (1978), Ogawa (1987), Kameyama et al (2001), Regenauer-lleb et al. (2001,2002,2003,2004), Kaus & Podladchikov (2006), Kelemen and Hirth (2007), Braeck et al. (2008,2009), John et al. (2009)

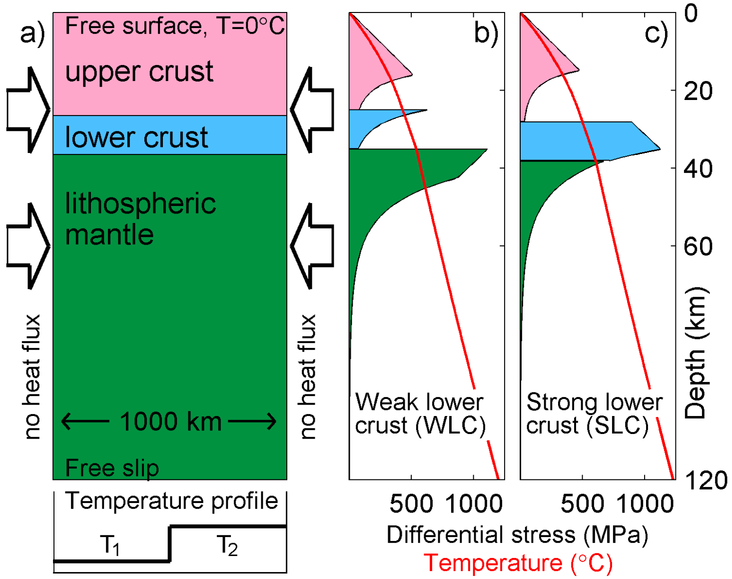
Let’s squeeze some continental lithosphere.

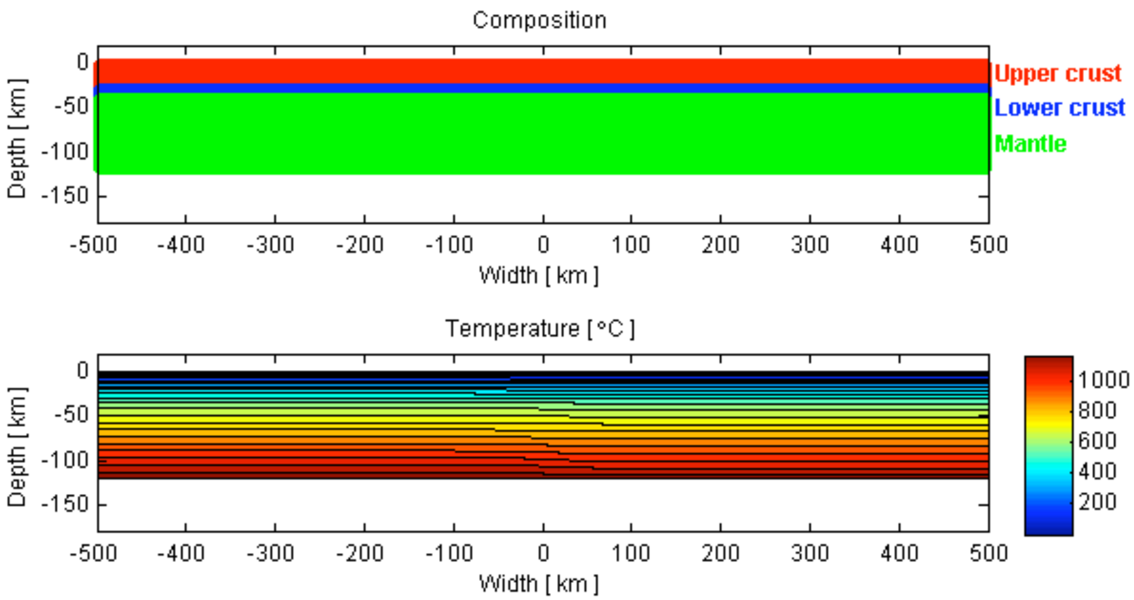


Shortening of the continental lithosphere

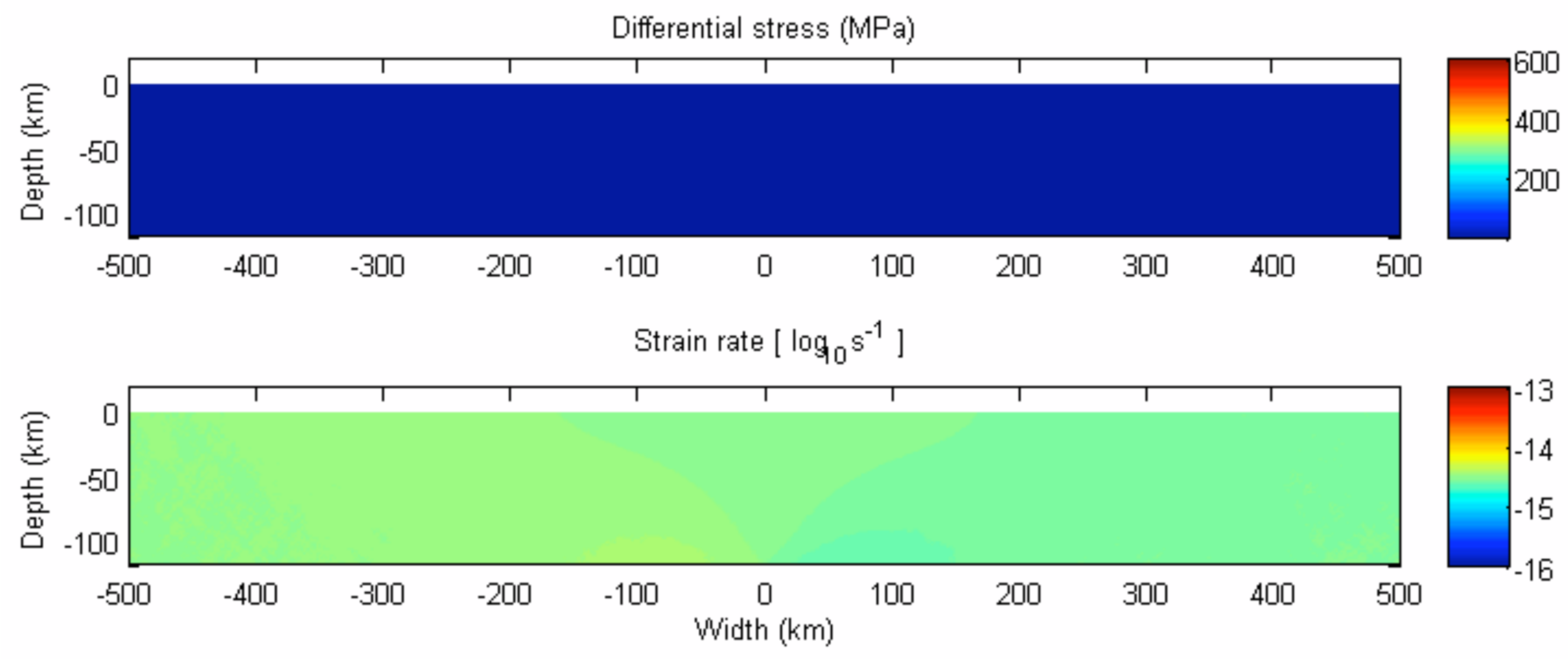
Numerical model:
- Lagrangian finite element model (MILAMIN_VEP)
- Visco-elasto-plastic rheology.
- Thermo-mechanical coupling.
- Laboratory-based (powerlaw) creep laws
- Kinematic shortening
- Gravity and isostasy
- Mohr-Coulomb plasticity in crust
- Low-temperature(Peierls) plasticity in mantle







Shortening of the continental lithosphere



- Very heterogeneous deformation.
- Shear localization in mantle lithosphere.

Shear heating and lithospheric shortening

What is the impact of shear heating and energy feed backs?

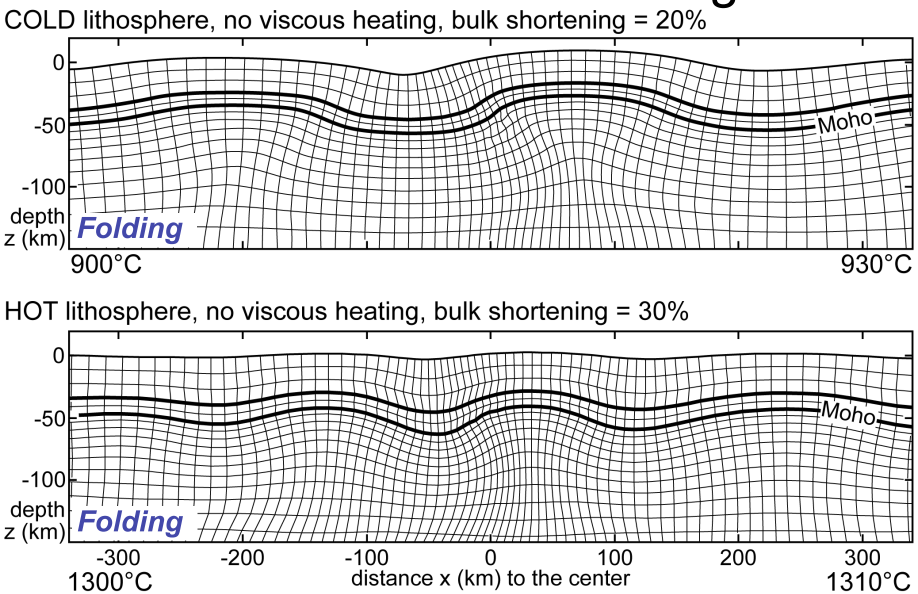
$$\rho c\left(\dot{T} + v_i \frac{\partial T}{\partial x_i}\right) = \frac{\partial}{\partial x_i}\left(k \frac{\partial T}{\partial x_i}\right) + A + \tau_{ij}\left(\dot{\varepsilon}_{ij}^{v} + \dot{\varepsilon}_{ij}^{p}\right)$$

Shear heating

$$\eta = A^{-\frac{1}{n}} \dot{\varepsilon}_{II}^{\frac{1}{n}-1} \exp\left(\frac{E}{nRT}\right)$$

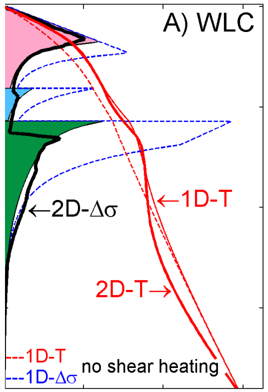
$$\tau_{ij} = 2\eta\dot{\varepsilon}_{ij}$$

Without shear heating

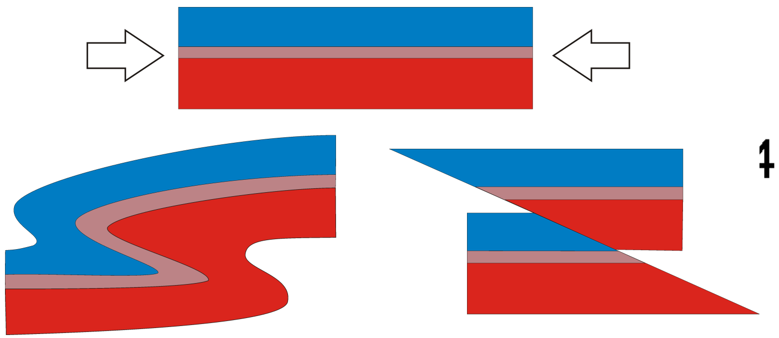


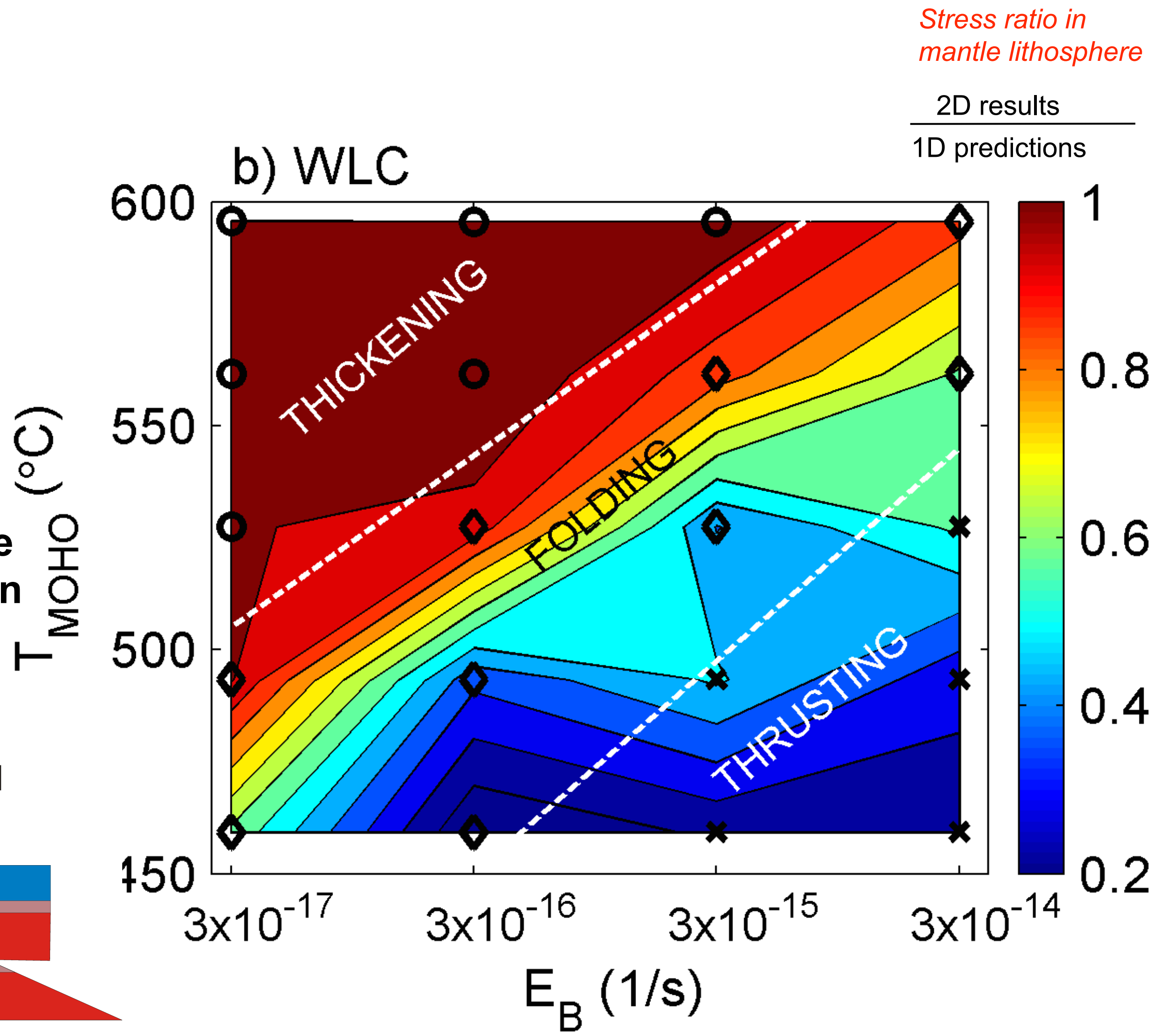
Burg & Schmalholz (2008)

Systematics

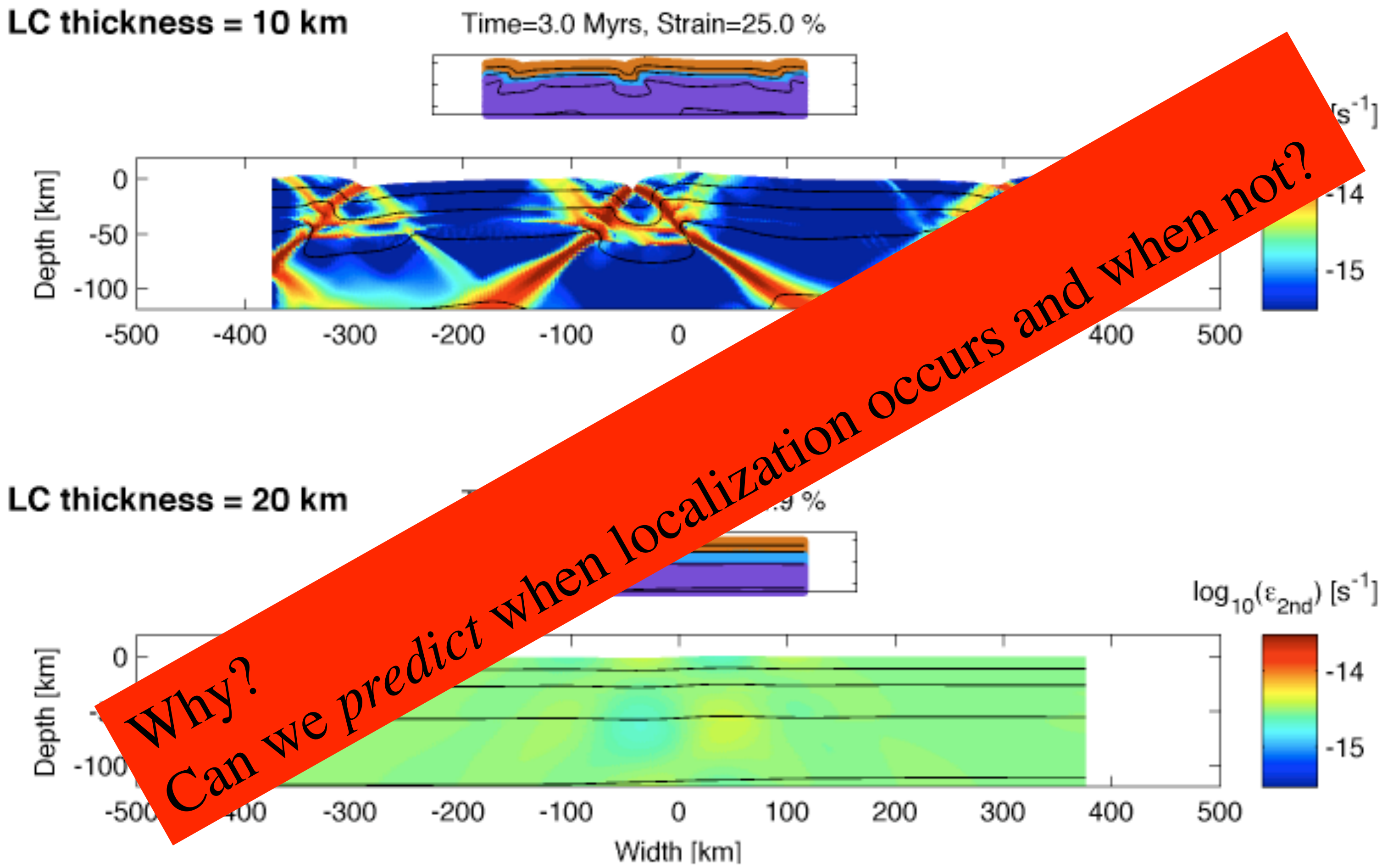


The deformation behavior of the lithosphere depends strongly on the Moho-temperature and the shortening rate!



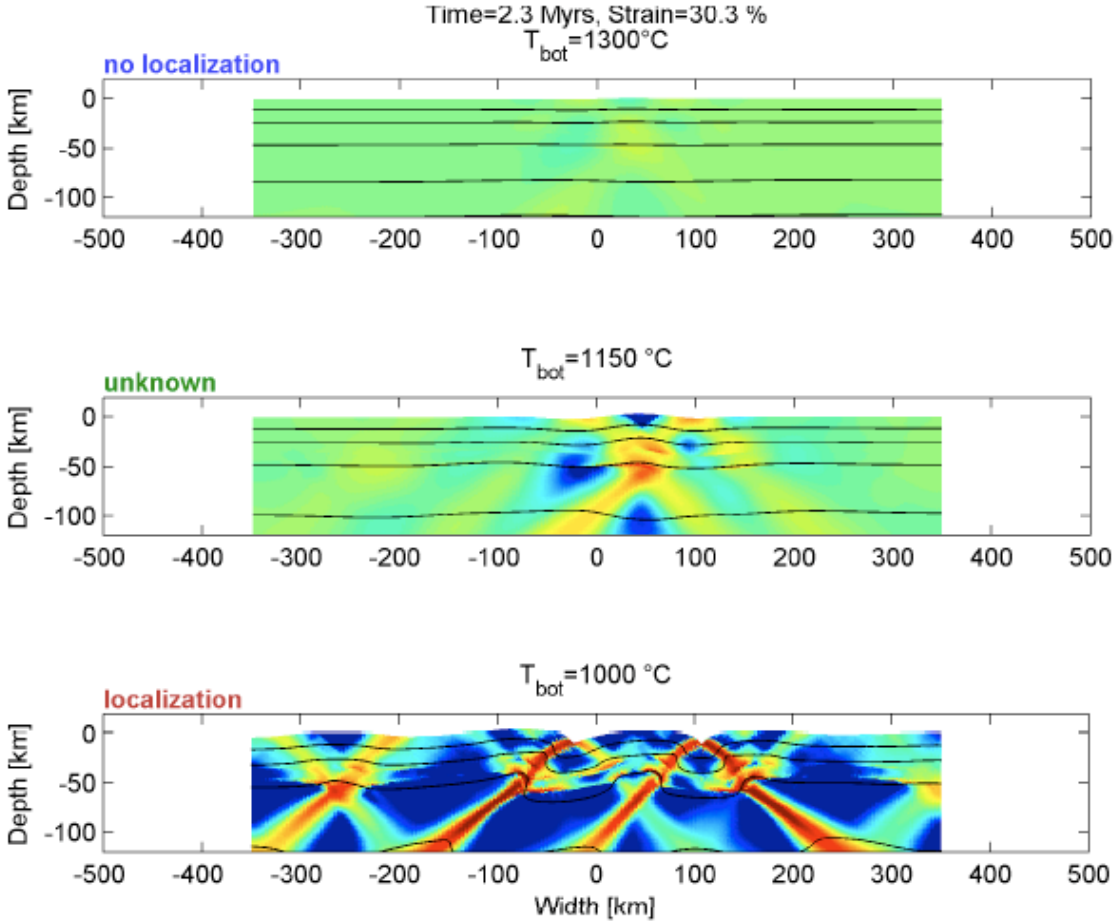


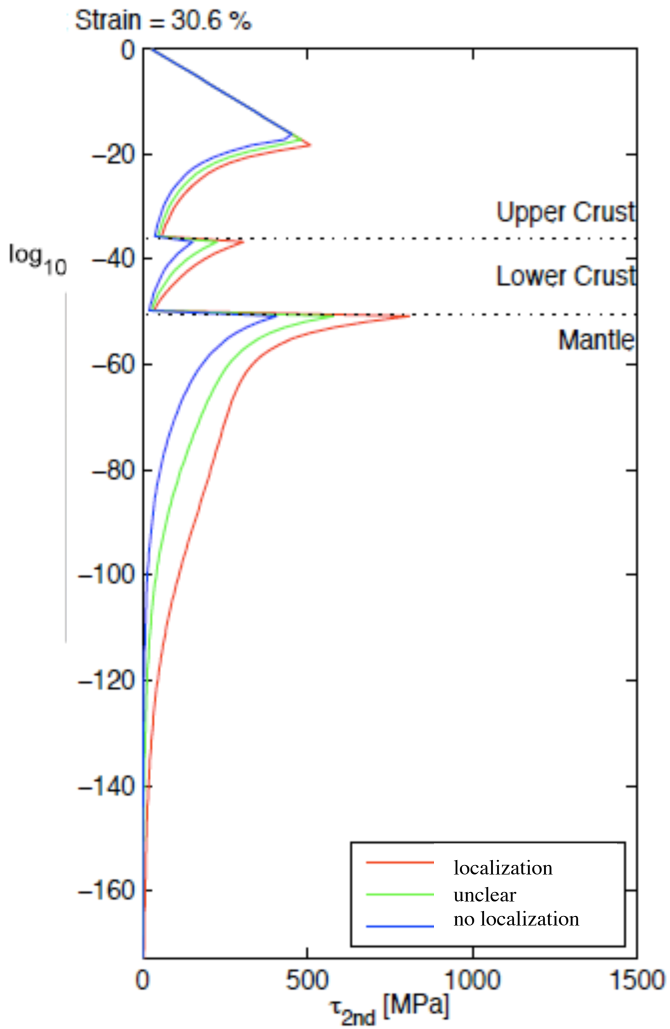
Schmalholz, Kaus & Burg, ***Geology***, 2009



Why?
Can we predict when localization occurs and when not?

Changing bottom temperature

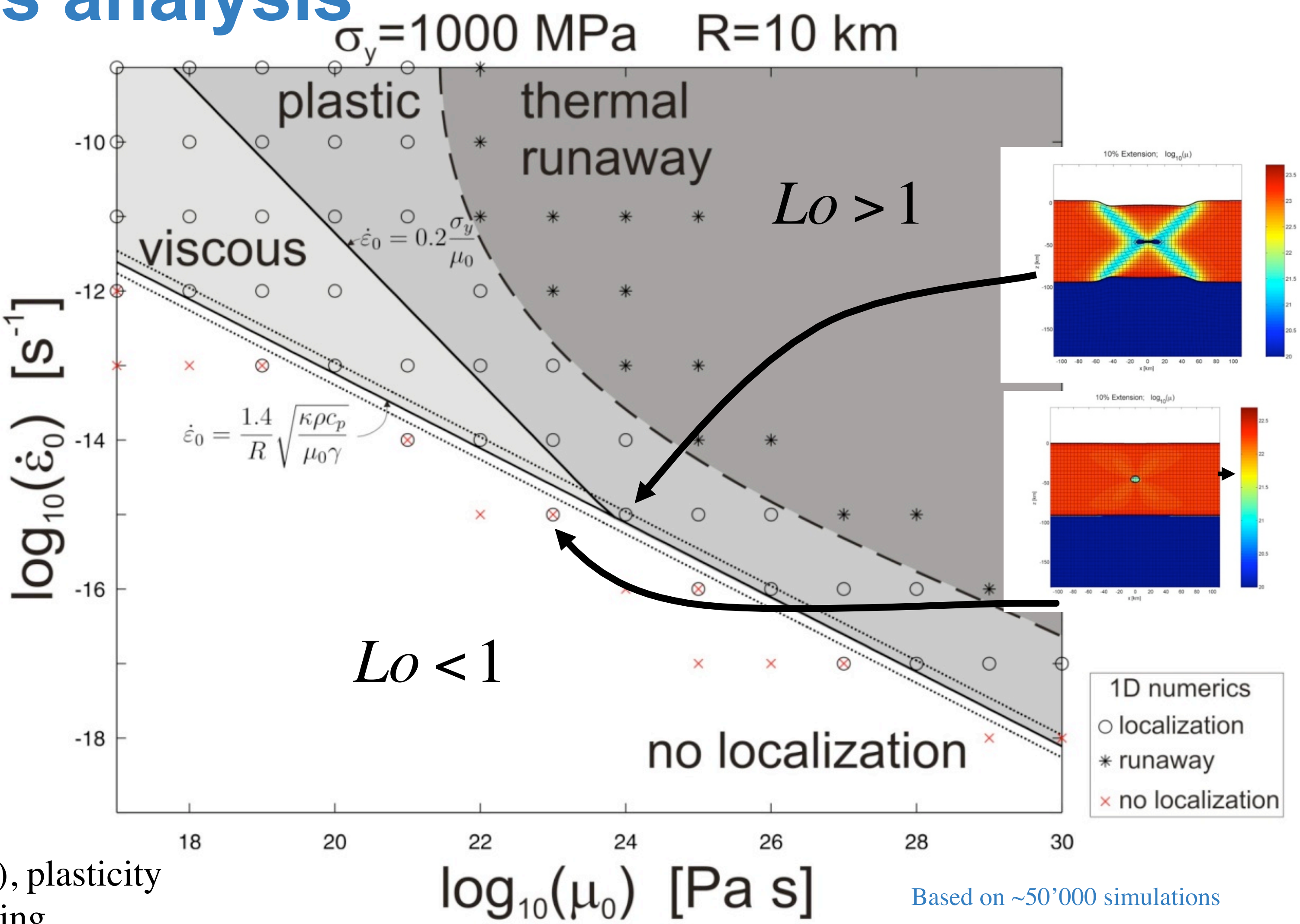




MSc-thesis Fabio Crameri

Previous analysis

$$Lo = R\frac{\dot{\varepsilon}_0}{1.4}\sqrt{\frac{\mu_0\gamma}{\kappa\rho c_p}}$$



Key ingredients:

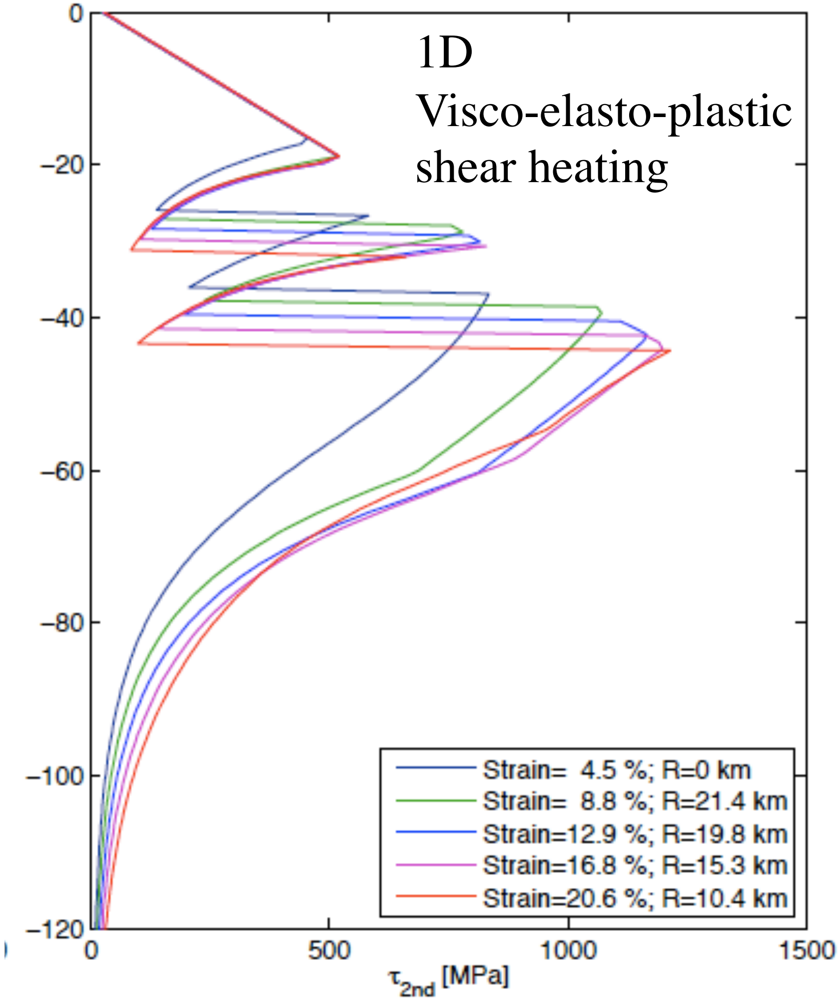
- (elasticity), plasticity
- shear heating.
- T-dependent viscosity

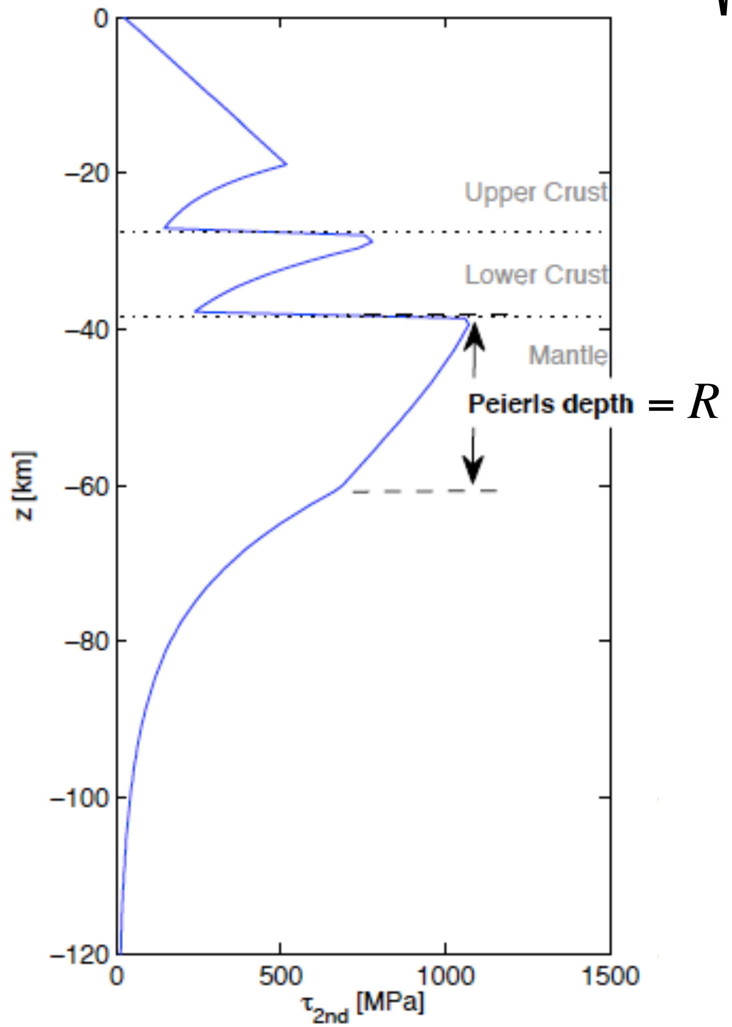
Based on ~50'000 simulations (0D,1D,2D)

Kaus & Podladchikov (2006)

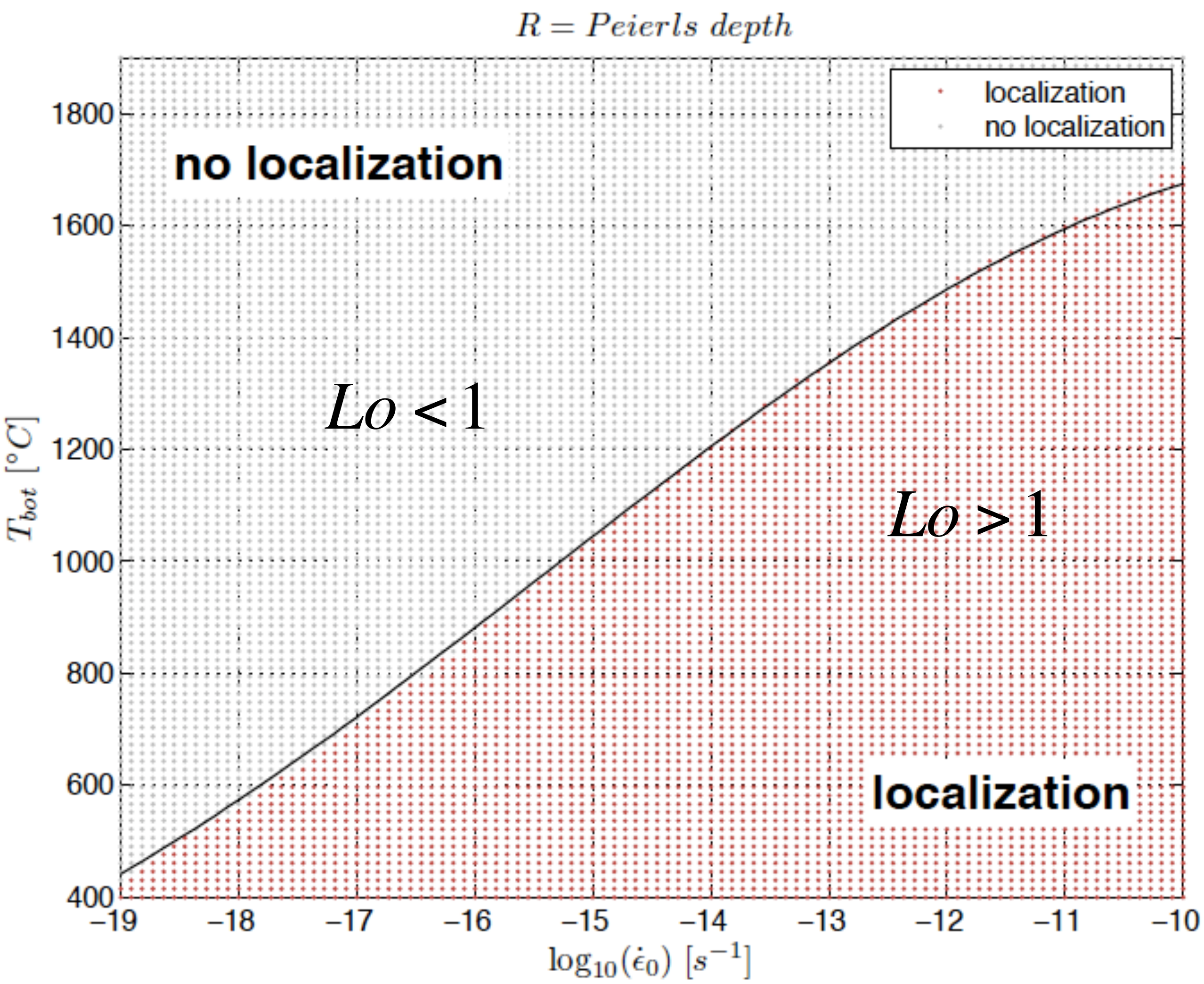
1-D model

$$Lo = R\frac{\dot{\varepsilon}_0}{1.4}\sqrt{\frac{\mu_0\gamma}{\kappa\rho c_p}}$$

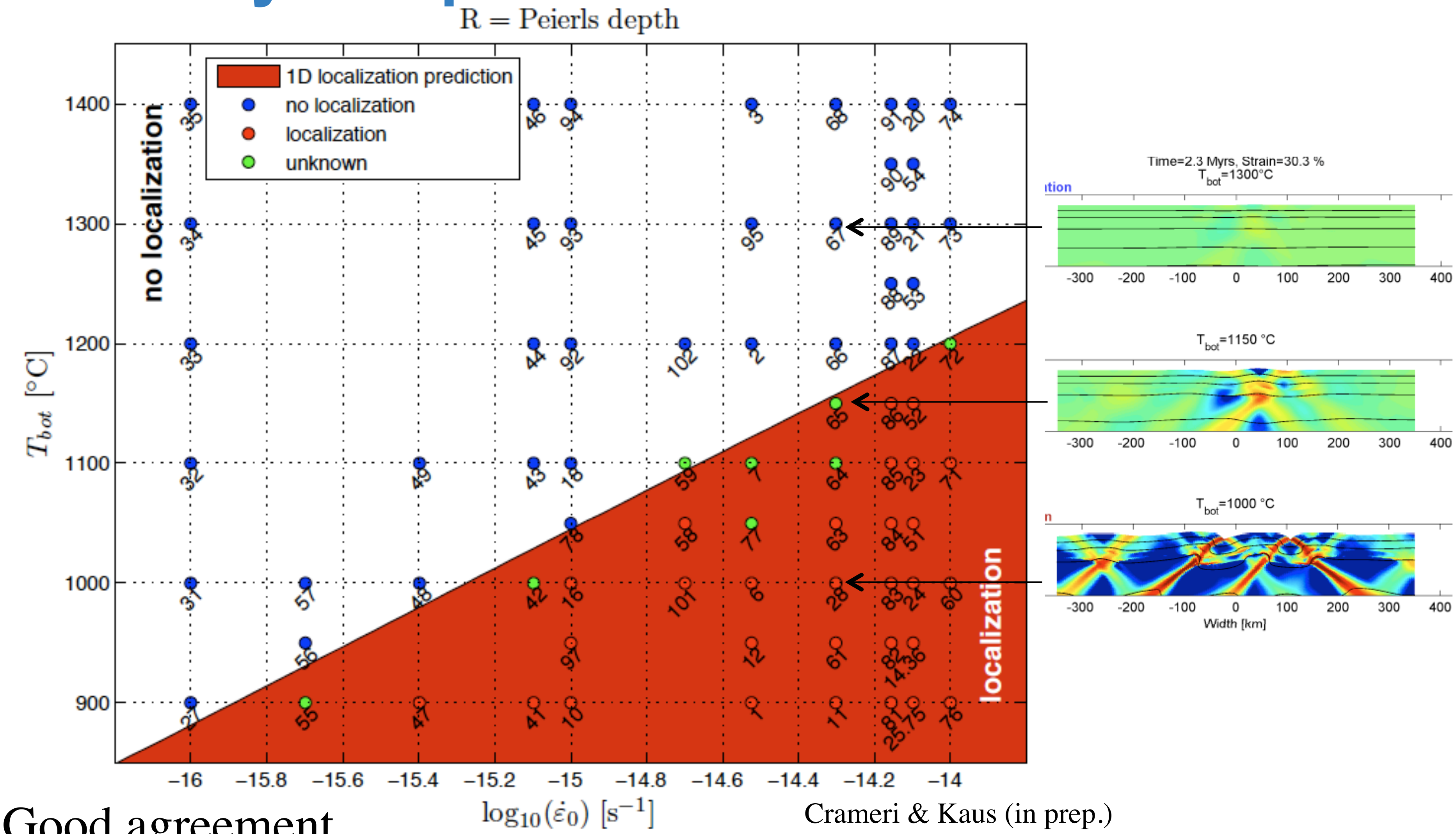




Predictions from 1-D model



1-D analytical predictions vs. 2D numerics



Crameri & Kaus (in prep.)

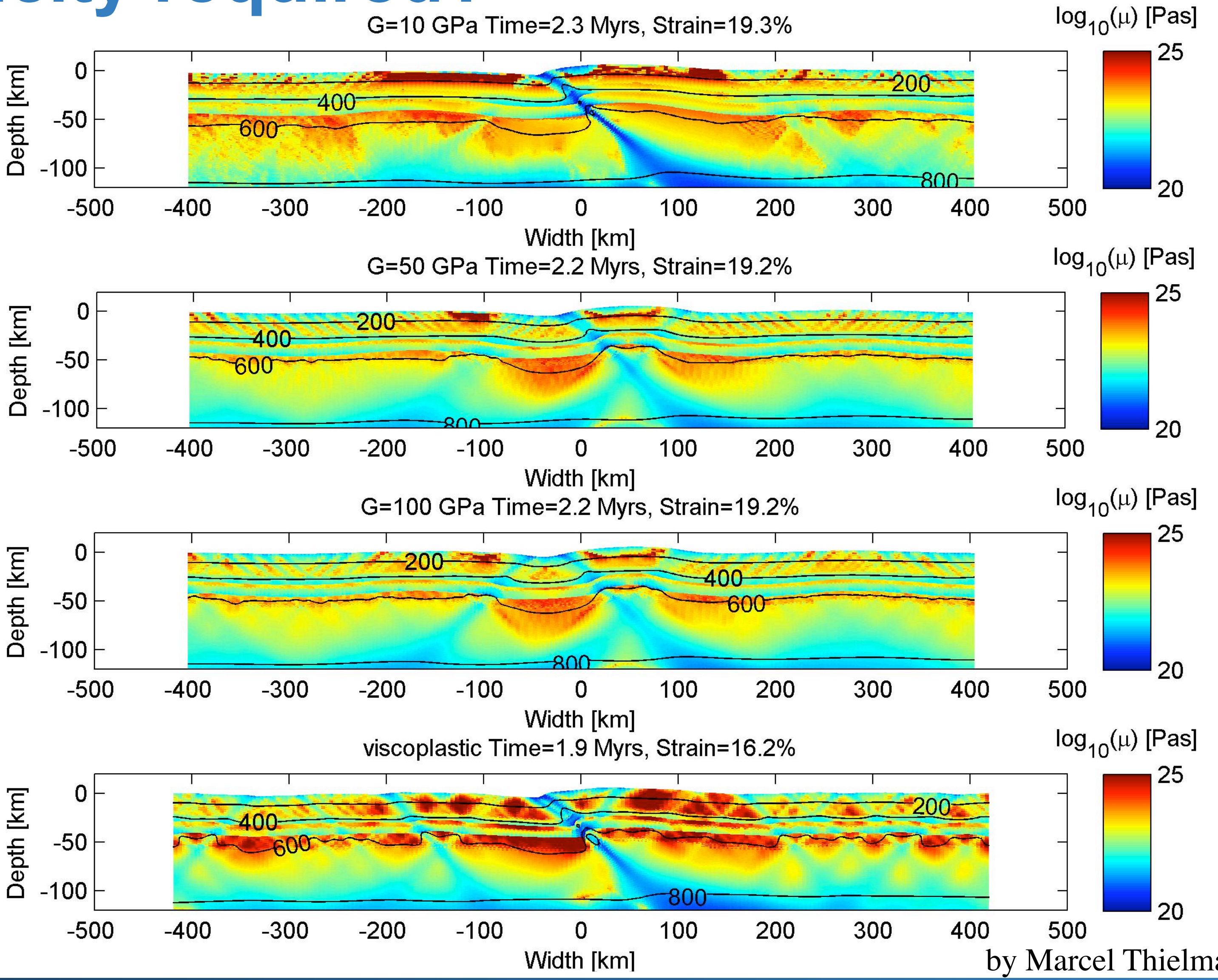
Good agreement.

1-D theory *predicts* occurrence of lithospheric-scale shear localization.

Is elasticity required?

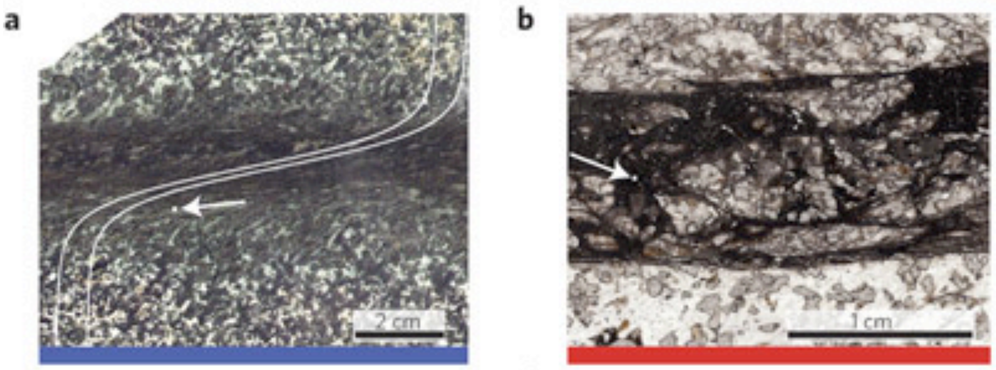
Elasticity

No elasticity

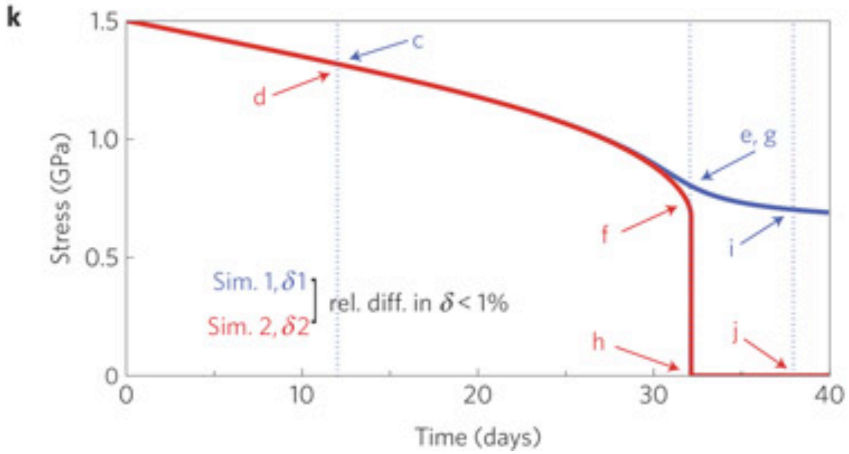


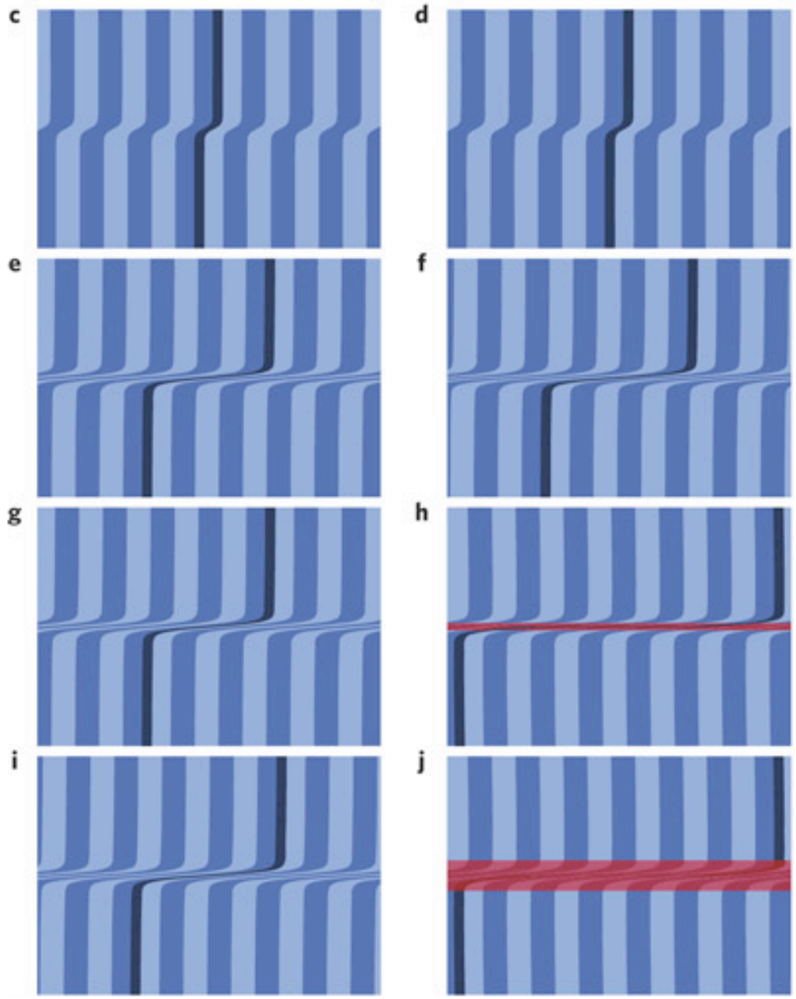
by Marcel Thielmann

Field evidence?



shear-zone pseudotachylyte

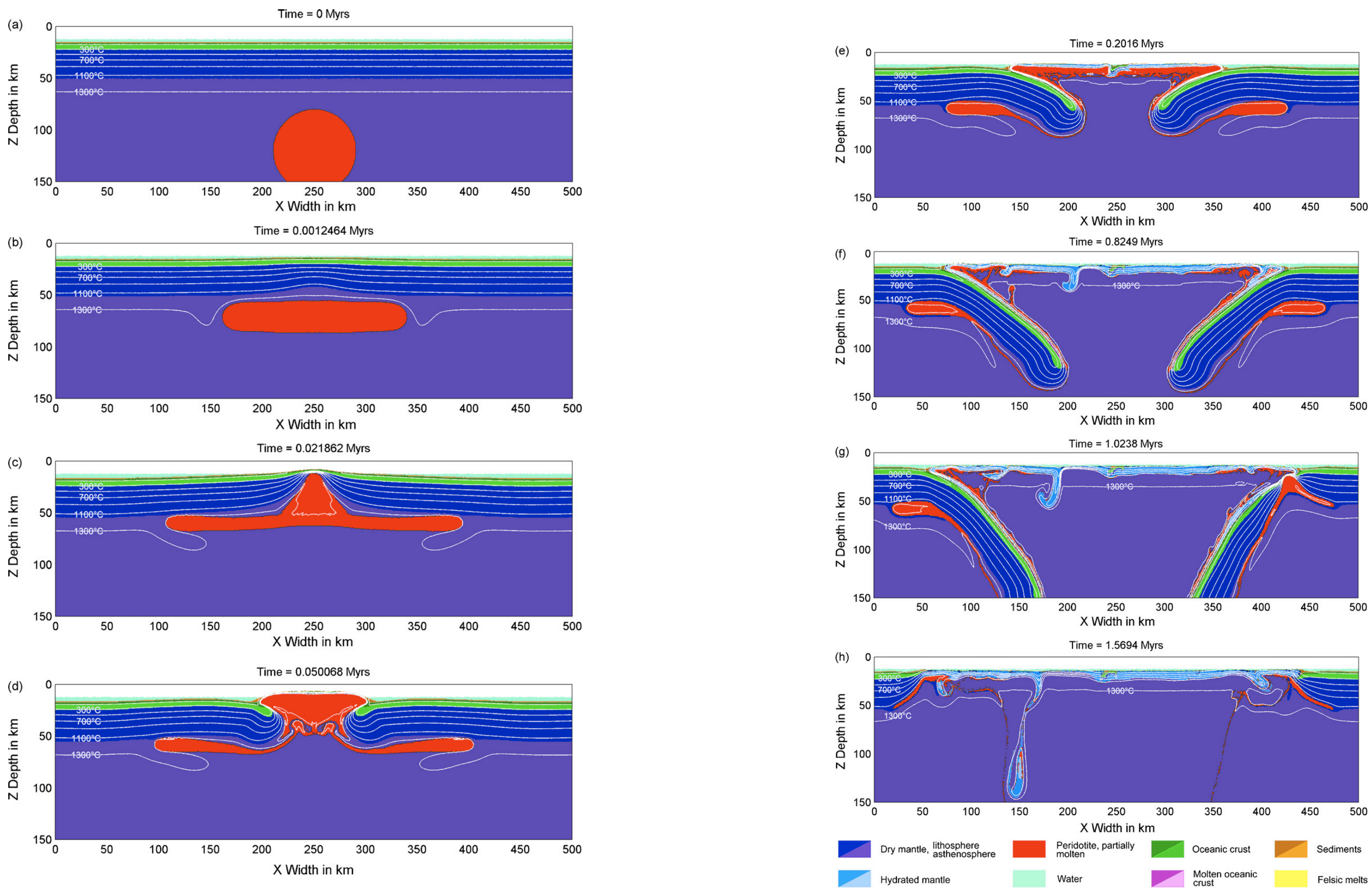




John et al. (2009) Nature geosciences.

Some recent models of subduction initiation

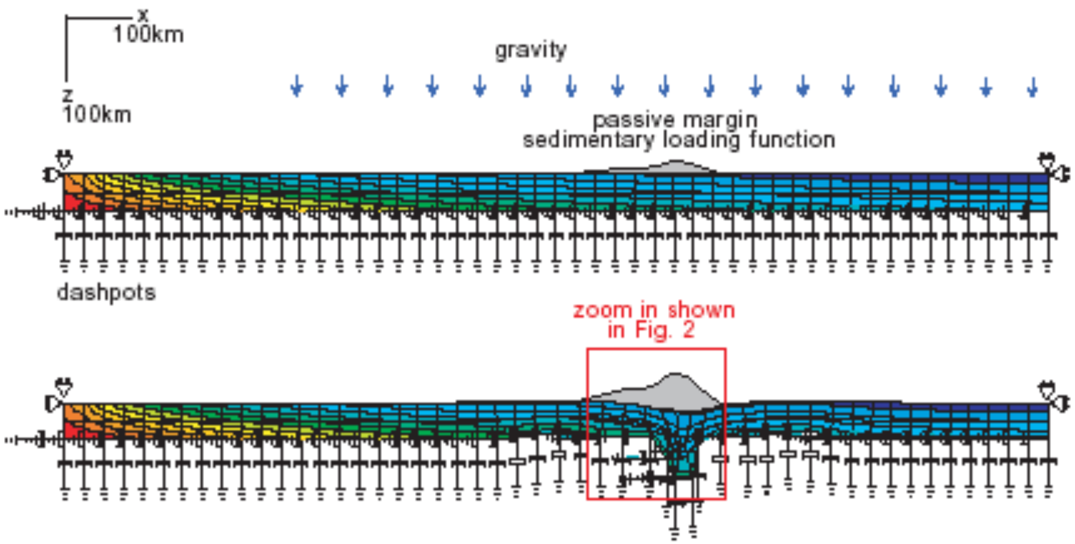
Subduction initiation (1): plumes

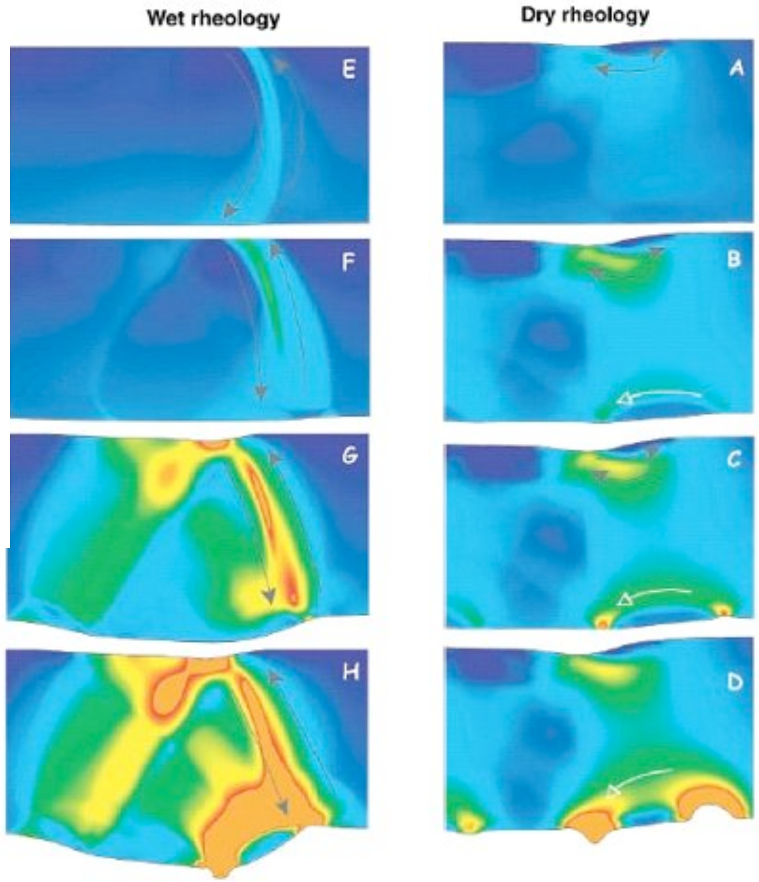


Mainly requires small frictional parameters
& very thin lithosphere.

Ueda et al. (2008)

Subduction initiation (2): sediment loading





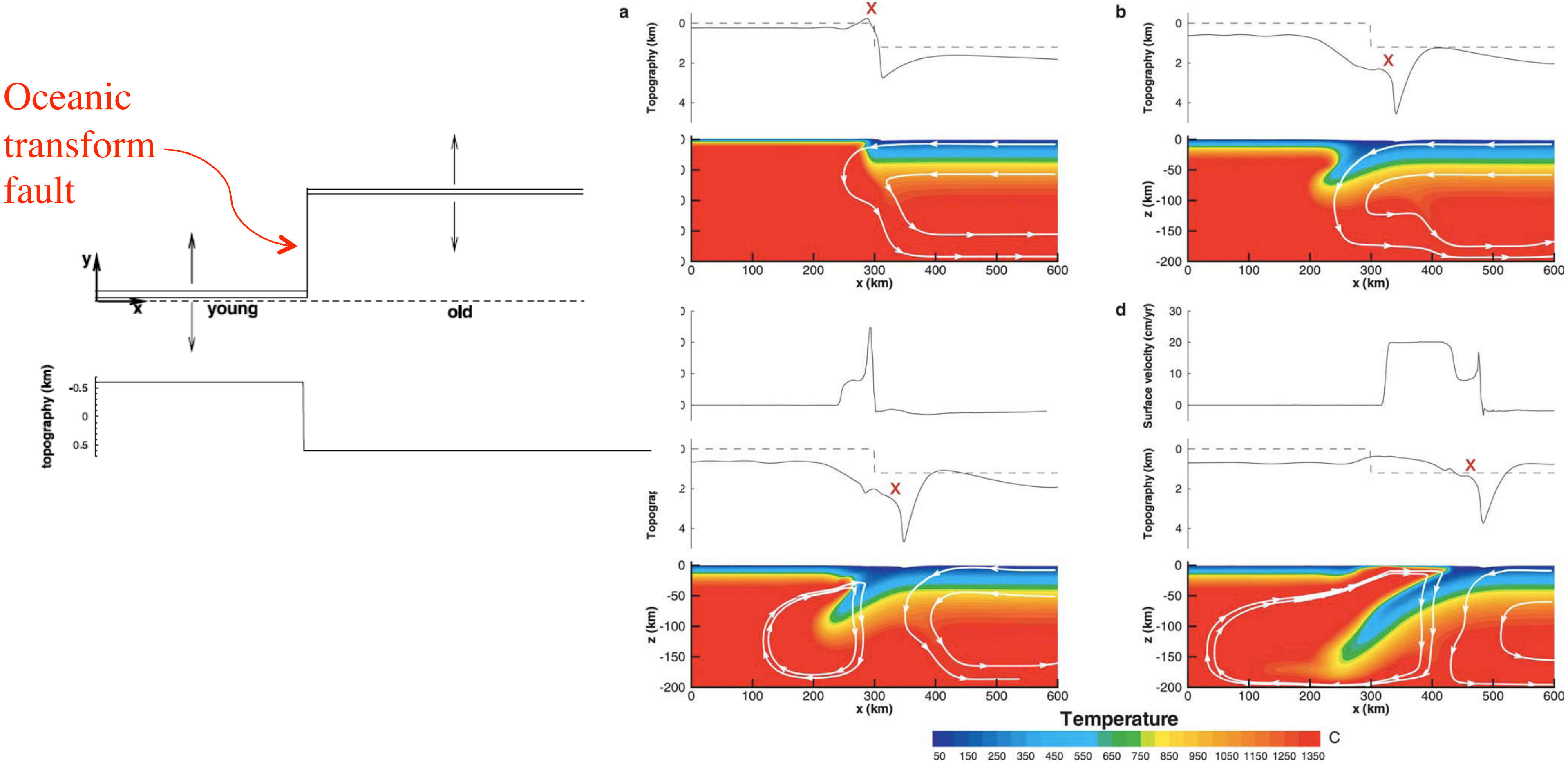
- Rheology quite complex
  (diffusion creep, dislocation creep, Peierls plasticity, elasticity, Mohr-Coulomb plasticity, elasticity).

- Probably a shear-heating instability.

- Unclear whether it will result in fully developed subduction zone.

Regenauer-Lieb et al. (2001)

Subduction initiation (3): transform faults



- Unclear what controls the physics.

Hall et al. (EPSL, 2000)
Gurnis et al. (G^3, 2002)

Summary

- Shear localization:
  - Brittle crust:
    - no problem.
  - Mantle lithosphere:
    - more difficult, requires additional weakening mechanisms.
    - Shear heating can do the job (sometimes).
    - Other mechanisms need to be studied in more detail.
- Subduction initiation
  - Unresolved topic.
  - Goal: find the simplest rheology/model that creates (one-sided) subduction from a convecting system.