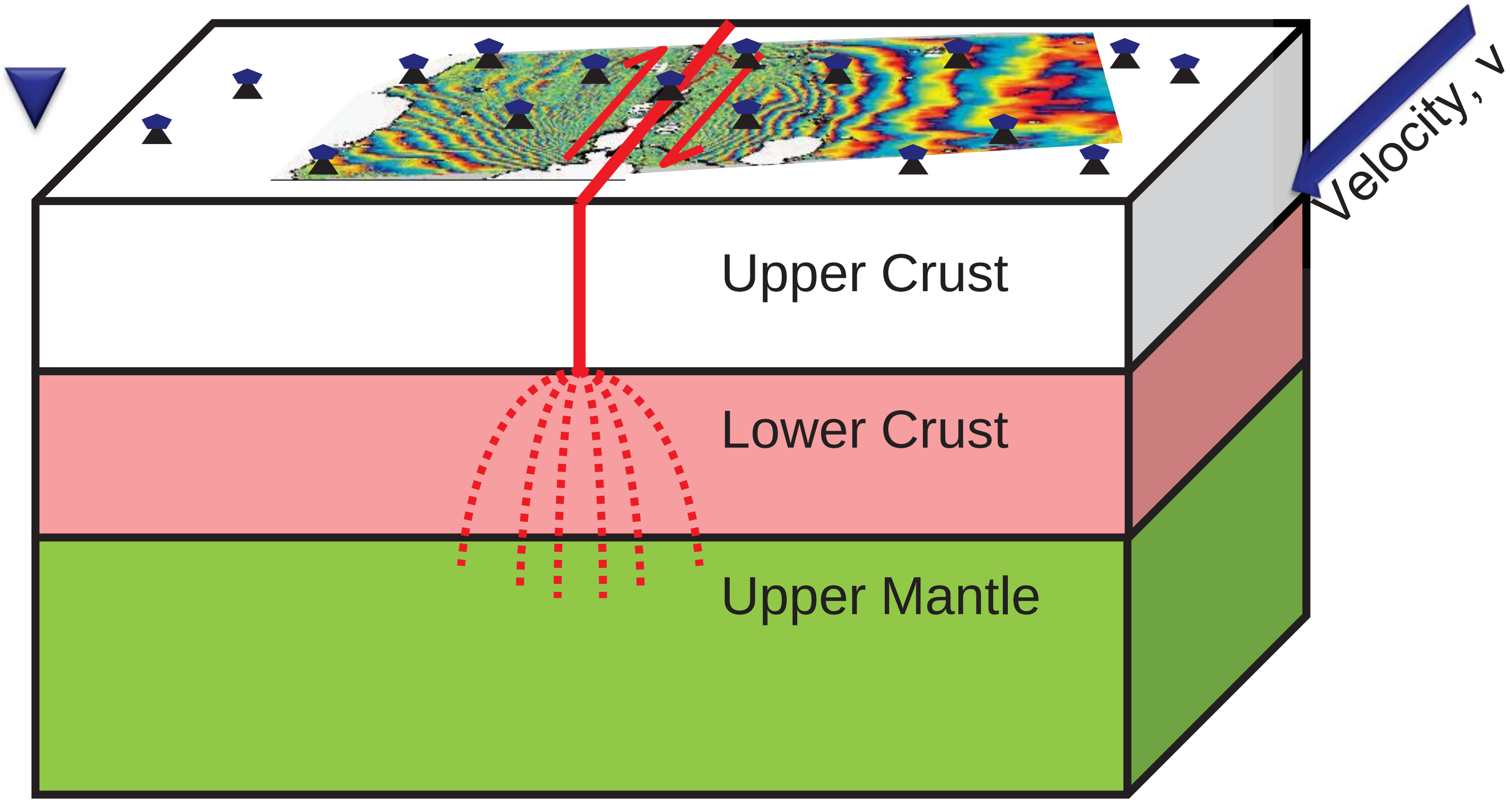
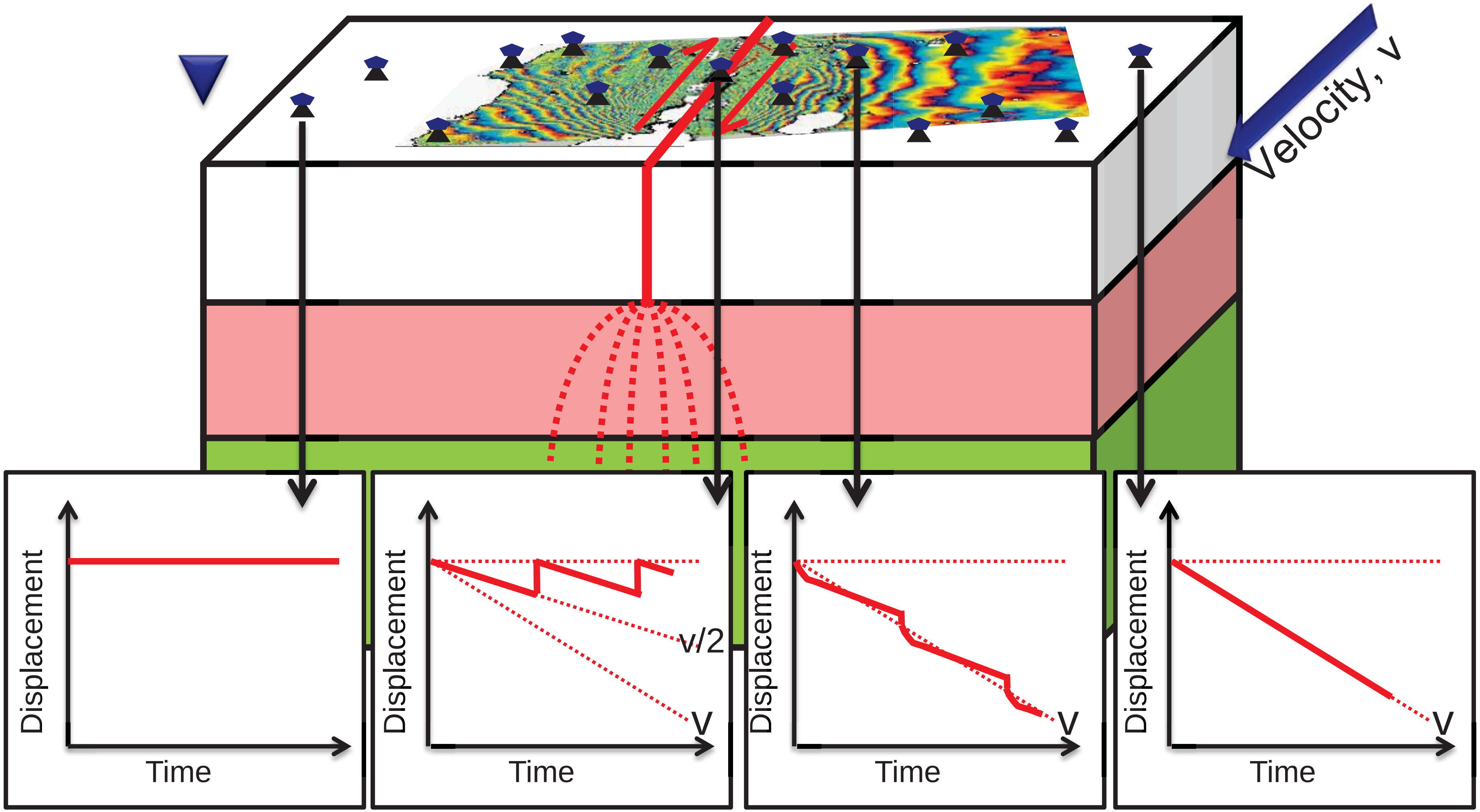
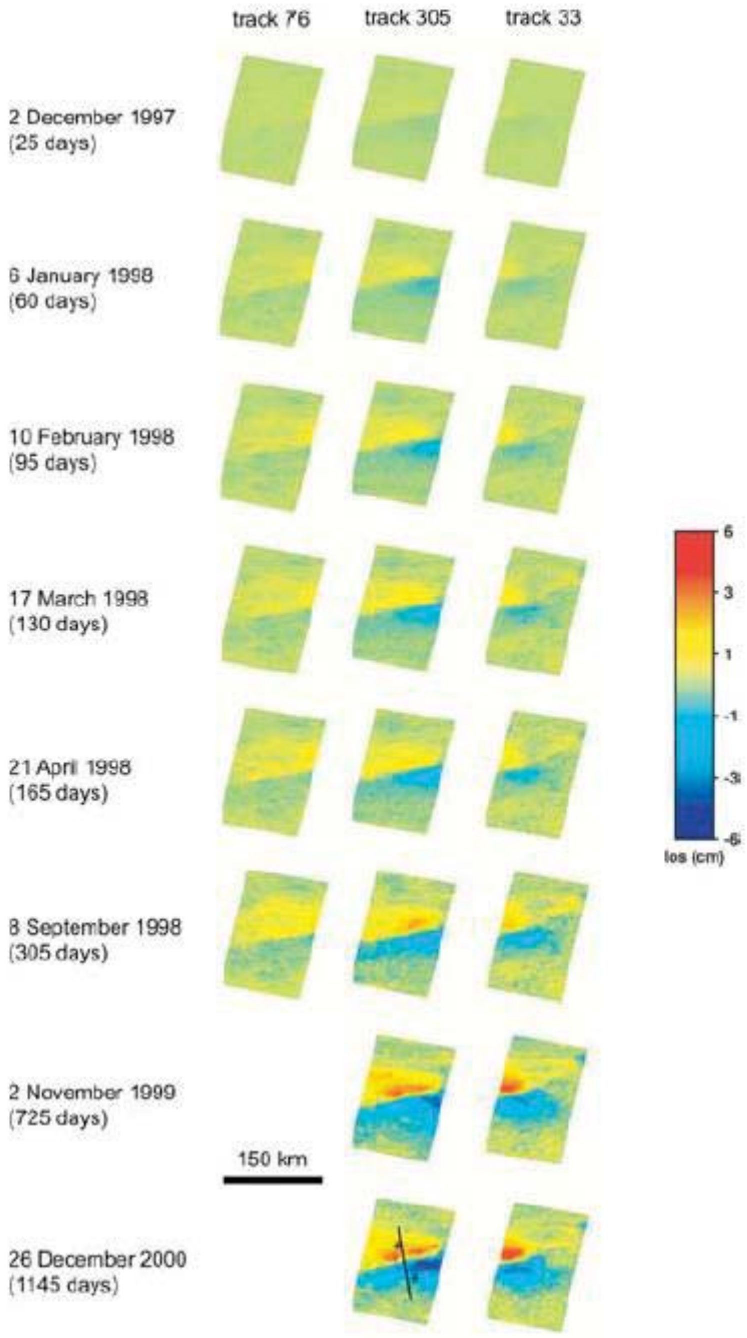
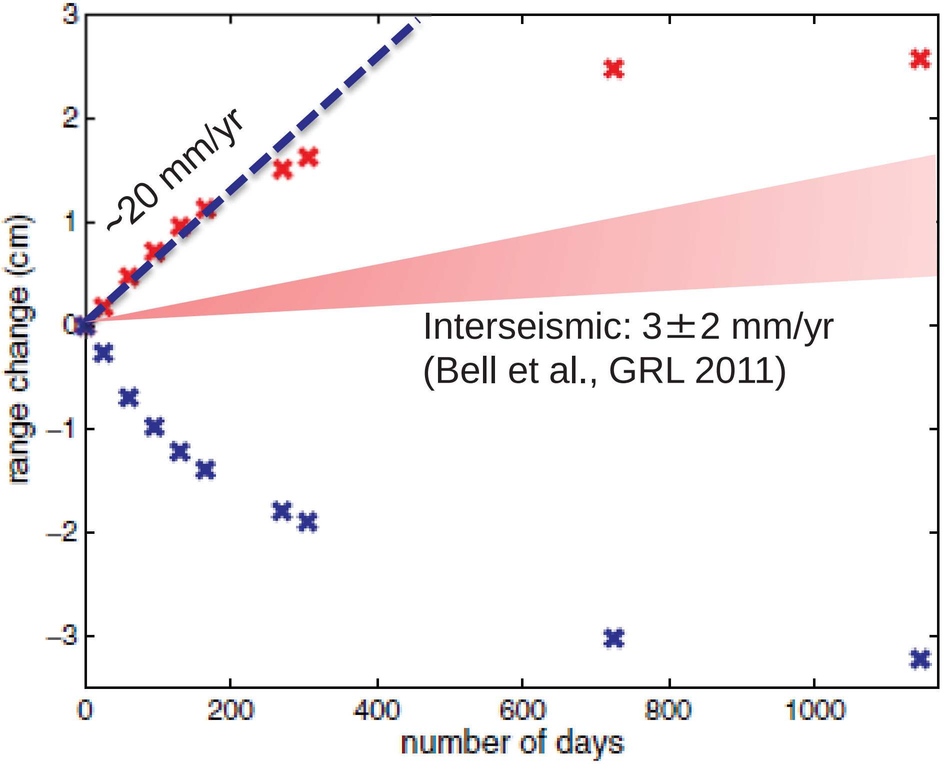
The Earthquake Deformation Cycle



The Earthquake Deformation Cycle







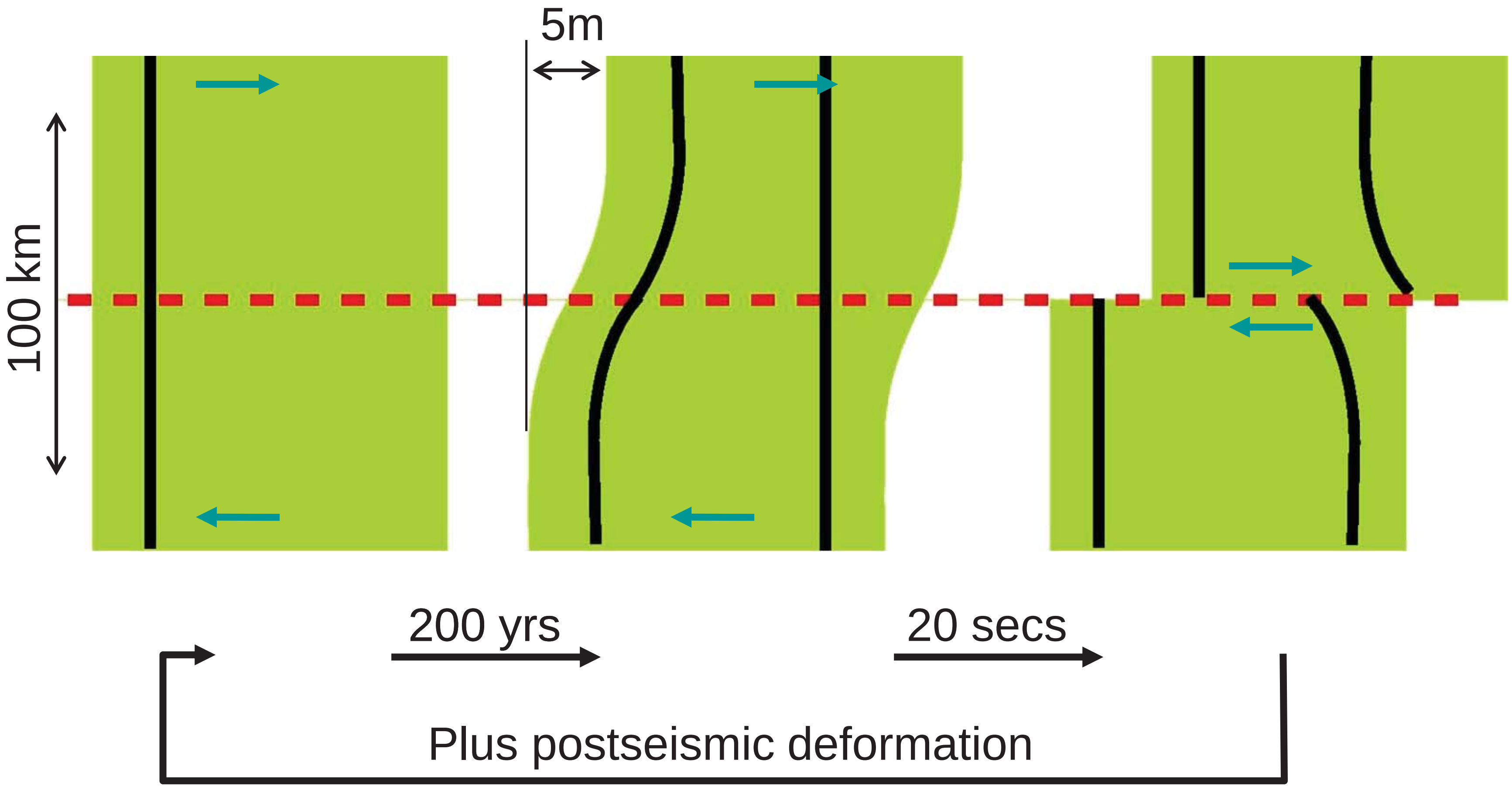
Interseismic: 3±2 mm/yr
(Bell et al., GRL 2011)

The Earthquake Cycle

Animation courtesy Ross Stein, USGS

http://quake.usgs.gov/research/deformation/modeling/animations

The Earthquake Cycle



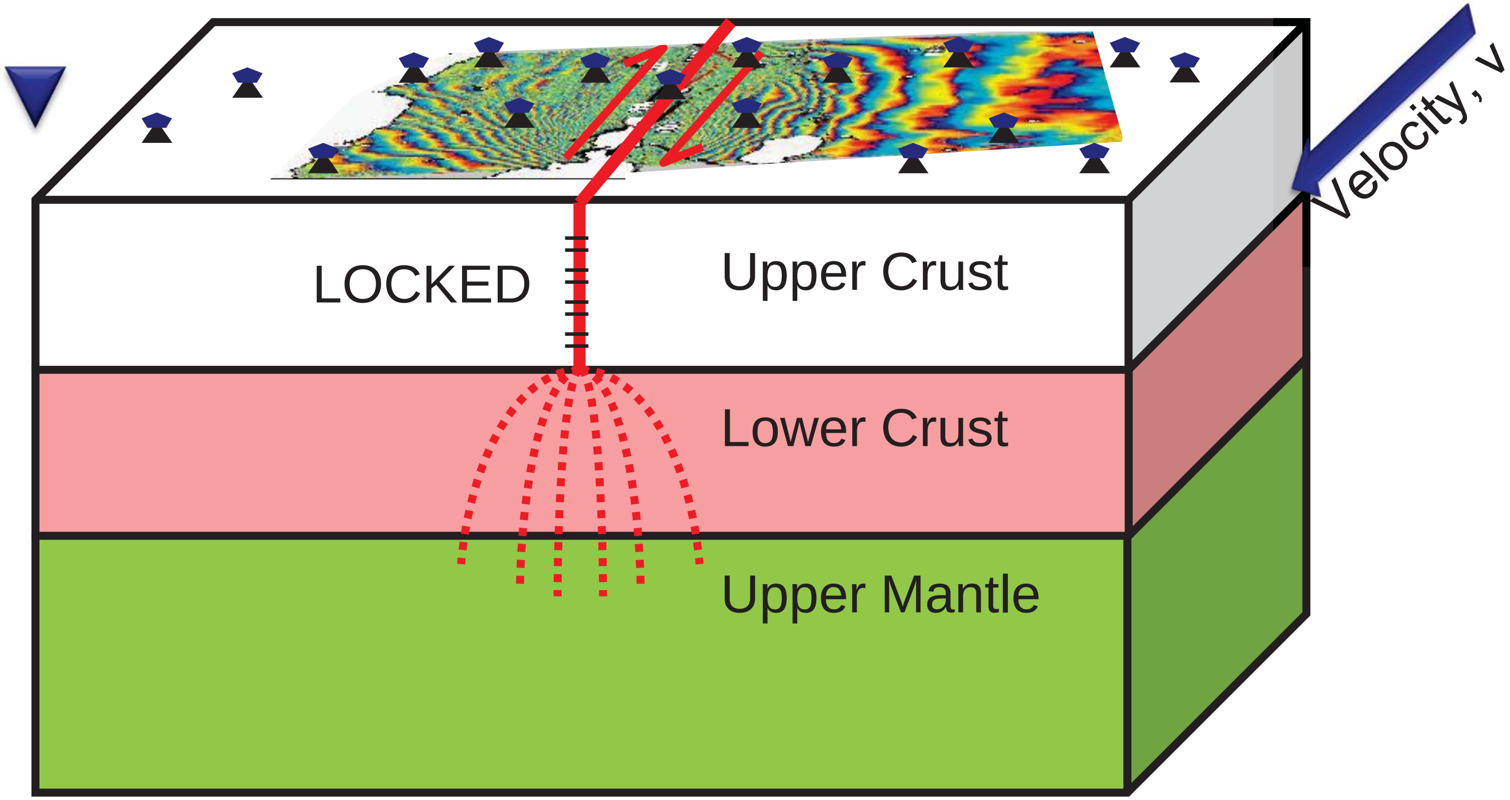
200 yrs

20 secs

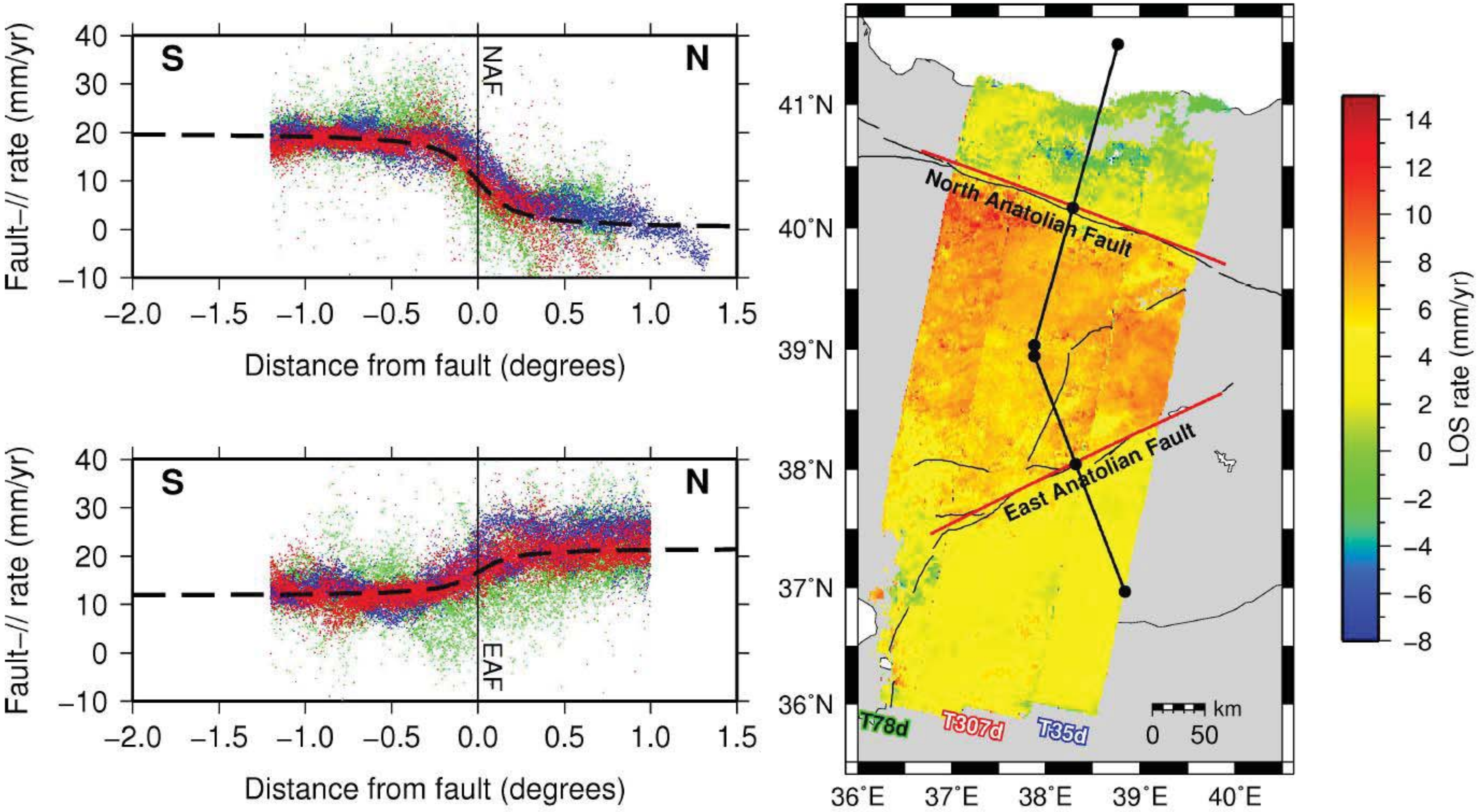
Plus postseismic deformation

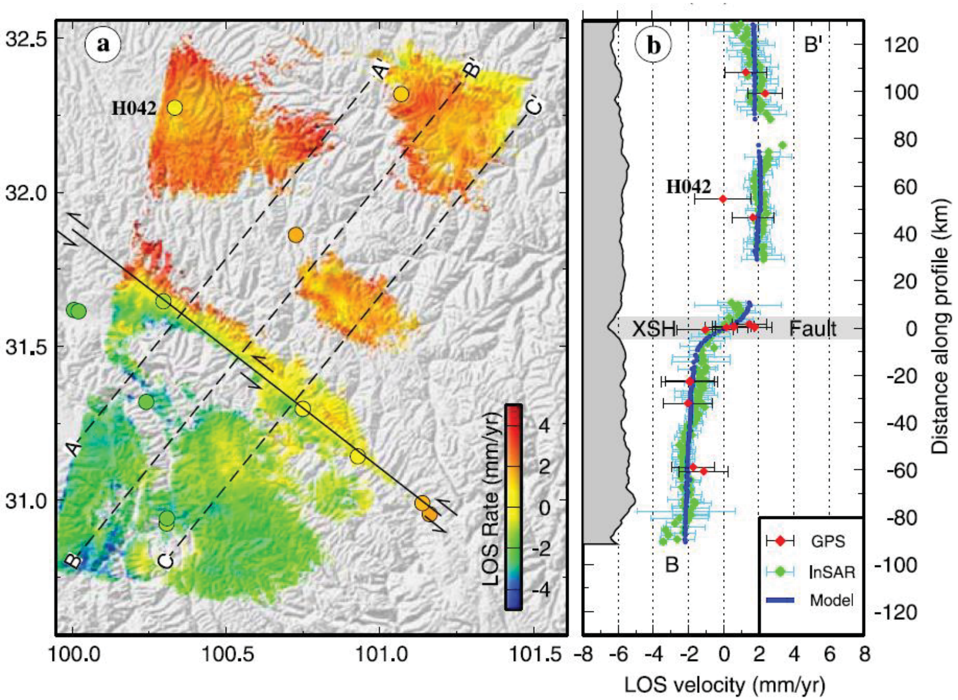
Note: Numbers vary for different faults

Interseismic Deformation



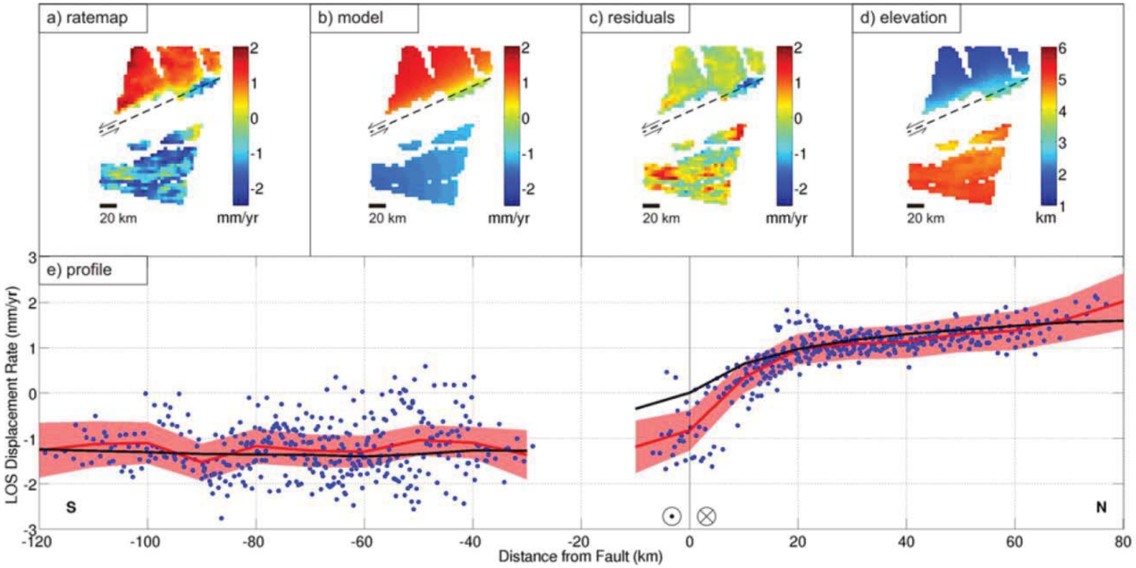
North and East Anatolian Fault (Richard Walters, PhD 2013)



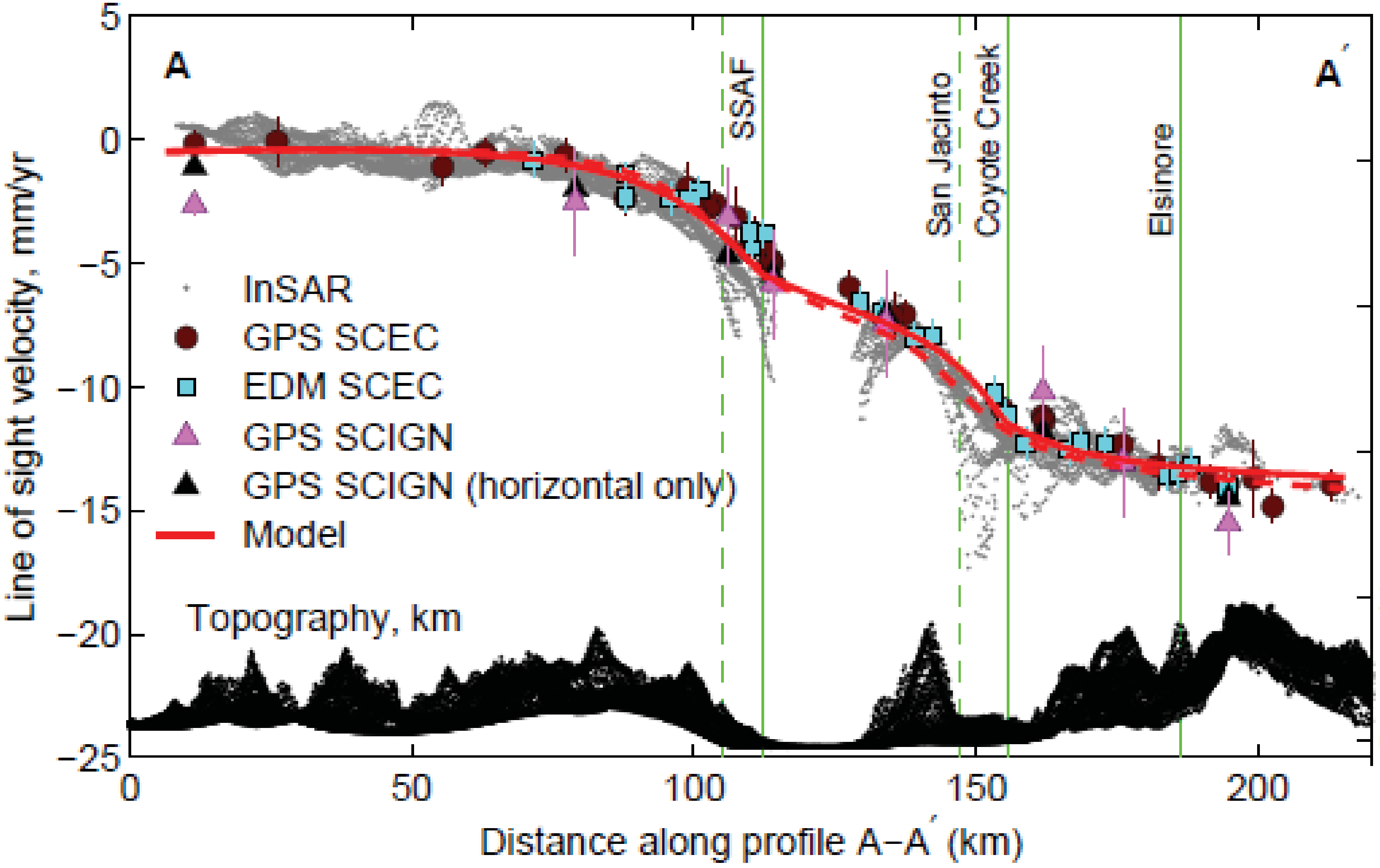


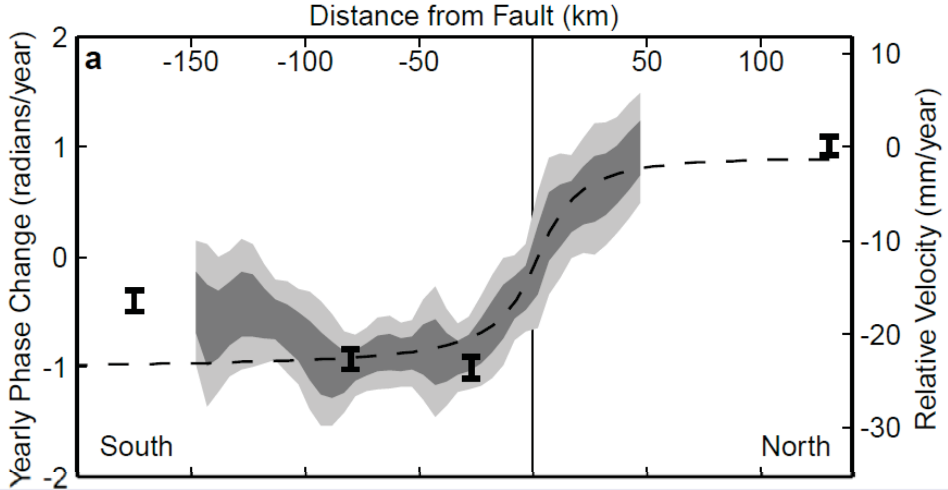
Xianshuihe Fault, East Tibet
Wang et al. (GRL, 2008)

Altyn Tagh Fault, Tibet
Elliott et al. (GRL, 2008)

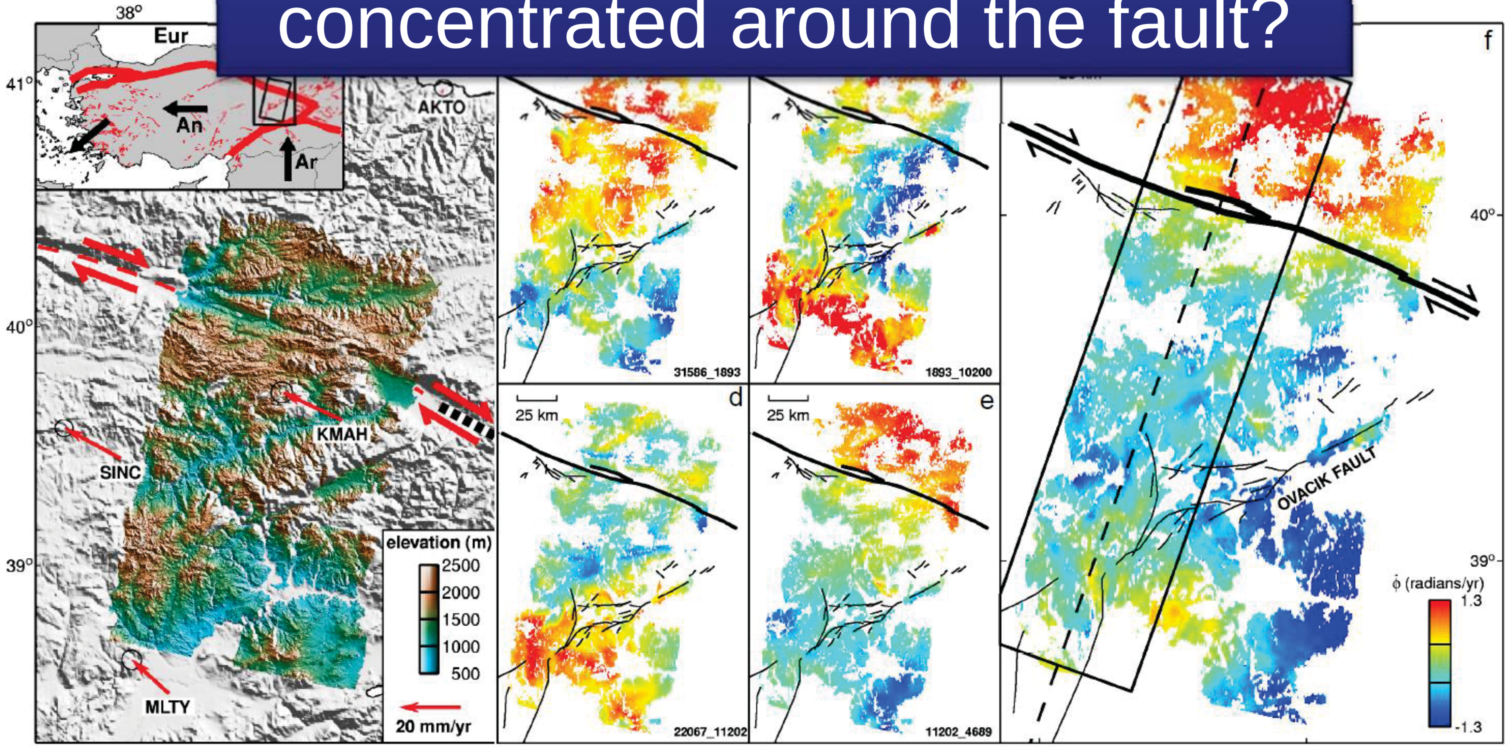


San Andreas Fault Zone (Fialko, Nature 2006)



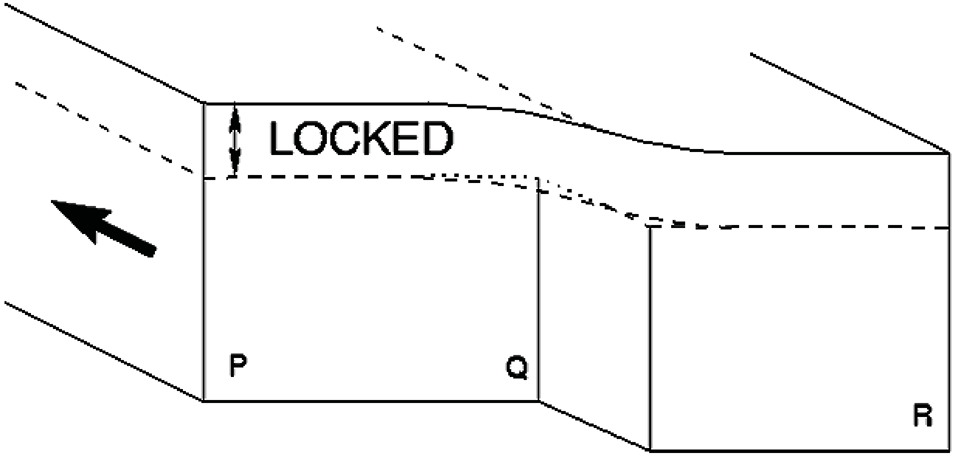


Why is “interseismic” strain concentrated around the fault?



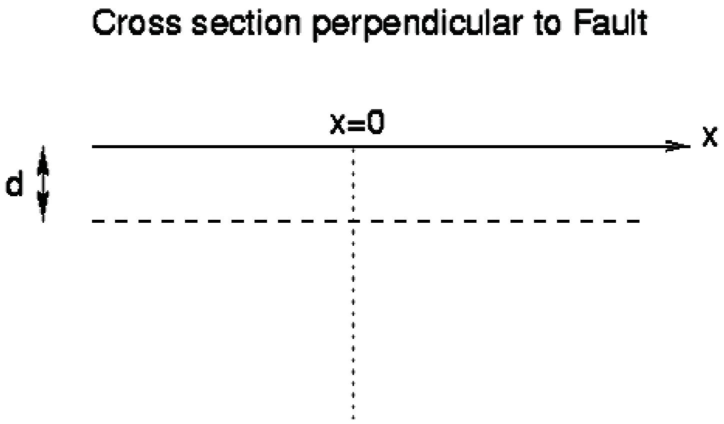
Wright et al., GRL 2001

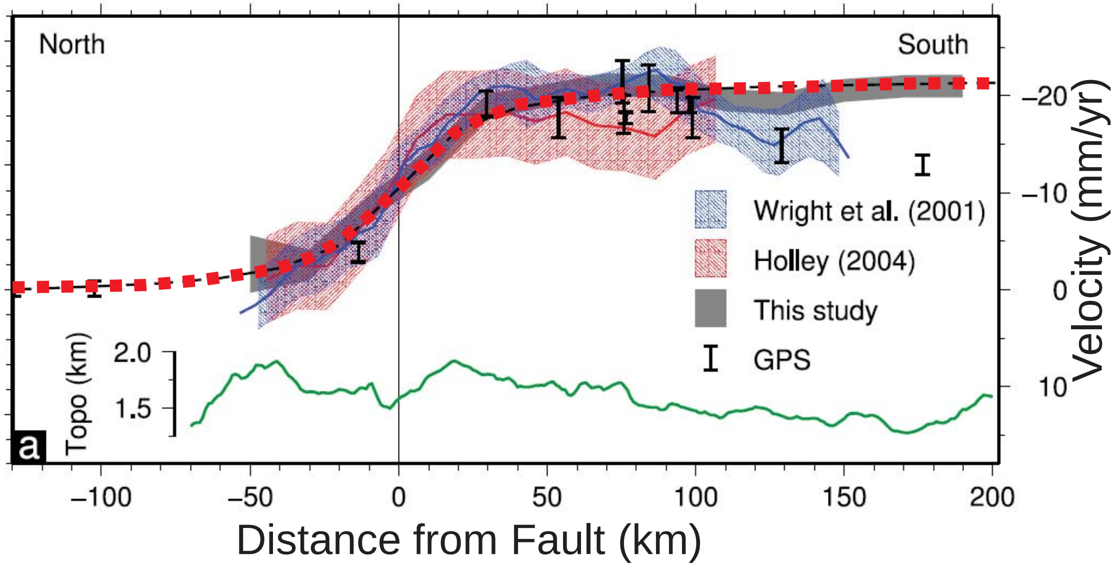
Interseismic Deformation



$$\boxed{y = \frac{s}{\pi}\tan^{-1}\frac{x}{d}}$$

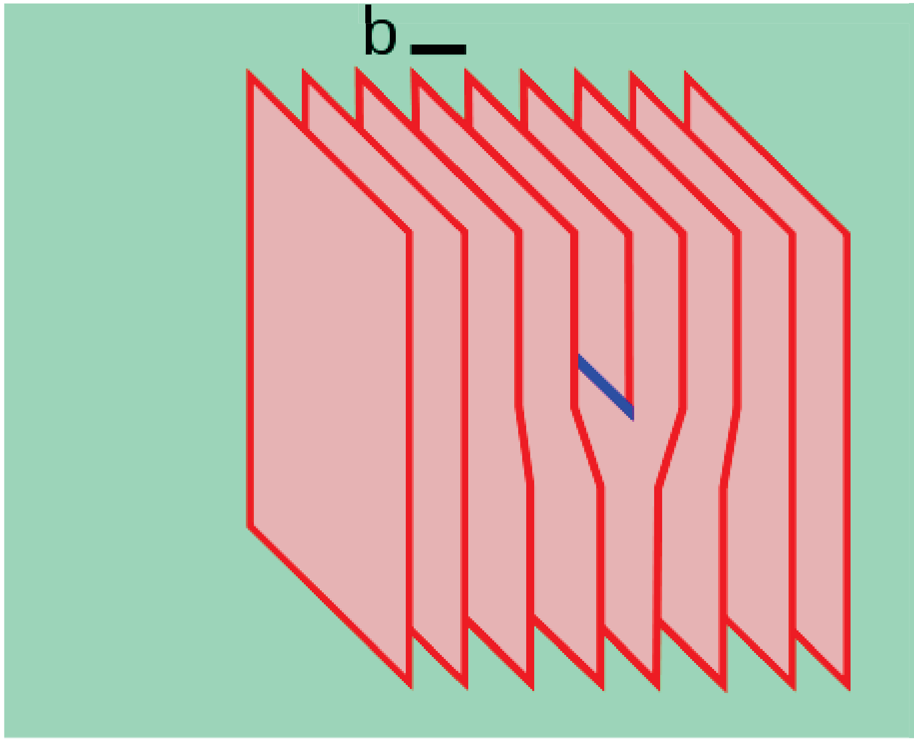
Screw dislocation model, after Weertman and Weertman (1964), Savage and Burford (1973)





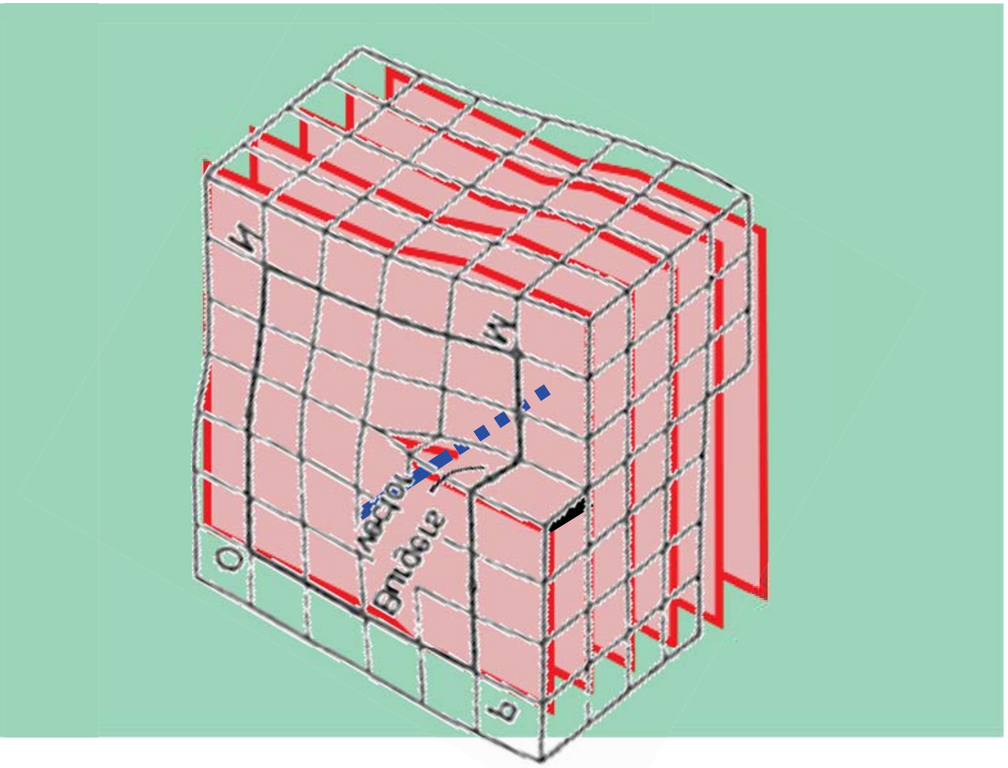
Interseismic deformation across the North Anatolian Fault, from Walters et al (GRL 2011)

Dislocations in Crystals



Edge dislocation

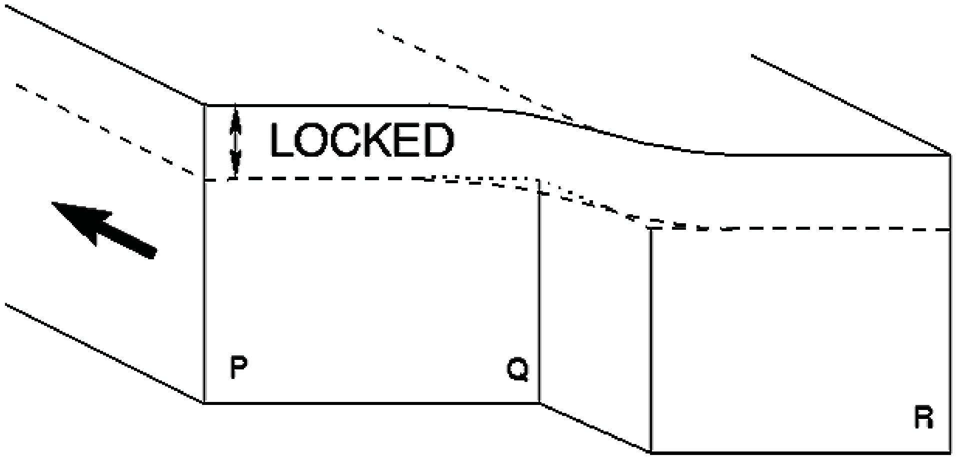
- Extra plane of crystals inserted into lattice
- Dislocation line (blue) perpendicular to Burger’s vector (black)
- Large scale analogy – dyke intrusions



Screw dislocation

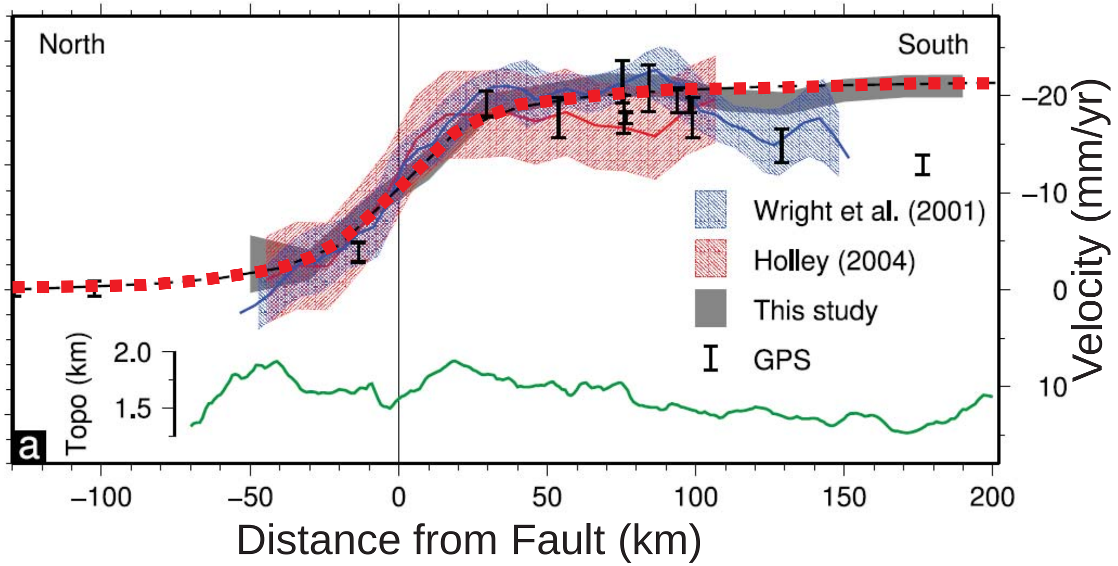
- Extra plane of crystals inserted into lattice
- Dislocation line (blue) parallel to Burger’s vector (black)
- Large scale analogy – faults

Interseismic Deformation

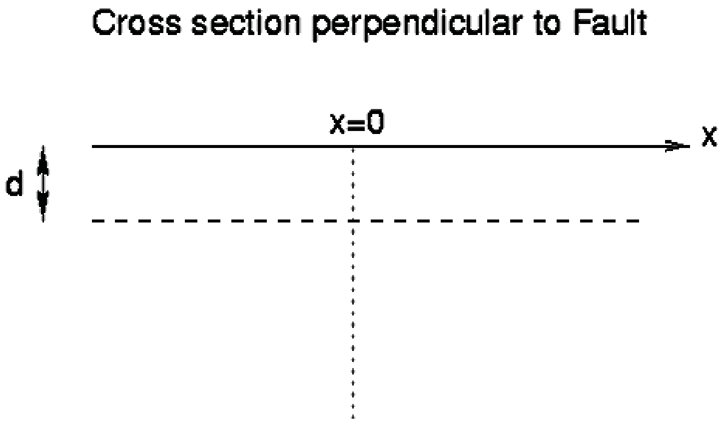


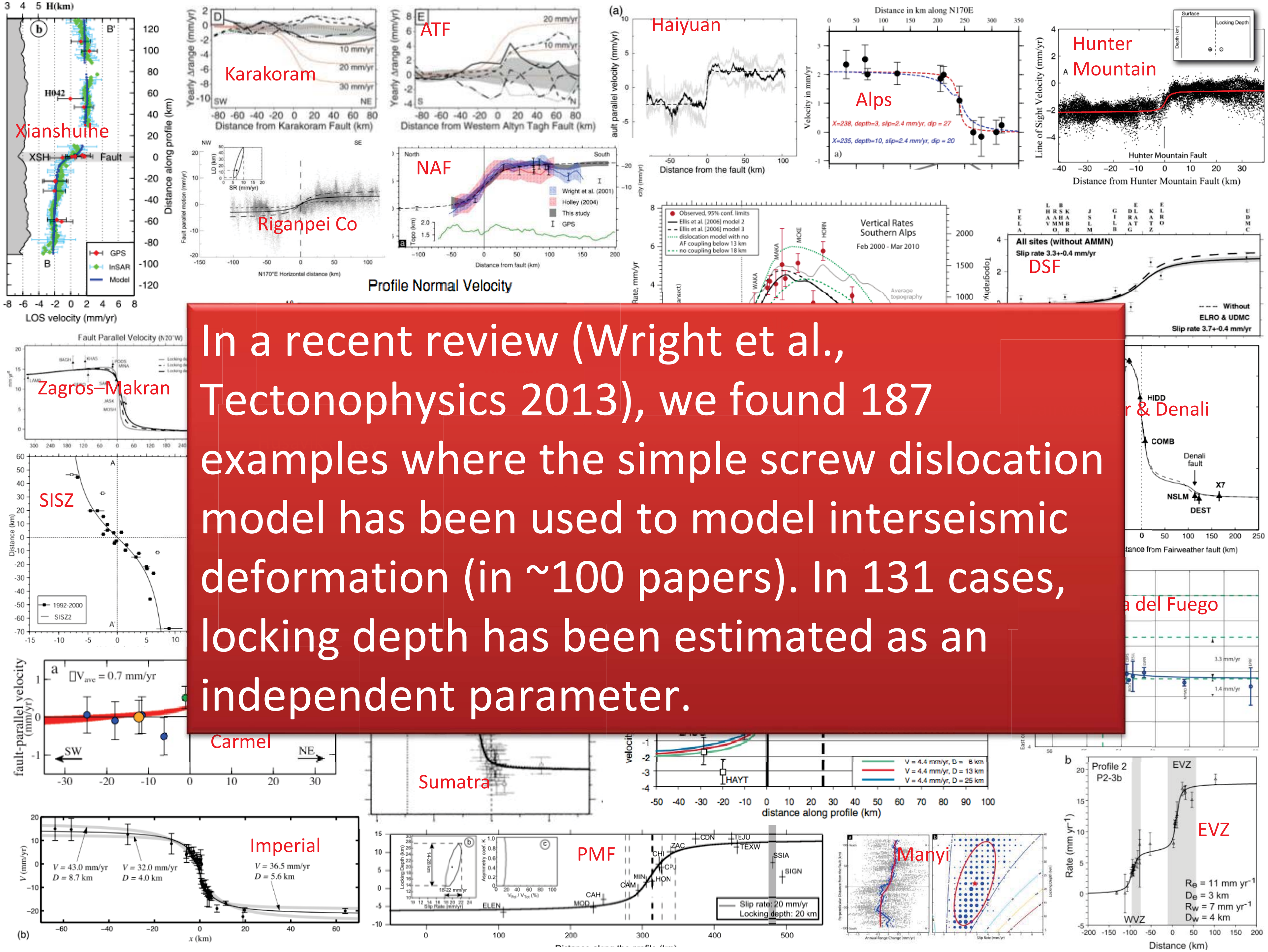
$$\boxed{y = \frac{s}{\pi} \tan^{-1} \frac{x}{d}}$$

Screw dislocation model, after Weertman and Weertman (1964), Savage and Burford (1973)



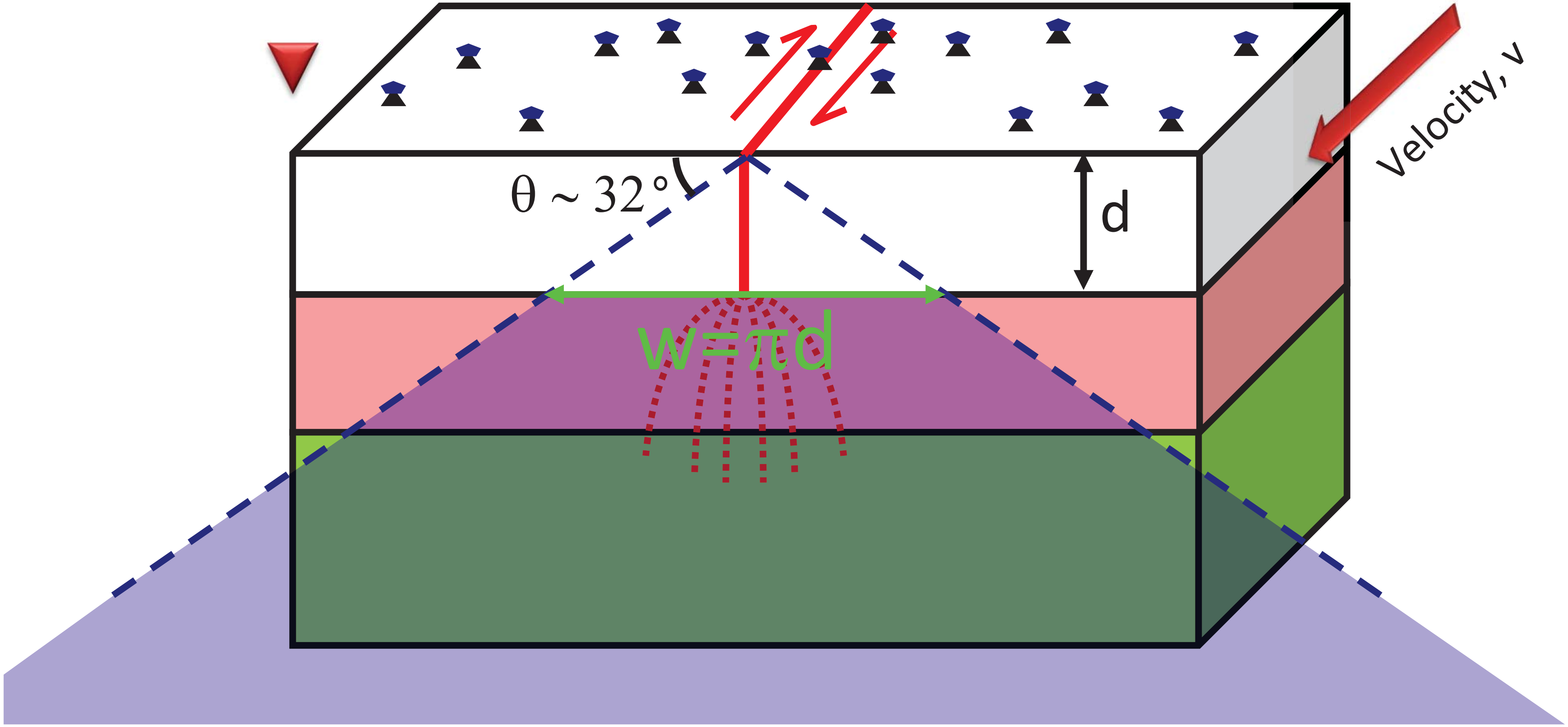
Interseismic deformation across the North Anatolian Fault, from Walters et al (GRL 2011)





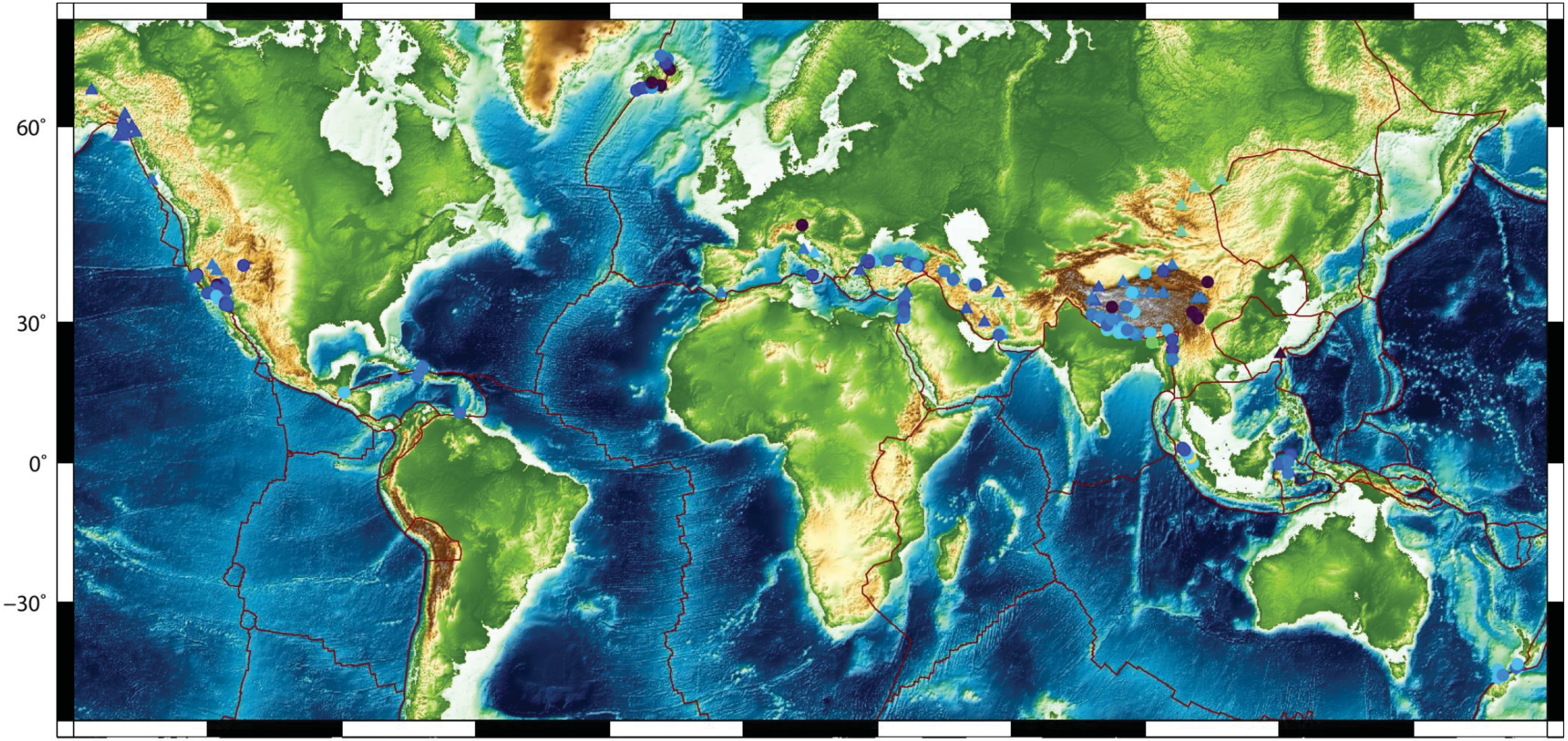
In a recent review (Wright et al., Tectonophysics 2013), we found 187 examples where the simple screw dislocation model has been used to model interseismic deformation (in ~100 papers). In 131 cases, locking depth has been estimated as an independent parameter.

Interseismic Deformation

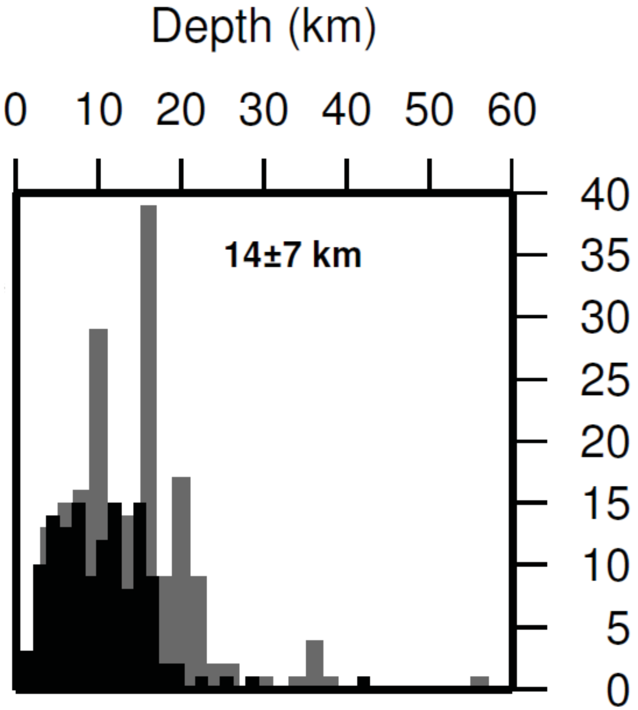


All anti-symmetric deformation in the blue zone gives surface motions that indistinguishable from slip on a single deep fault.

Interseismic Deformation



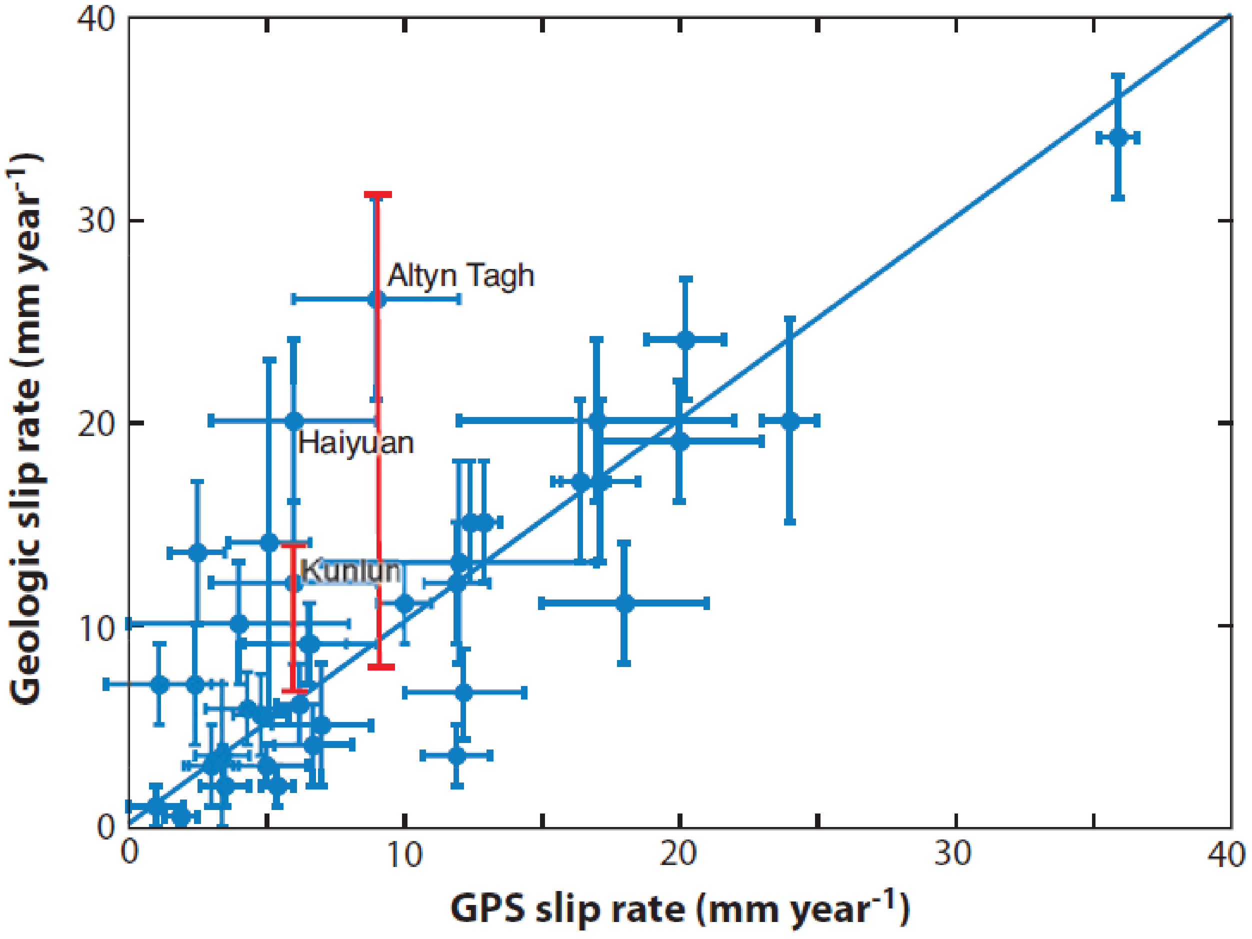
Interseismic Deformation



Results from the 131 faults where locking depth has been estimated as a free parameter (black in histogram),

$T_{seismogenic}$ is mostly <20 km (i.e. strain is concentrated around faults)

Geologic vs Geodetic rates for major faults



Thatcher, Annual Reviews 2009

Summary of Observations

Coseismic deformation:

Earth behaves elastically

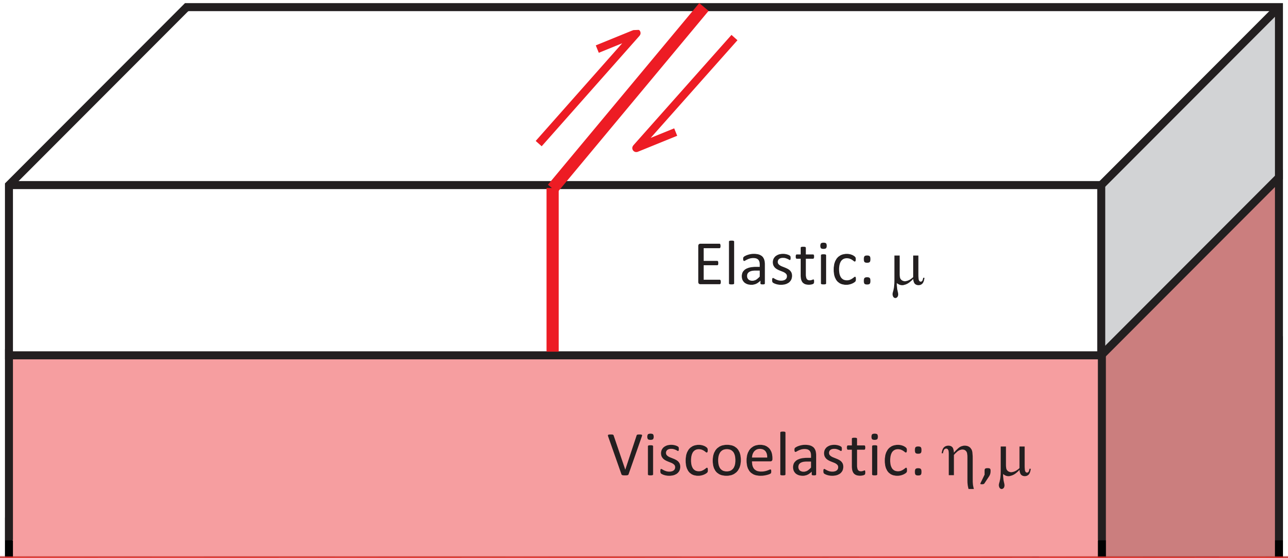
Interseismic deformation:

Strain is focussed around major faults

Postseismic deformation:

Rapid deformation transients occur

Simplest earthquake cycle model



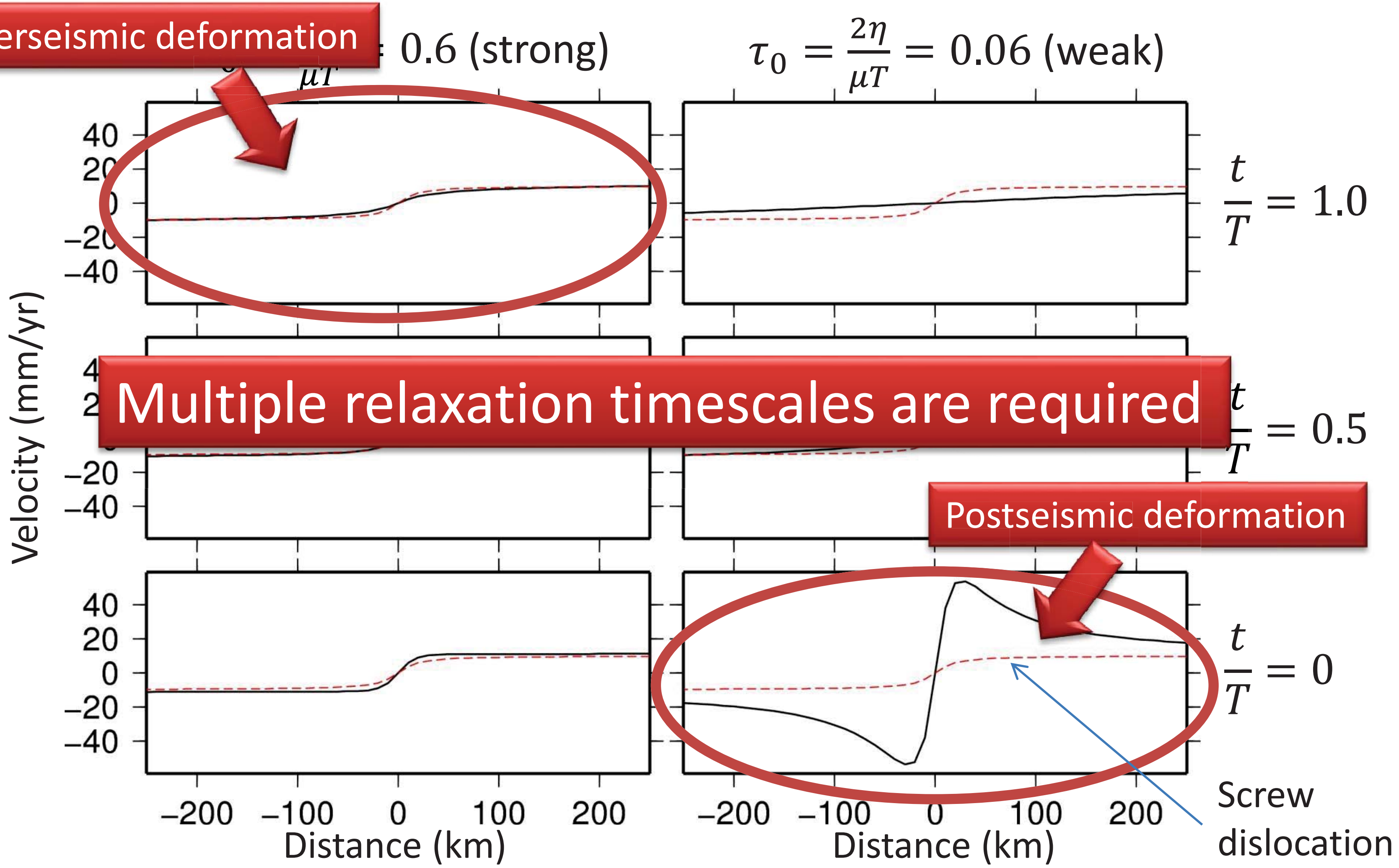
Key parameter is the ratio (τ_0) between Maxwell relaxation time, ($2\eta/\mu$), and earthquake repeat time (T):

$$\tau_0 = \frac{2\eta}{\mu T}$$

Viscoelastic coupling model, Savage & Prescott 1978; Savage 2000

Simplest earthquake cycle model

Interseismic deformation

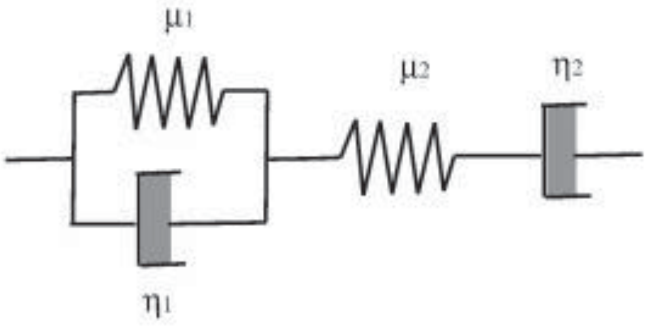


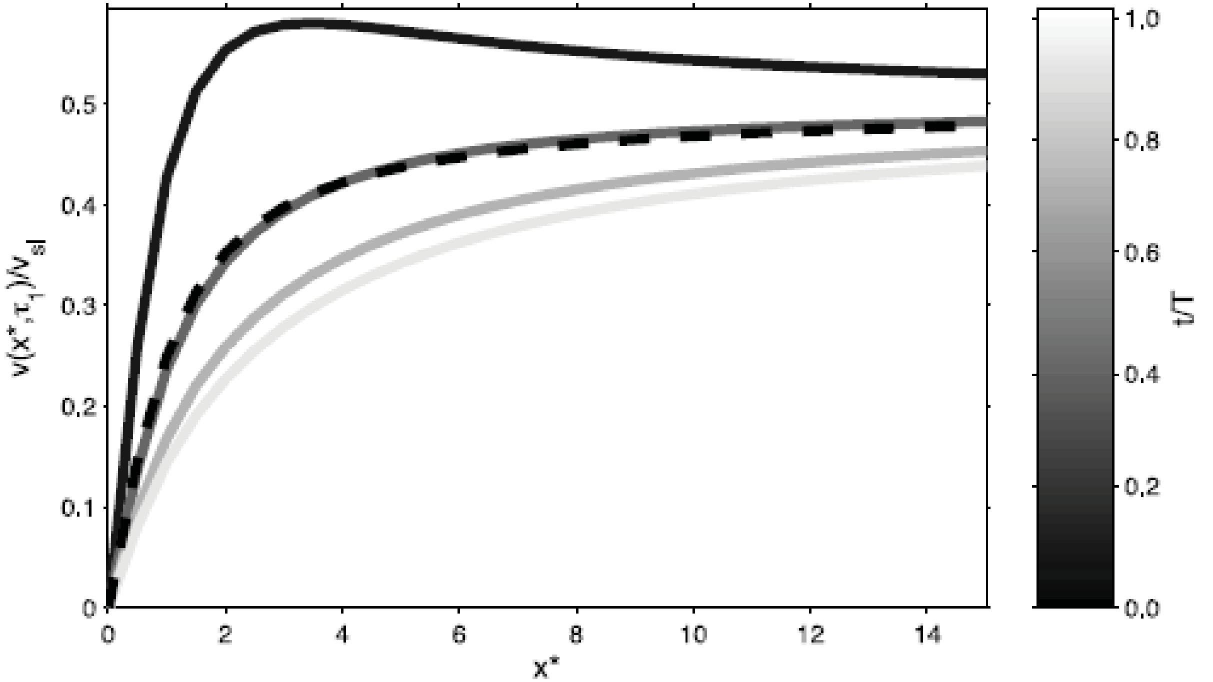
Multiple relaxation timescales are required

Postseismic deformation

Viscoelastic coupling model, Savage & Prescott 1978; Savage 2000

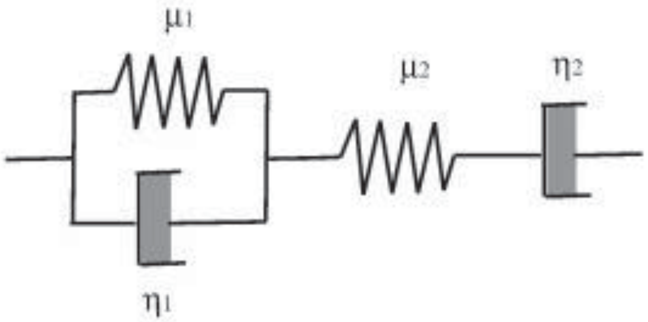
Alternatives: 1. Burger’s body rheology

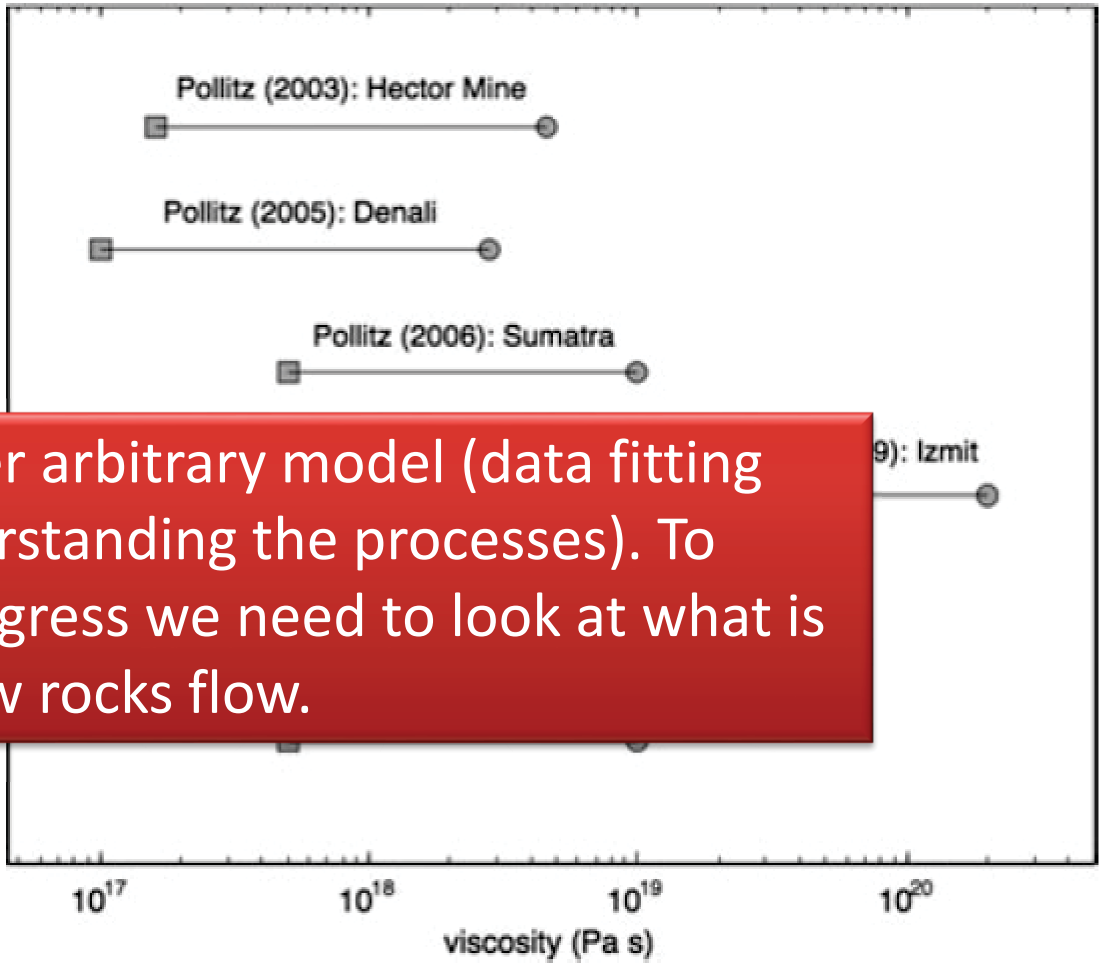




Hetland and Hager, JGR 2005

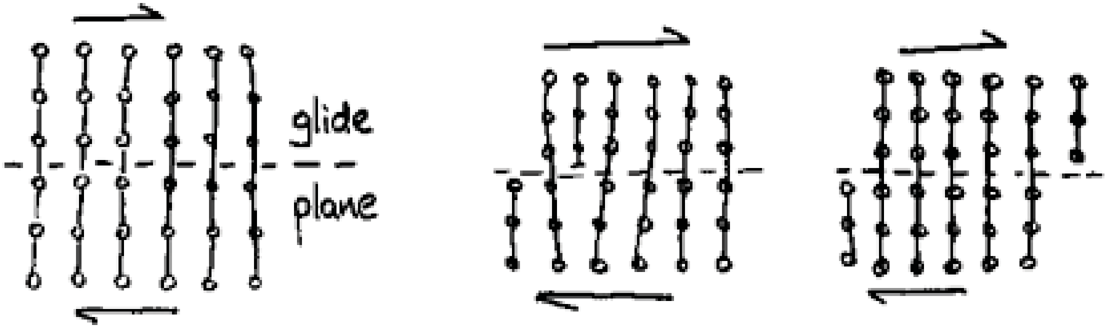
Alternatives: 1. Burger’s body rheology

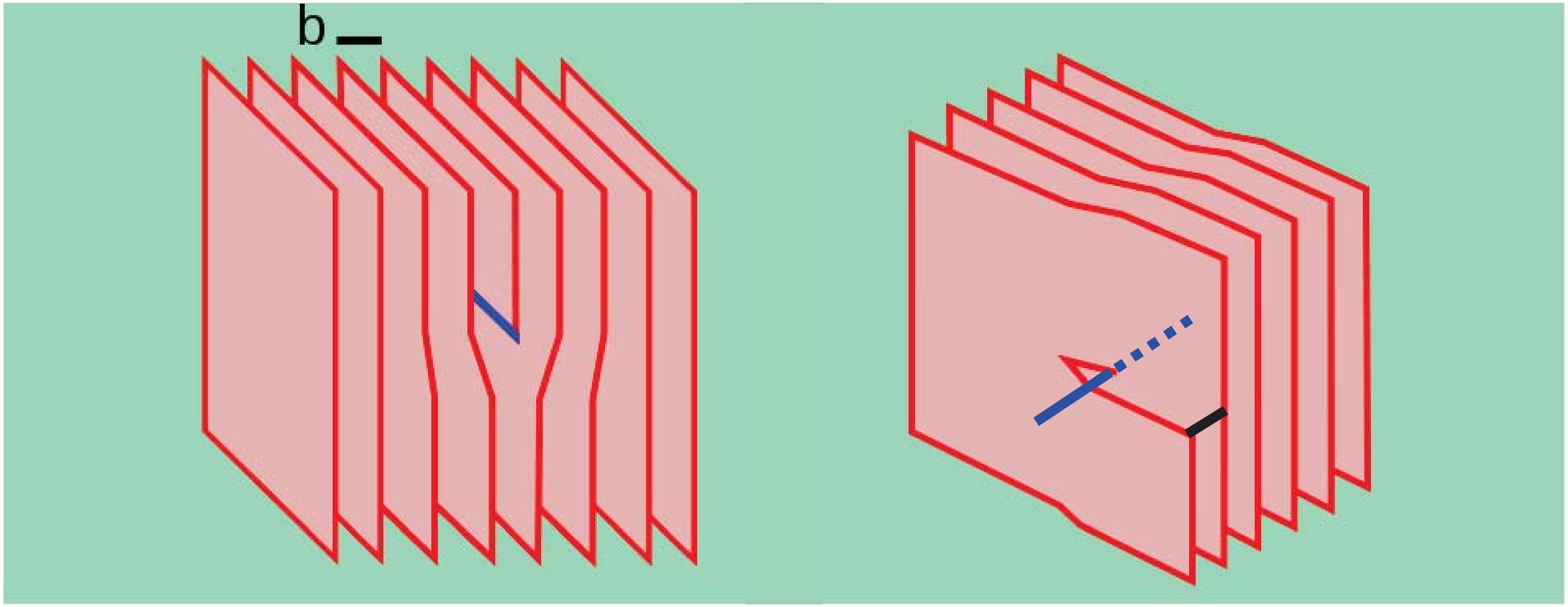




Ryder et al, GJI 2011

But this is a rather arbitrary model (data fitting rather than understanding the processes). To make further progress we need to look at what is known about how rocks flow.

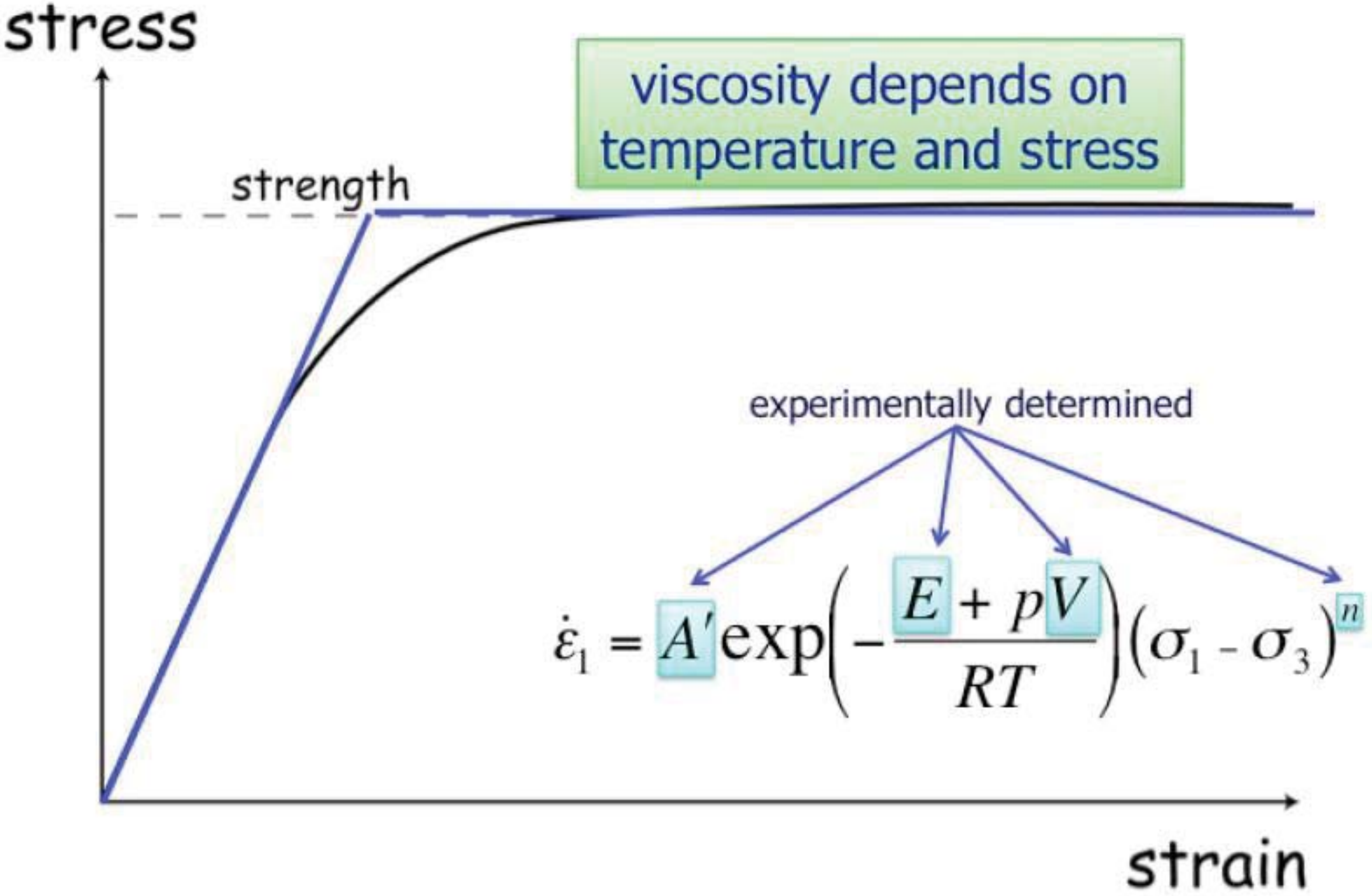




- Occurs when dislocation lines move through the crystal lattice
- Plane along which the movement takes place is called a glide plane
- Strain rate is dependent on $(\text{stress})^n$, hence sometimes called “power-law creep”

[Cartoon from http://ijolite.geology.uiuc.edu/07fallclass/geo411/Ductile/ductile.html]

Viscous flow by *power-law creep*

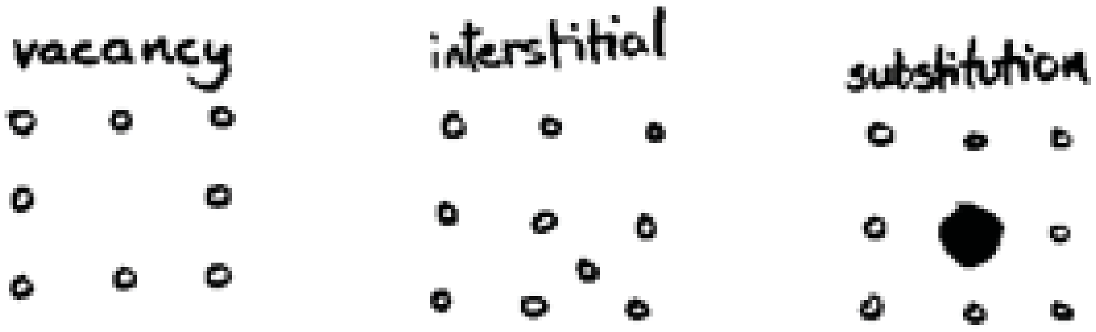


viscosity depends on temperature and stress

experimentally determined

$$\dot{\varepsilon}_1 = \boxed{A'}\exp\left(-\frac{\boxed{E}+p\boxed{V}}{RT}\right)(\sigma_1-\sigma_3)^{\boxed{n}}$$

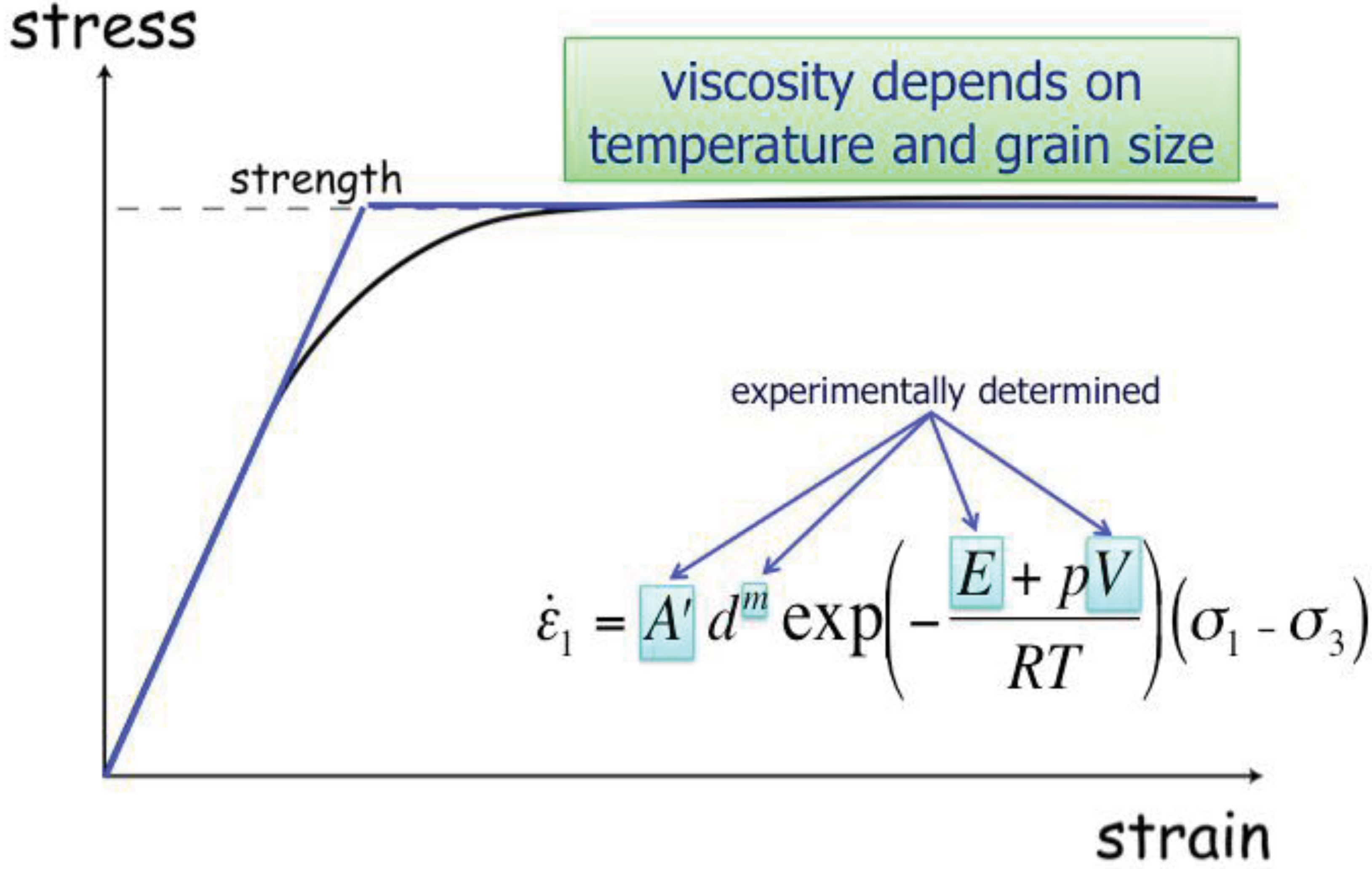
Diffusion Creep



- Point defects come in three basic forms:
  - (i) Vacancies (where an atom is missing from the lattice, leaving a hole)
  - (ii) Interstitial defects (where an extra atom is inserted into the lattice)
  - (iii) Substitutional defects (where a different atom replaces what should be there, inducing strain in the crystal lattice)
- Defects move through crystal by diffusion – thermally activated process.
- Linearly dependent on stress, but grain size is important

[Cartoon from http://ijolite.geology.uiuc.edu/07fallclass/geo411/Ductile/ductile.html]

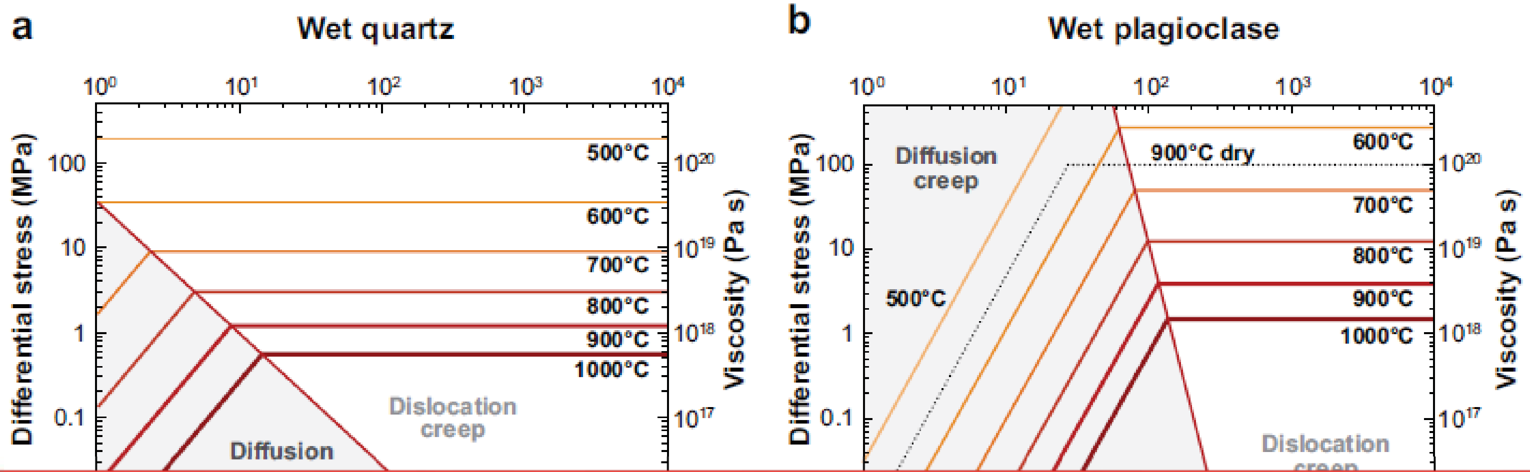
Viscous flow by *diffusion creep*



viscosity depends on temperature and grain size

experimentally determined

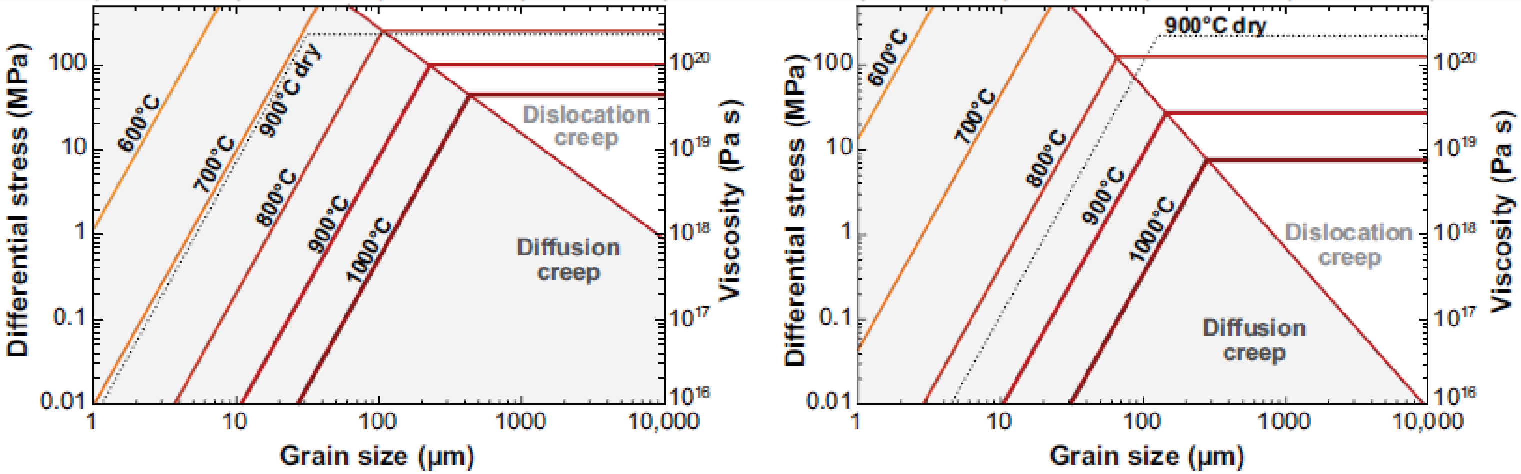
$$\dot{\varepsilon}_1 = \boxed{A'}\, d^{\boxed{m}} \exp\left(-\frac{\boxed{E} + p\boxed{V}}{RT}\right)(\sigma_1 - \sigma_3)$$



High stress or large grain size -> dislocation creep (power-law)

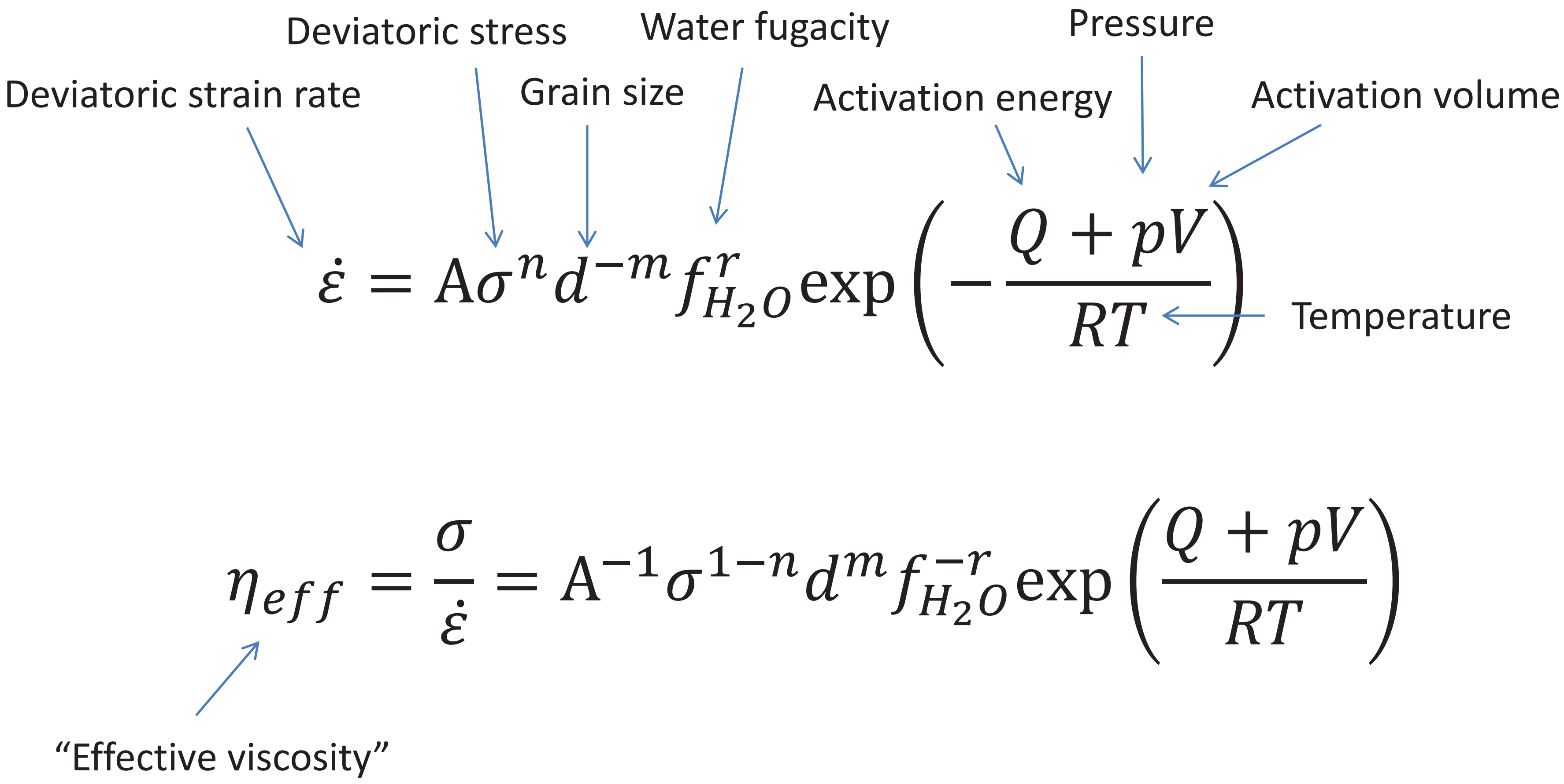
Low stress or small grain size -> diffusion creep (Maxwell)

Wet rocks weaker than dry rocks



Strain rates 10^{-12} s^{-1}; Burgmann and Dresen, Ann Rev 2008

Laboratory experiments



Deviatoric stress

Water fugacity

Pressure

Deviatoric strain rate

Grain size

Activation energy

Activation volume

$$\dot{\varepsilon} = \mathrm{A}\sigma^{n} d^{-m} f_{H_2O}^{r} \exp\left(-\frac{Q+pV}{RT}\right)$$

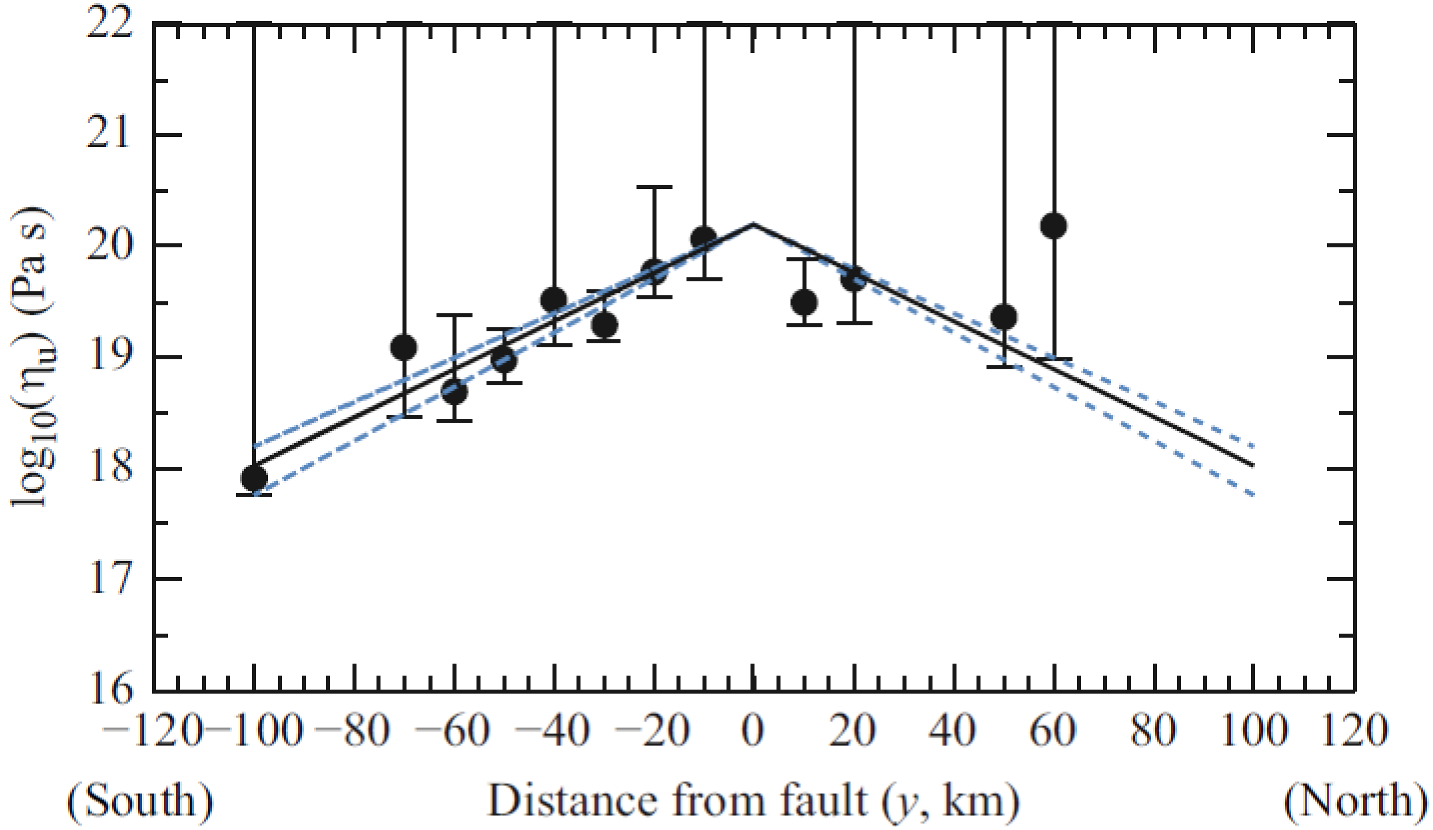
Temperature

$$\eta_{eff} = \frac{\sigma}{\dot{\varepsilon}} = \mathrm{A}^{-1}\sigma^{1-n} d^{m} f_{H_2O}^{-r} \exp\left(\frac{Q+pV}{RT}\right)$$

“Effective viscosity”

Temperature (Depth) dependence

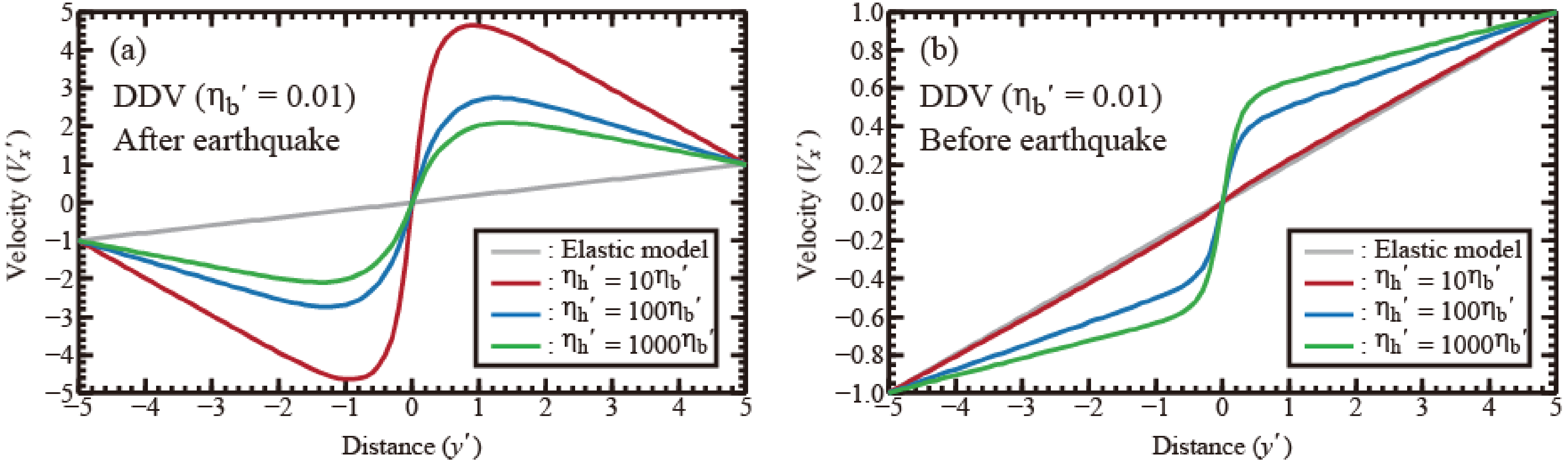
$$\eta_{eff} = A^{-1}\cancel{\sigma^{1-n}}\cancel{d^{m}}\cancel{f_{H_2O}^{-r}}\exp\left(\frac{Q+\cancel{pV}}{R\textcircled{T}}\right)$$



Yamasaki and Houseman, EPSL 2012

Temperature (Depth) dependence

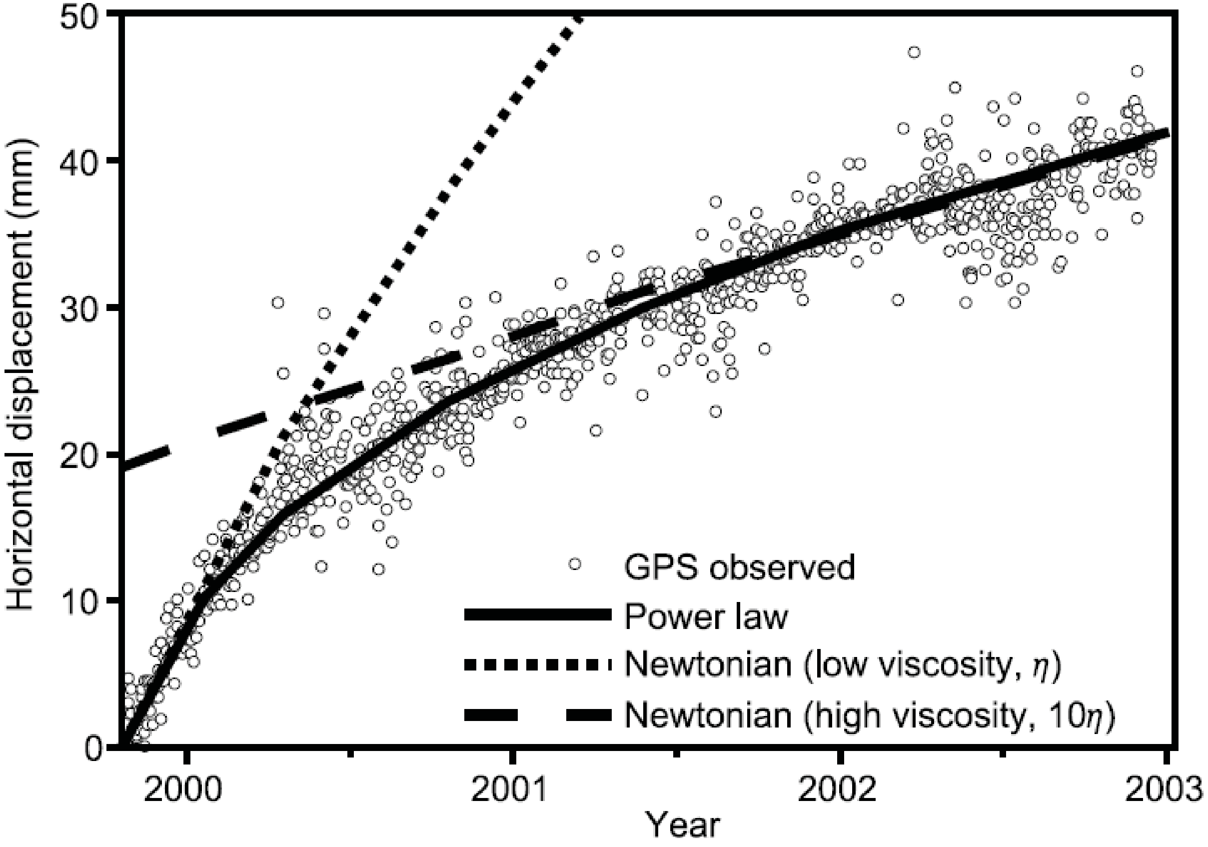
$$\eta_{eff} = \mathrm{A}^{-1}\cancel{\sigma^{1-n}}\cancel{d^{m}}\cancel{f_{H_2O}^{-r}}\exp\left(\frac{Q+\cancel{pV}}{R\boxed{T}}\right)$$



Yamasaki , Wright and Houseman, in revision 2013

Power-law

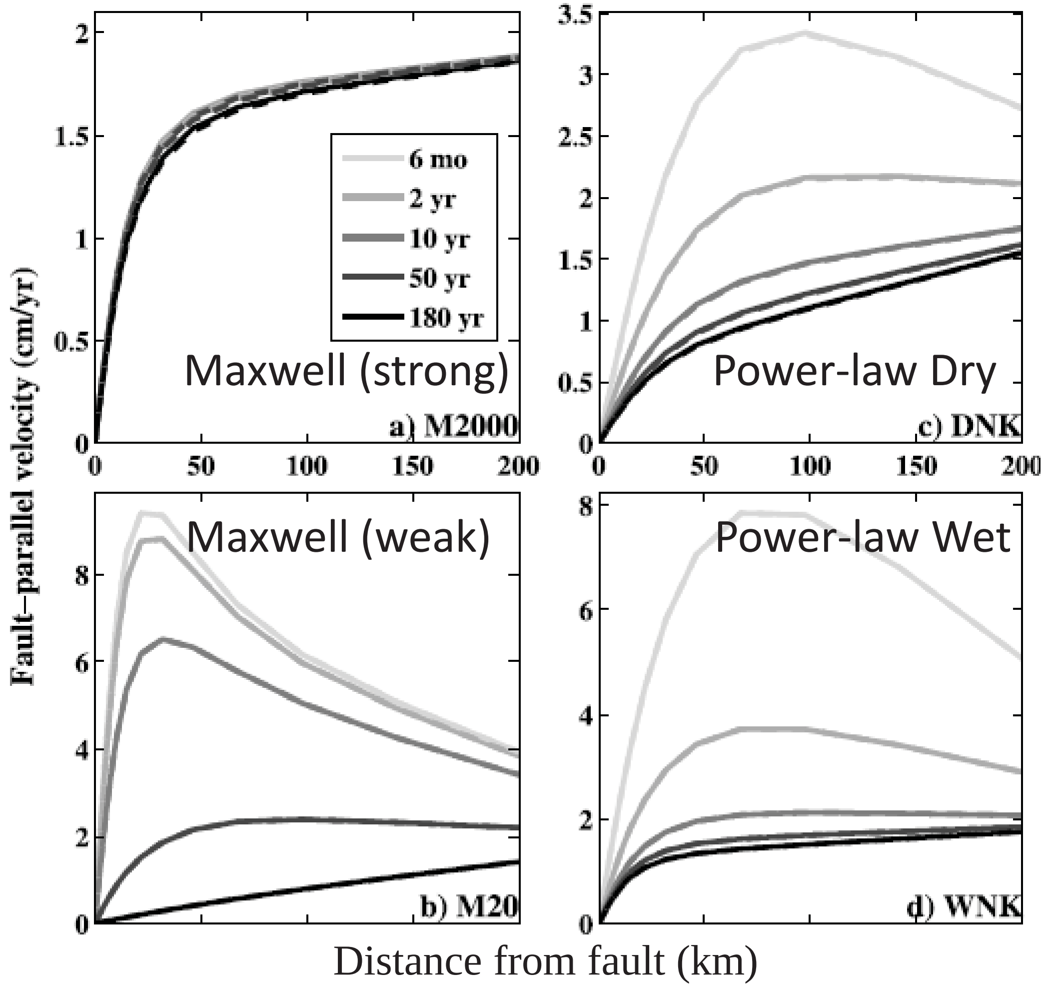
$$\eta_{eff} = \mathrm{A}^{-1}\sigma^{1\enclose{circle}{-n}}\cancel{d^{m}}\,\cancel{f_{H_2O}^{-r}}\exp\left(\frac{Q+\cancel{pV}}{R\enclose{circle}{T}}\right)$$



n~3-3.5: Freed and Burgmann, Nature 2004

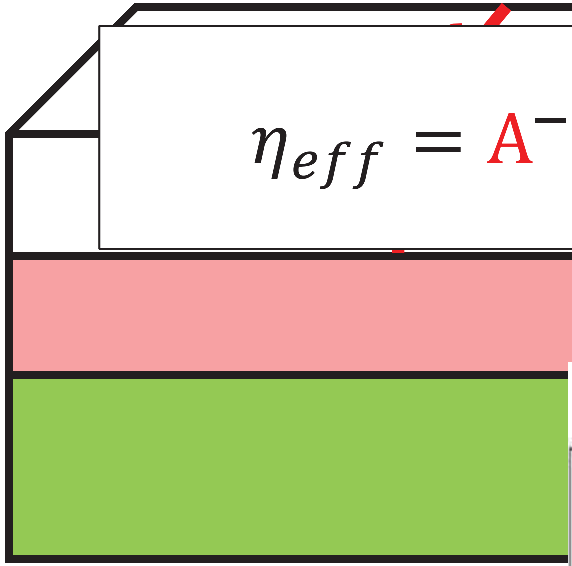
Power-law

$$\eta_{eff} = A^{-1}\sigma^{1\boxed{-n}}\cancel{d^{m}}\,\cancel{f_{H_2O}^{-r}}\exp\left(\frac{Q+\cancel{pV}}{R\boxed{T}}\right)$$



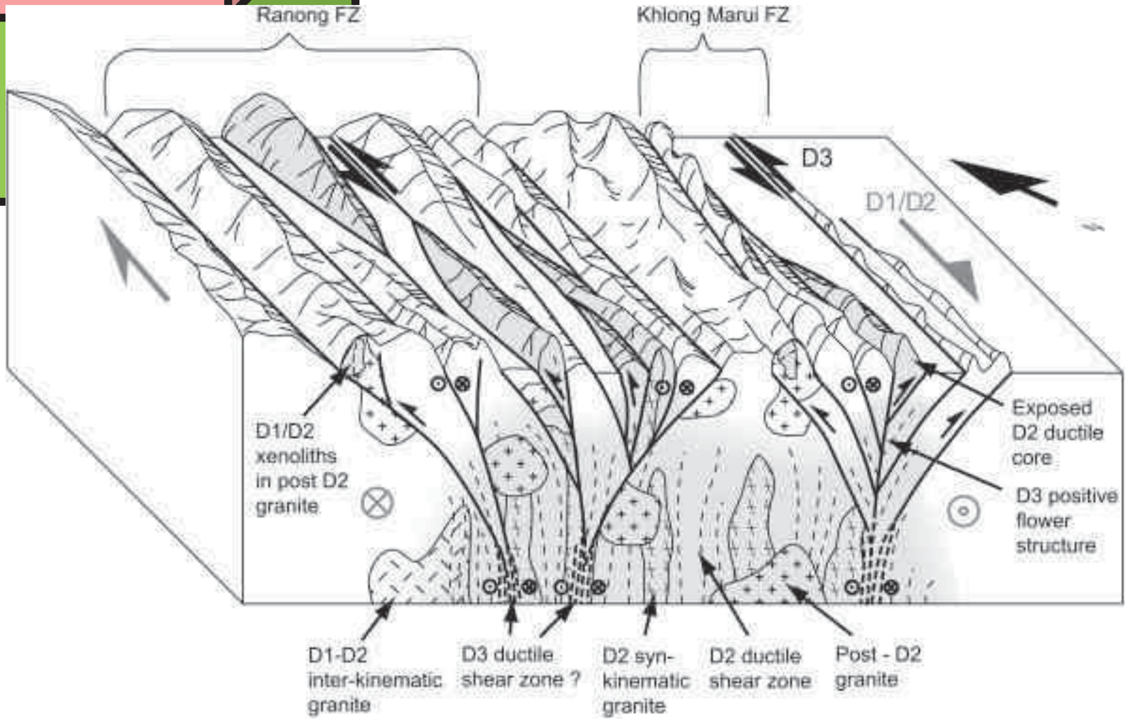
Takeuchi and Fialko (JGR, 2012)
Earthquake cycle with power law + Temperature dependence

Spatial variations in properties



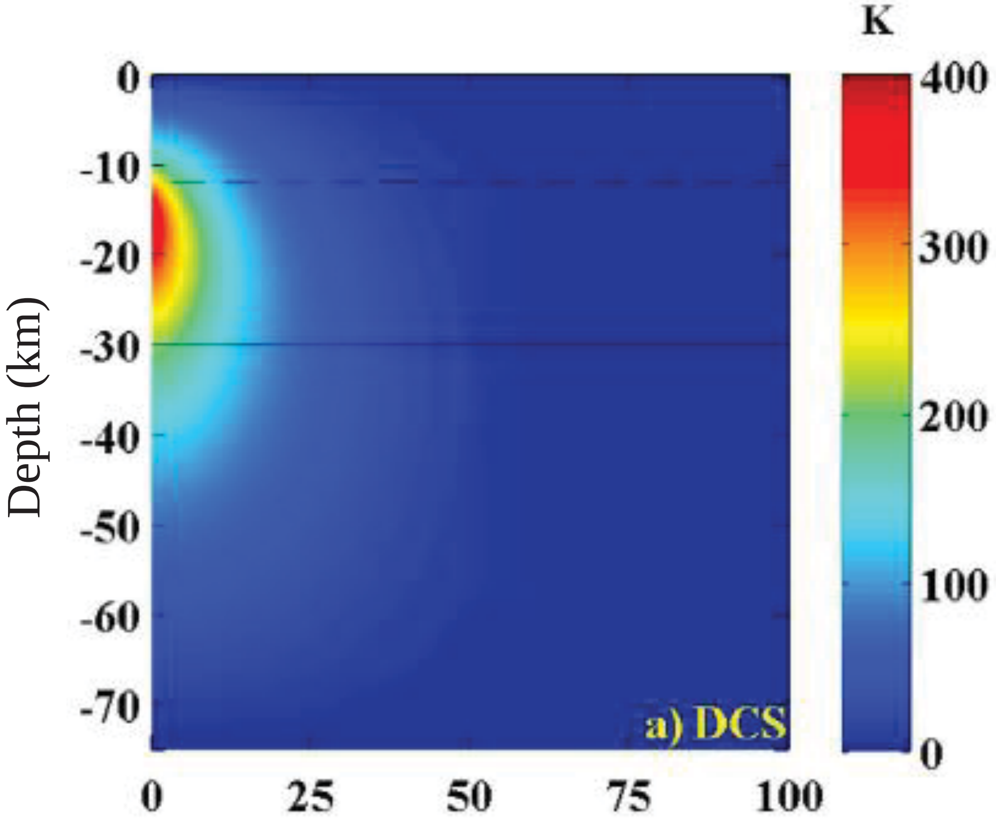
$$\eta_{eff} = A^{-1}\sigma^{1-n}d^{m}f_{H_2O}^{-r}\exp\left(\frac{Q+pV}{RT}\right)$$

Geologist’s view of a fault zone



Watkinson et al., J. Struct. Geol. 2008

Spatial variations in properties:
1. Shear heating



Takeuchi and Fialko (JGR, 2012)

Spatial variations in properties:
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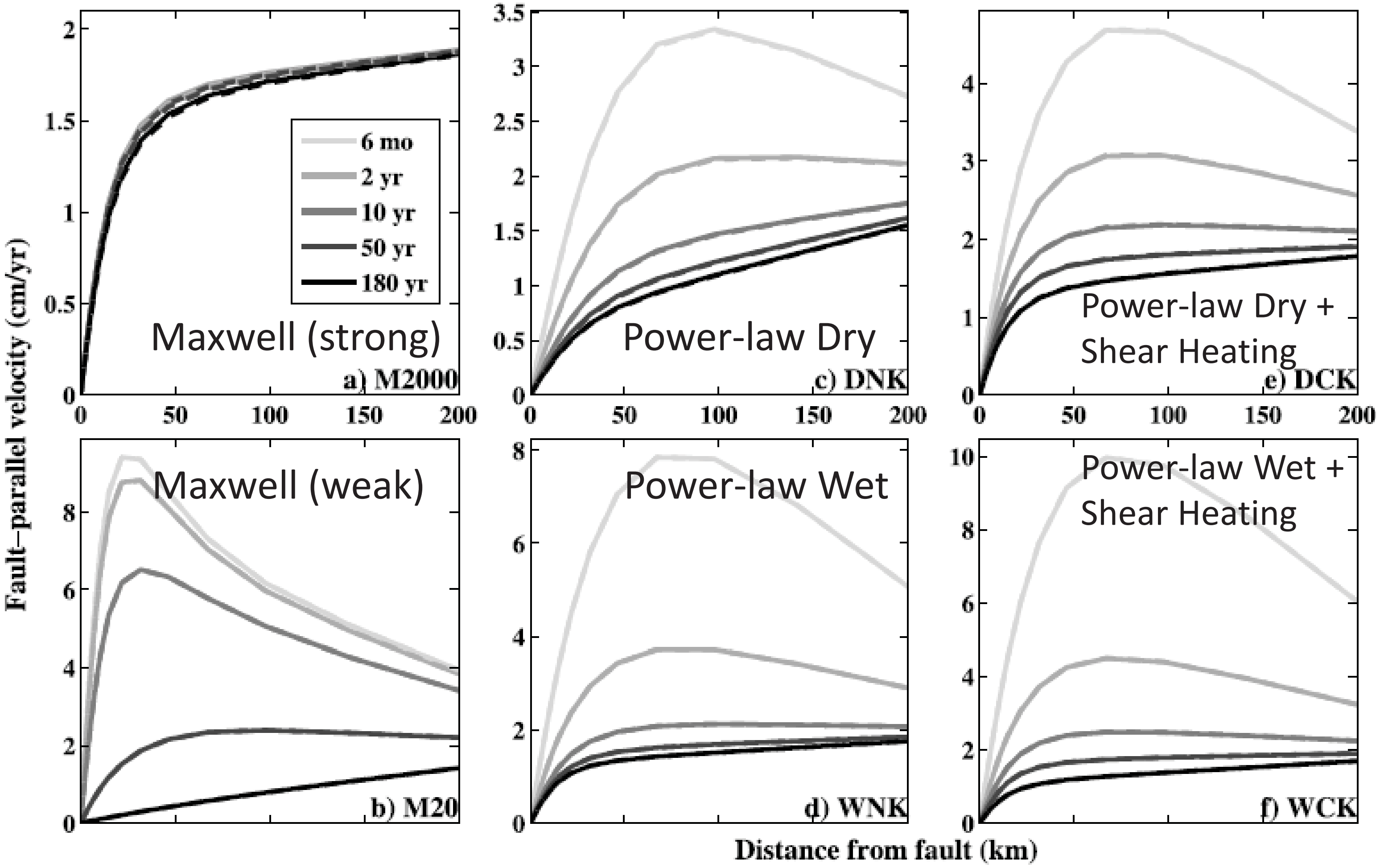
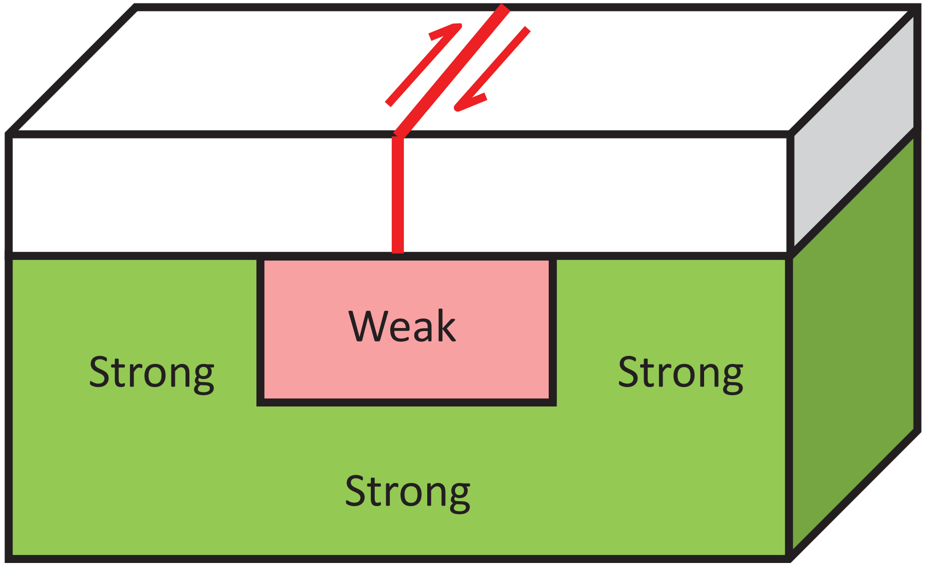


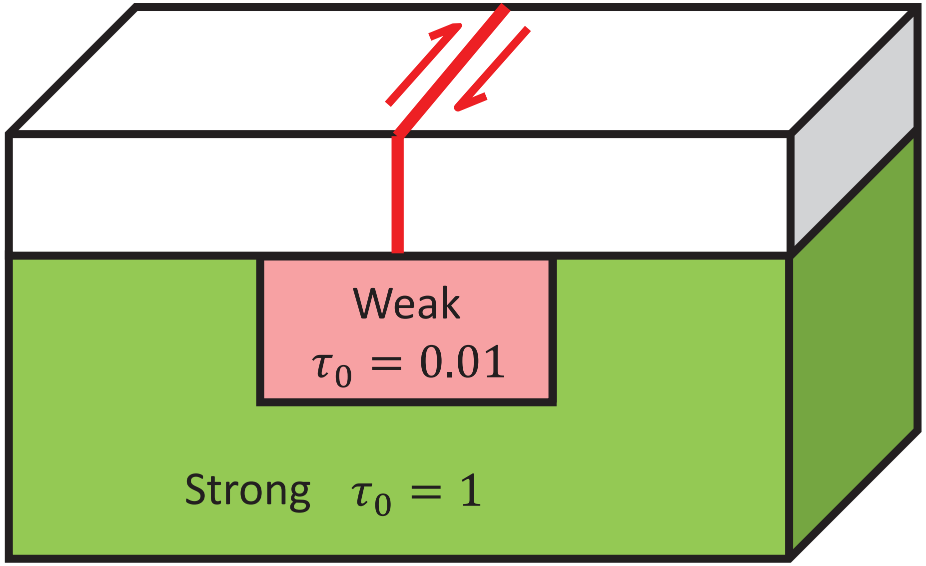
Takeuchi and Fialko (JGR, 2012)

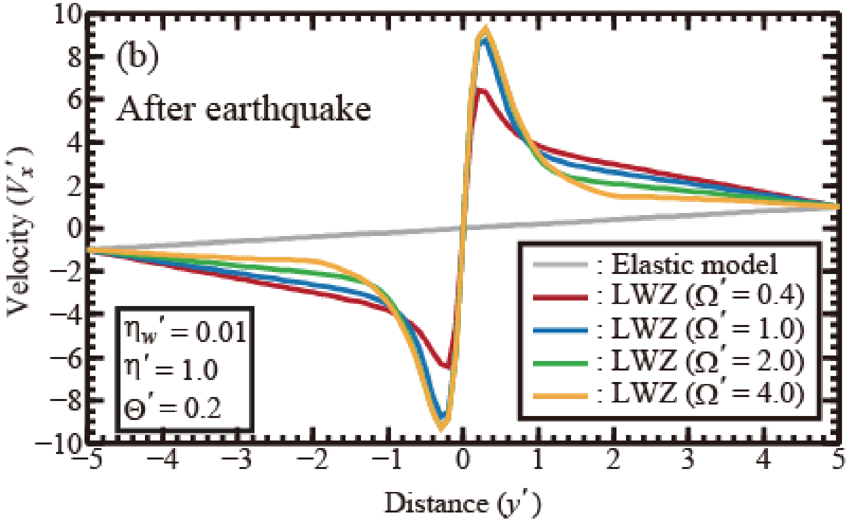
Spatial variations in properties:
2. Material properties (weak zone)

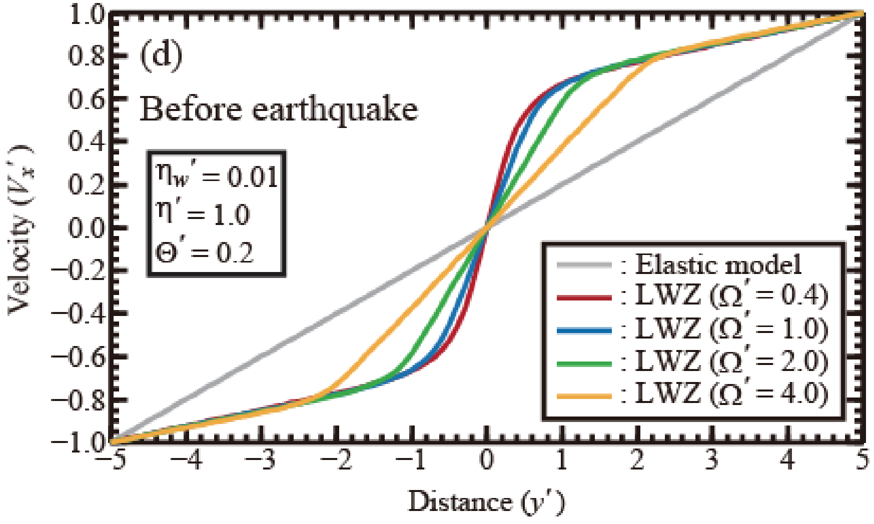
$$\eta_{eff} = \mathrm{A}^{-1}\sigma^{1-n}d^{m}f_{H_2O}^{-r}\exp\left(\frac{Q+pV}{RT}\right)$$



Spatial variations in properties:
2. Material properties (weak zone)

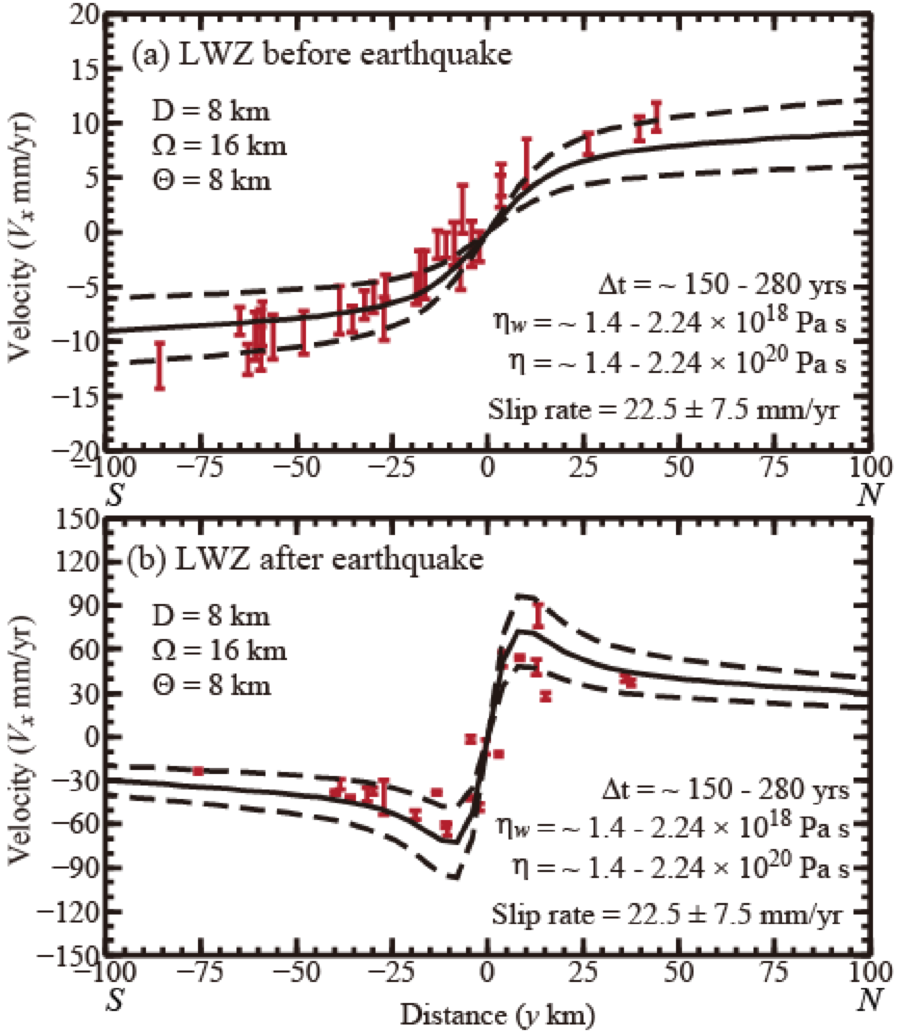


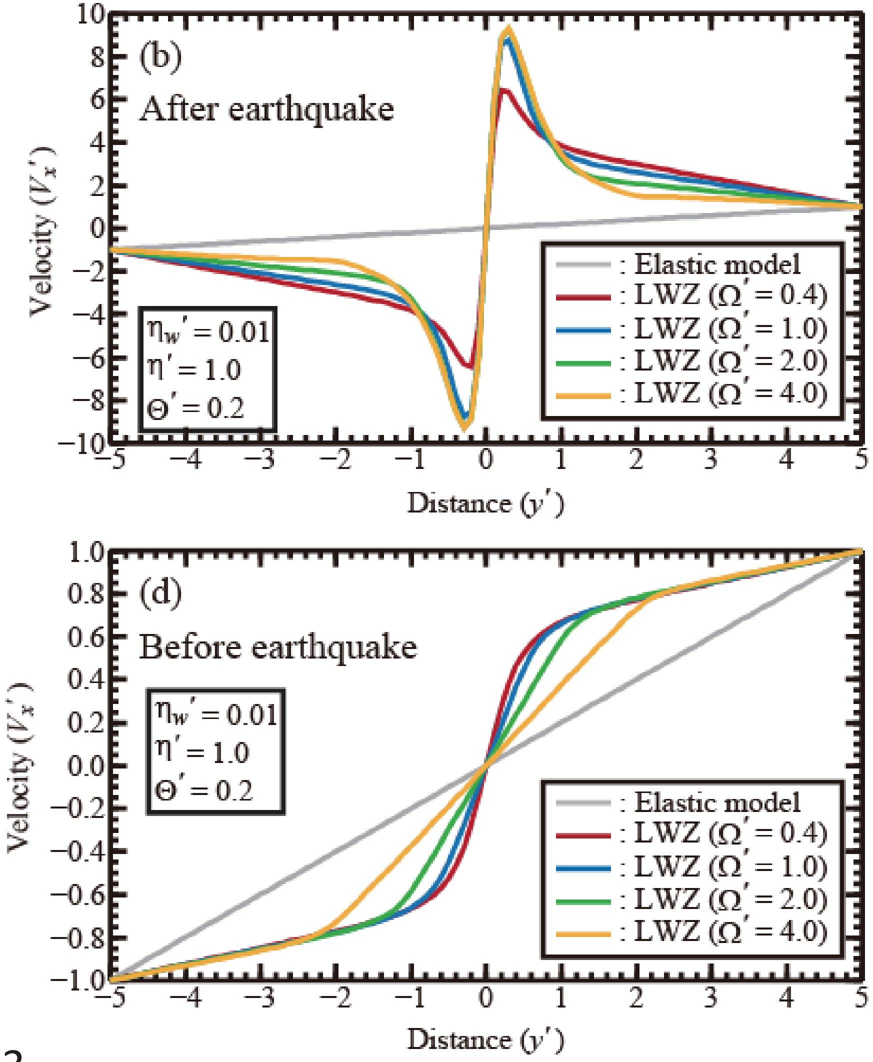




Yamasaki , Wright and Houseman, in prep 2013

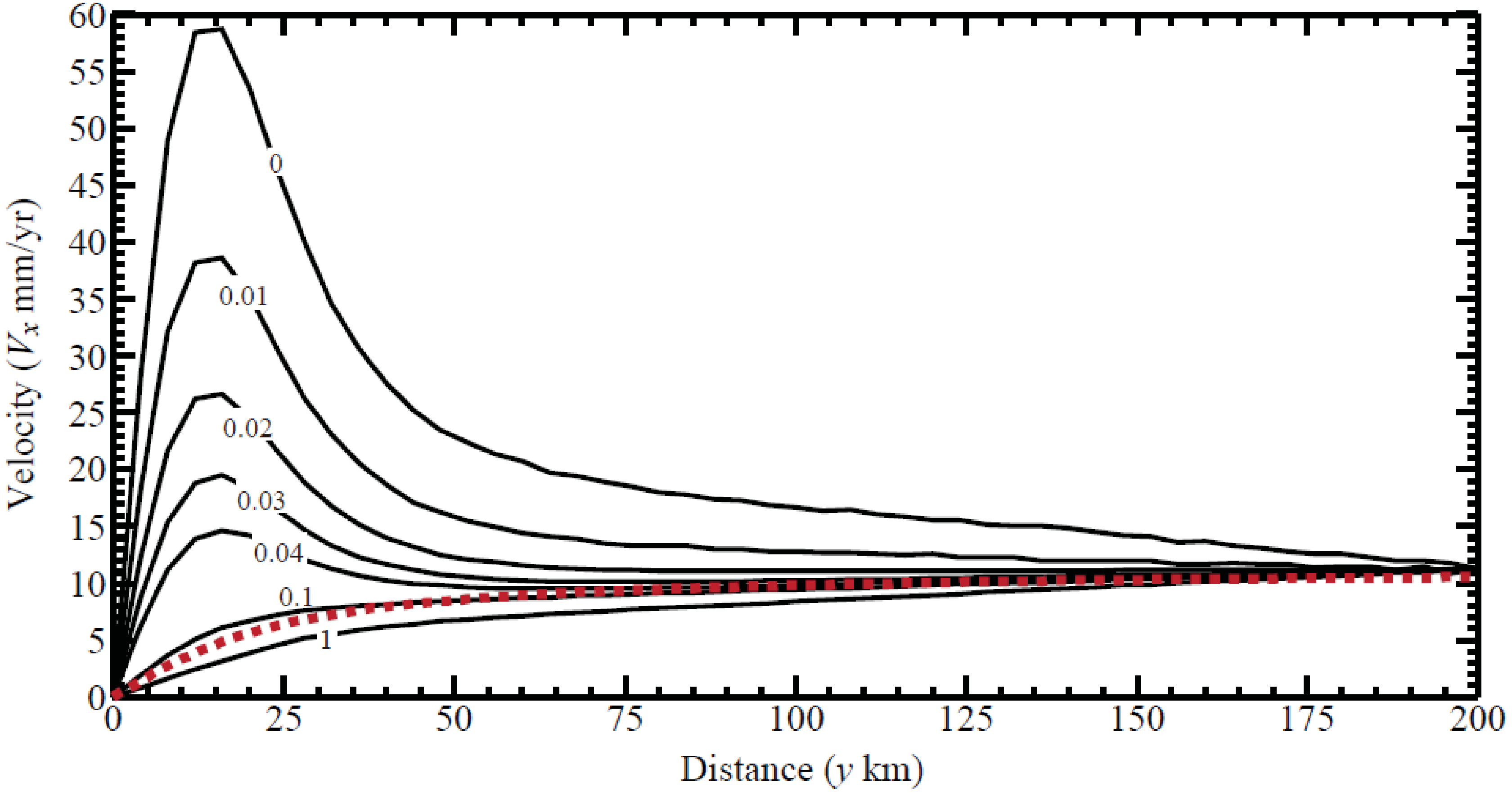
Spatial variations in properties:
2. Material properties (weak zone)





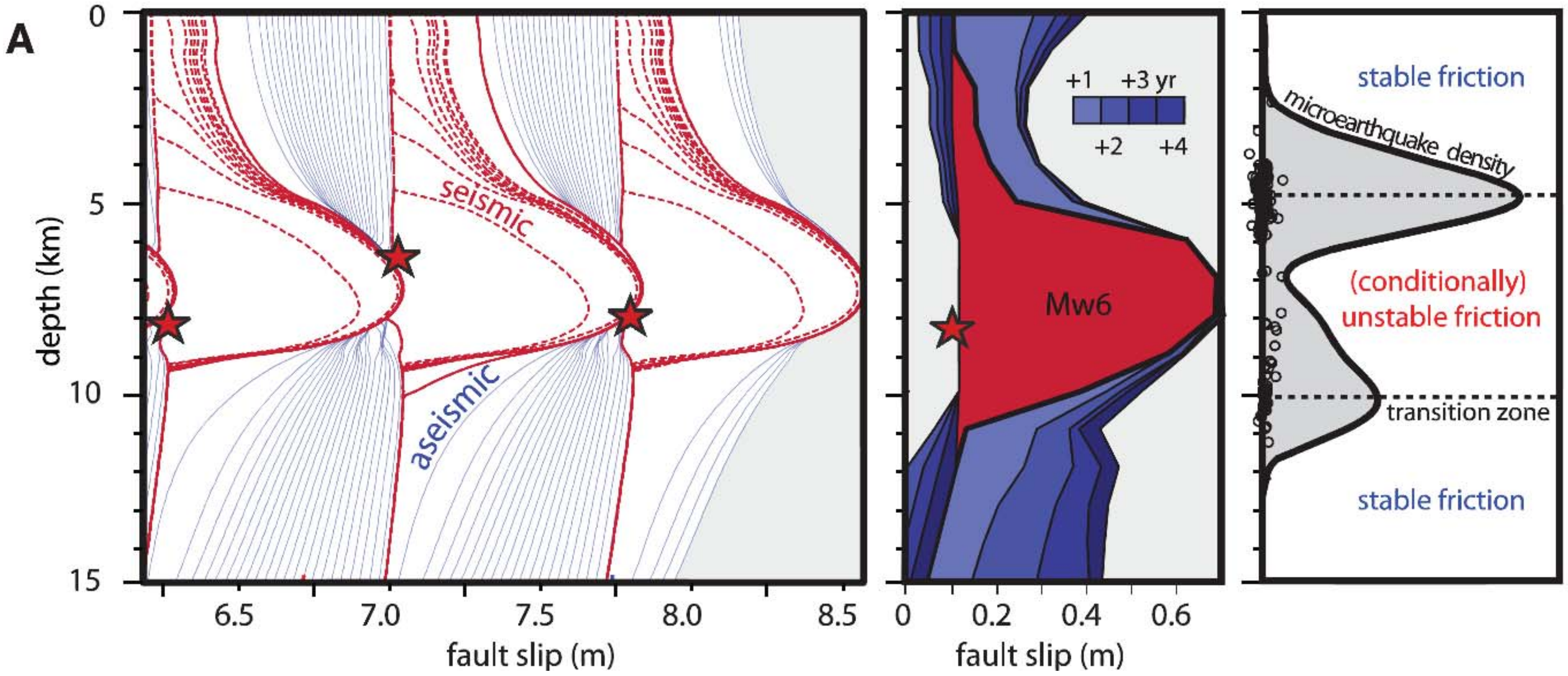
Yamasaki , Wright and Houseman, in revision 2013

Spatial variations in properties: 2. Material properties (weak zone)



Yamasaki , Wright and Houseman, in revision 2013

Alternative approach: Friction, deep fault extension

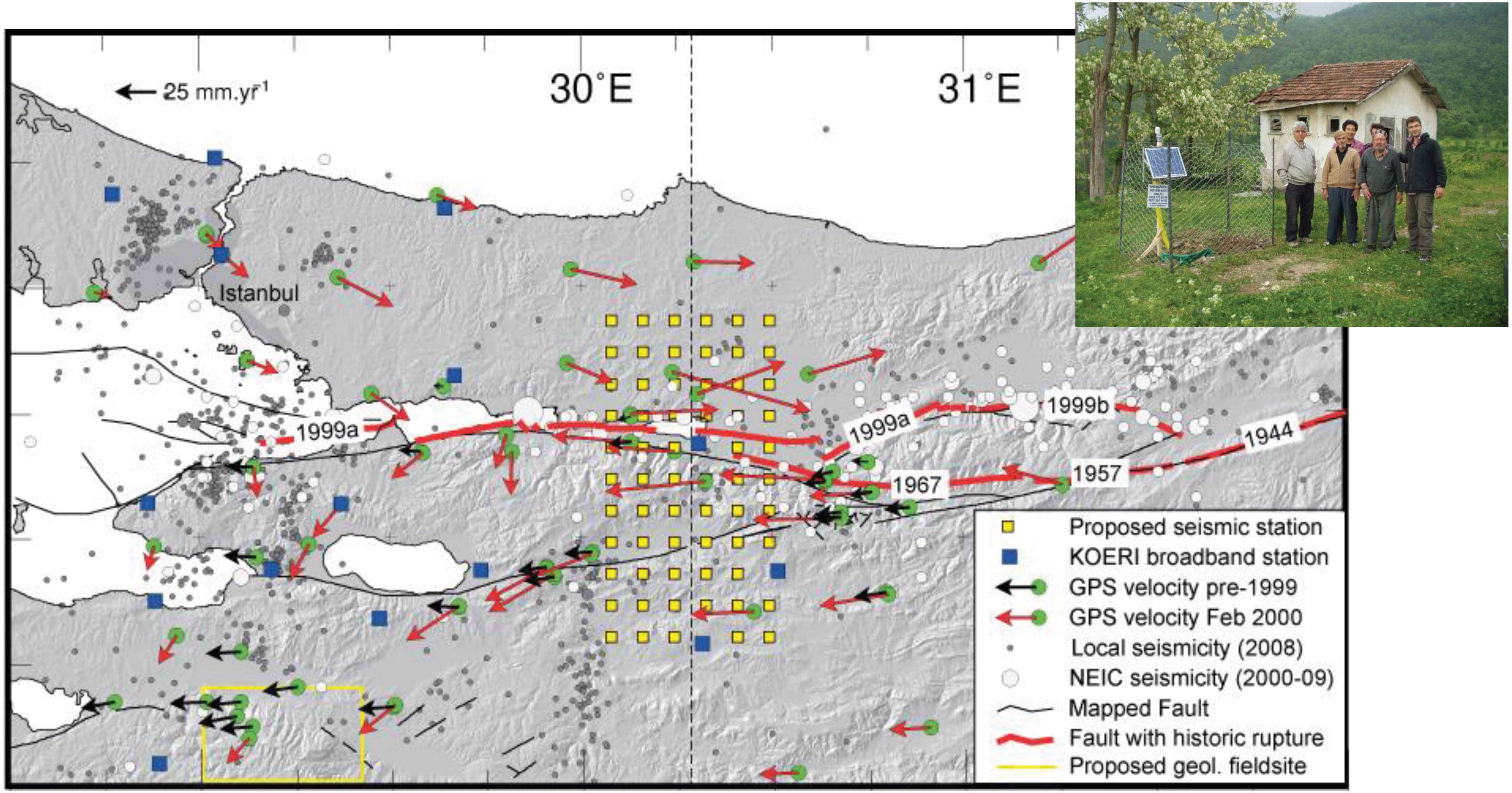


Barbot, Lapusta and Avouac, Science 2012

Summary of modelling

- Strong material required to match interseismic deformation
- Weak material required to match postseismic deformation
- Several strategies can fit both coseismic and postseismic simultaneously.
- Spatial variation in material properties is most likely explanation (power law may not be required).
- Geodetic data are non-unique – independent constraints required

Future perspectives
Fault Lab Experiment: North Anatolian Fault



Conclusions

- Quantity and quality of geodetic observations of earthquake cycle deformation has dramatically increased in last 20 years.
- Simple rheologies are incompatible with both postseismic and interseismic deformation.
- Spatial variations in material properties provide the most satisfactory solution.
- Further work required to integrate geological, geodetic, seismic, model, and lab views of fault zones.