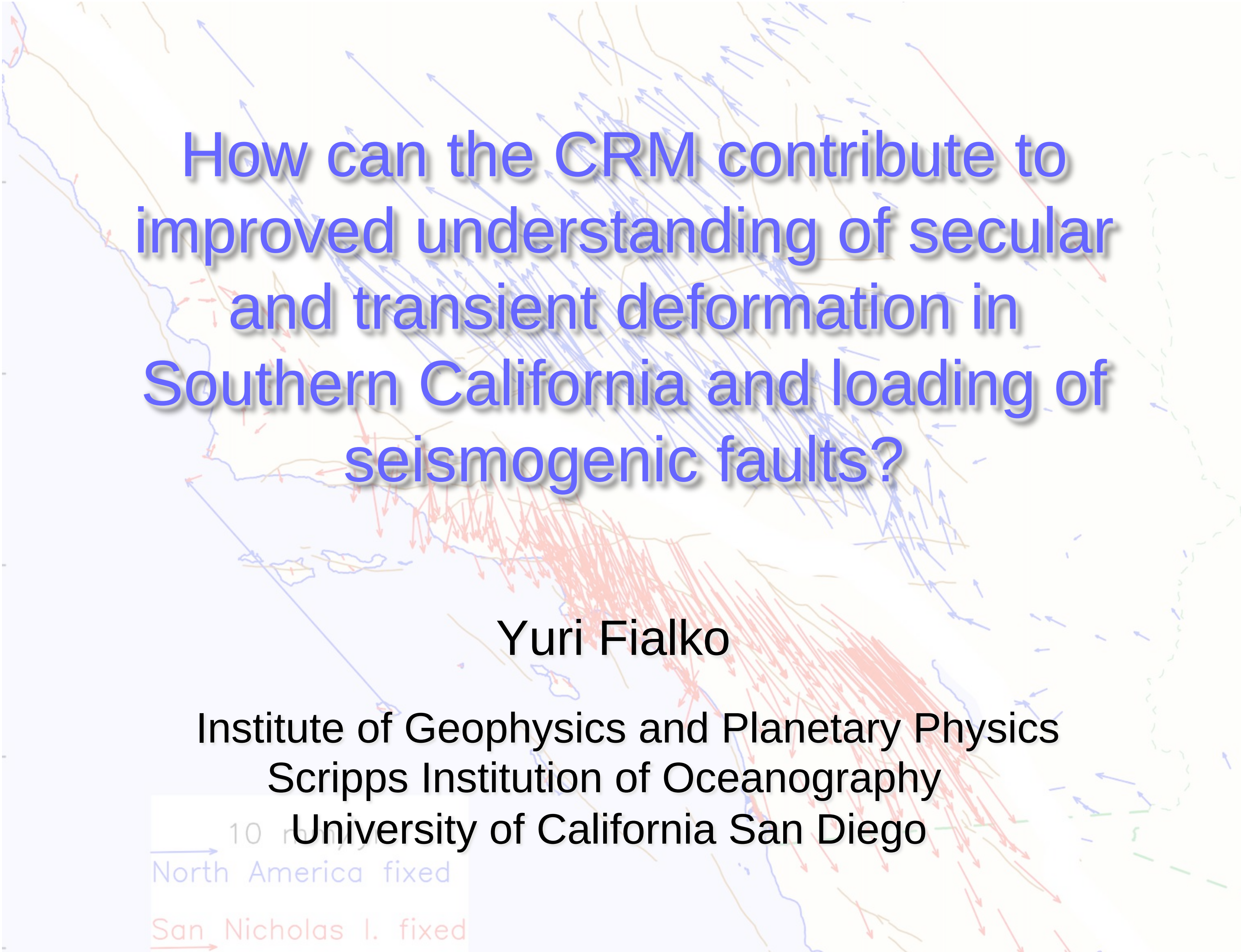
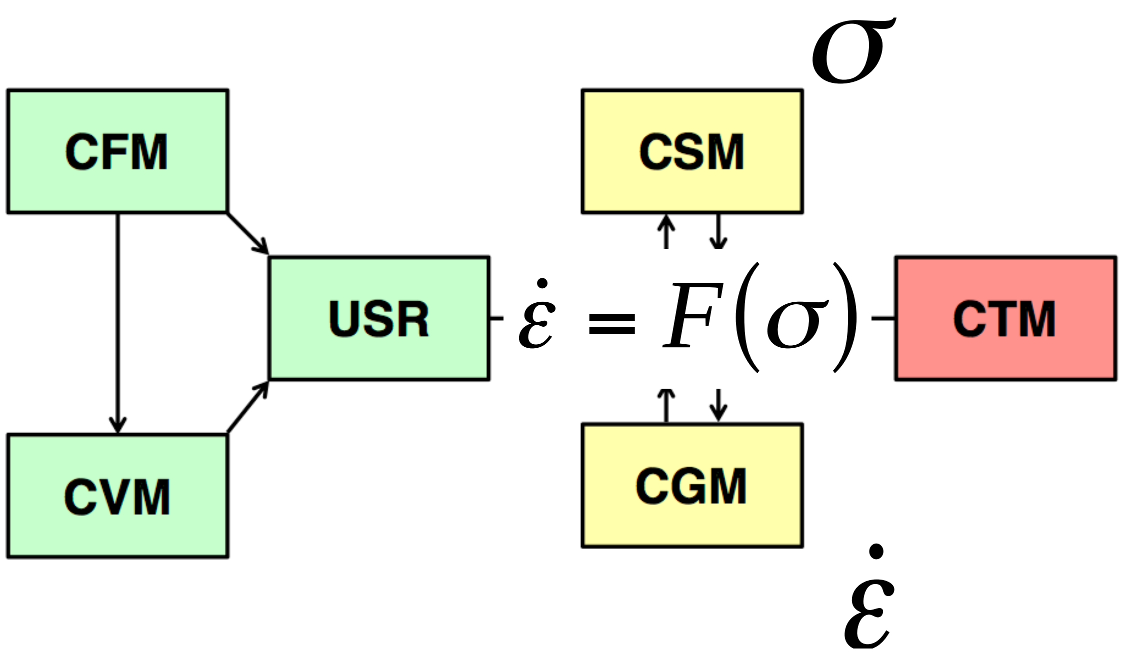
How can the CRM contribute to improved understanding of secular and transient deformation in Southern California and loading of seismogenic faults?



Yuri Fialko

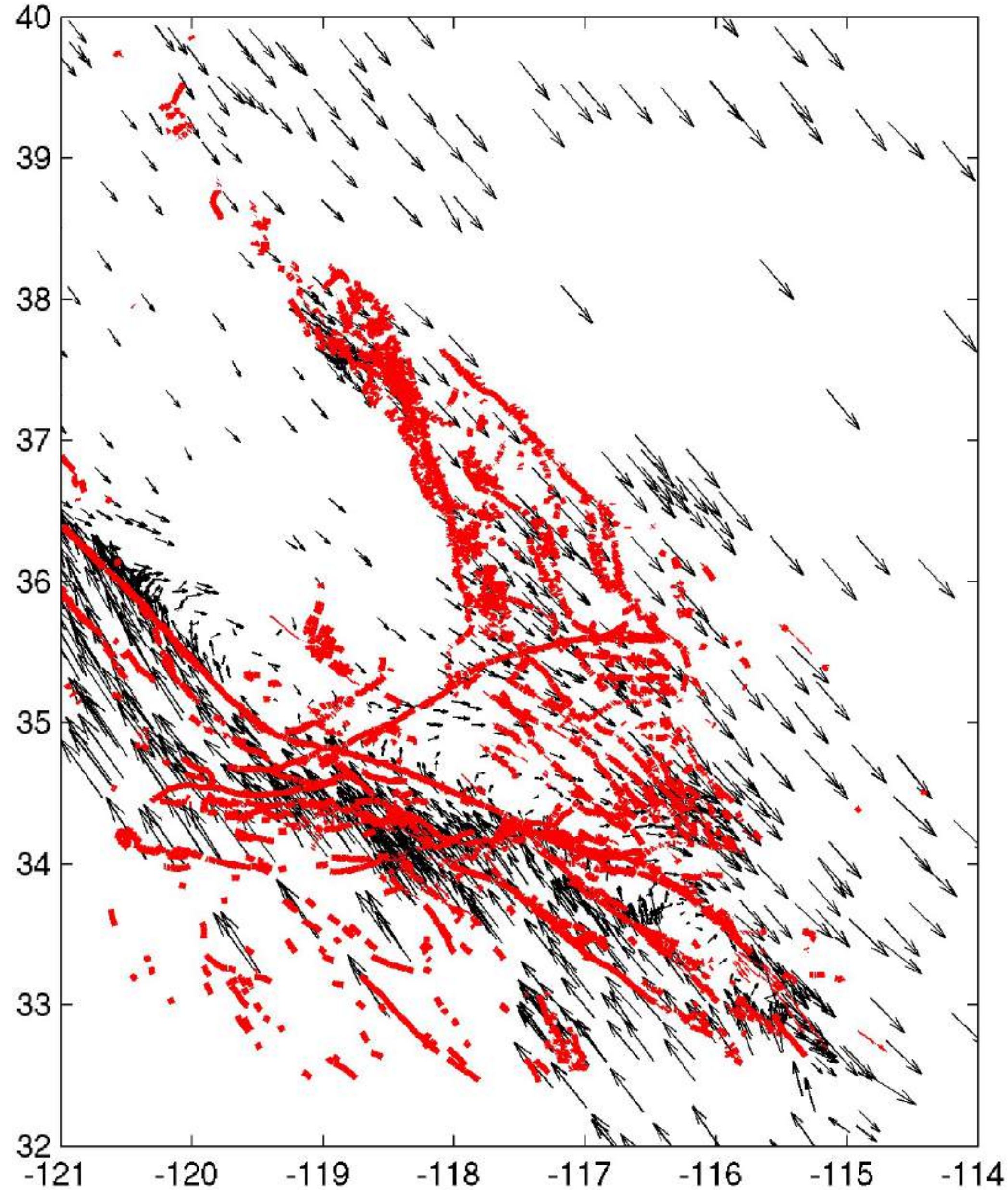
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California San Diego

CRM in SCEC5



Model key:

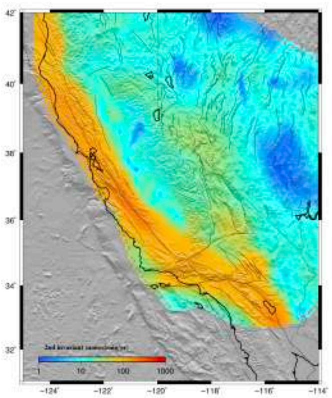
F = Fault S = Stress
G = Geodetic T = Thermal
R = Rheology V = Velocity
USR = Unified Structural Representation



Secular velocities (CMM4)

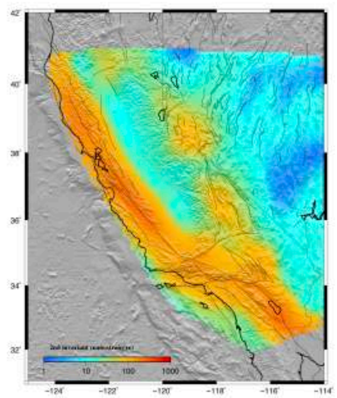
Comparison of Strain-Rate Maps of Western North America

becker



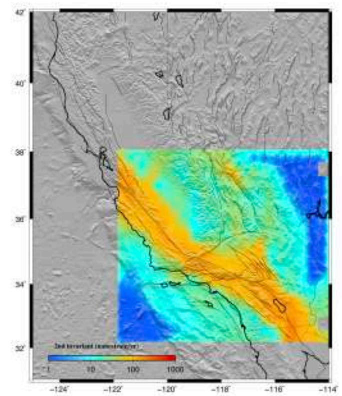
Crustal strain-rates based on a high quality subset of the 2007 release of the horizontal GPS velocity solution from EarthScope PBO. Processing assumes continuous deformation, uses modified Generic Mapping Tool software, and strives for a smooth representation of the velocity gradients (see Platt et al, EPSL, 2008, for details).

fialko



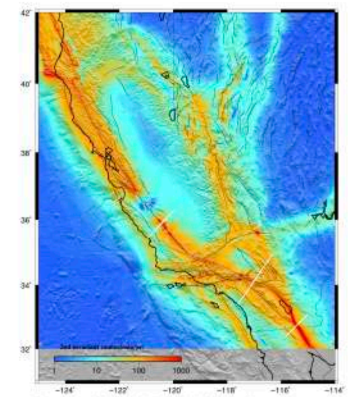
The second invariant of the strain rate tensor is calculated from a set of 722 continuous GPS sites within the area of interest for which velocity solutions are available from either SOPAC or PBO. The two horizontal velocity components were first approximated on a regular grid by least-square fitting of a smooth surface using a modified ridge estimator. The resulting velocity fields were differentiated to obtain components of the strain rate tensor. A Gaussian low-pass filter of size 0.75 degrees and standard deviation of 0.25 degrees was applied to the calculated second invariant of the strain rate.

freed



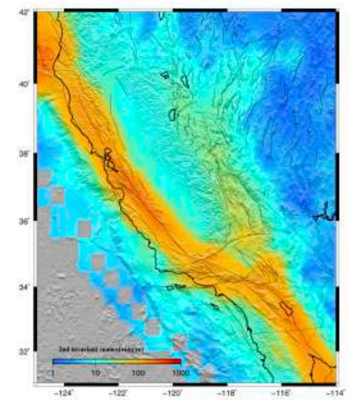
Strain rates were derived based on 810 SCEC 3 velocity vectors (http://epicenter.usc.edu/cmm3/). We linearly interpolated the velocity data to an evenly spaced grid with increments of 0.1 degrees across the region using a weighted nearest neighboring scheme to dampen any locally sharp velocity contrasts. For grid points outside of the SCEC 3 region, we extrapolated the velocity field based on a fixed North America plate and a Pacific plate with a velocity of 48 mm/yr. We then triangulated the evenly spaced grid points using Delaunay triangulation (e.g., Shewchuk, 1996), and the strain tensor is determined for each triangle using minimum norm least squares. Reference: Freed et al., 2007.

harvard



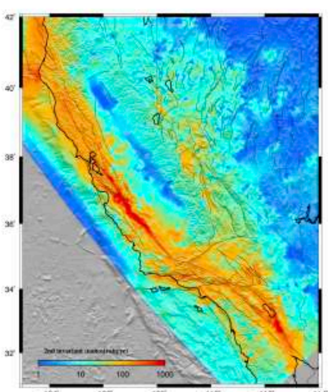
The strains are calculated analytically using elastic dislocation theory in a homogeneous elastic halfspace. The model is subset of a western US block model geodetically constrained by a combination of the SCEC CMM 3.0, McClusky ECSZ, Hammond Walker Lane, McCaffrey PNW, d'Allessio Bay Area, and PBO velocity fields. These are combined by minimizing residuals (6-parameter) at collocated stations. In southern California the block geometry is based on and the Plesch et al., CFM-R and features dipping faults in the greater Los Angeles regions which end up producing some intricate strain rate patterns. The model features fully coupled (locked from the surface to some locking depth) faults everywhere except for Parkfield, the SAF just north, and the Cascadia subduction zone. For Parkfield and Cascadia we solve for smoothly varying slip on surfaces parameterized using triangular dislocation elements.

holt

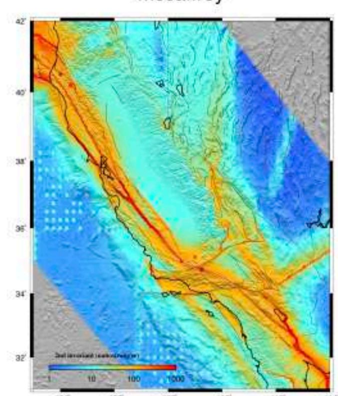


Second invariant of strain rate obtained from bi-cubic spline interpolation of 4948 campaign and EarthScope PBO GPS velocities. Model parameters are estimated through a weighted least-squares inversion of the GPS within a grid region extending from Alaska to the Rivera Plate. The reference frame for each GPS study was solved for in the inversion in order to place all observations into a best fit North America model reference frame.

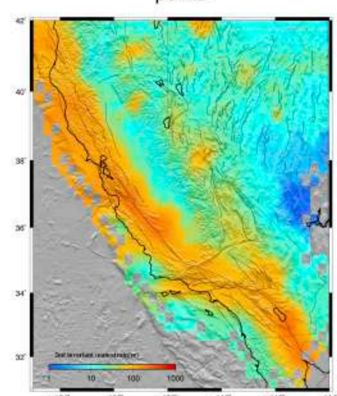
kreemer



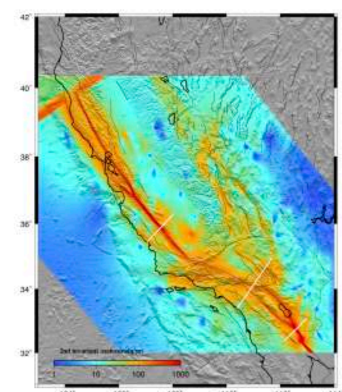
mccaffrey



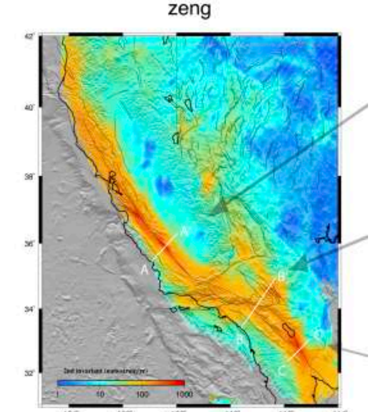
pollitz



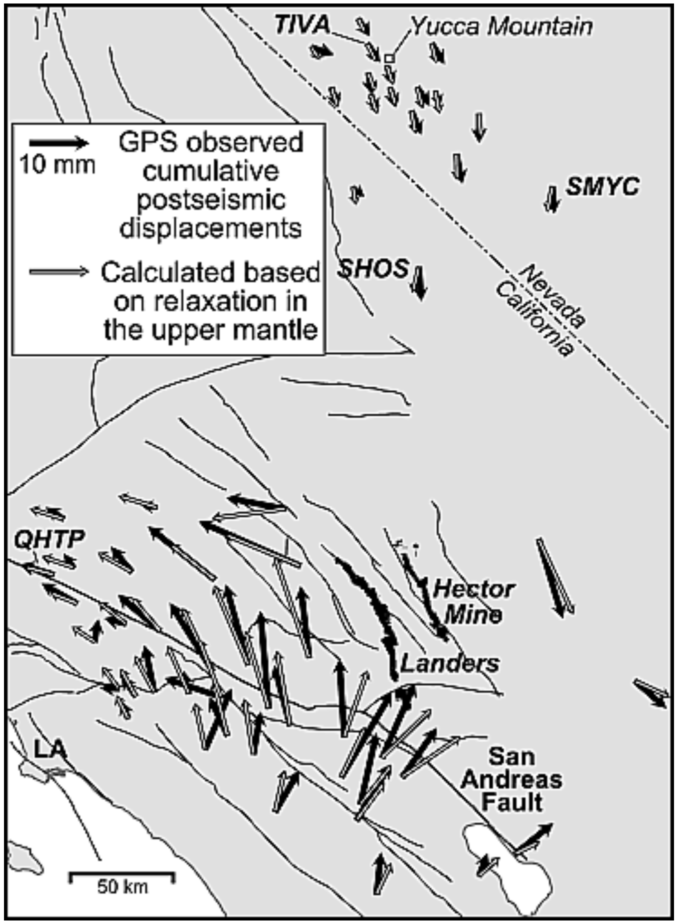
smith_konter

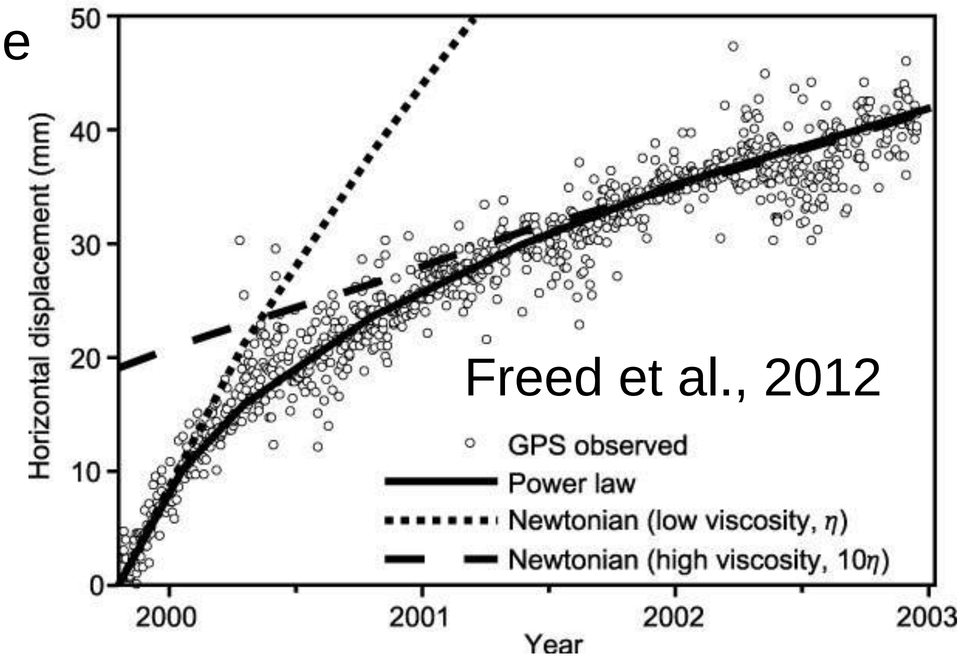


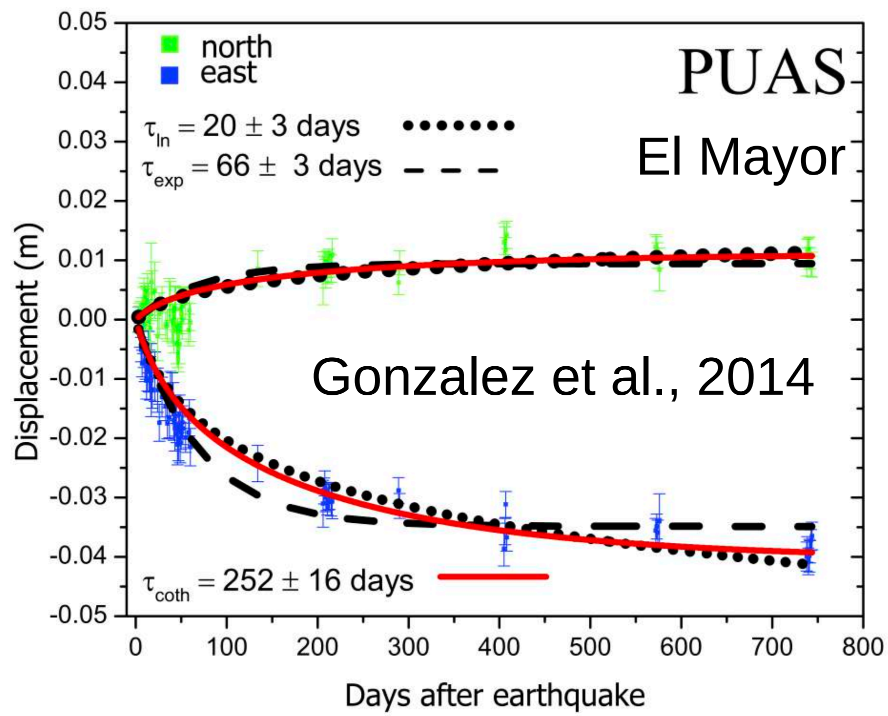
zeng



Hector Mine

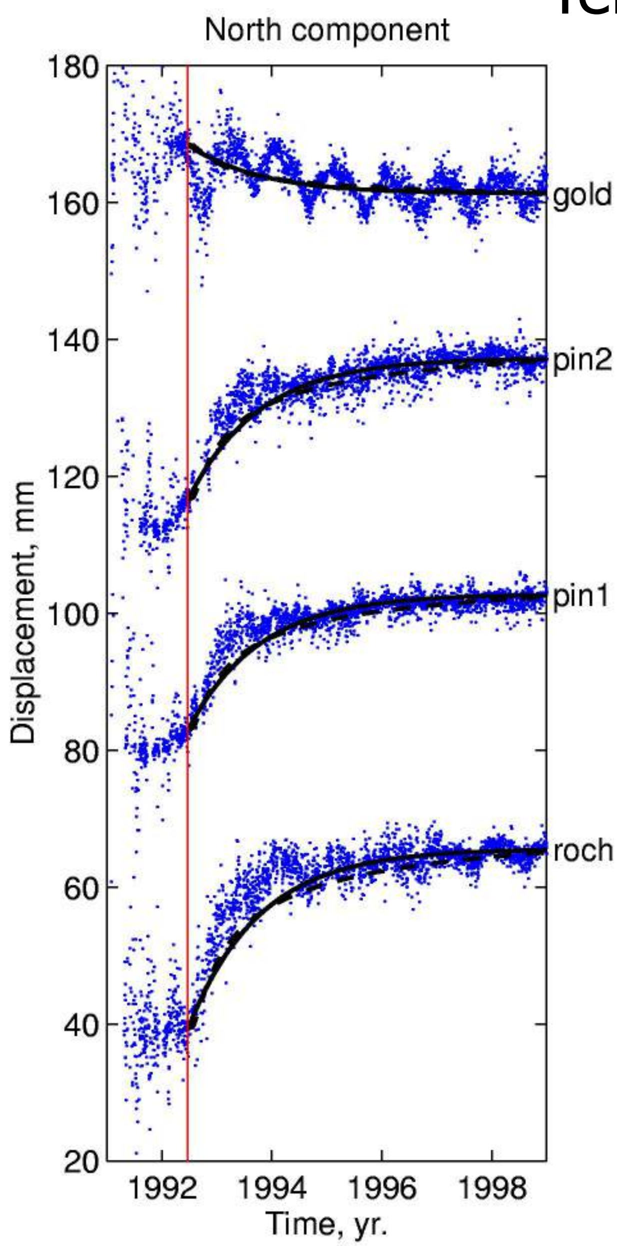






Transient deformation (e.g., post-seismic relaxation)

Temporal evolution of surface deformation



Post-Landers CGPS data (Fialko, 2004)

-Rapid initial transient followed by a more gradual decay

-Difficult to fit assuming exponential dependence (not consistent with linear Maxwell viscoelastic behavior)

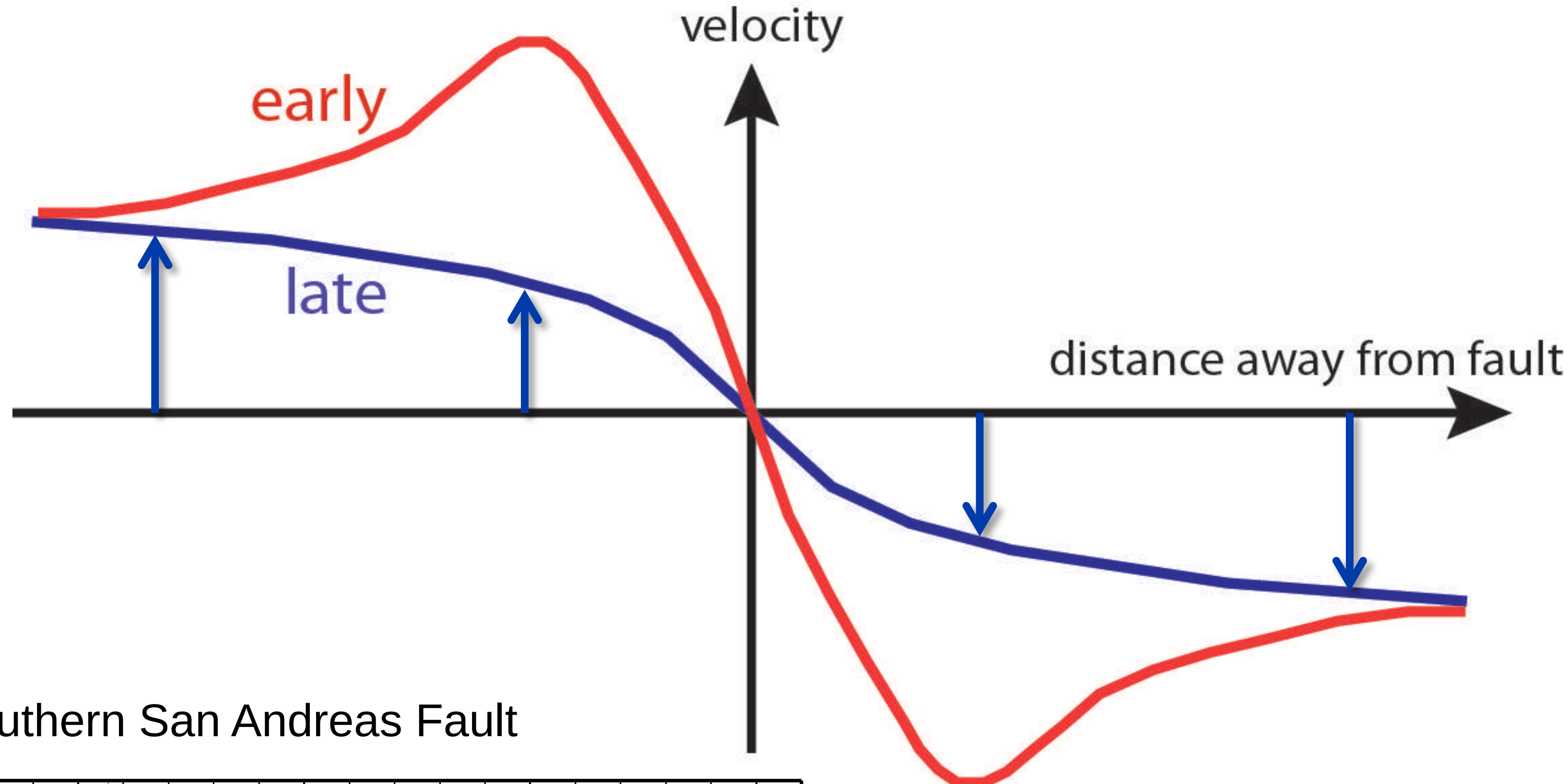
-Possible explanations:

Bi- (or multi-) viscous rheology (Pollitz, 2005)

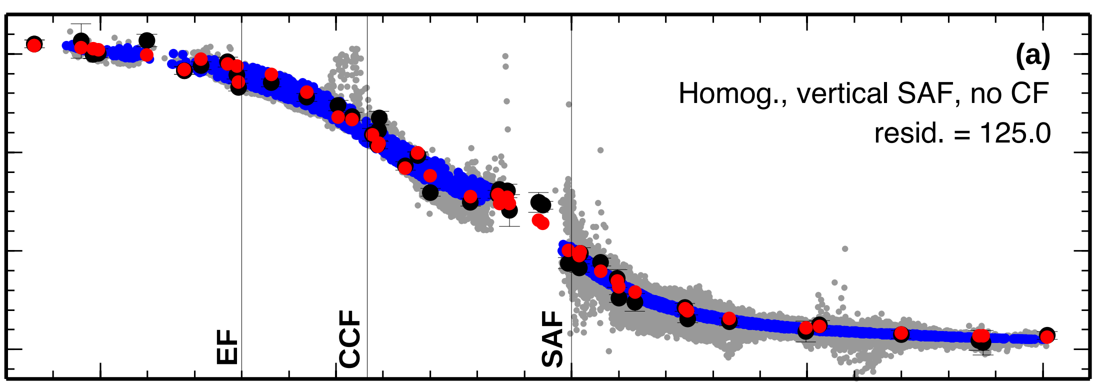
Power-law rheology (Freed and Burgmann, 2004)

Rate-and-state friction (or some other form of localized creep, e.g., Hearn et al., 2002; Perfettini and Avouac, 2005)

Surface velocity due to a strike-slip fault



Southern San Andreas Fault

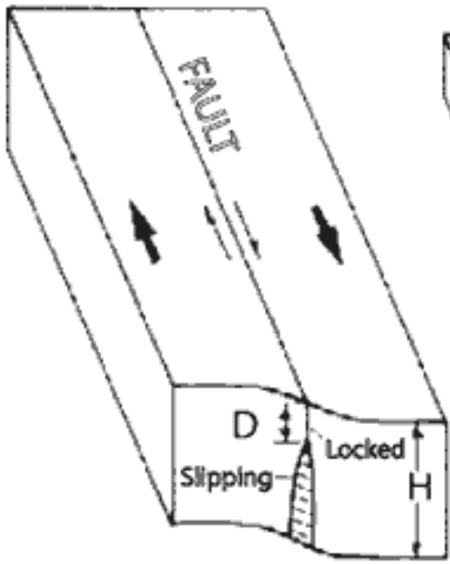


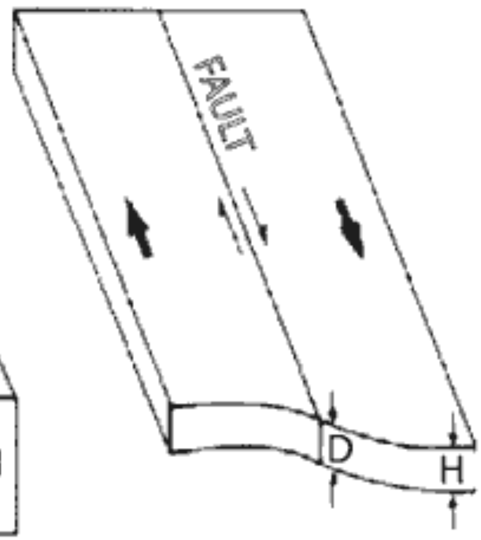
Lindsey & Fialko 2013

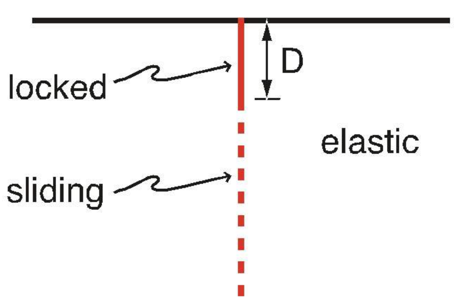
Thick Lithosphere Model D/H << 1

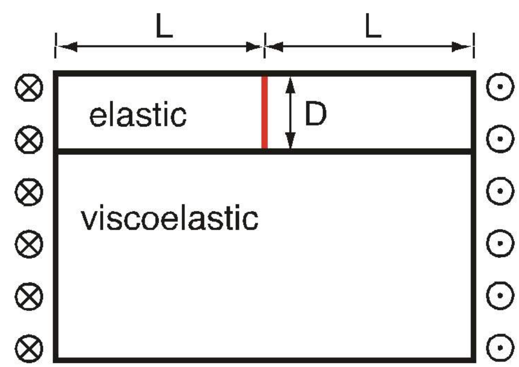
vs

Thin Lithosphere Model D/H = 1









Savage and Burford, 1973
Turcotte and Spence, 1974

Elsasser, 1969
Savage and Prescott, 1978

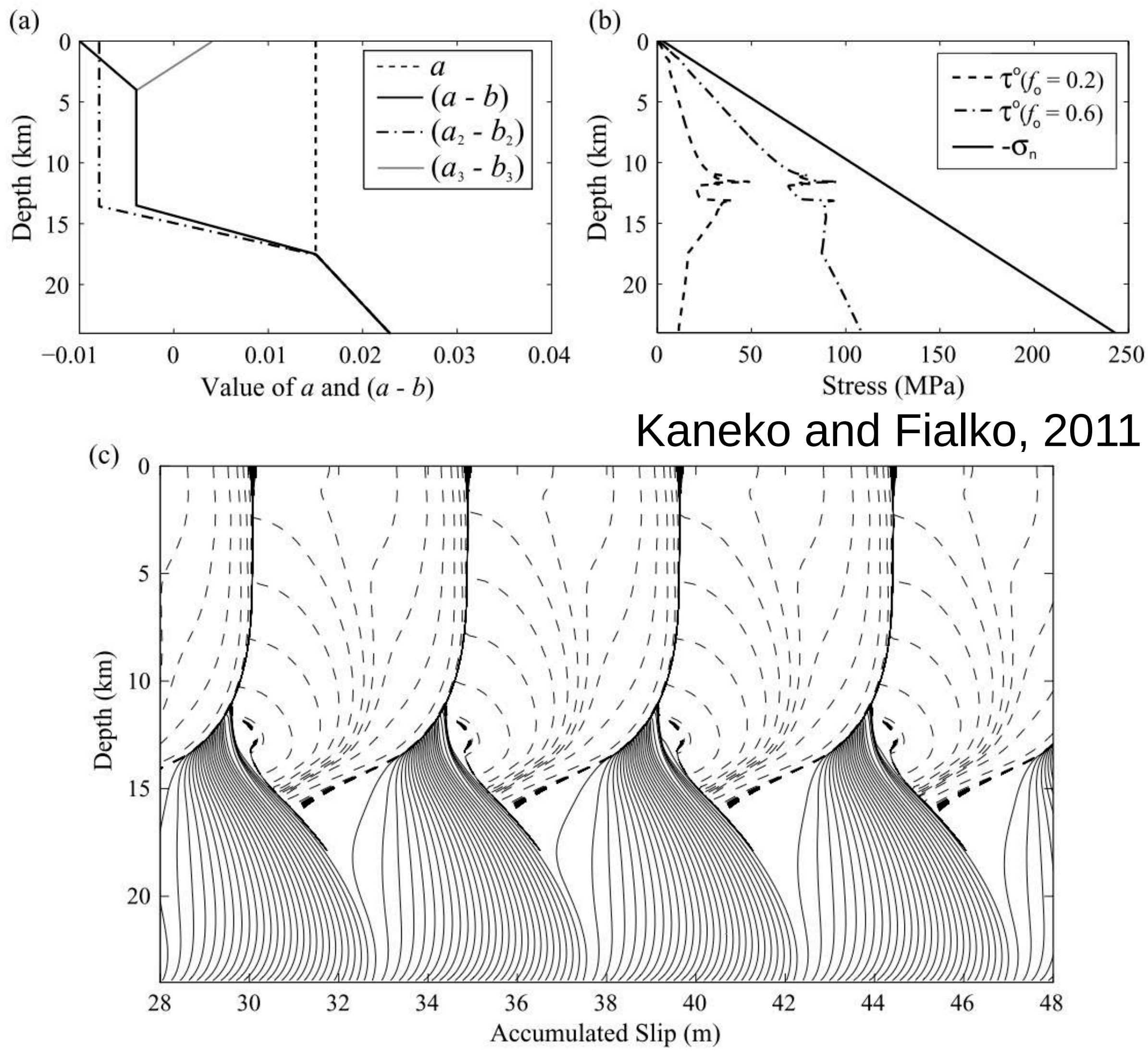
"Fault-block vs Viscous sheet"
"Crème Brûlée vs Jelly Sandwich"
"Bottom-driven vs Side-driven"

Geodetic slip rates and fault locking depths depend on model assumptions

Difference between the models results from oversimplified model assumptions?

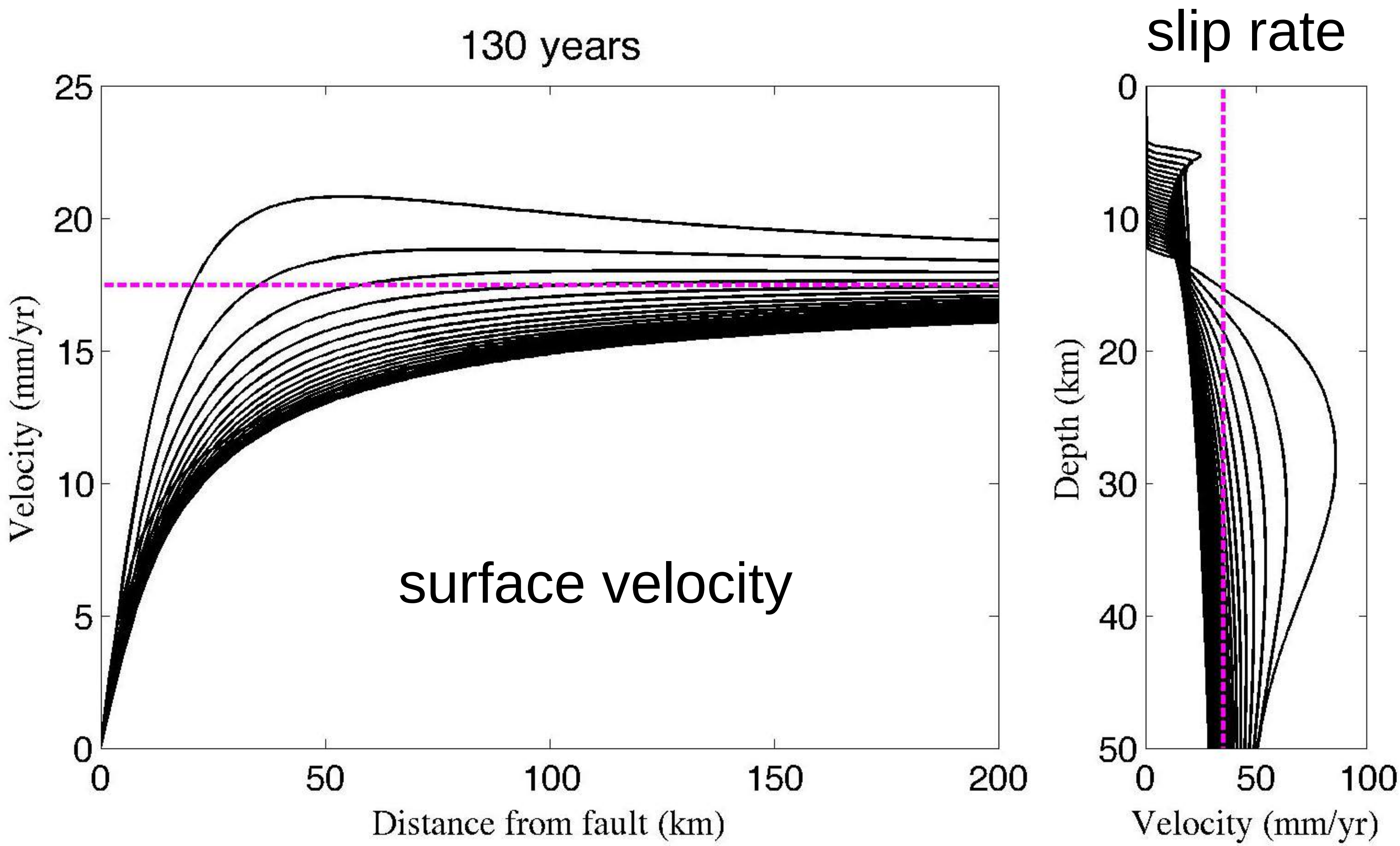
Li and Rice, 1987
Johnson and Segall, 2004

Earthquake cycles on a rate-and-state fault

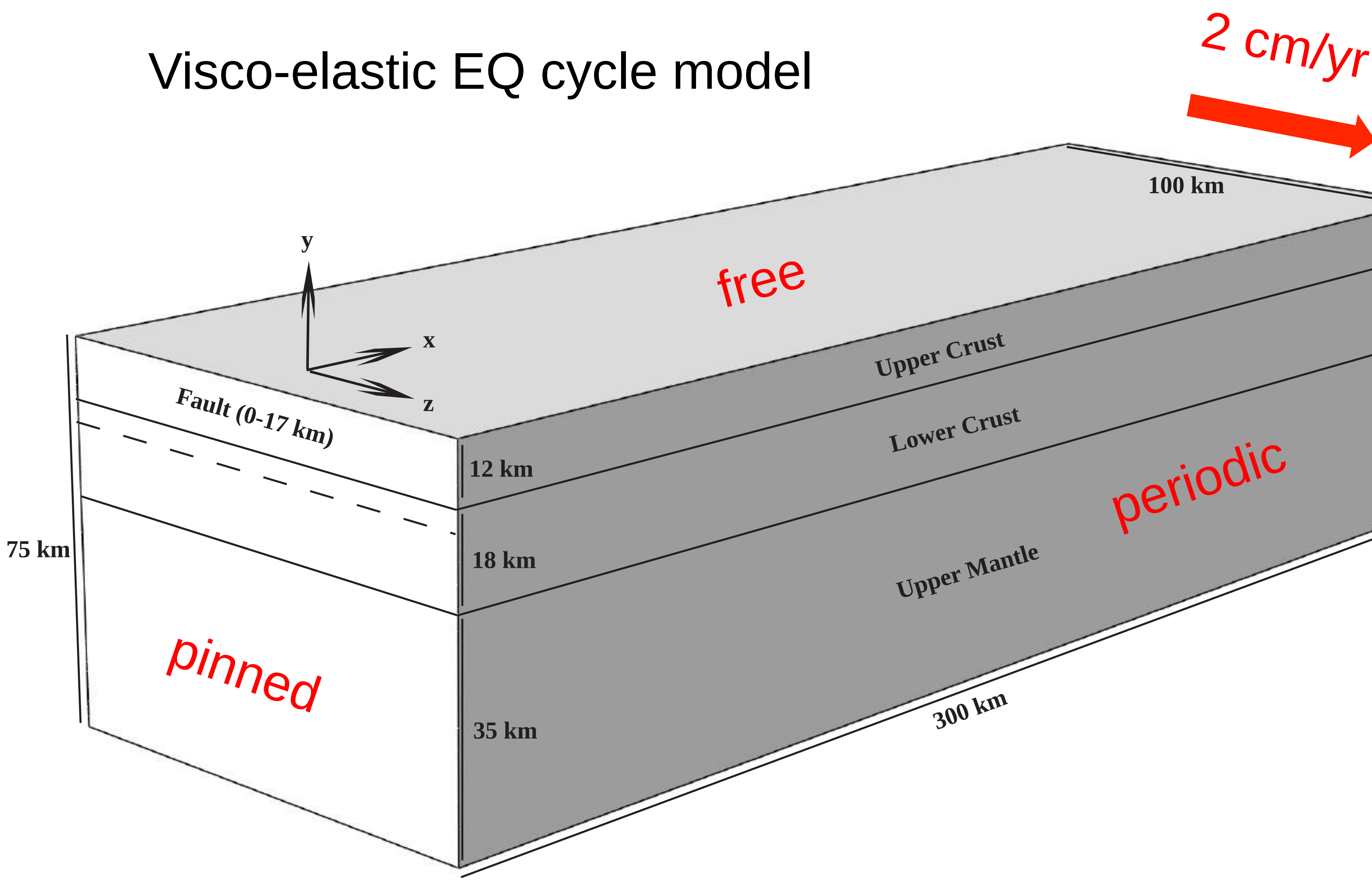


Kaneko and Fialko, 2011

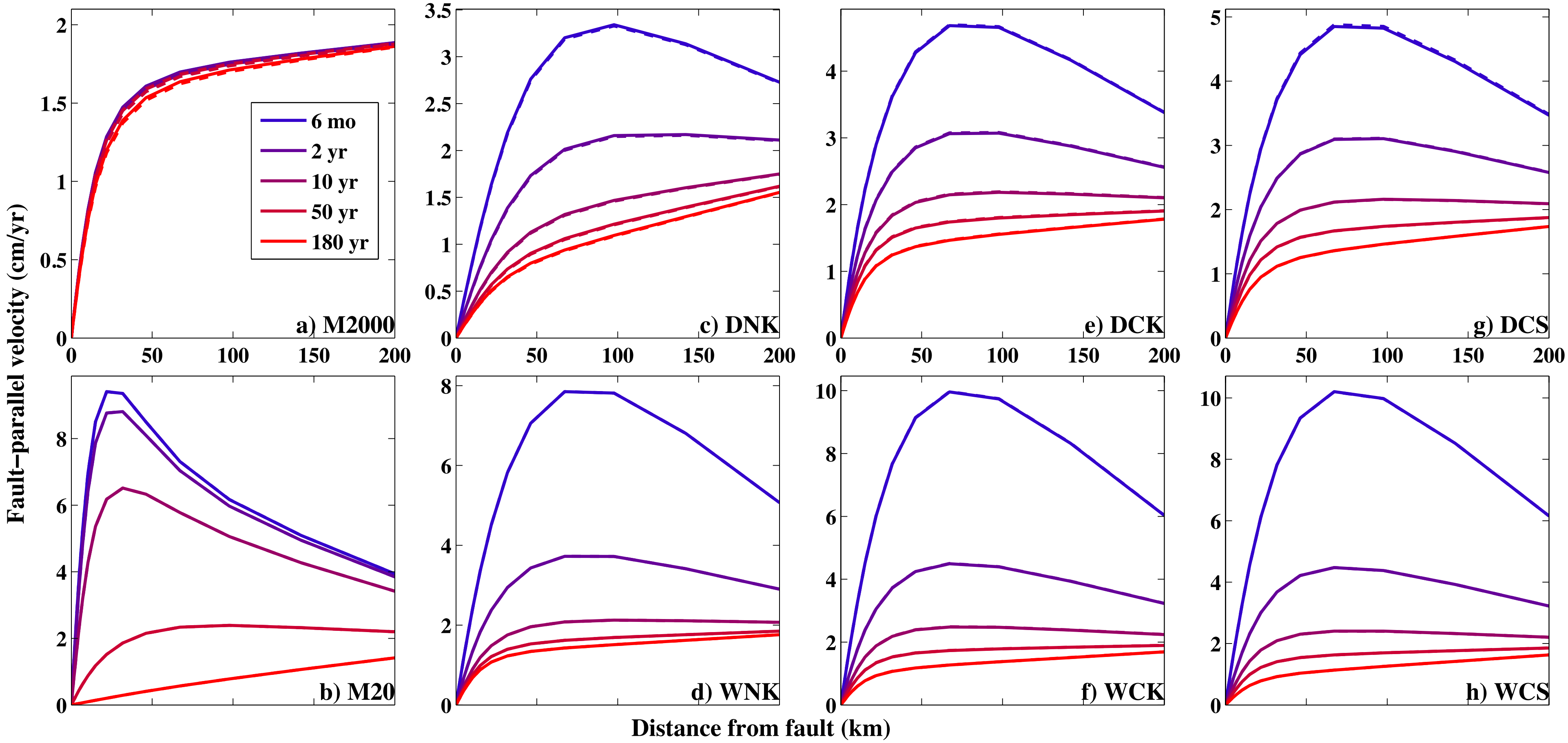
Tse and Rice, 1987
Lapusta et al., 2001



130 years
Velocity (mm/yr)
Distance from fault (km)
surface velocity
0
5
10
15
20
25
0
50
100
150
200
slip rate
Depth (km)
Velocity (mm/yr)
0
10
20
30
40
50
0
50
100


Visco-elastic EQ cycle model
2 cm/yr
100 km
y
x
z
free
Fault (0-17 km)
Upper Crust
Lower Crust
Upper Mantle
periodic
12 km
18 km
35 km
75 km
pinned
300 km

Surface velocities



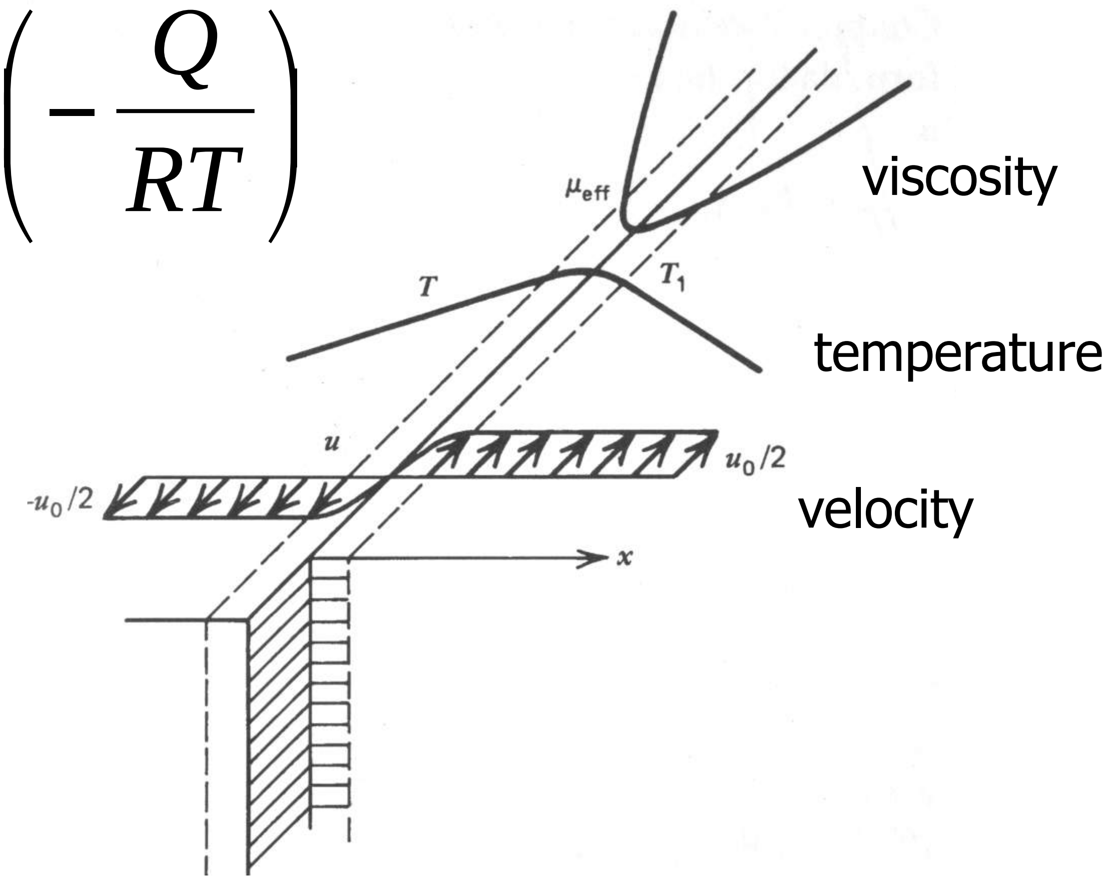
linear visco-elastic

power-law

Realistic rheologies lead to localization

$$\dot{\varepsilon} = C\sigma^n \exp\left(-\frac{Q}{RT}\right)$$

$$T \propto \dot{\varepsilon}\sigma$$



Yuen et al., 1978; Fleitout and Frodivaux, 1980;
Turcotte and Schubert, 2002

Strain localization mechanisms

- Thermo-mechanical coupling
- Grain size reduction
- Foliation / fabric development
- Mineral alteration
- Pressure solution
- …

All lead to the development of shear zones and strength reduction

Grain size evolution

$$\dot{\varepsilon}_v = \dot{\varepsilon}_D + \dot{\varepsilon}_G = A_D \sigma^{n_D} + A_G d^{-m} \sigma^{n_G}$$

dislocation creep — diffusion creep

$n_D \sim 3$

$n_G \sim 1$

$m \sim 3$

$$\dot{d}_+ = B_G p^{-1} d^{1-p} \exp\left(-\frac{H}{RT}\right)$$

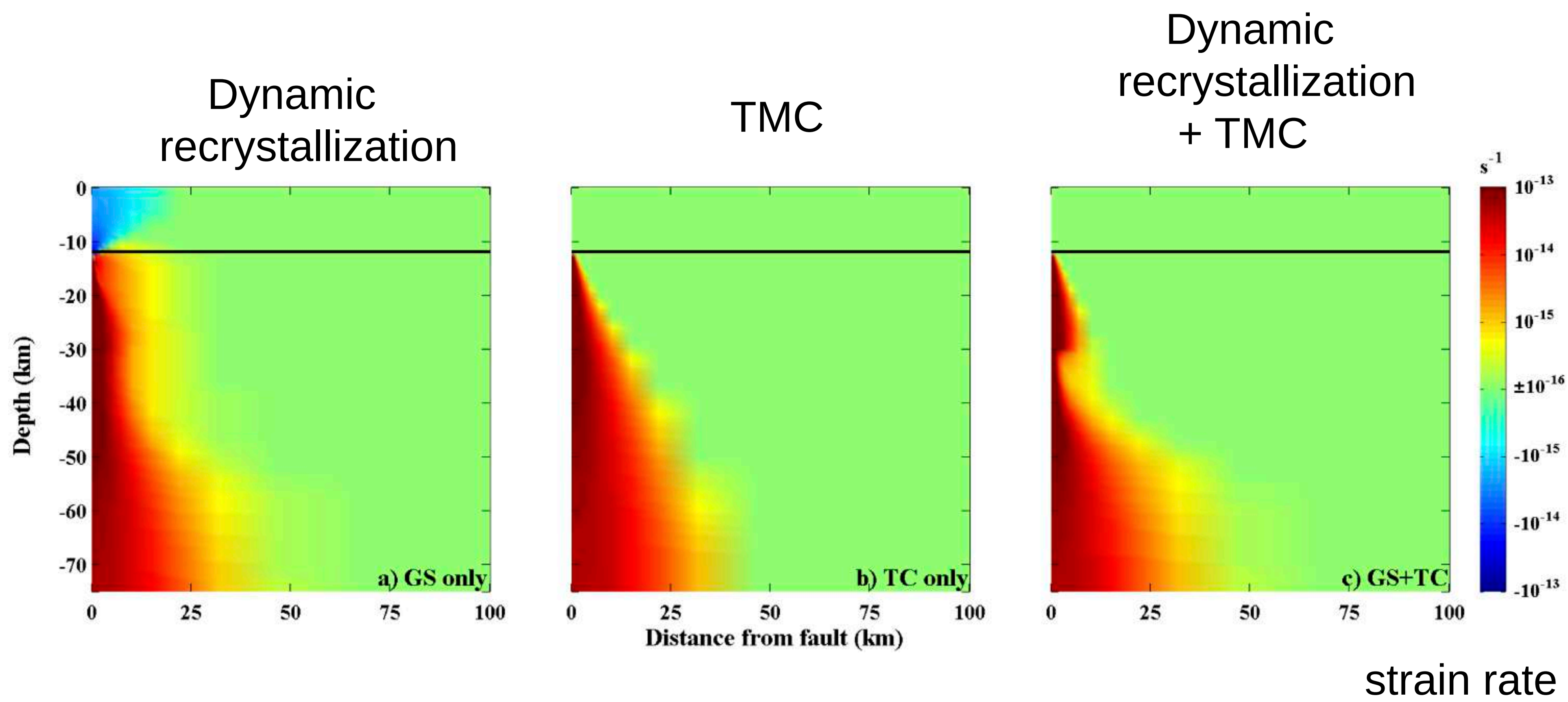
static grain growth

$$\dot{d}_- = -\lambda d \dot{\varepsilon}_G$$

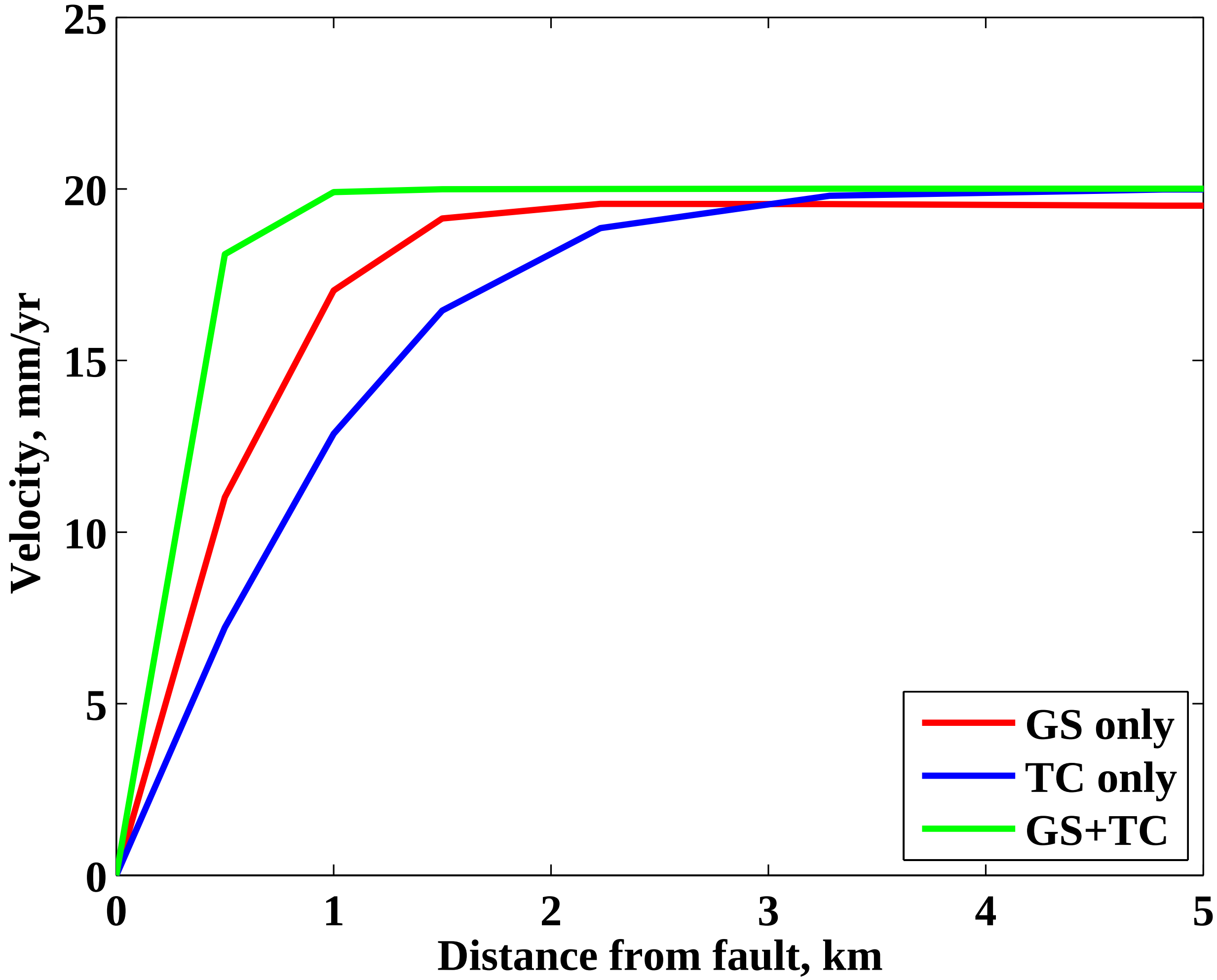
dynamic recrystallization

de Bresser et al. (1998; 2001)
Hall and Parmentier (2003)

Effects of dynamic recrystallization



Strain localization at 20 km depth



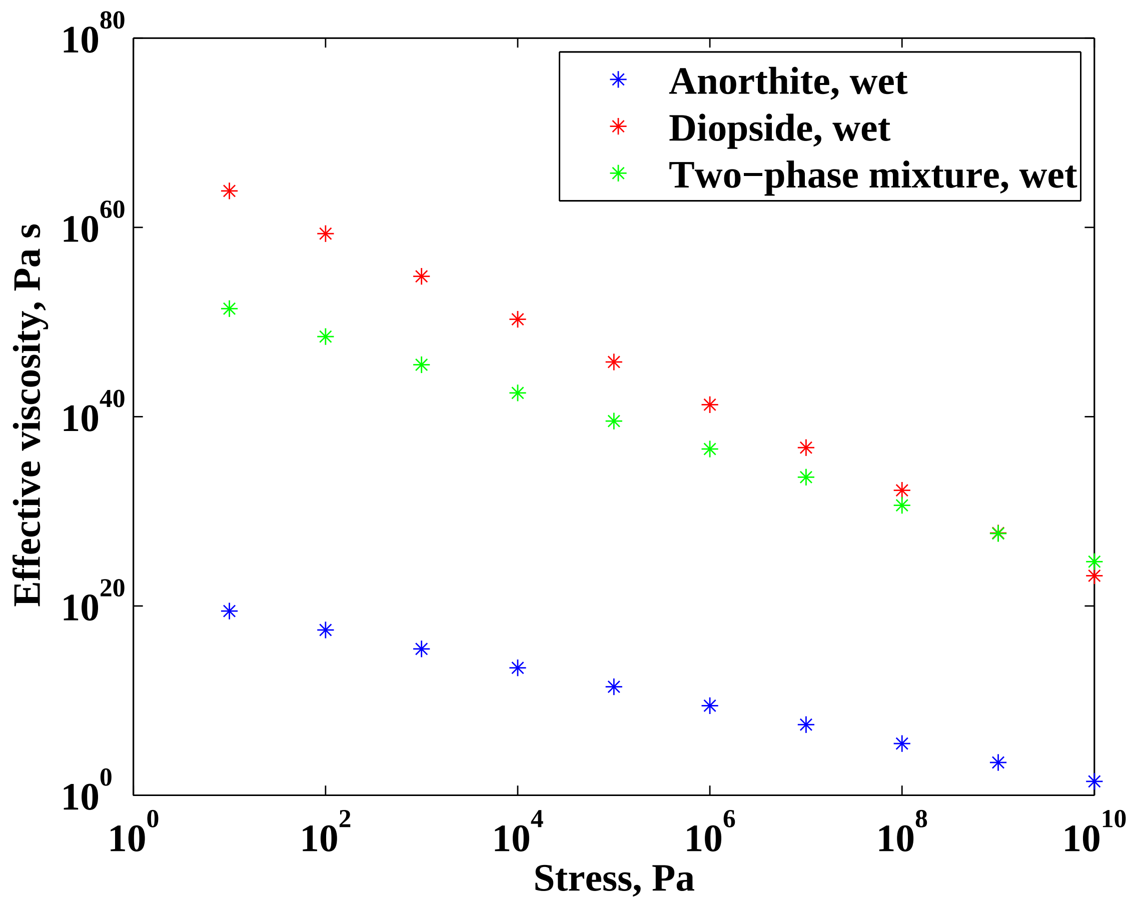
Foliation

Strain-induced separation of weak and strong mineral phases; development of anisotropic fabric

$$\dot{\varepsilon}_{tot} = \sum_{i=1}^{N} \dot{\varepsilon}_i \phi_i$$

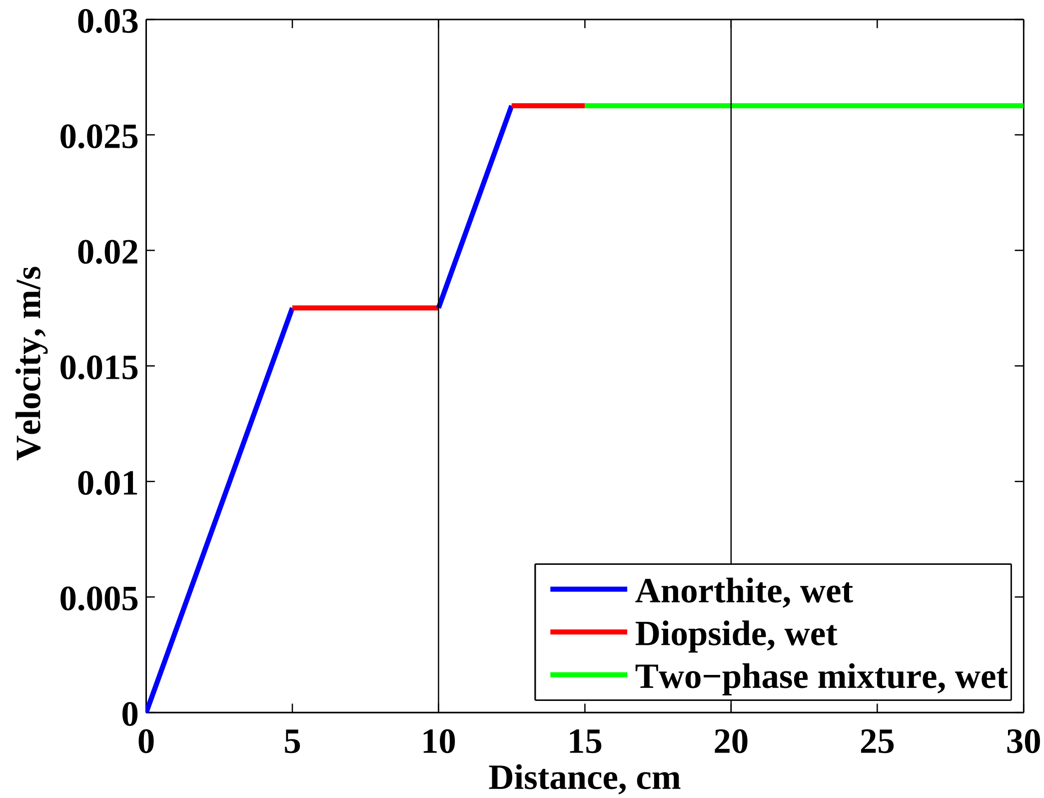
$$\sum_{i=1}^{N} \phi_i = 1$$

Aggregate vs individual phase rheologies

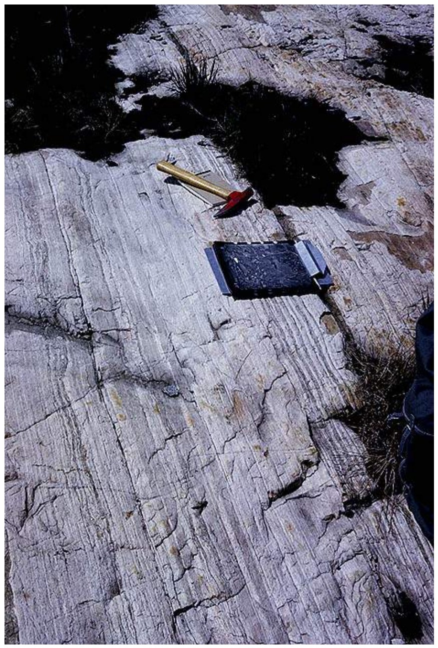


flow law parameters from Dimanov and Dresen (1995)

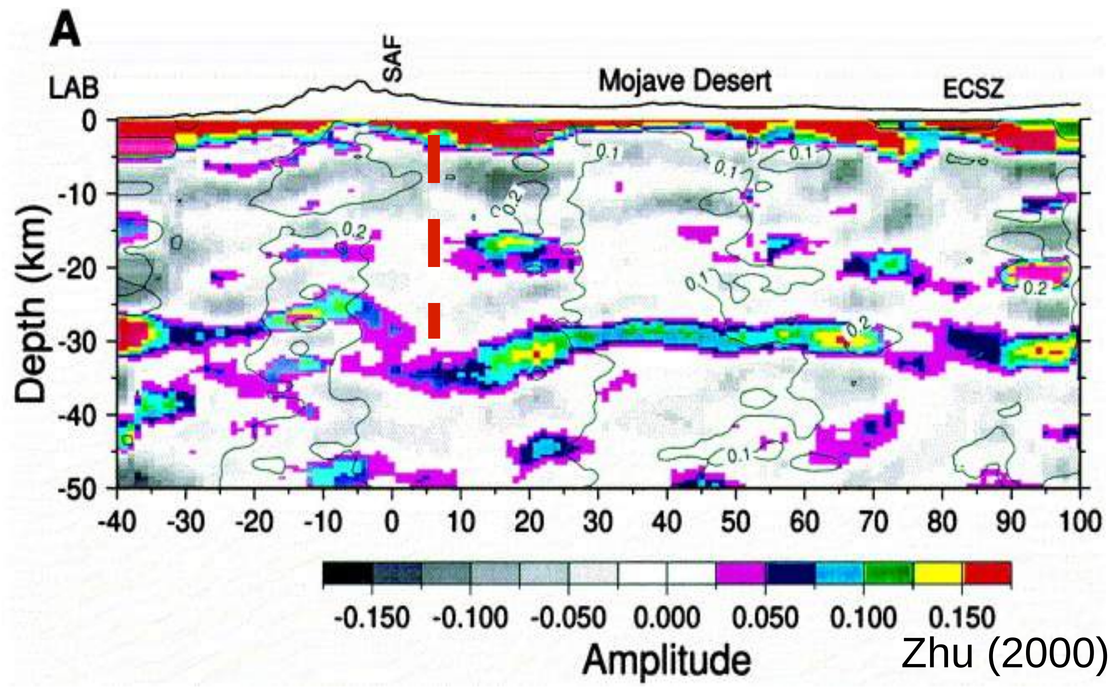
Deformation (and strength) is controlled by the weakest phase



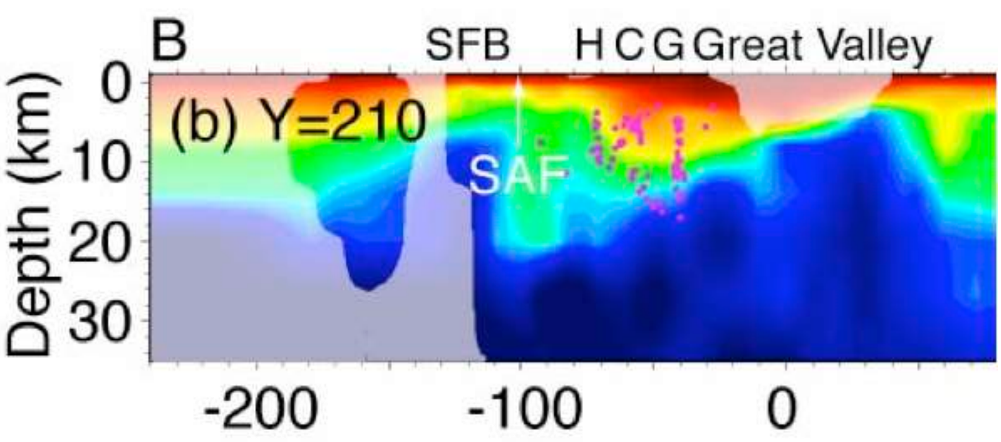
flow law parameters from Dimanov and Dresen (1995)



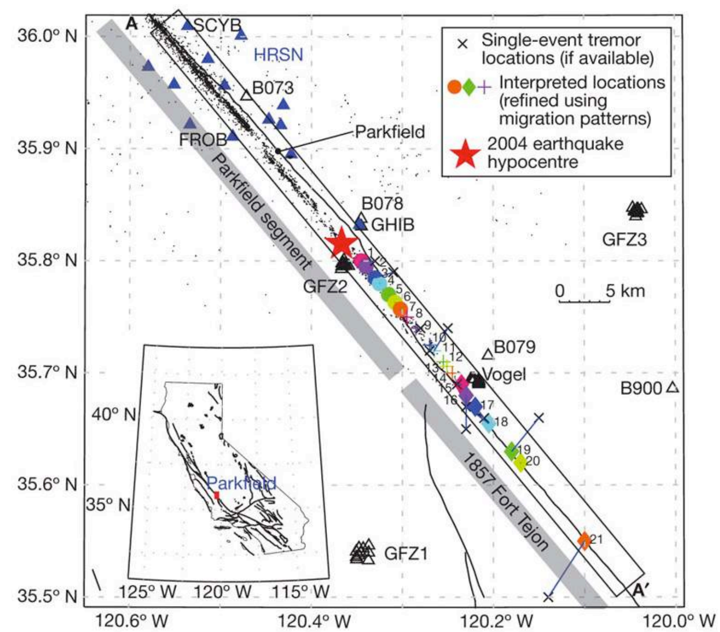
Mylonite zone (Ontario, Canada)



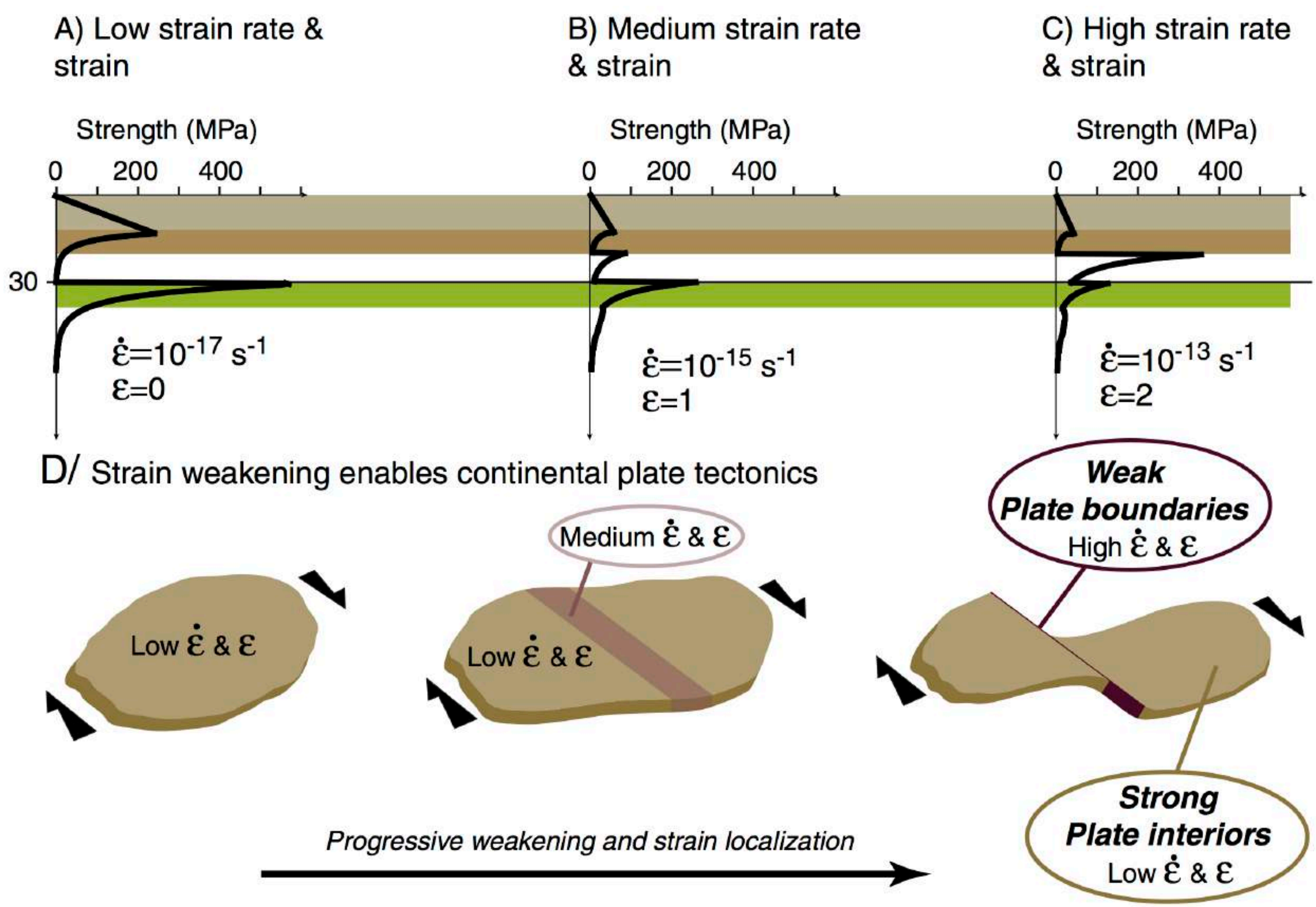
Zhu (2000)



Thurber et al. (2006)

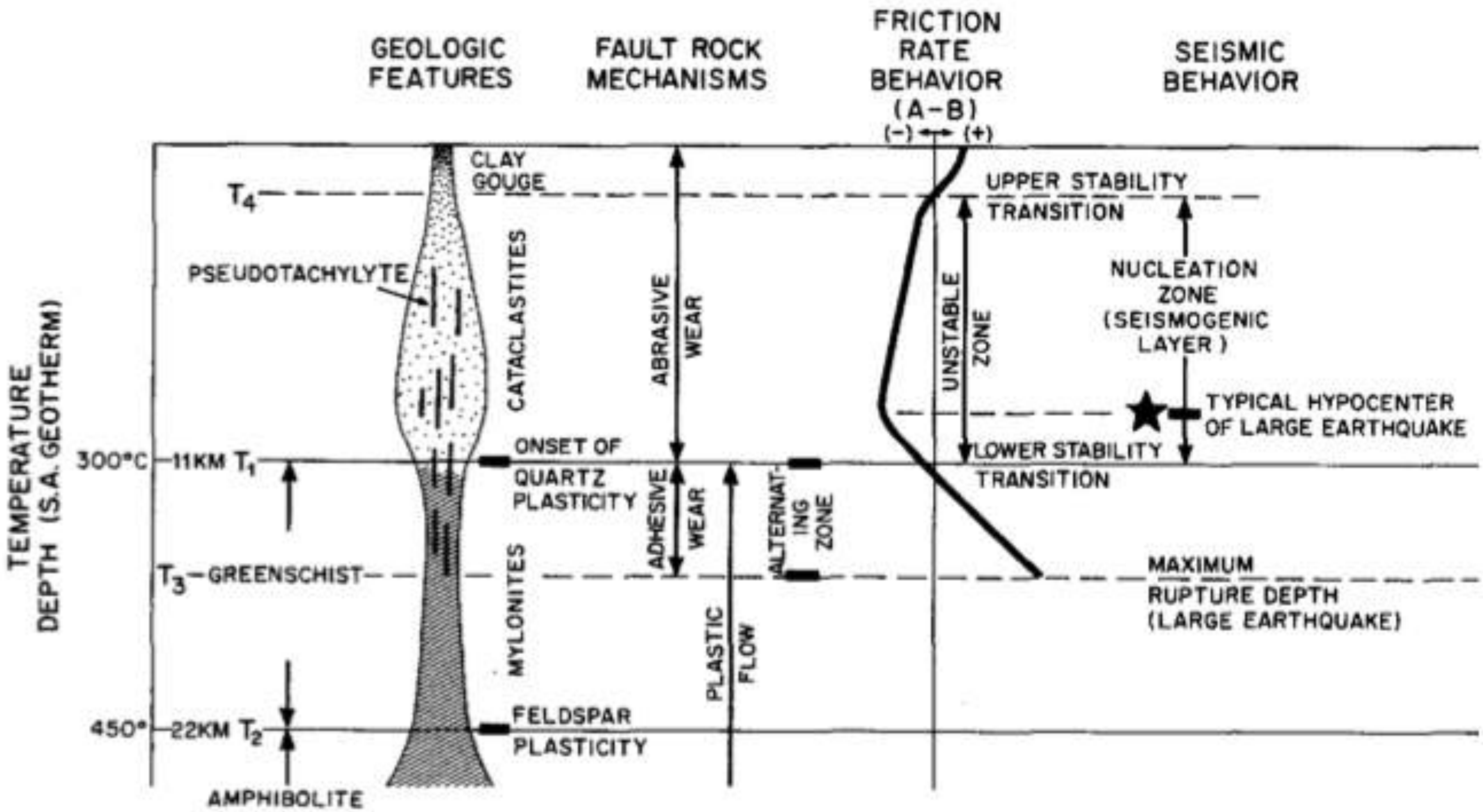


Shelly (2010)



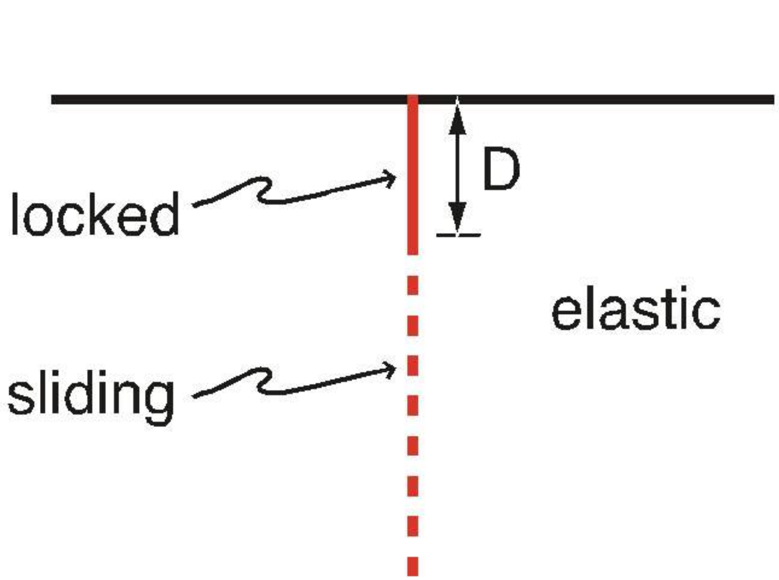
Gueydan et al., 2014

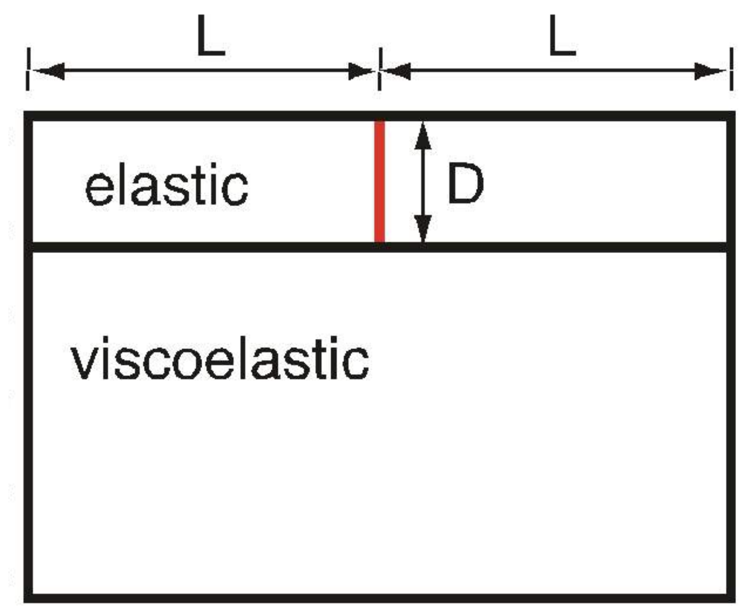
Field geology & laboratory view of a major crustal fault



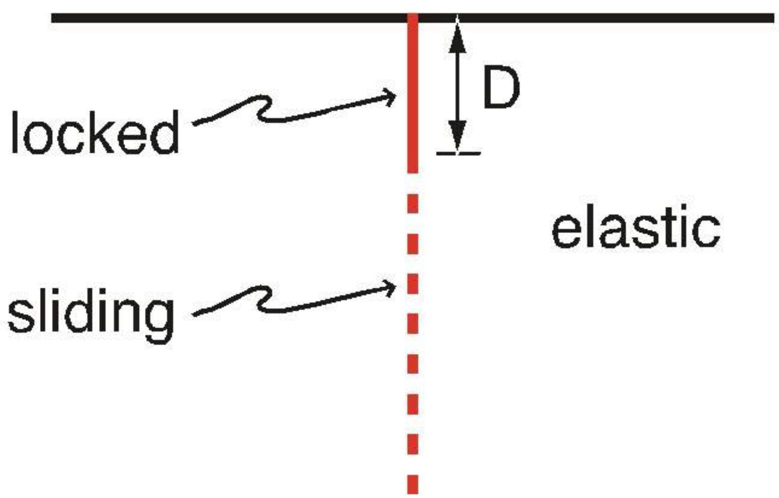
Scholz, 1988

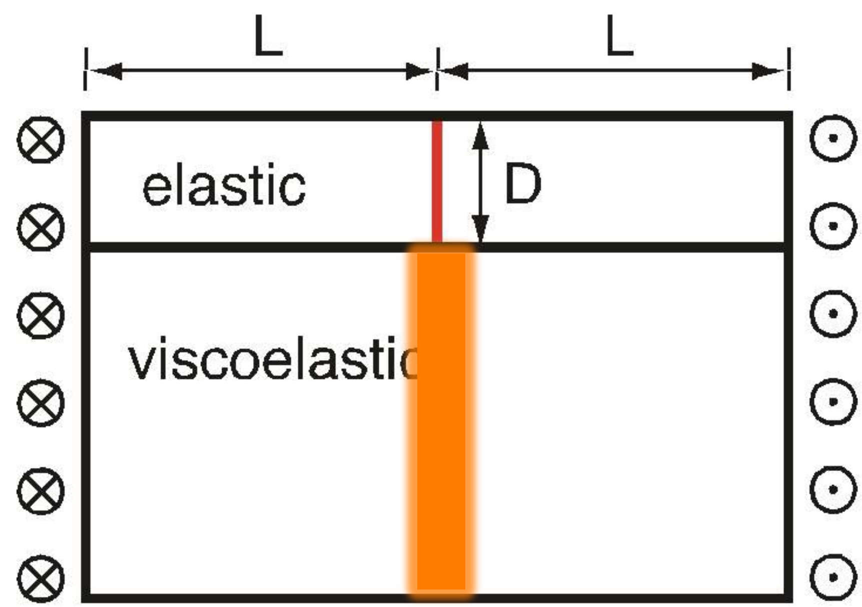
simple conceptual models of interseismic deformation (both wrong)



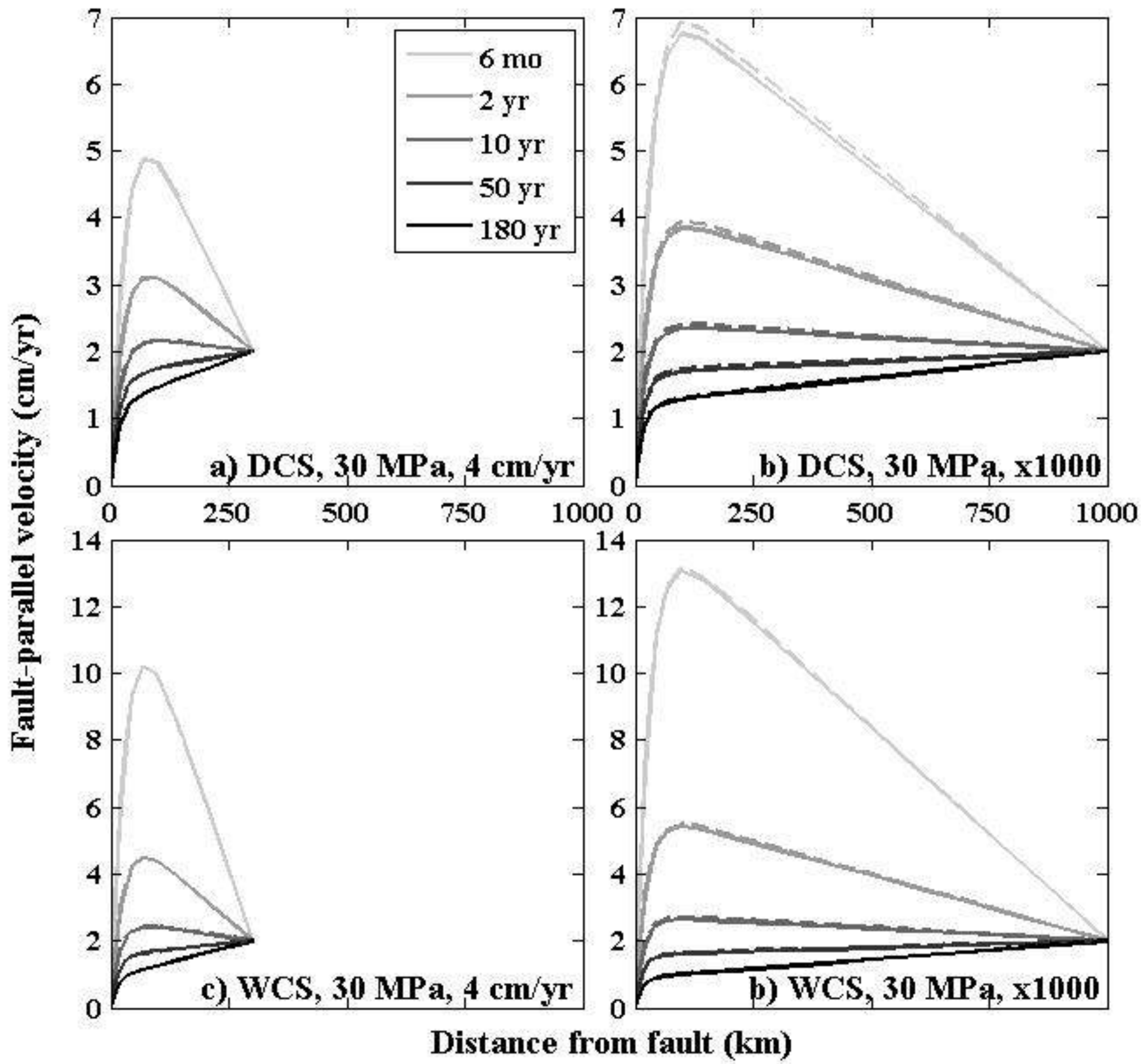


VS

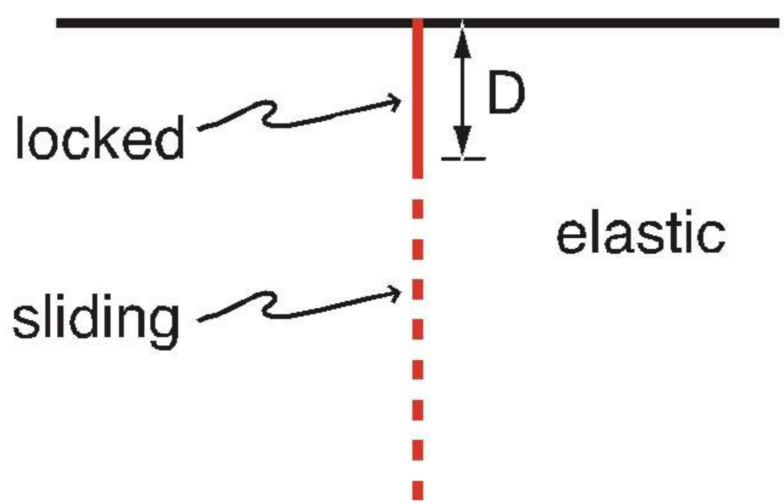


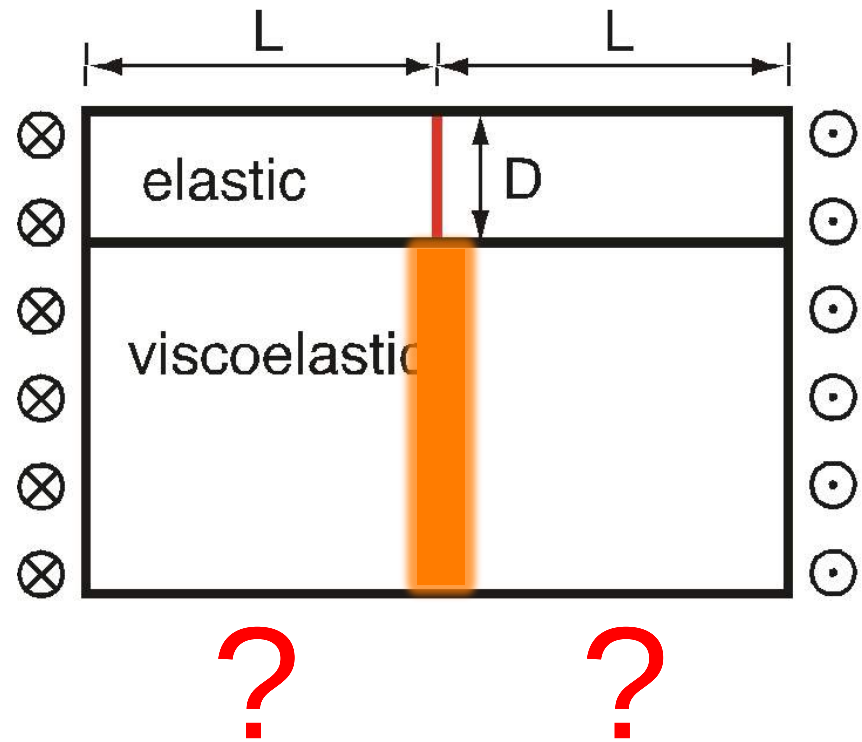


Effect of the model size

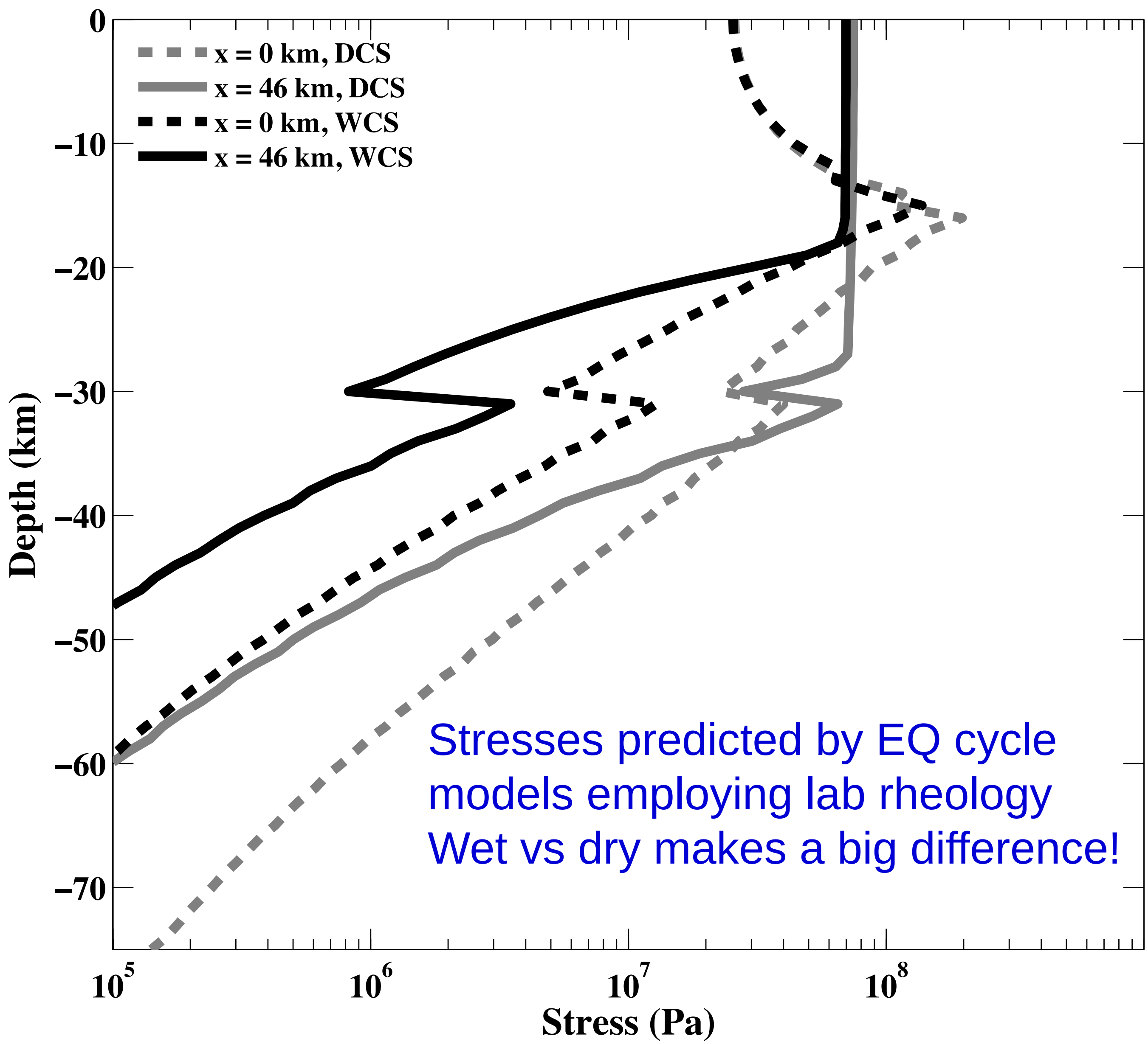


VS

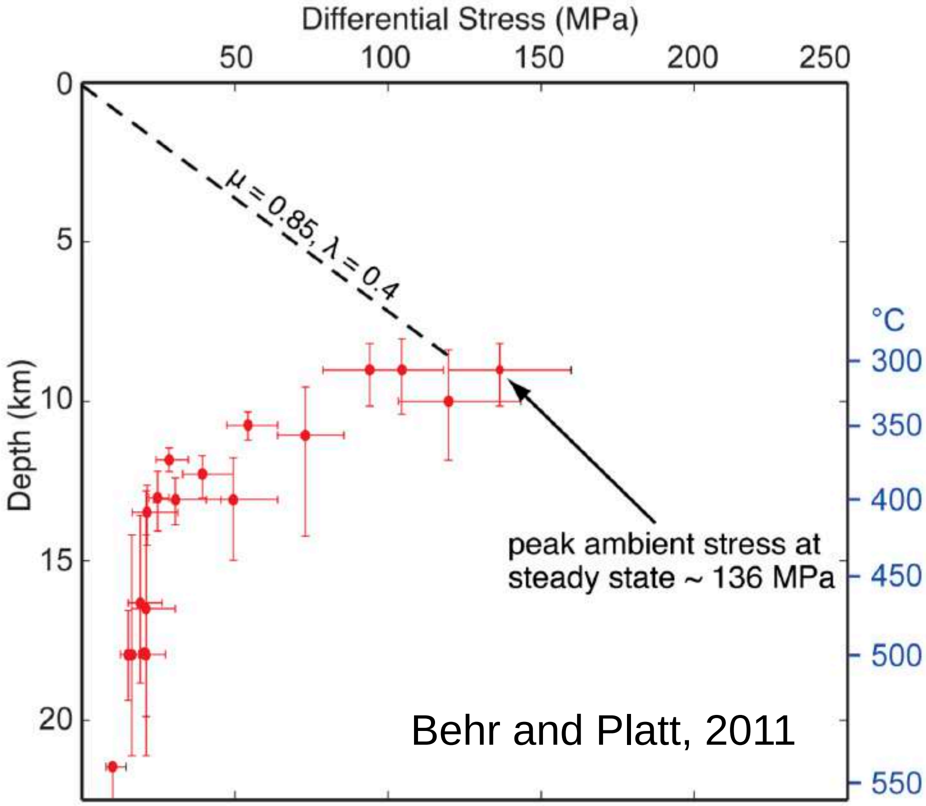




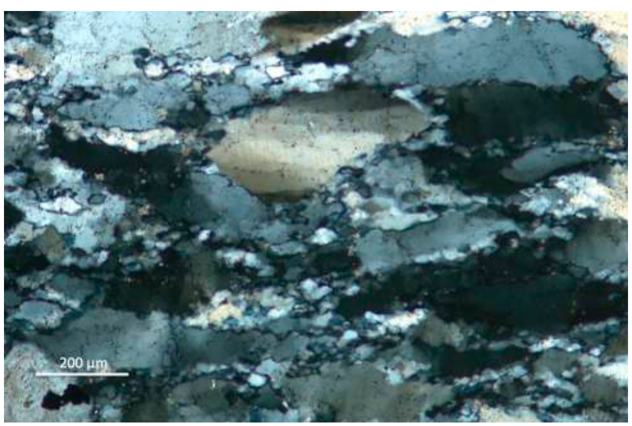
bottom tractions?

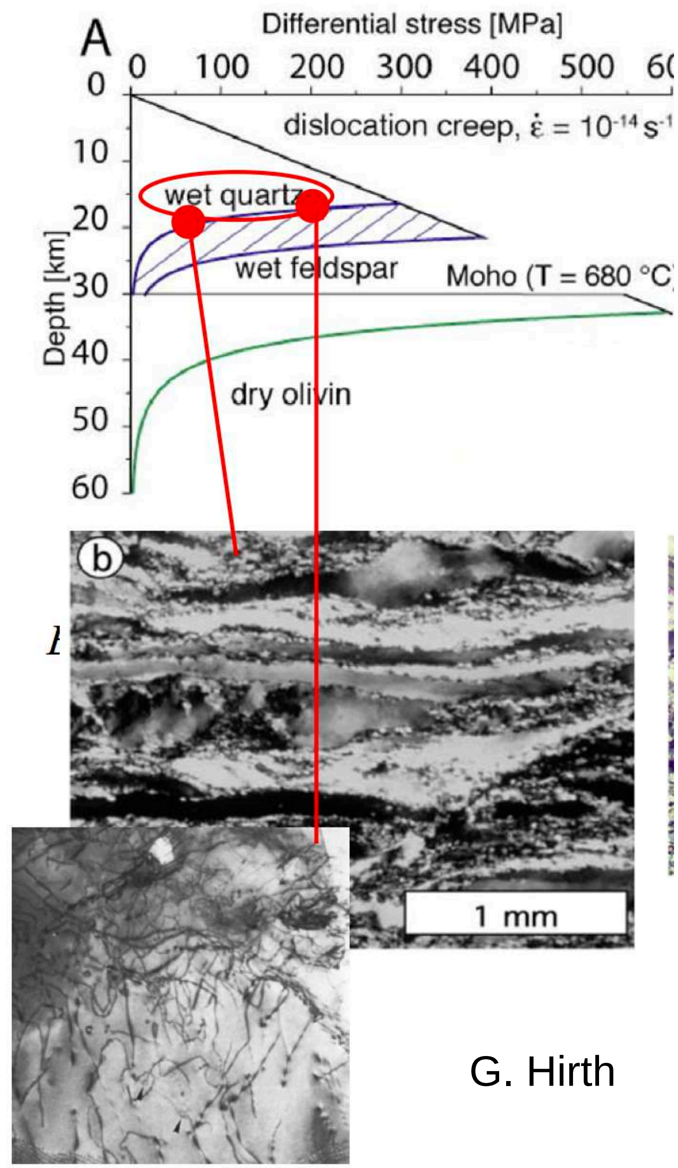

x = 0 km, DCS
x = 46 km, DCS
x = 0 km, WCS
x = 46 km, WCS
Depth (km)
0
−10
−20
−30
−40
−50
−60
−70
10^5
10^6
10^7
10^8
Stress (Pa)
Stresses predicted by EQ cycle
models employing lab rheology
Wet vs dry makes a big difference!

Stress: constraints from the rock record

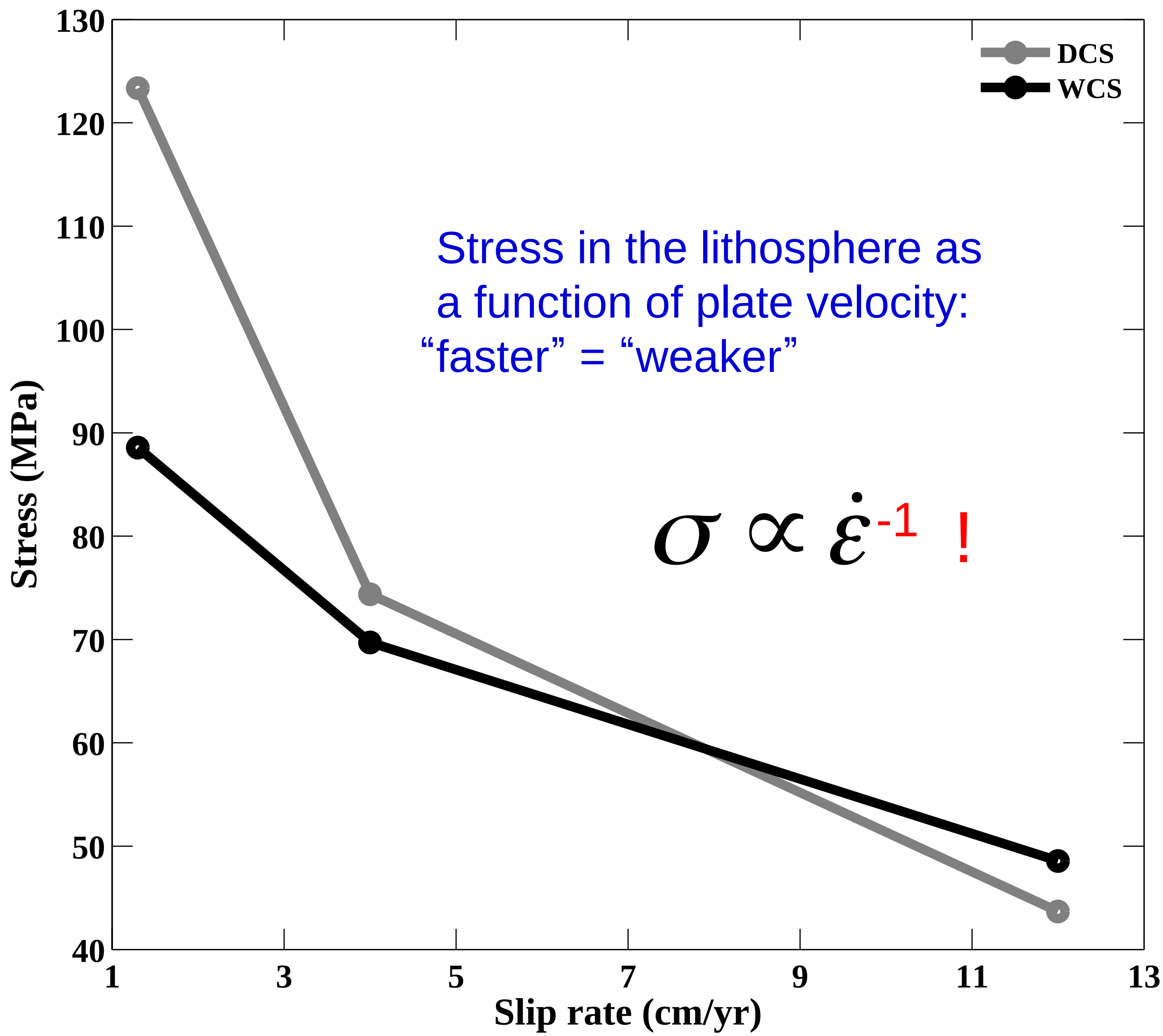


Behr and Platt, 2011





G. Hirth



Stress in the lithosphere as
a function of plate velocity:
"faster" = "weaker"
$\sigma \propto \dot{\varepsilon}^{-1}$!
DCS
WCS
Stress (MPa)
Slip rate (cm/yr)
130
120
110
100
90
80
70
60
50
40
1
3
5
7
9
11
13

Challenges for CRM

- Effective rheology: linear or non-linear?
- Are steady-state constitutive laws appropriate (“transient rheology”?)
- Strain localization: how to quantify and incorporate in the model?
- Need better understanding of a transition from rate-state friction to ductile deformation
- Water content: as important as temperature. CWM?