The View of Lithosphere Rheology from Interseismic Deformation:

Potential Biases Due to Model Simplification

E.A. Hetland & S.B. Moore
Univ. Michigan

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University of Michigan
Geological Sciences

overview

1. continental strength profiles
    a. rock deformation view
    b. the geodetic view
2. lessons from the Central Nevada Seismic Belt
3. postseismic deformation from dipping faults
4. sensitivity of horizontal postseismic deformation on depth dependent rheology
5. non-Maxwellian rheologies
    a. non-linear viscosity (power-law creep)
    b. transient viscoelasticity & North Anatolian Fault

- Not necessarily a 1-1 mapping between models and Earth.
- Still room to develop better mechanical models, to understand the tectonic Earth, or to clean the observations (ideally both).

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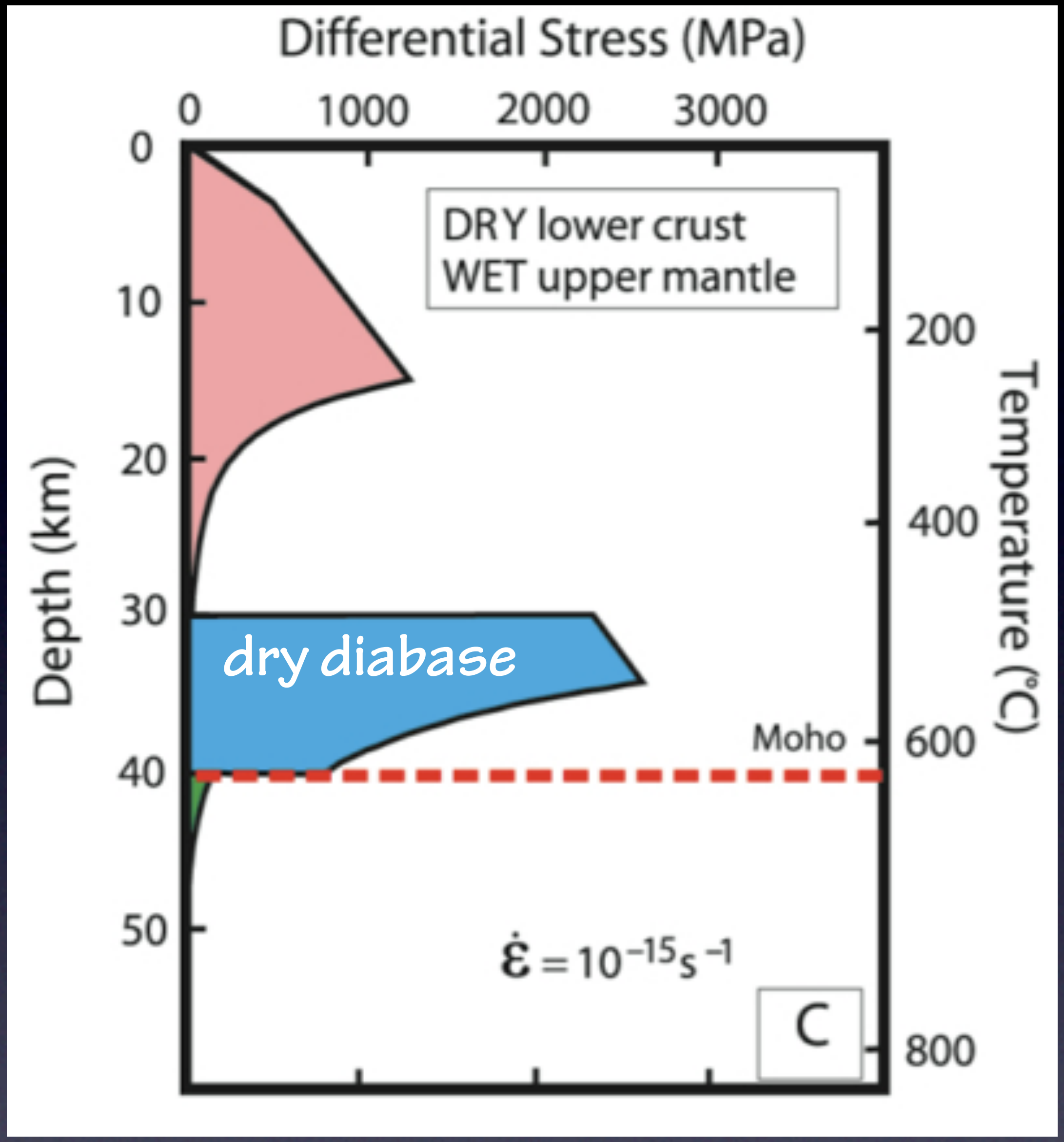
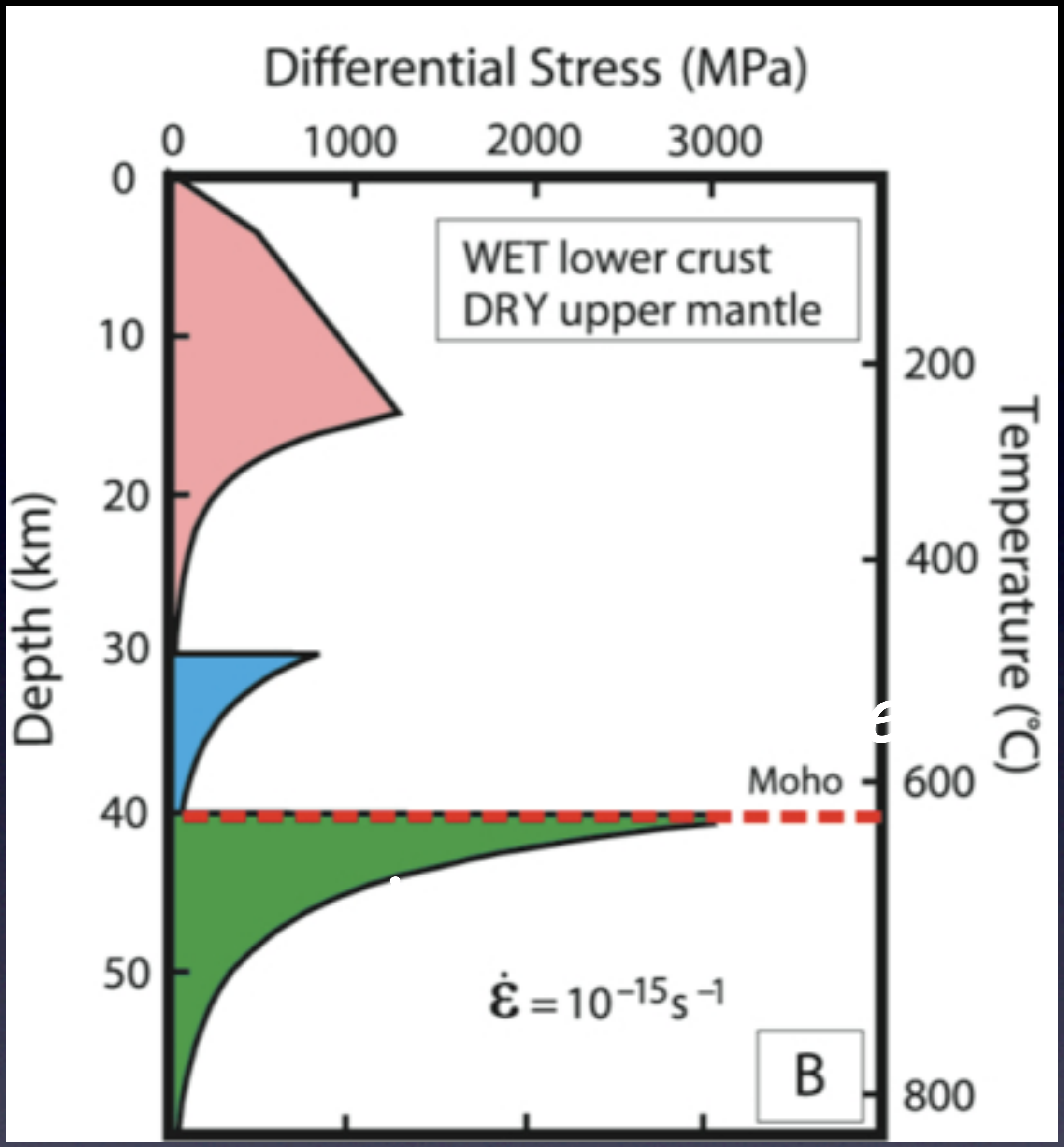
continental strength profiles



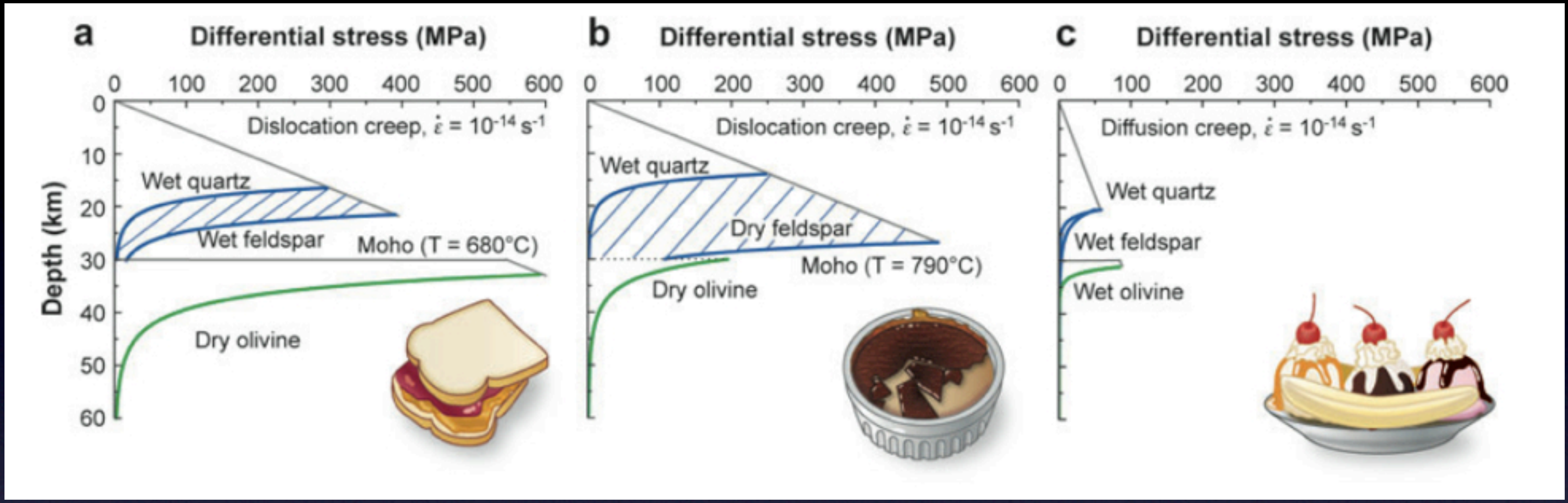
lower crust weaker than upper mantle



lower crust stronger than upper mantle

Jackson (2002)

continental strength profiles



lower crust weaker than upper mantle

lower crust stronger than upper mantle

lower crust & upper mantle both weak

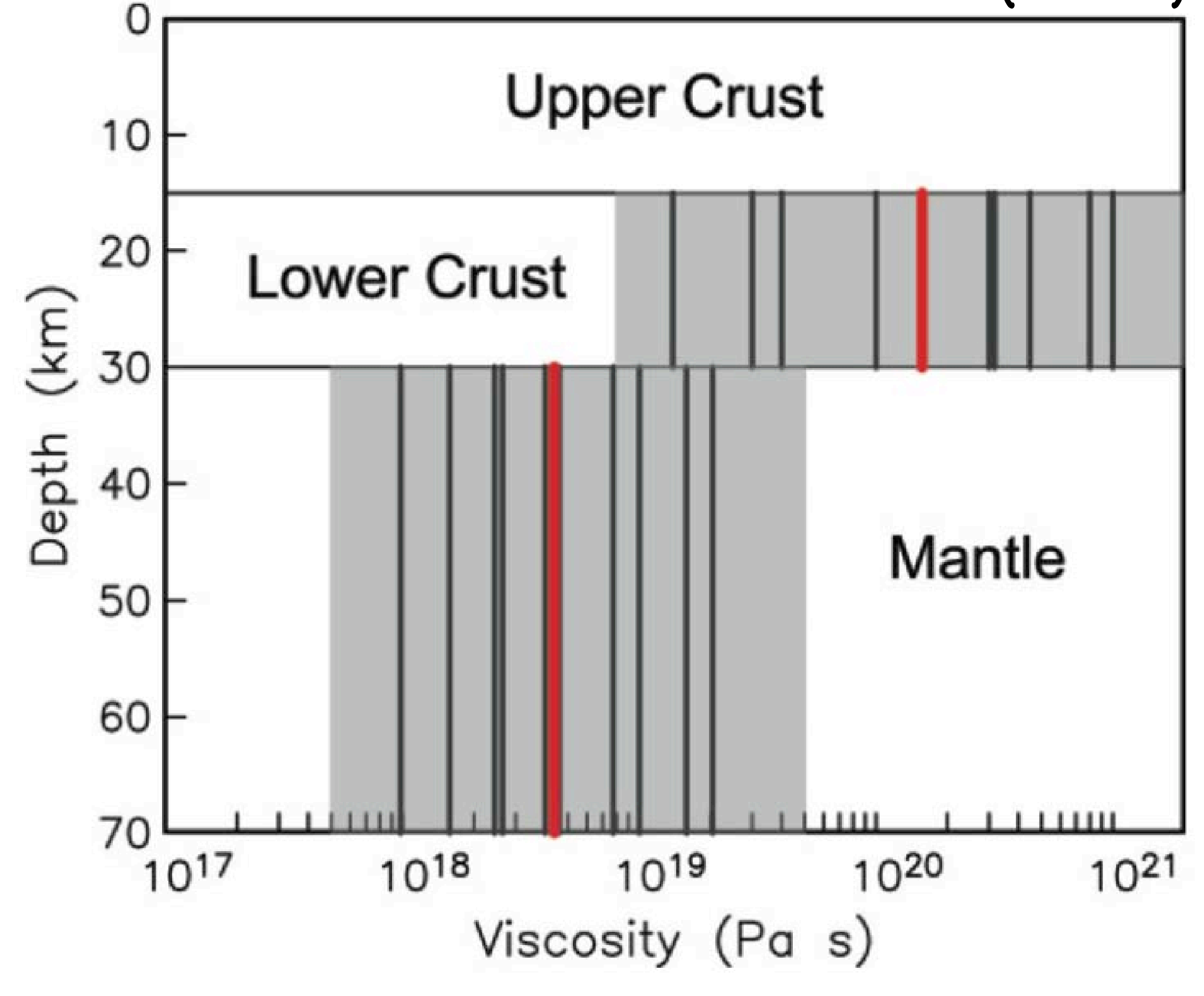
"intact" lithosphere

faulted lithosphere

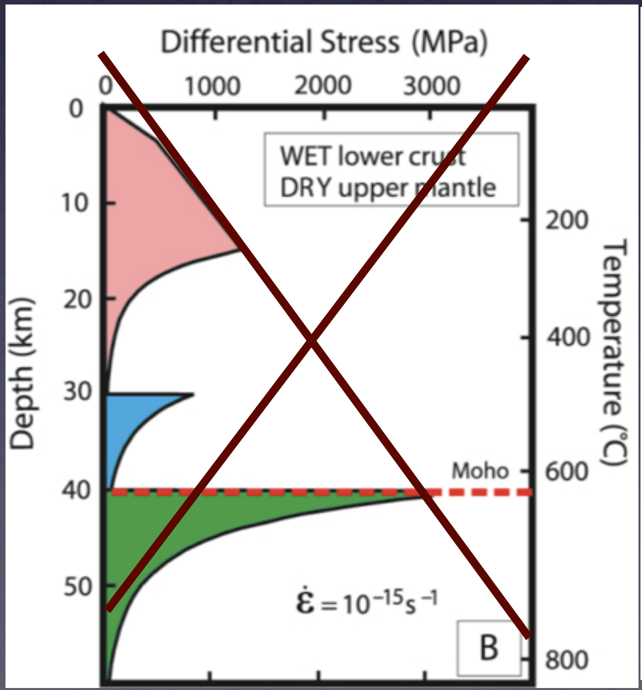
Bürgmann & Dresen (2008)

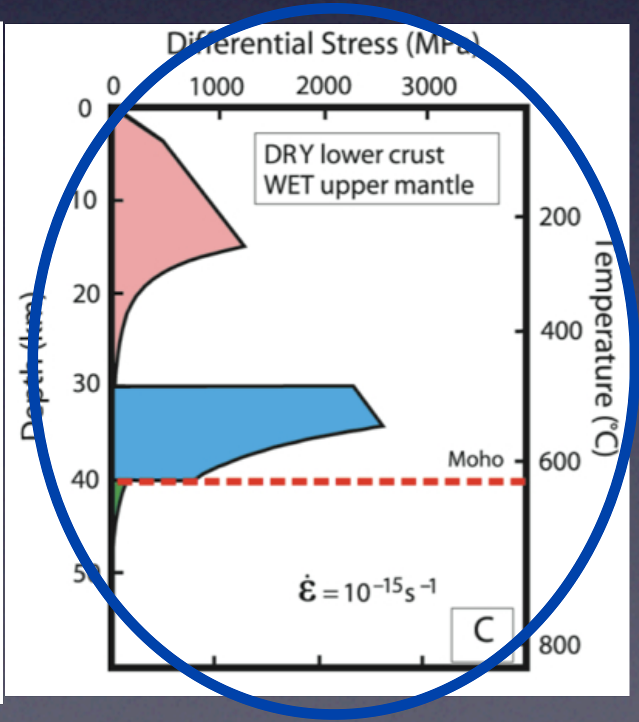
the geodetic view

Thatcher & Pollitz (2008)

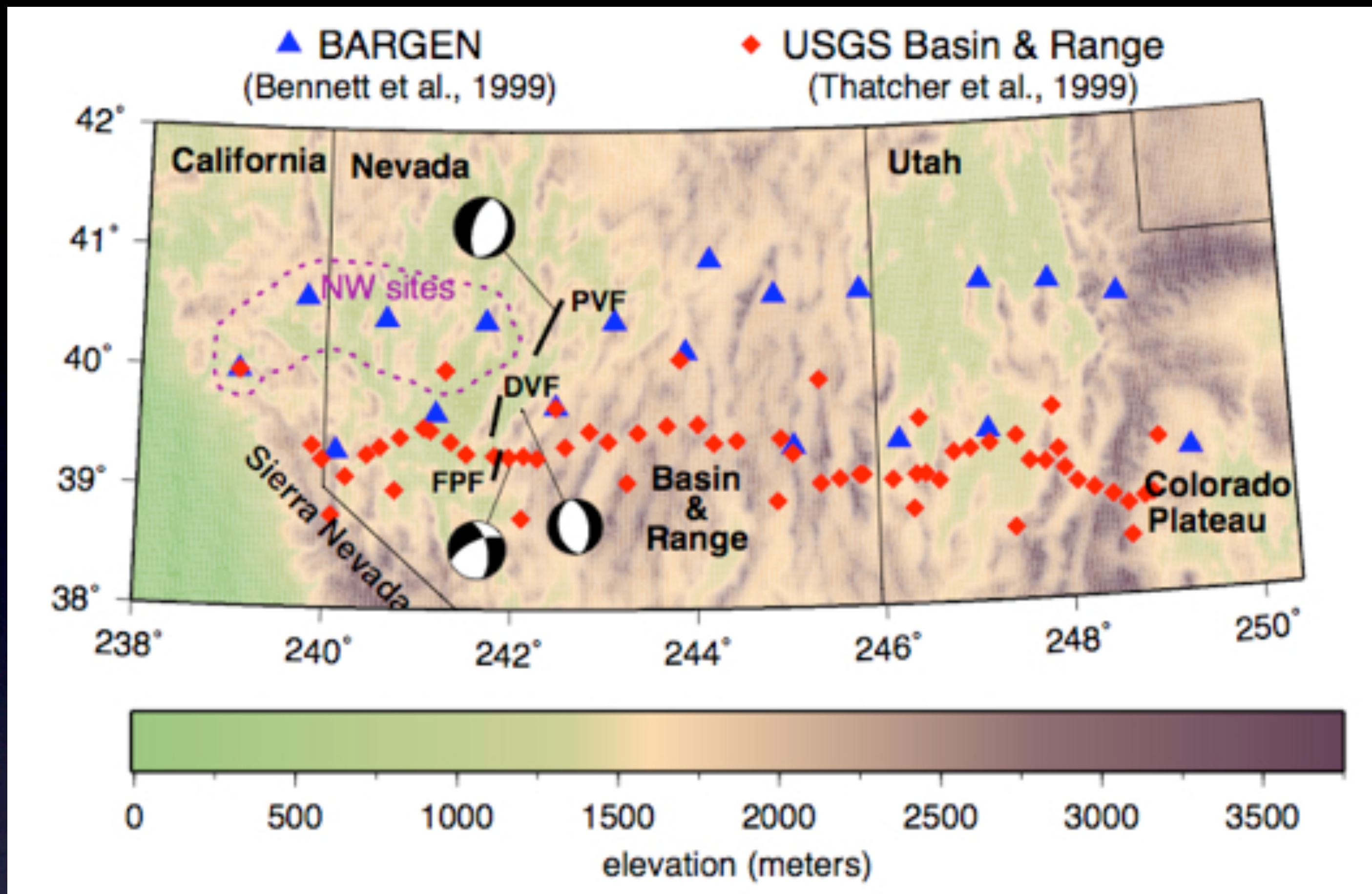


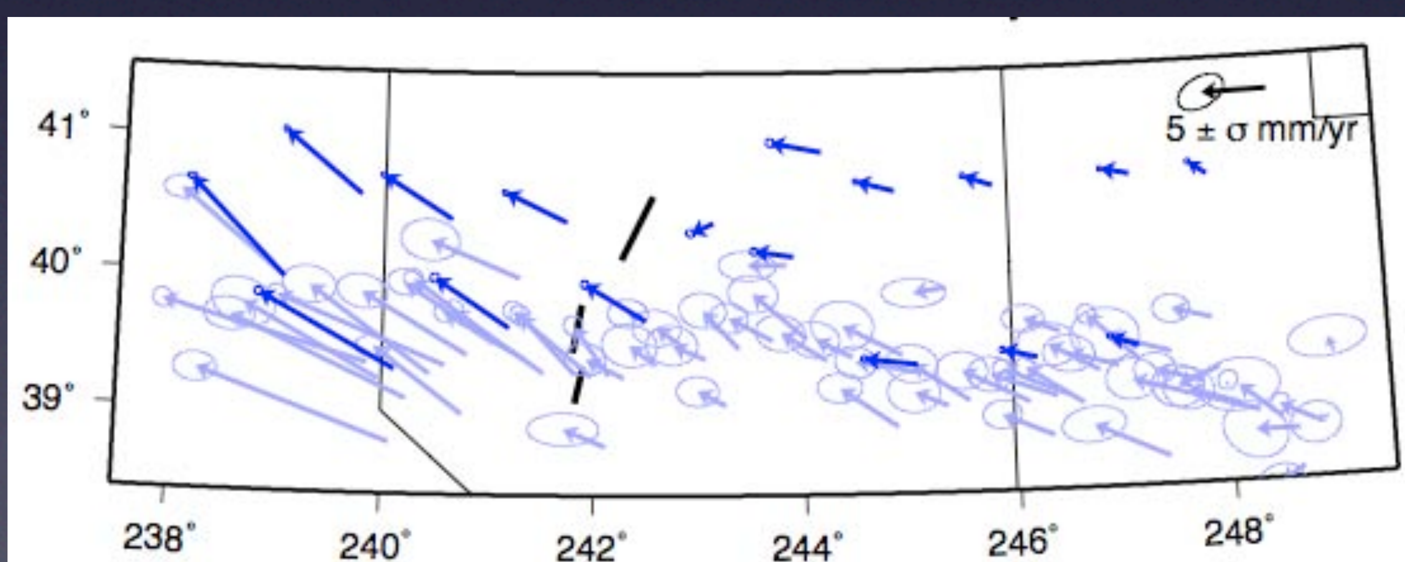
with few exceptions, models of post/interseismic deformation find that the viscosity of the lower crust is systematically larger than the uppermost mantle





ex: CNSB postseismic deformation

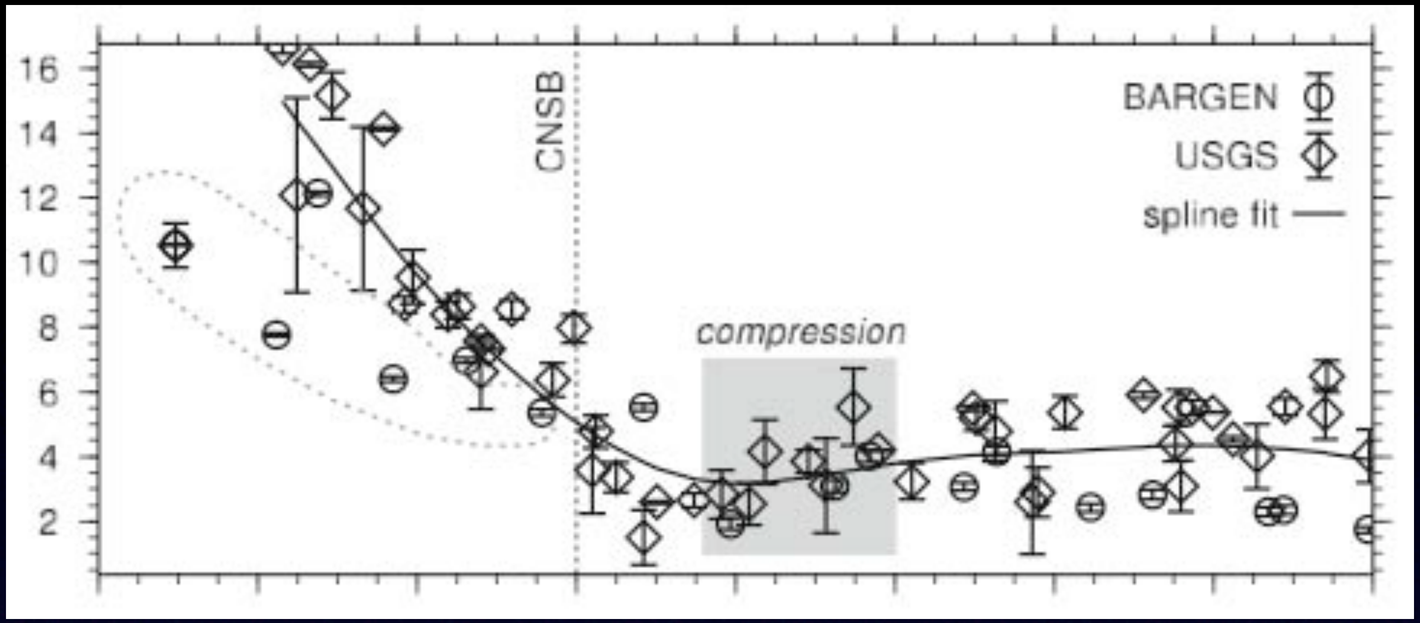


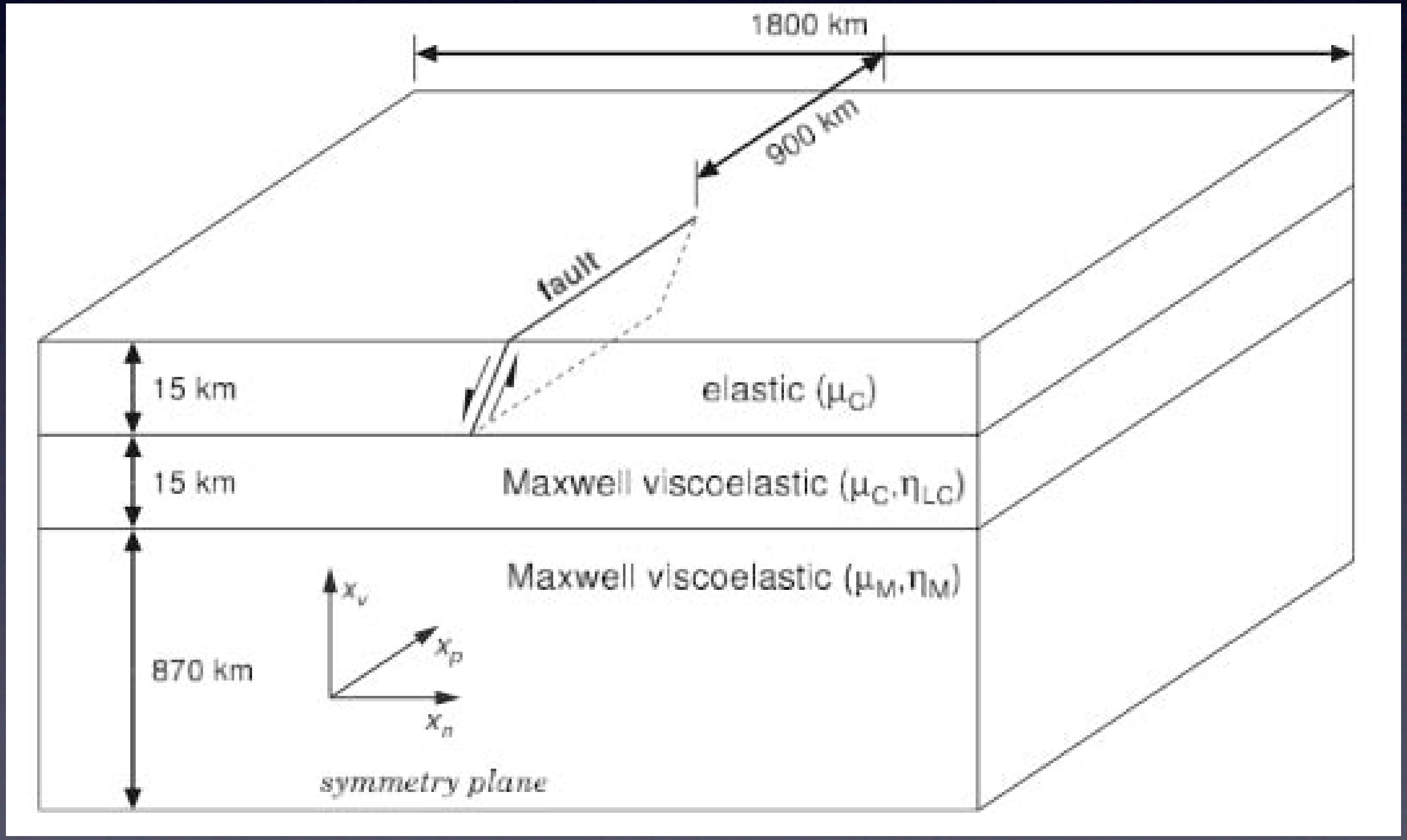


anomalous contraction in the horizontal GPS east of CNSB

proposed to be transient postseismic deformation from 20'th century CNSB earthquakes (Wernicke et al,. 2000)

CNSB postseismic model



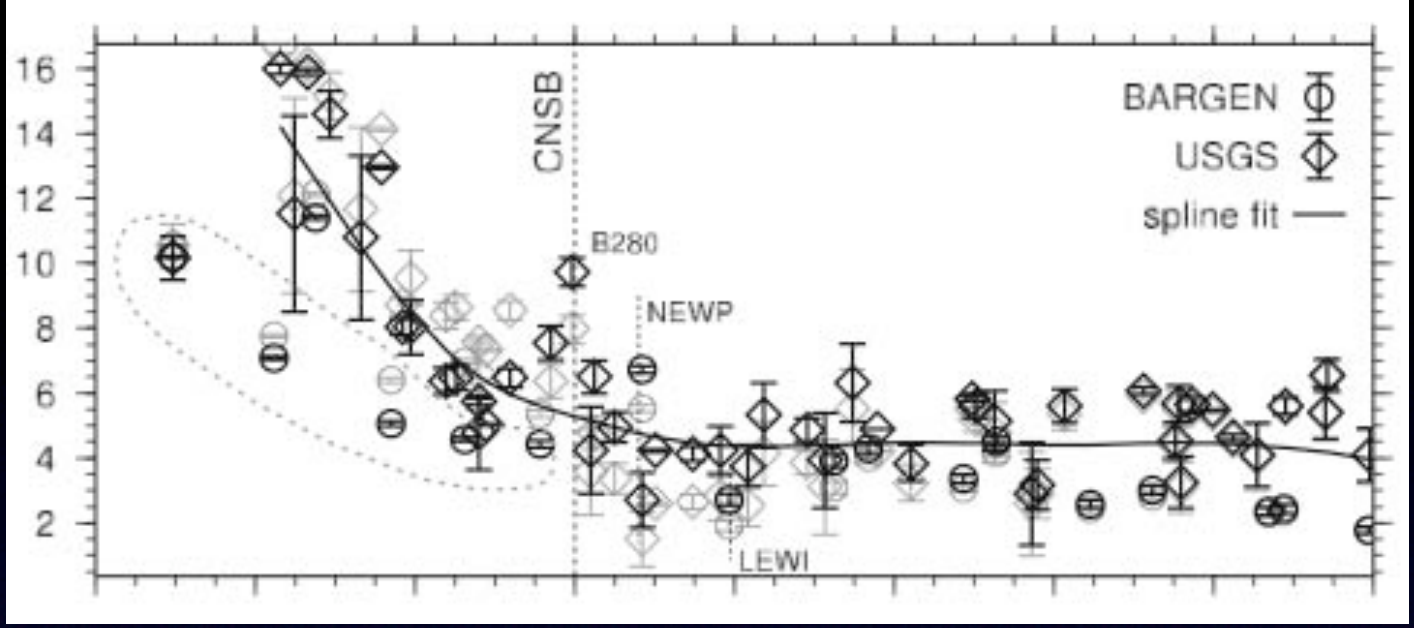


model cumulative postseismic from CNSB earthquake:

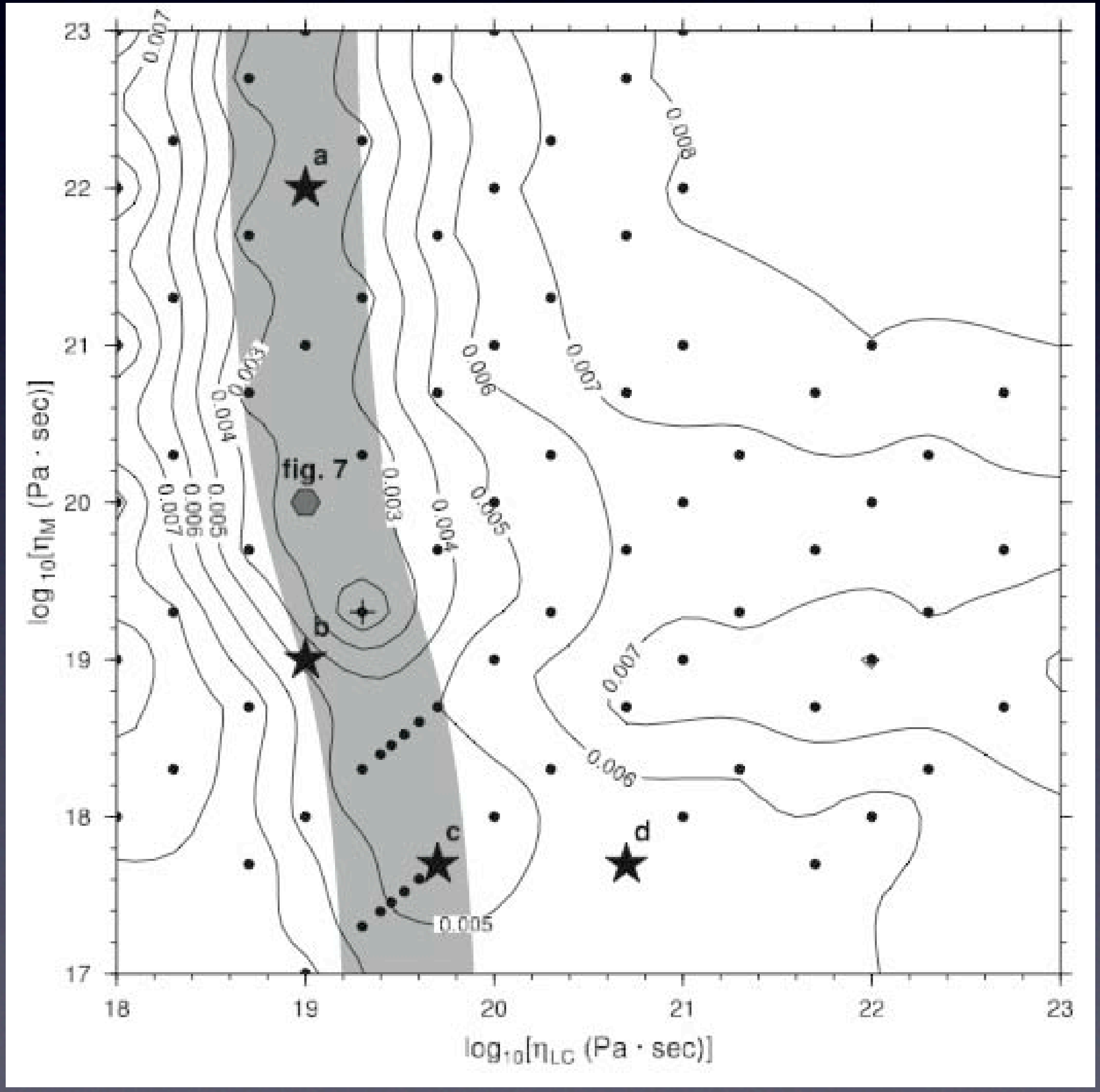
- Maxwell viscoelasticity (linear)
- no fault reloading, no constraints on secular rates
- only horizontal velocities
- three layer model w/ homogenous lower crust & mantle

Hetland & Hager (2003)

CNSB - the GPS perspective



- contraction removed with postseismic models
- η_{LC} =5-50x10^{19} Pa-sec
- no constraints on η_M



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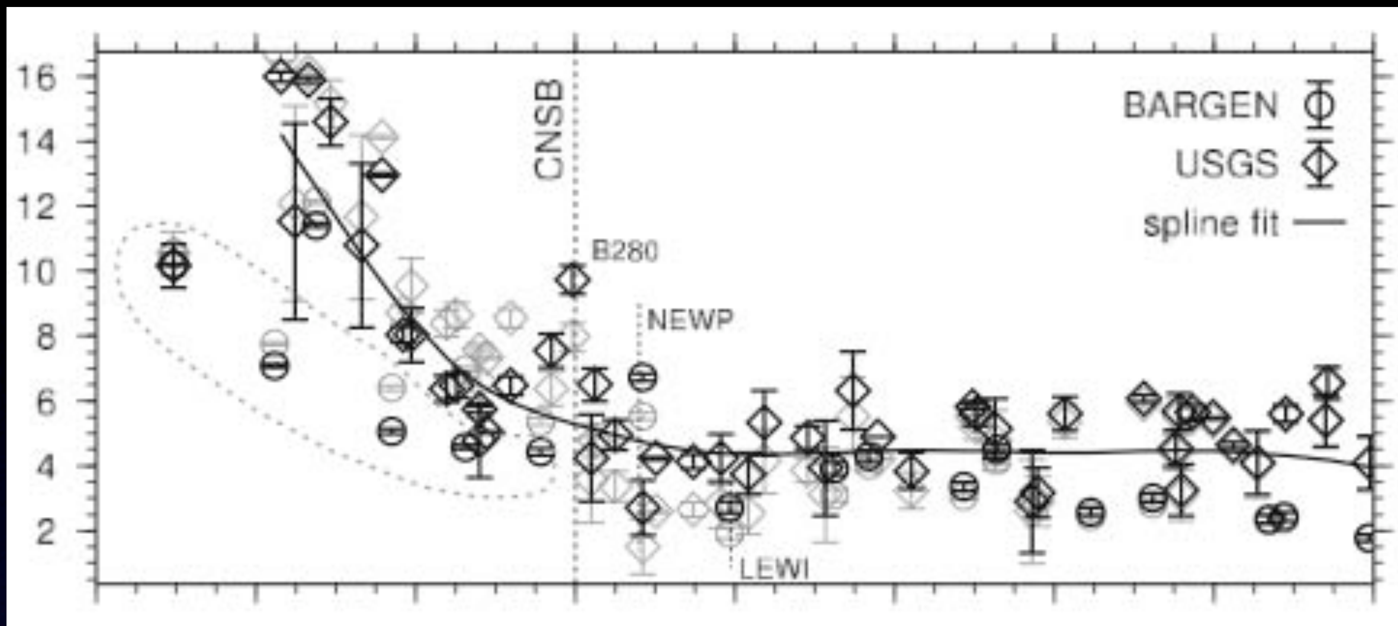

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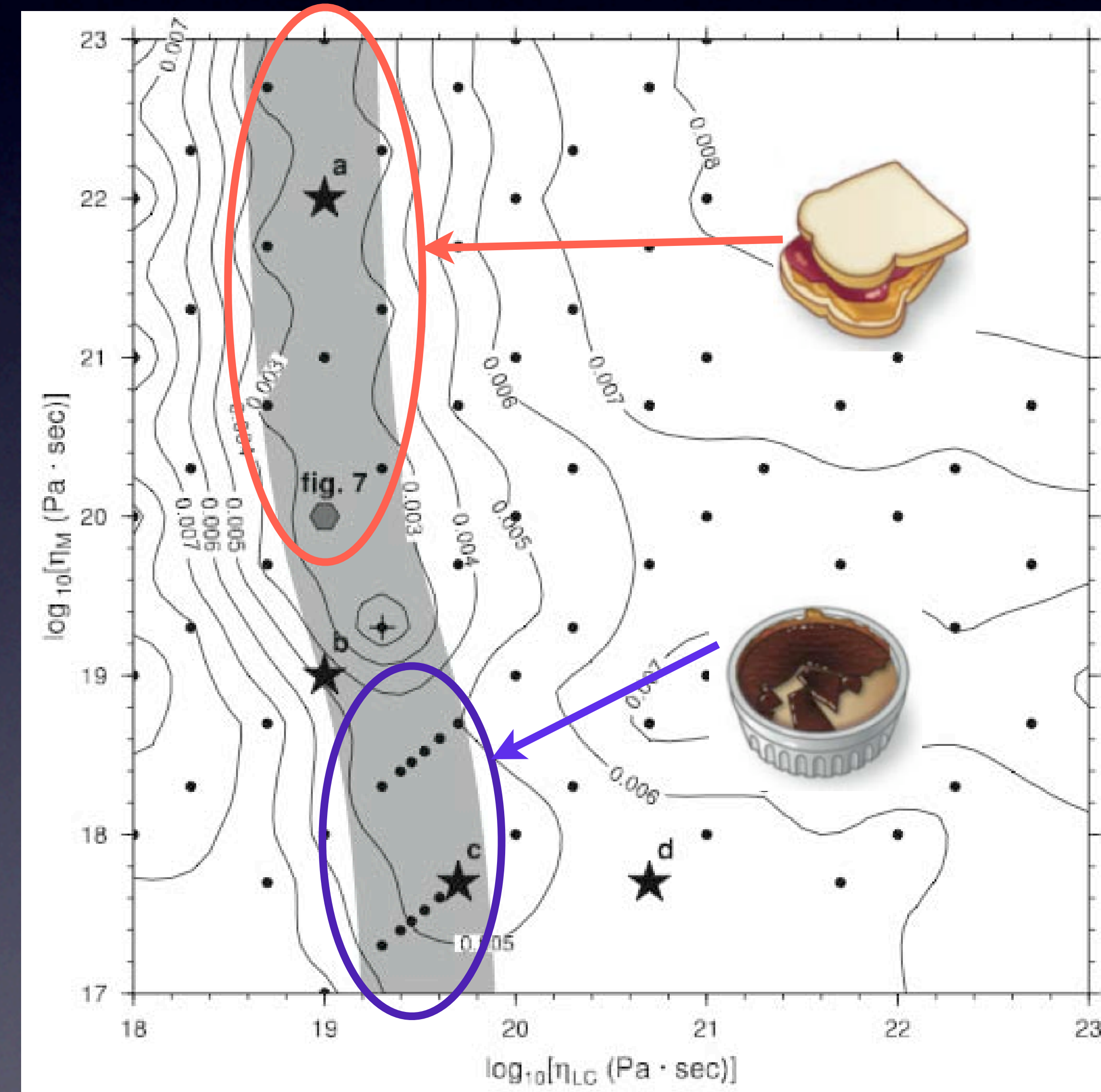
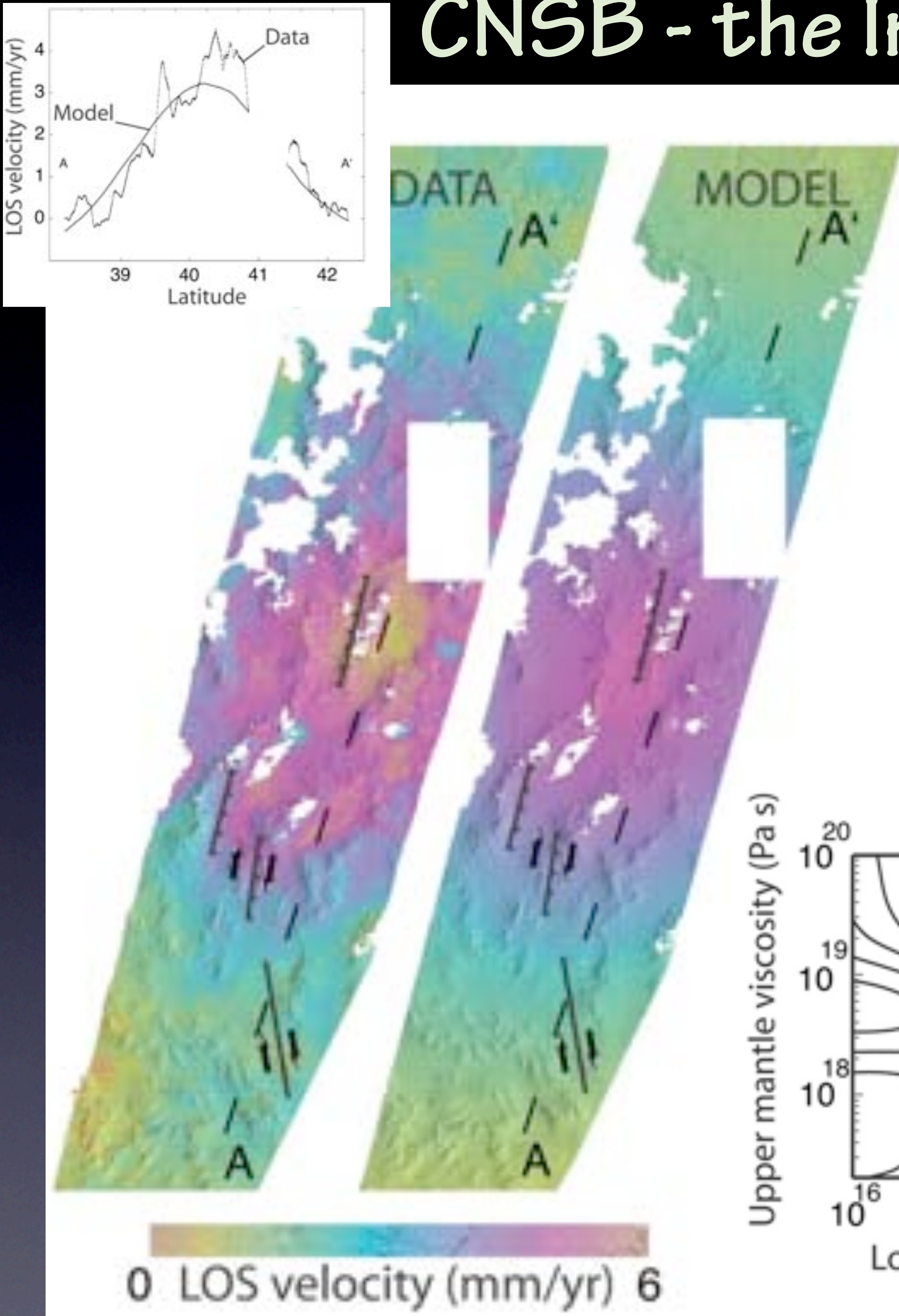
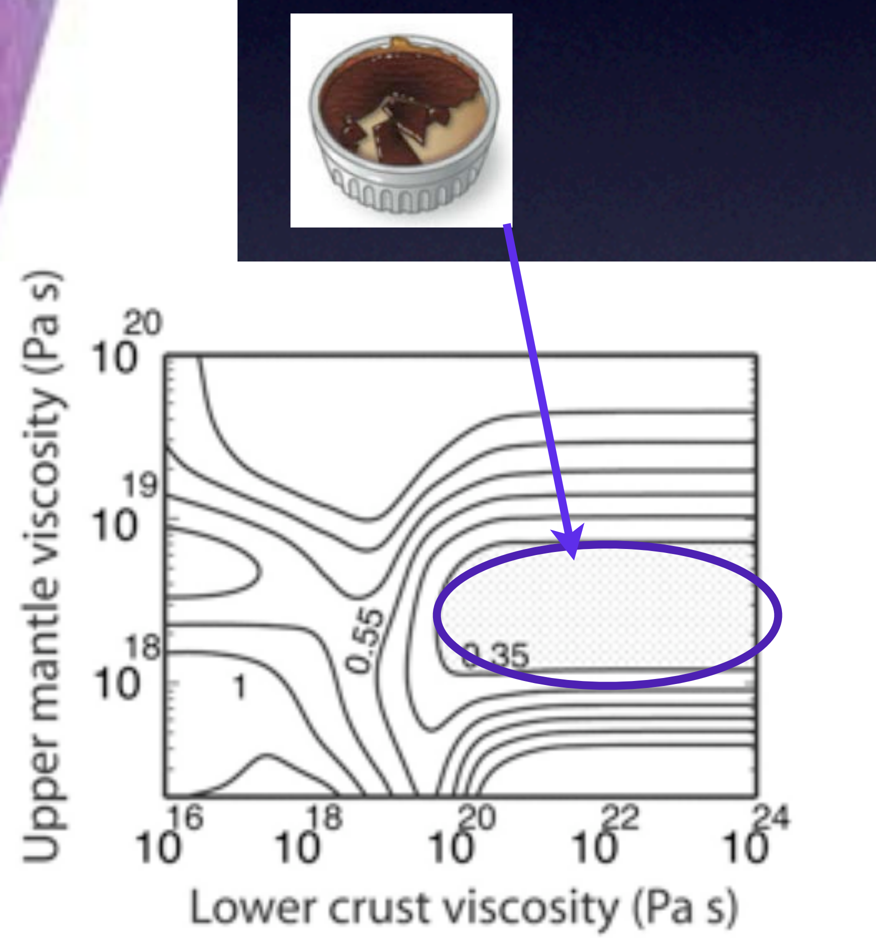


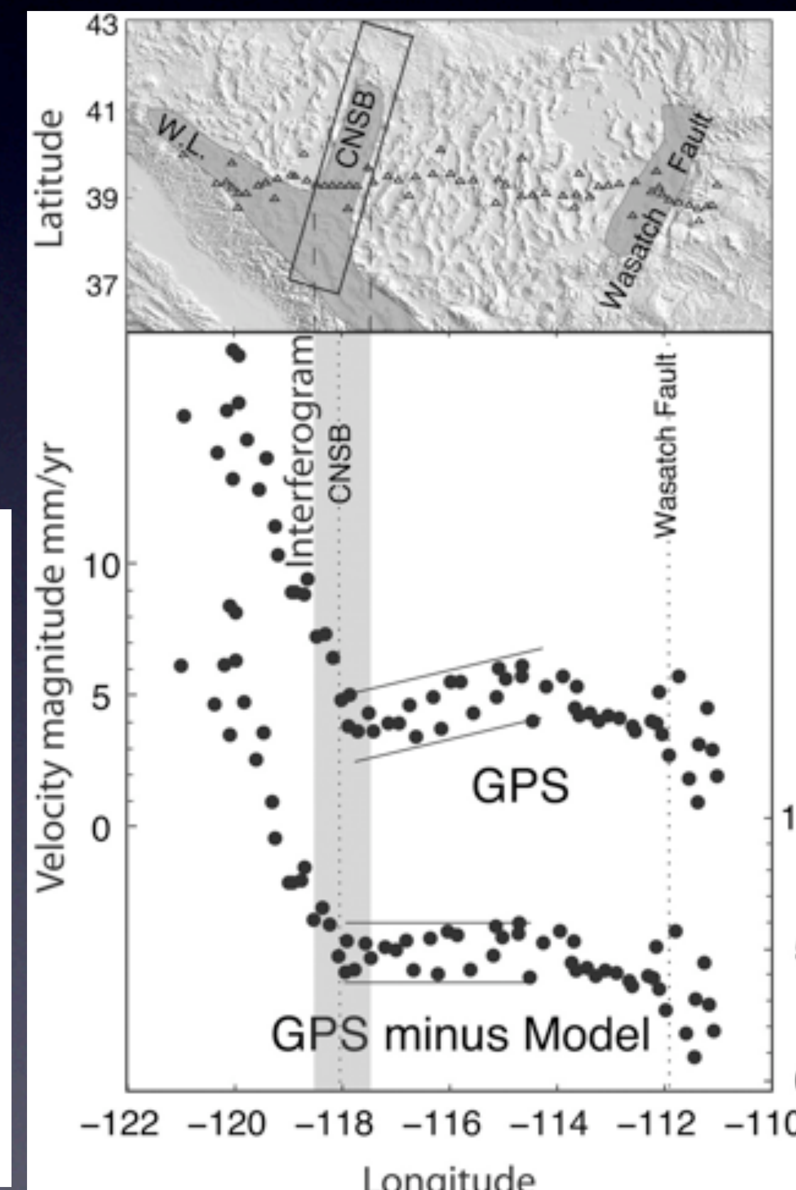
Hetland & Hager (2003)

CNSB - the InSAR perspective



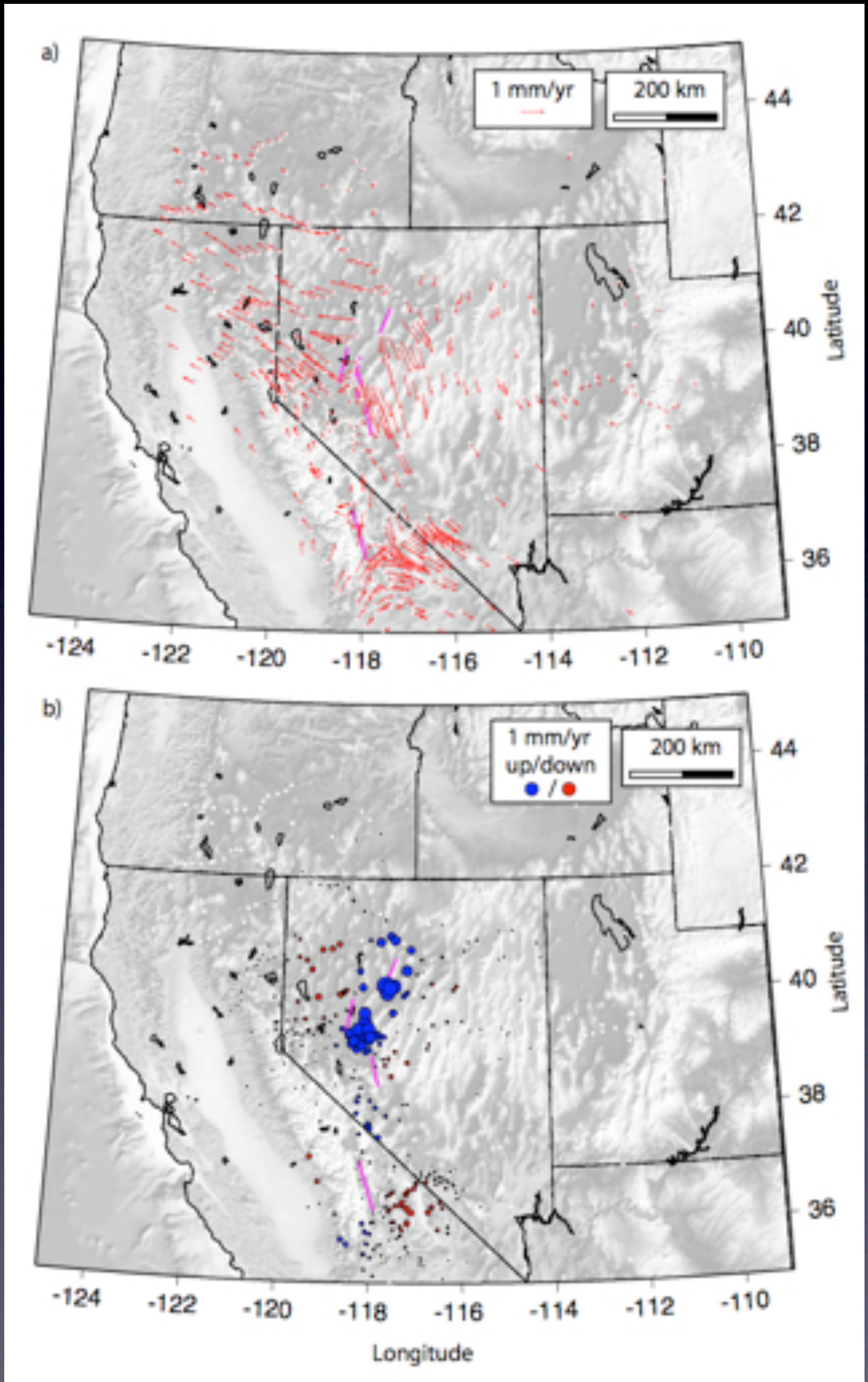
- η_{LC} >8-10x10^{19} Pa-sec
- η_M =1–5x10^{18} Pa-sec



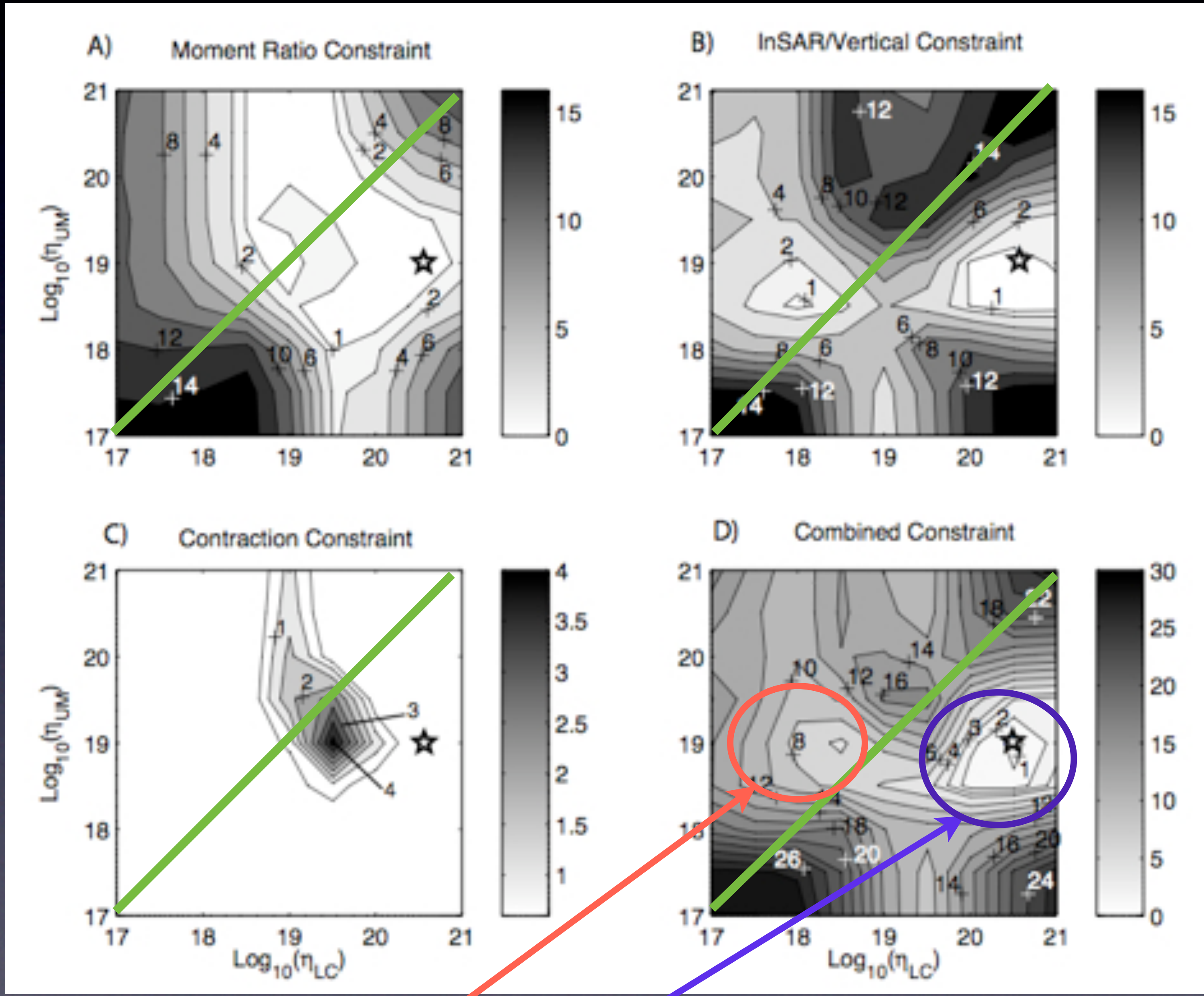


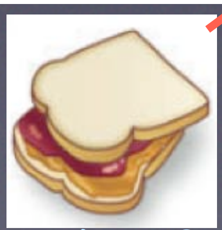
Gourmelen & Amelung (2005)

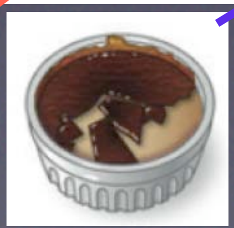
CNSB - the complete perspective



- $\eta_{LC} = 1\text{-}10 \times 10^{20}$ Pa-sec
- $\eta_{M} = 2\text{-}20 \times 10^{18}$ Pa-sec

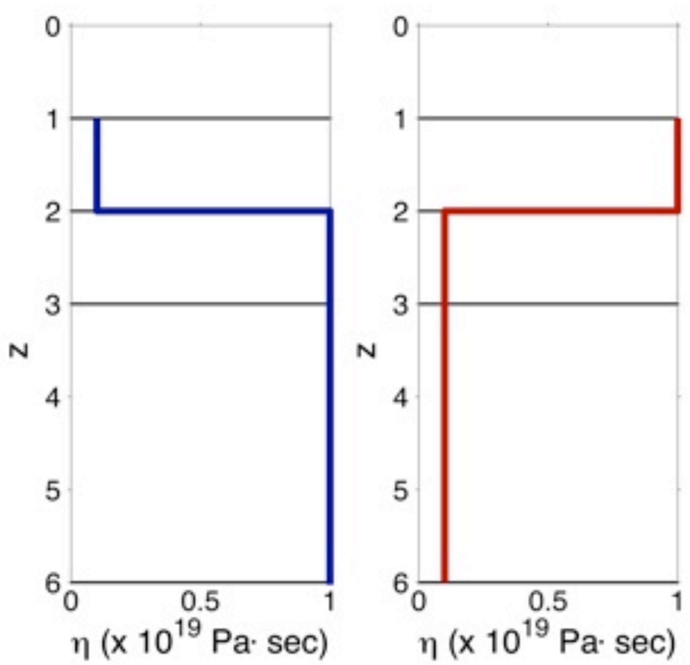


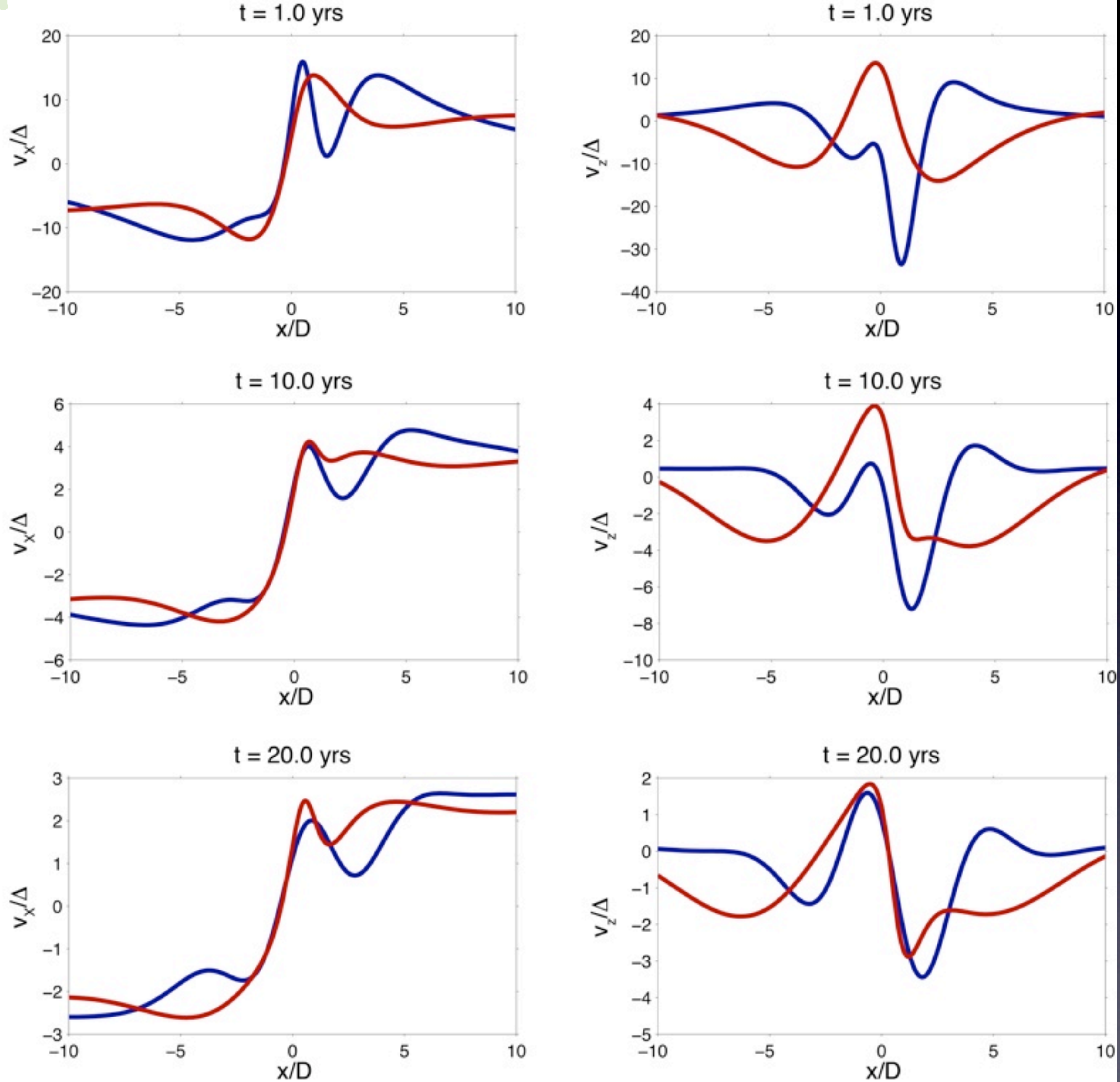


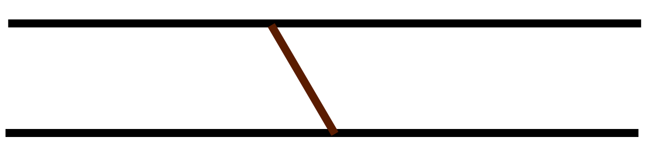


Hammond et al. (2009)

postseismic models I



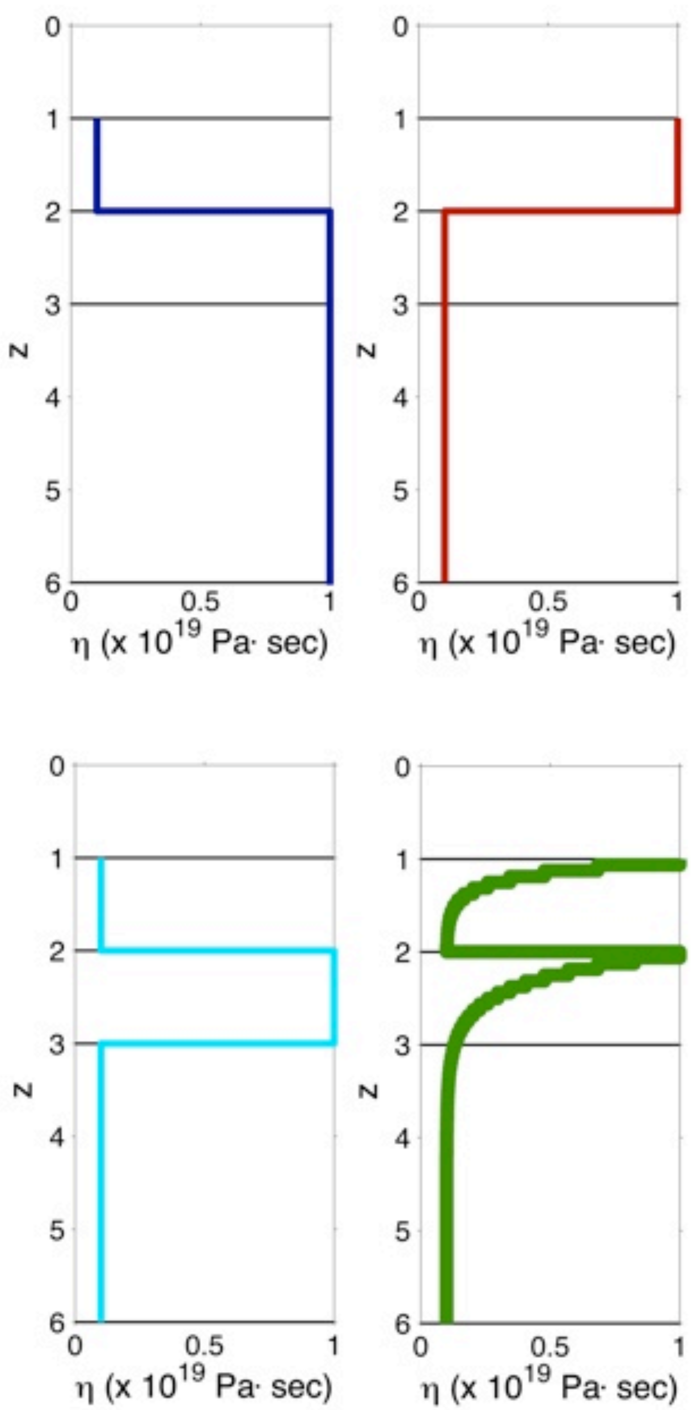


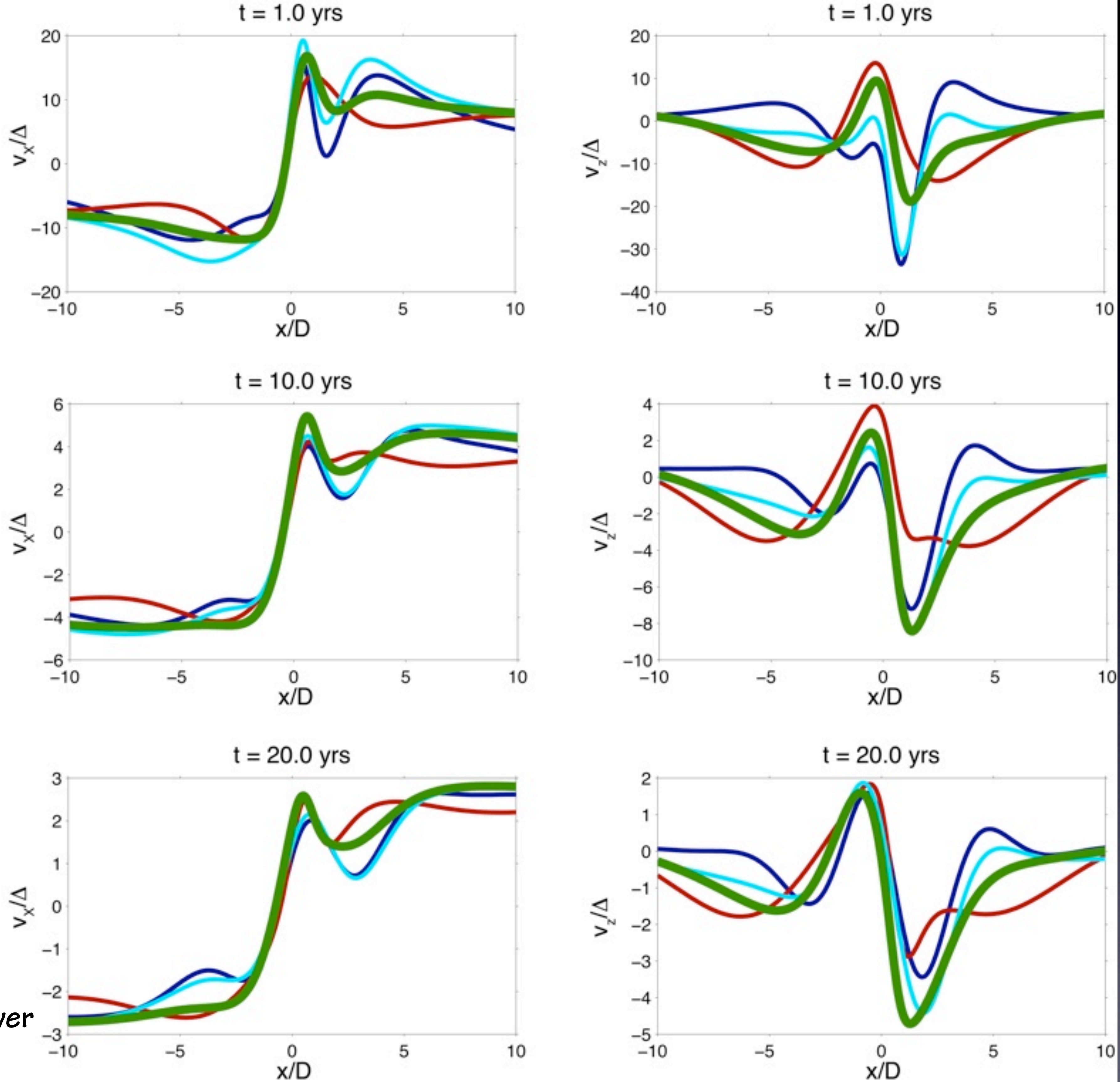


Maxwell viscoelastic

NOTE: ∞ length fault

postseismic models II

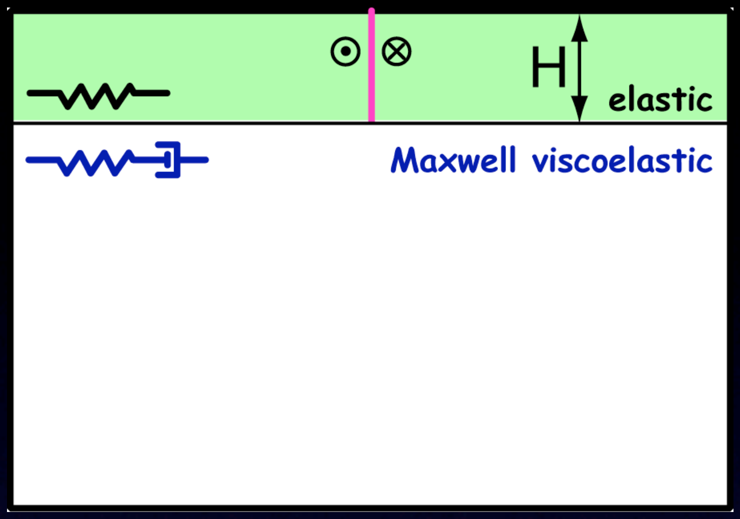




NOTE: ∞ length fault

NOTE: viscosities are <10x lower than proposed for the CNSB

horizontal interseismic velocities



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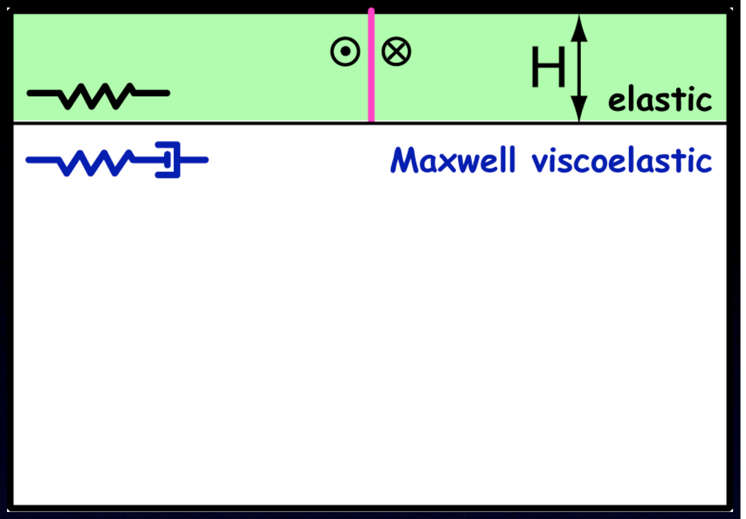
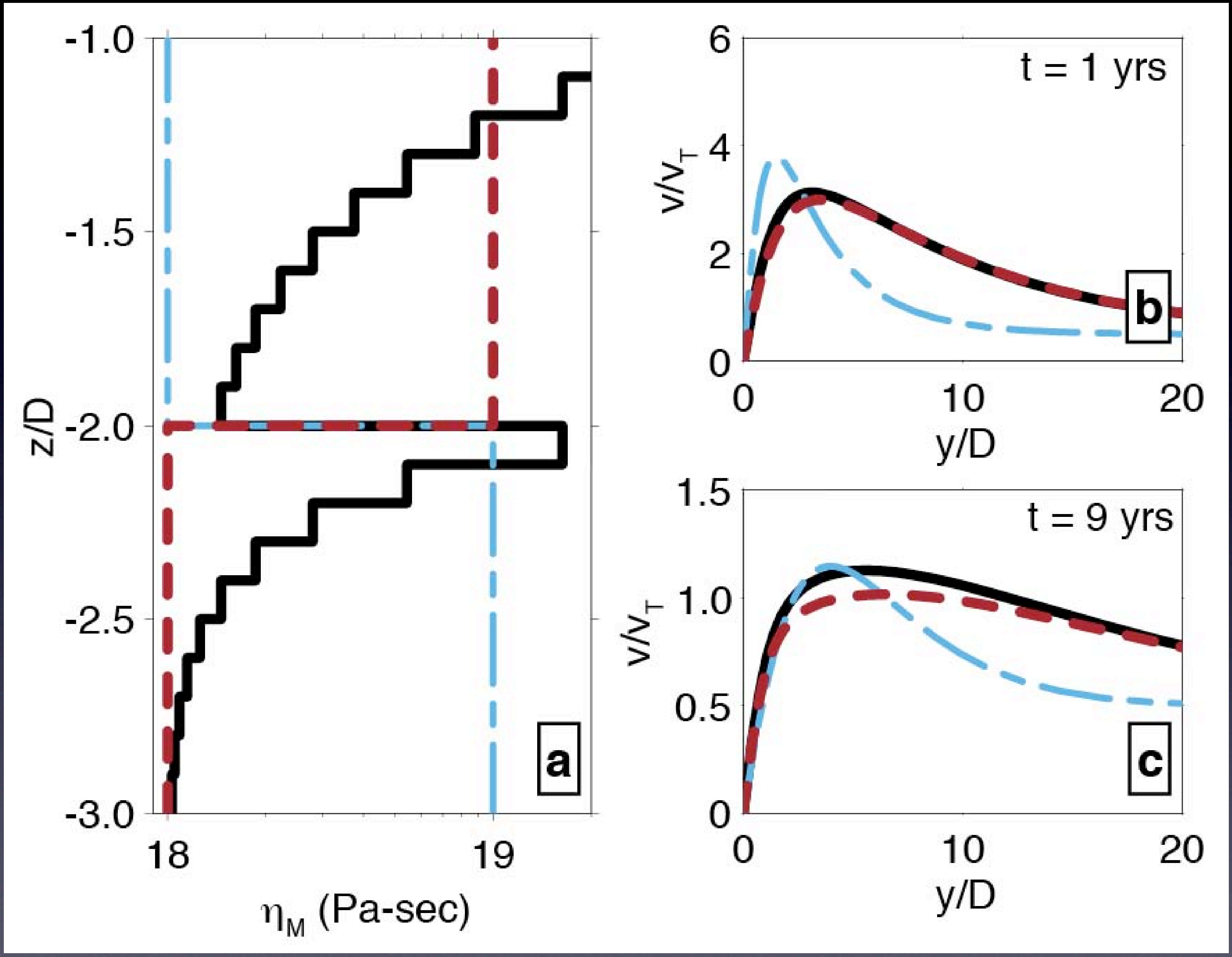
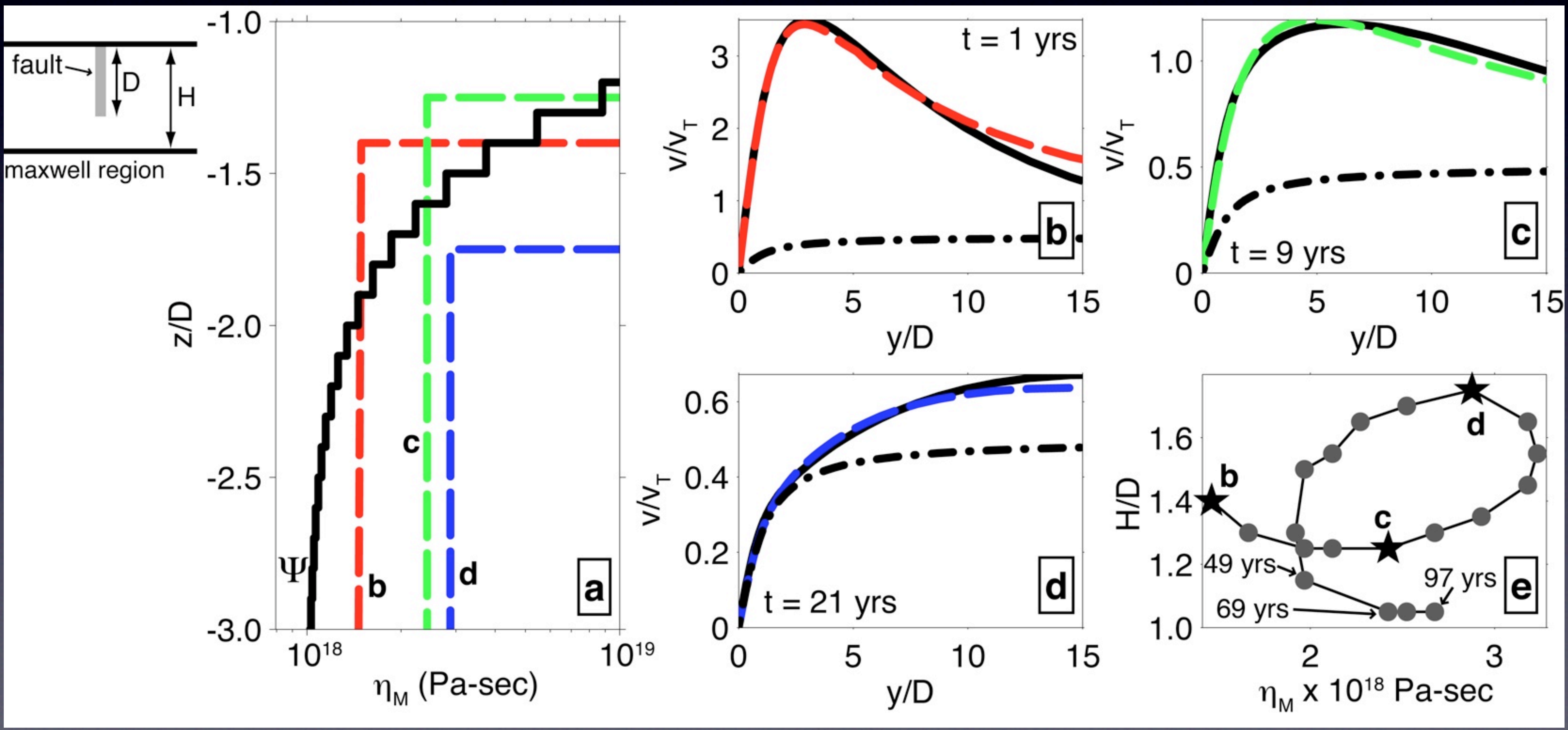


- lower crust "appears" strong
- mantle "appears" weak

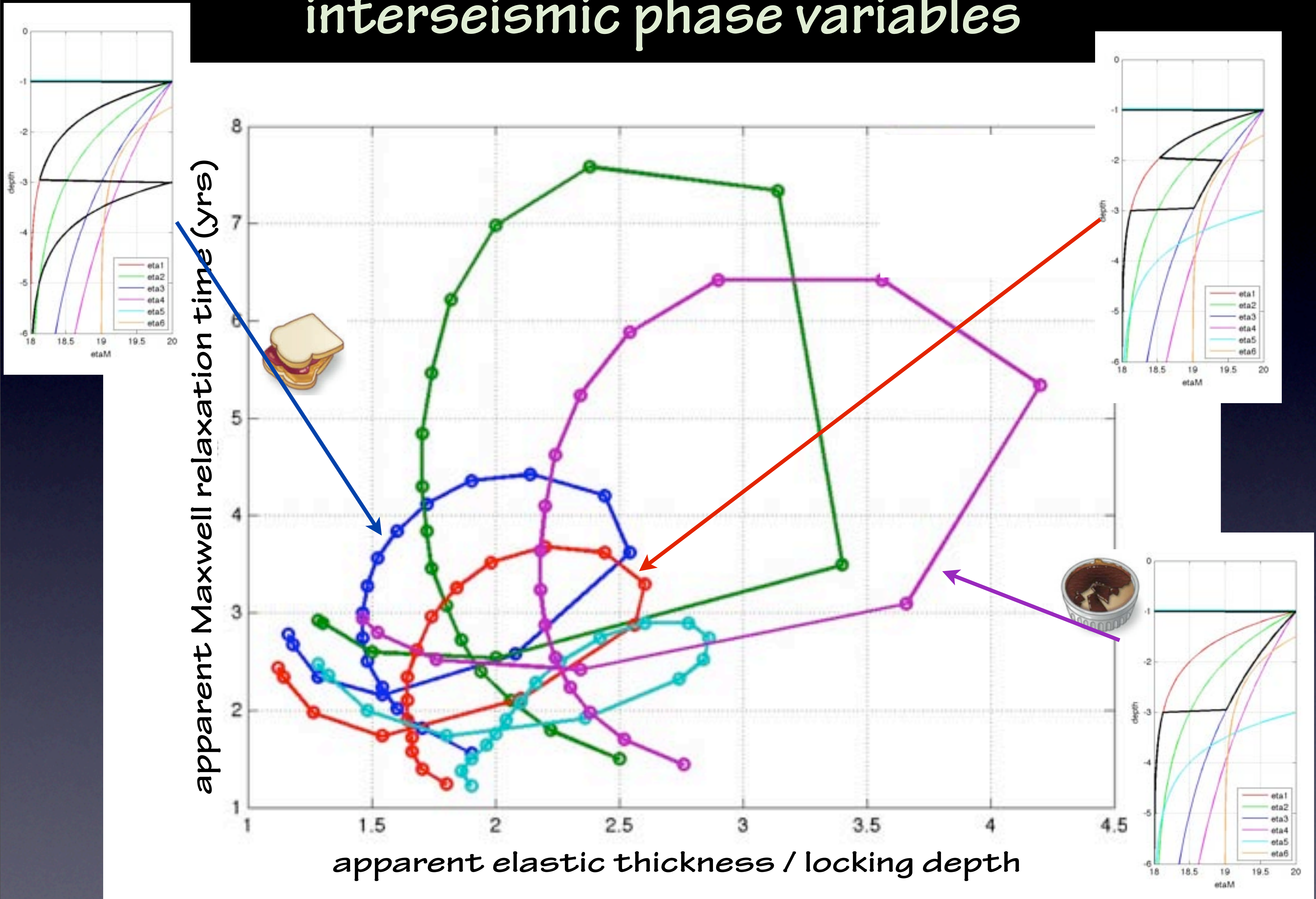


sensitivities throughout the interseismic

surface deformation "sees":
postseismic – lower viscosities & elastic layer seems thicker
early interseismic – larger viscosities & thickening effective elastic layer
late interseismic – viscosity ≈ "average" & actual elastic layer

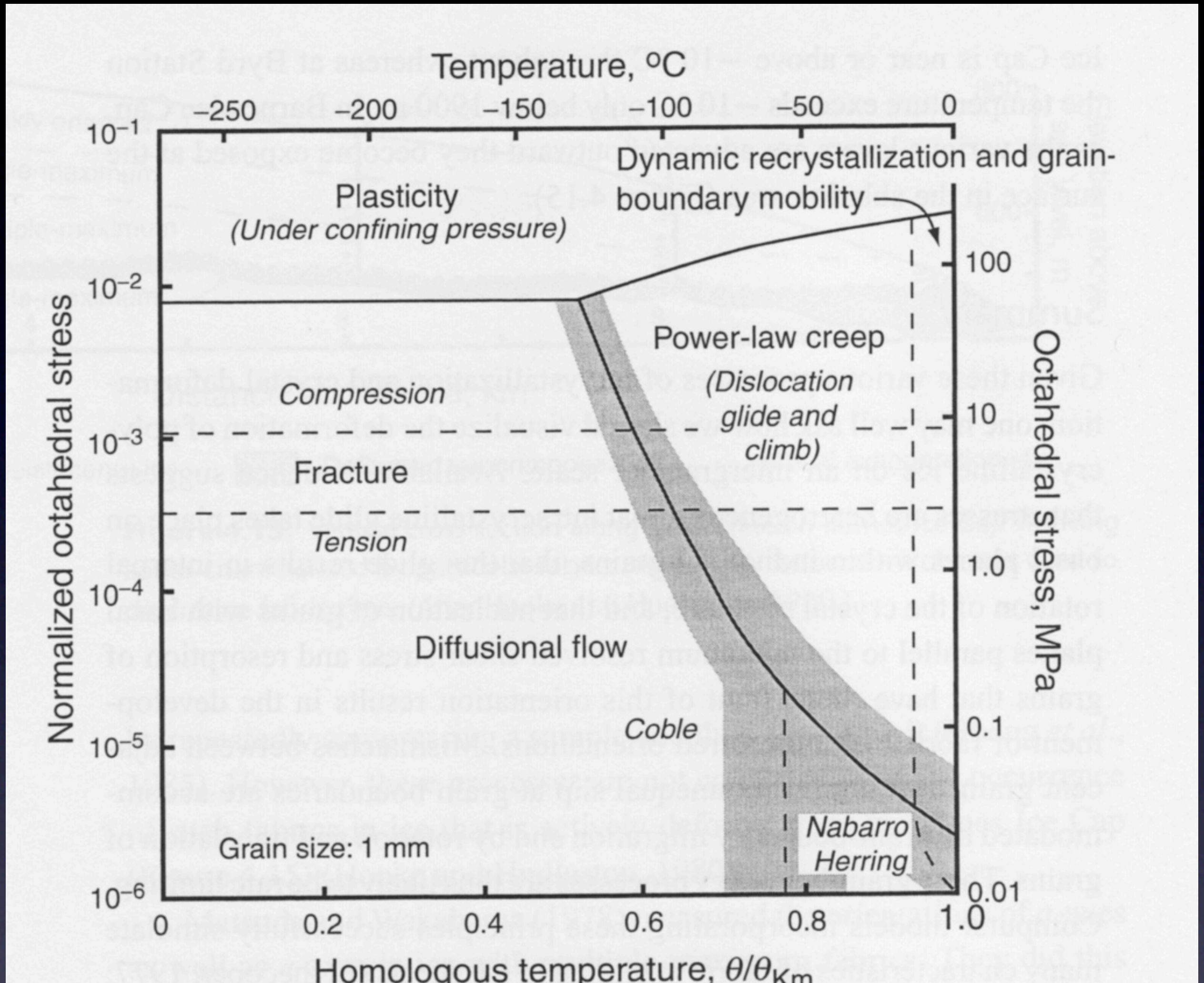


interseismic phase variables



non-Maxwellian rheologies

NOTE: deformation map for ice!, but qualitatively similar for rock



Hooke, 2005, Principals of Glacier Mechanics

diffusional flow (Maxwell viscosity)

$$\dot{\varepsilon} \propto \tau$$

$$\eta = \tau / \dot{\varepsilon}$$

dislocation creep (non-linear viscosity)

$$\dot{\varepsilon} \propto \tau^{n}$$

$$\eta_{\mathrm{eff}} \propto \tau^{1-n}$$

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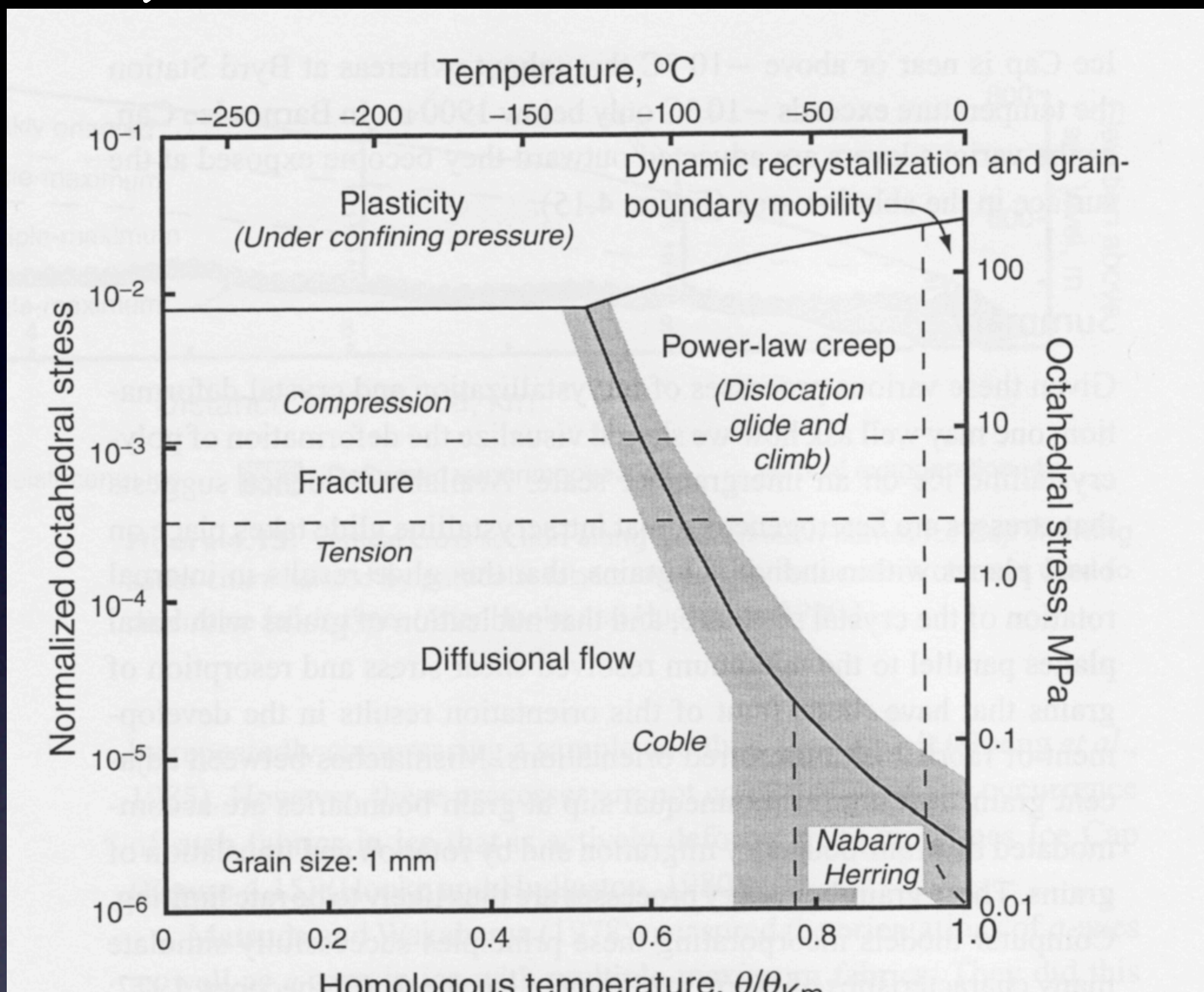

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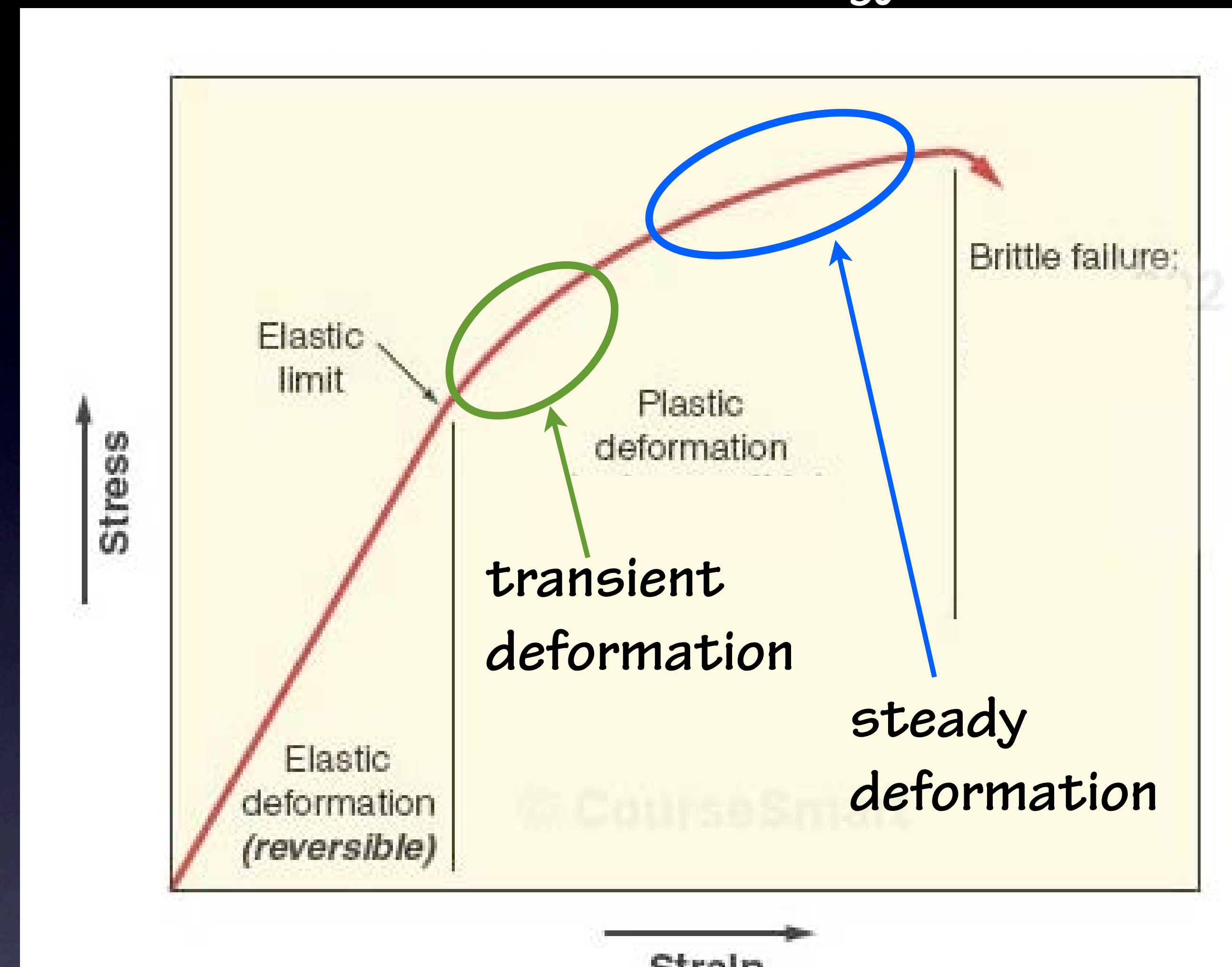
intro textbook view of rock rheology:



Hyndman & Hyndman

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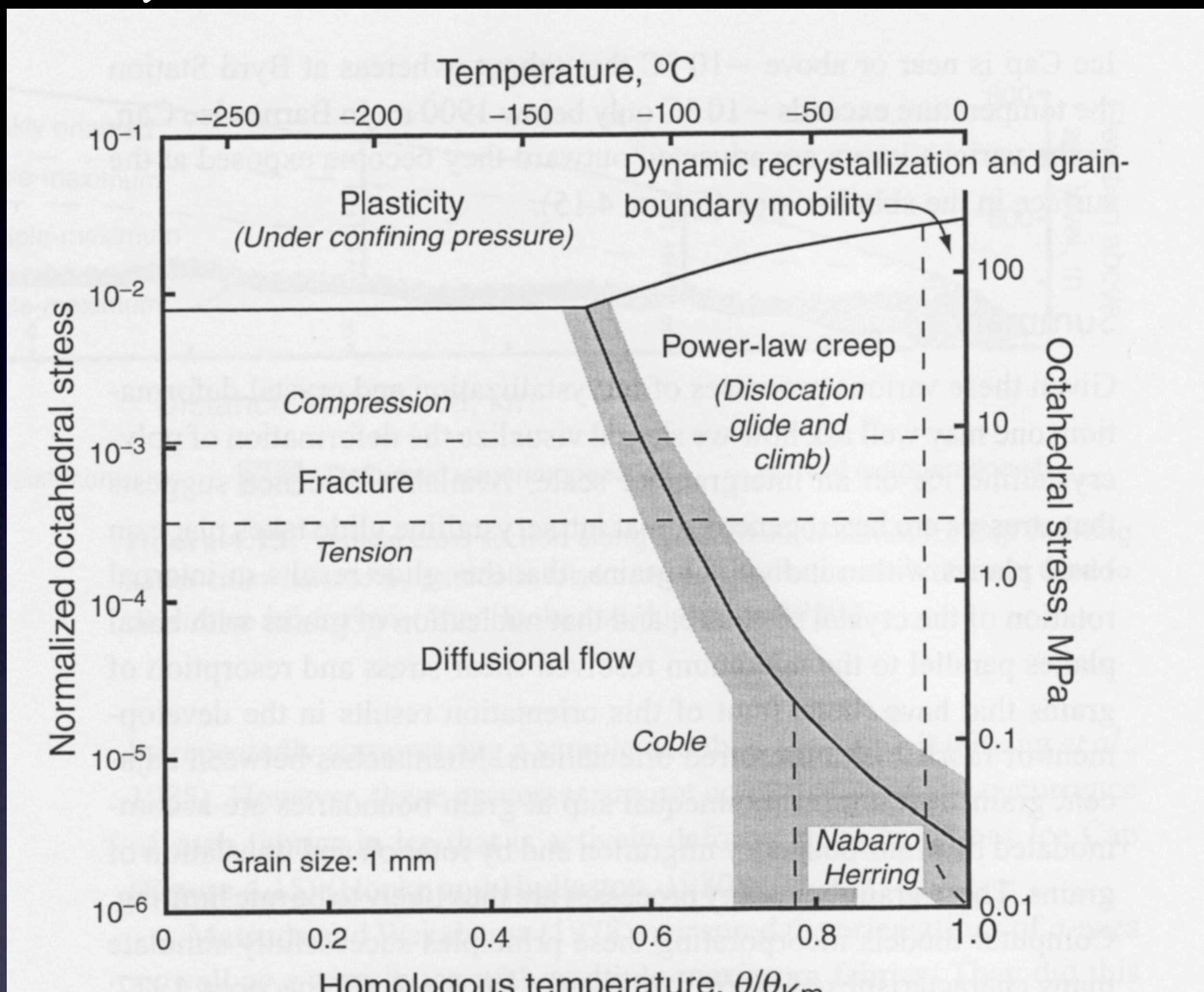

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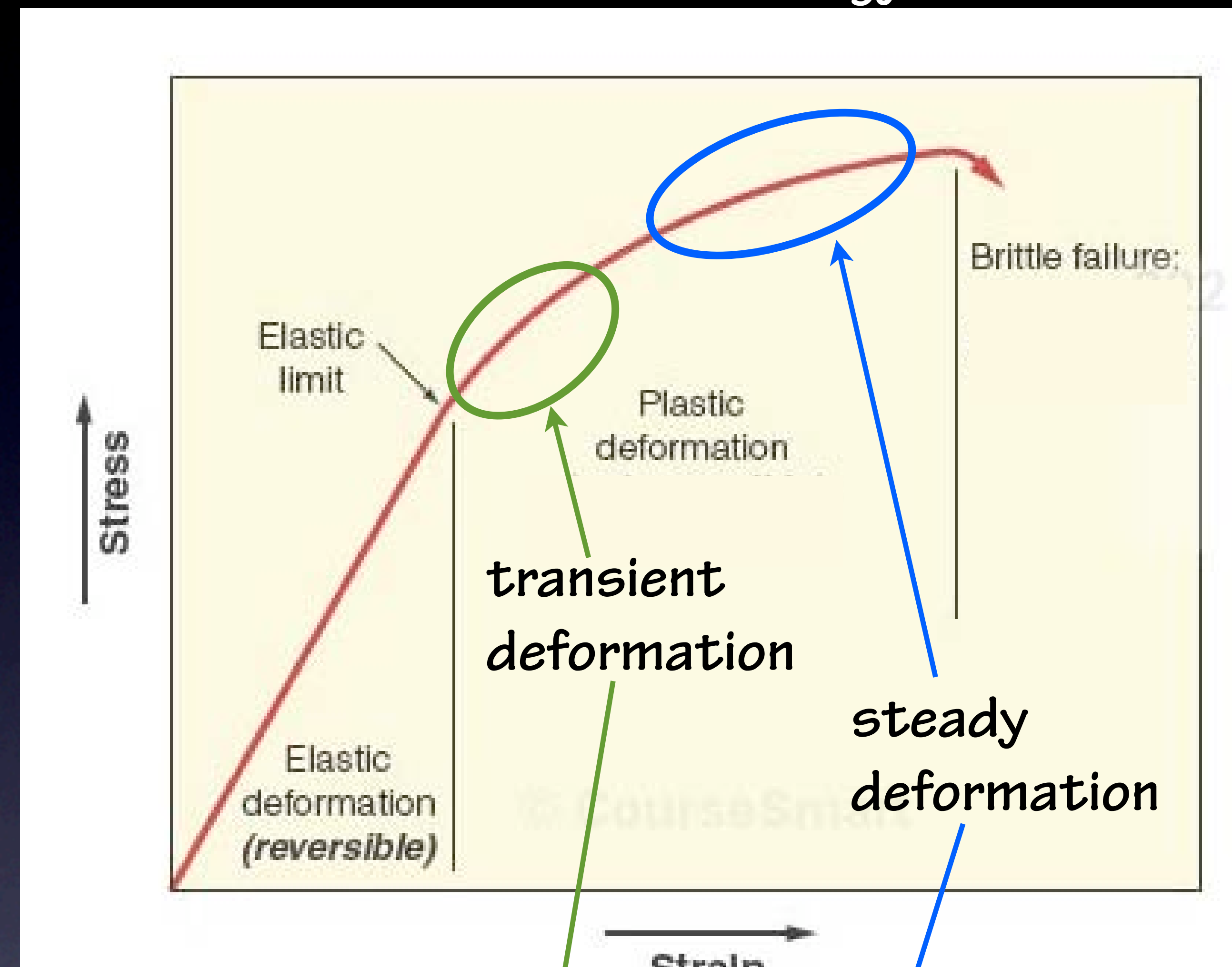

Hyndman & Hyndman

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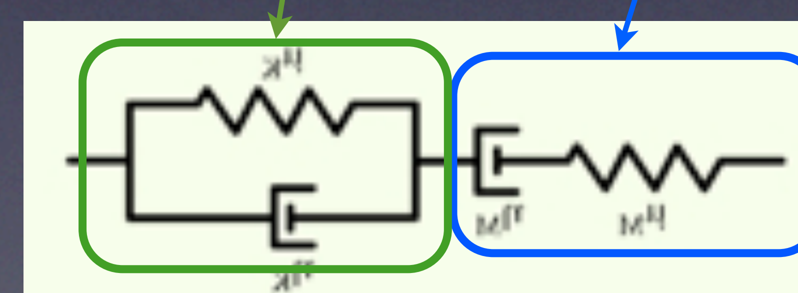
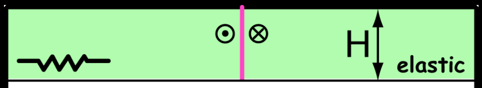
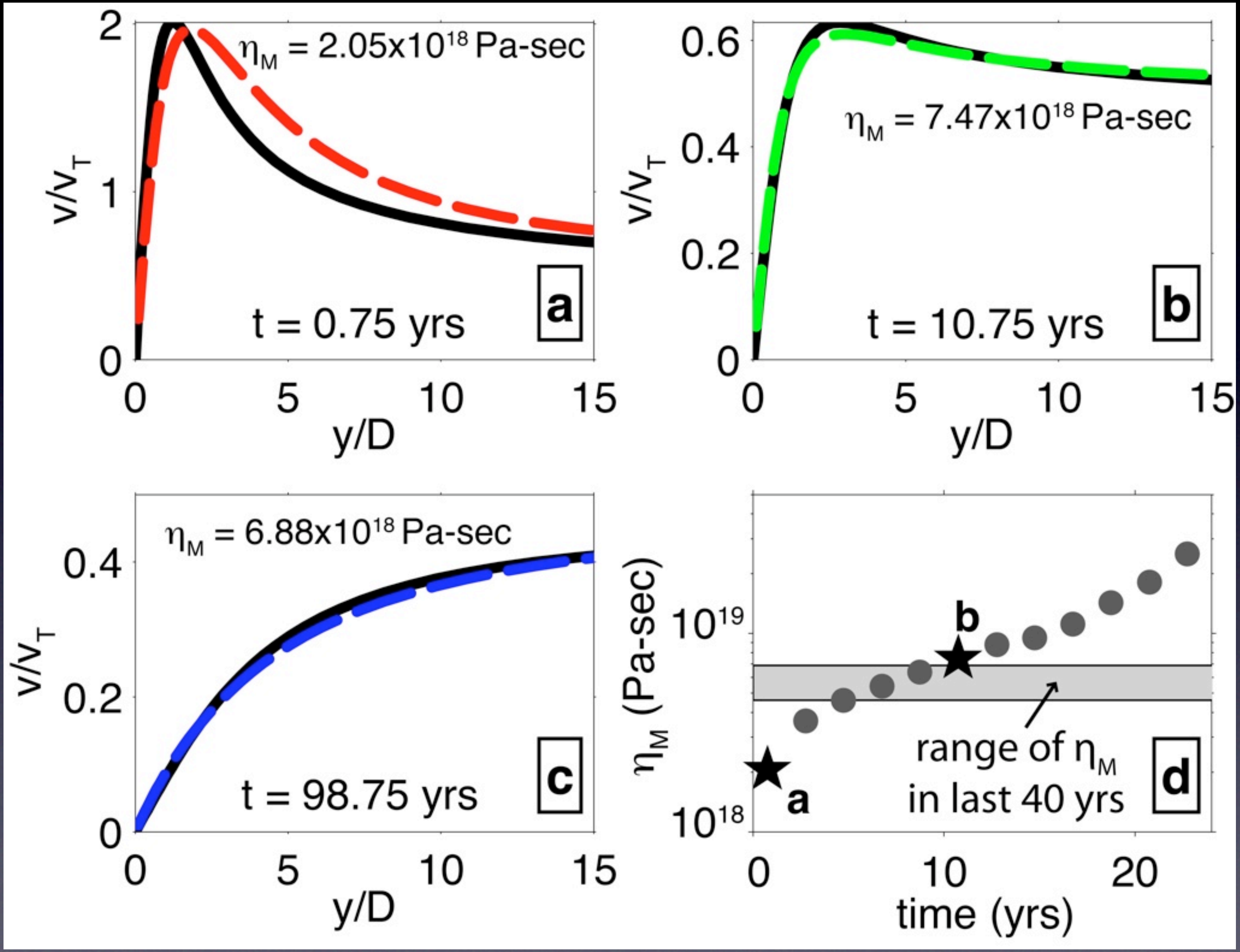


Burgers model of viscoelasticity

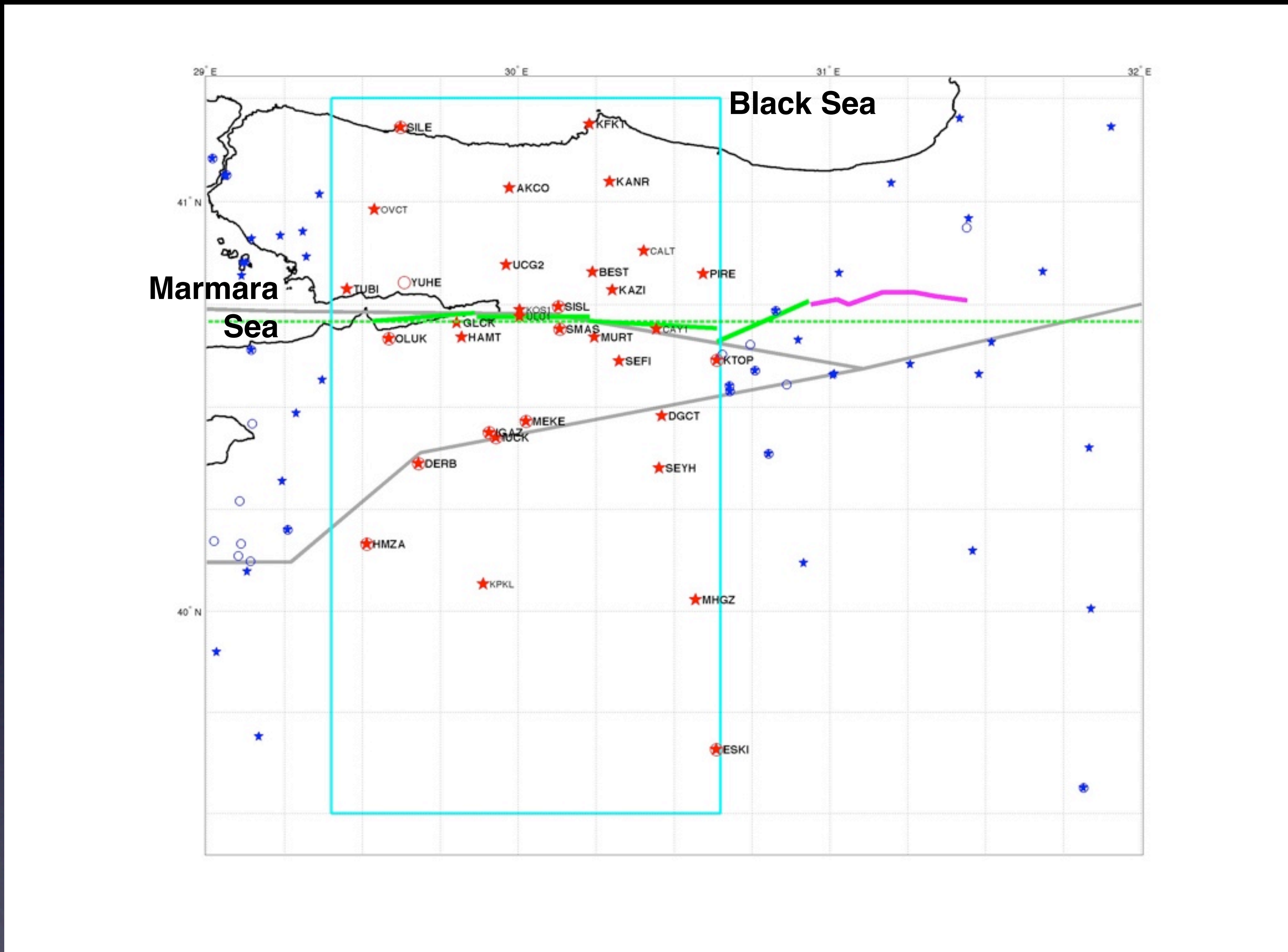
Maxwell vs. non-linear viscoelasticity



Maxwell VE
-or-
power-law creep



1999 (M7.4) Izmit eathquake



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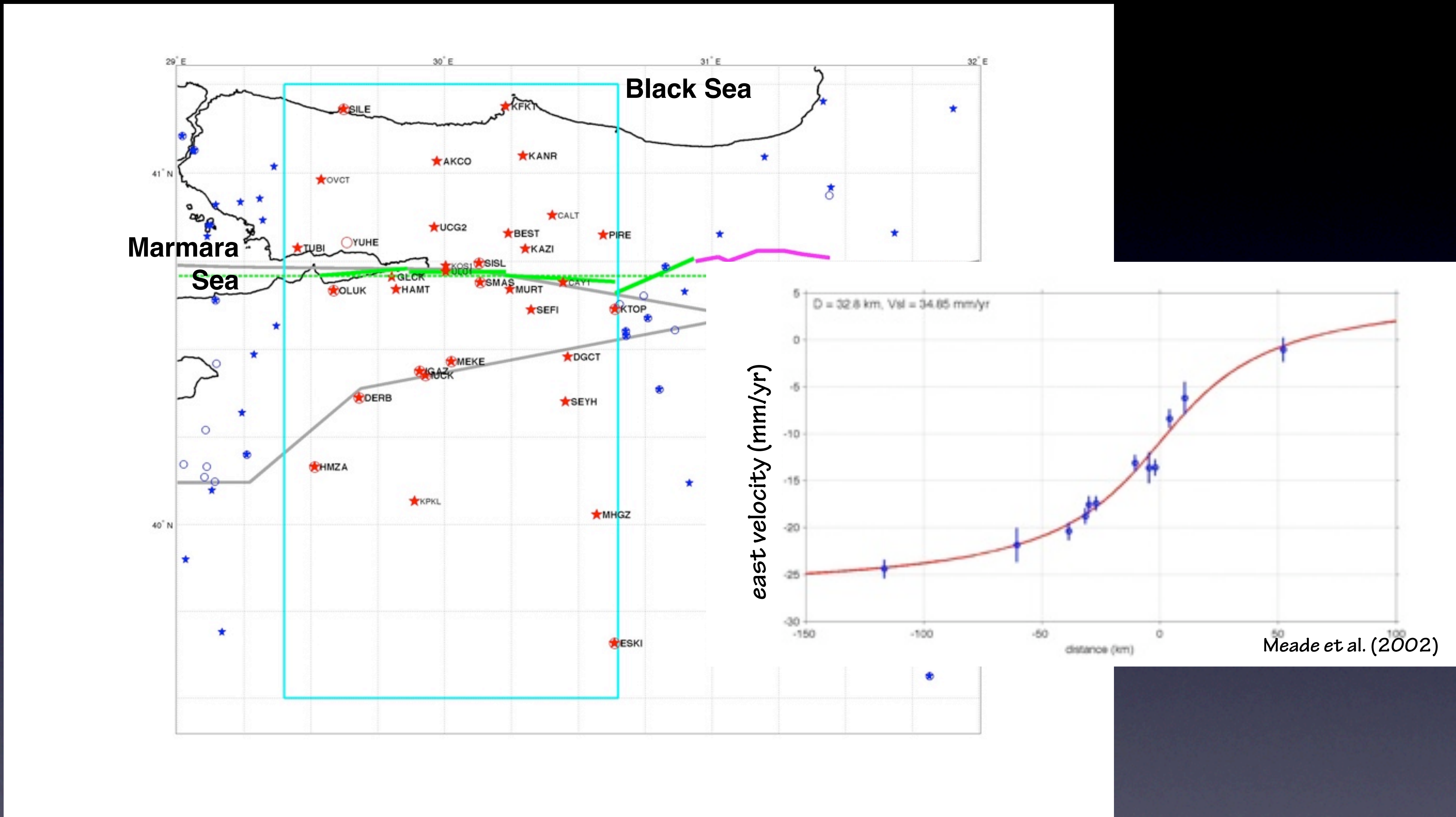

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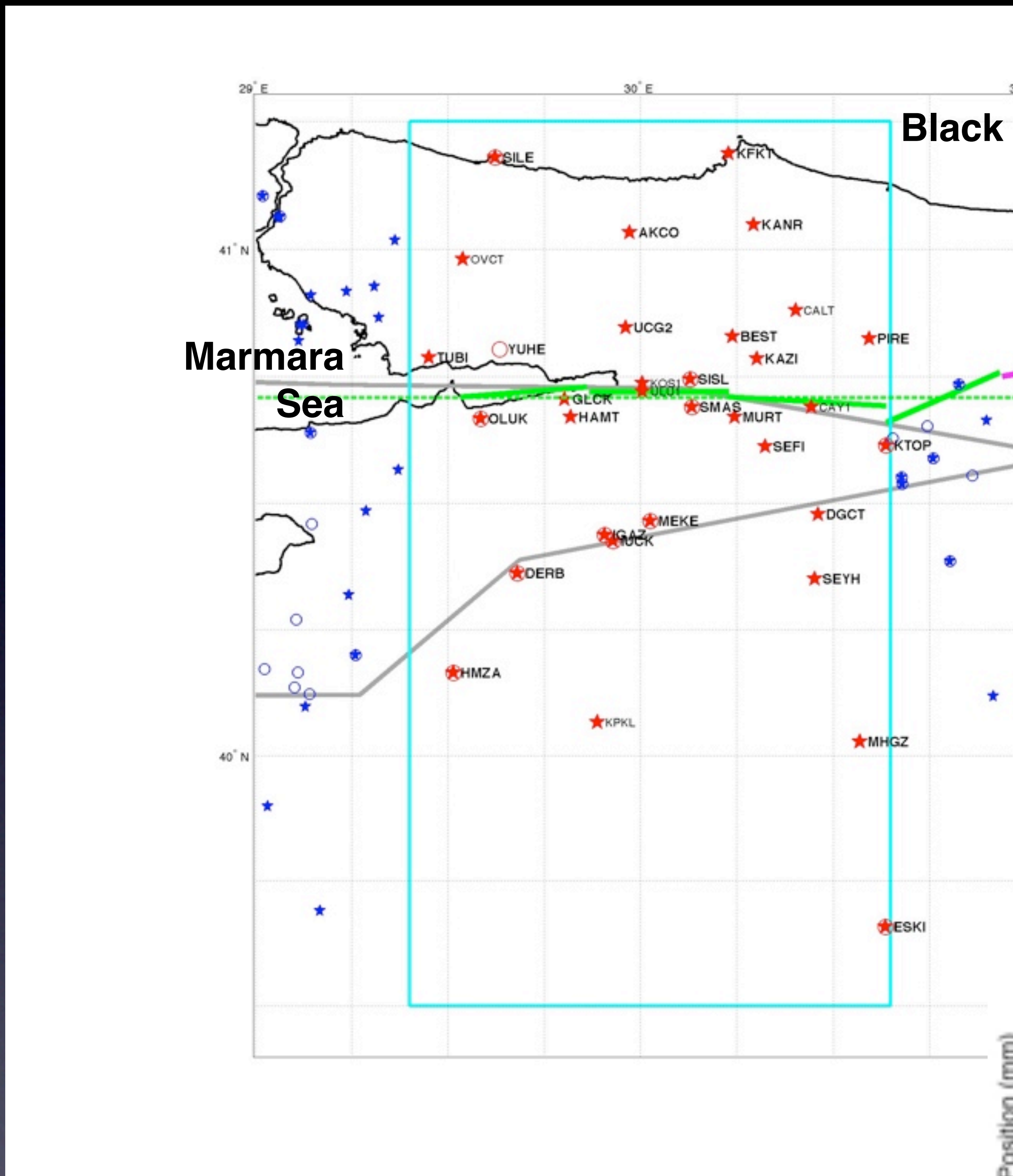
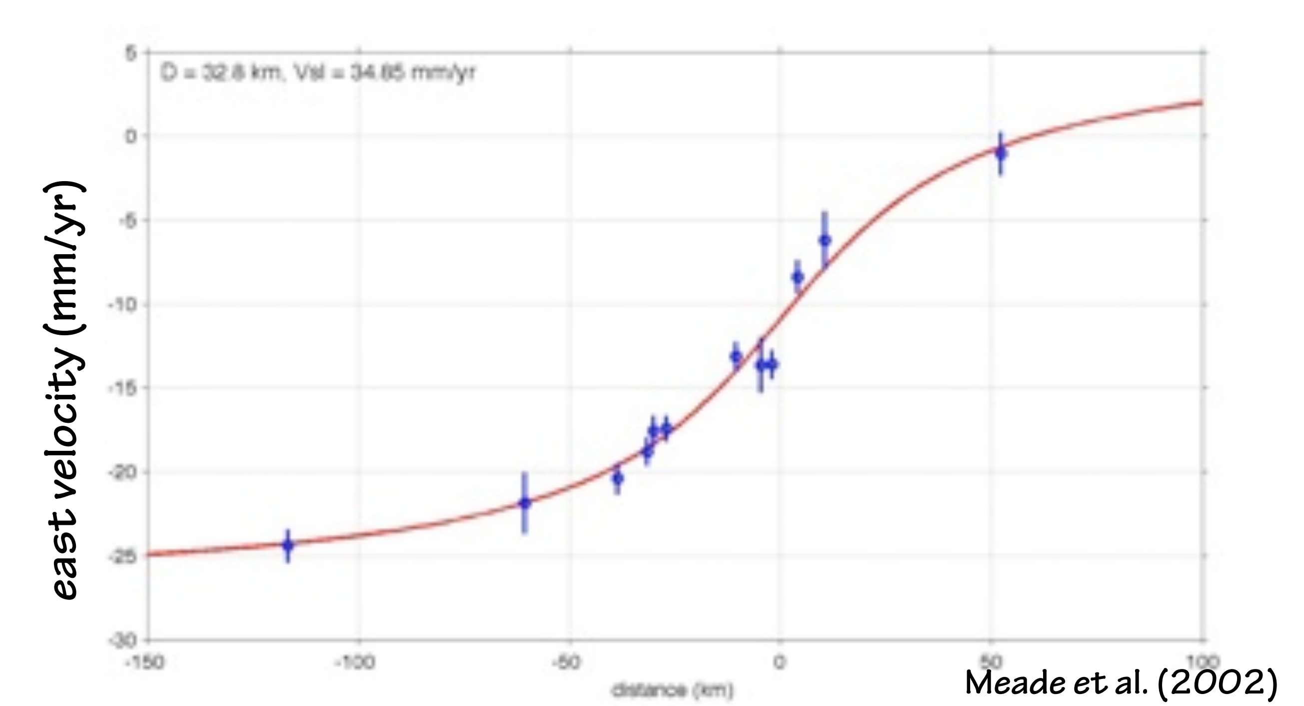
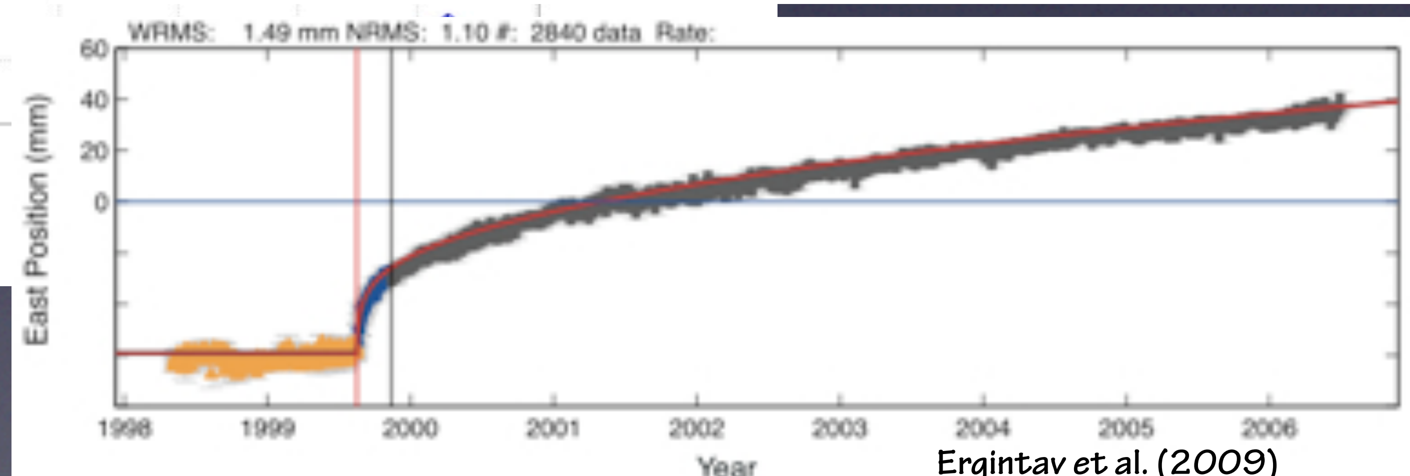


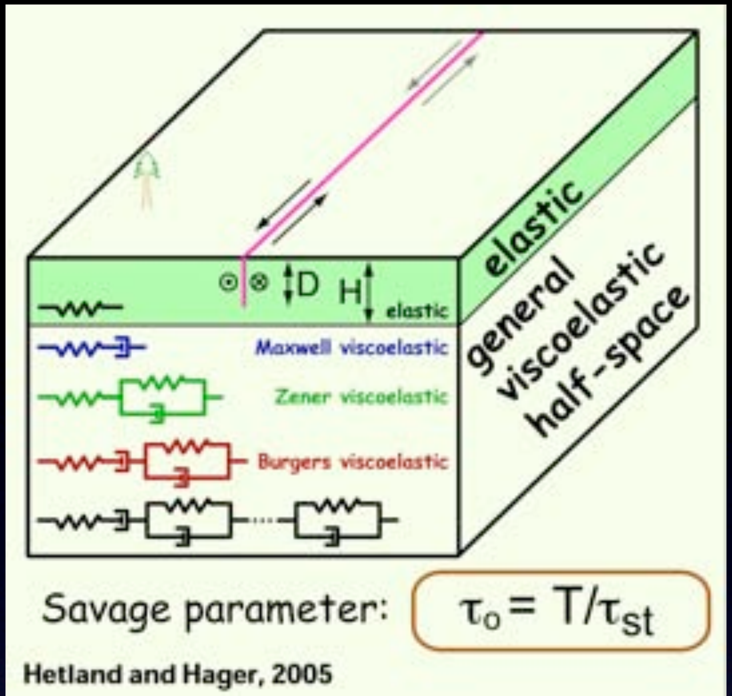


Meade et al. (2002)



Ergintav et al. (2009)

NAF perspective on lithosphere rheology



earliest phase of postseismic ignored

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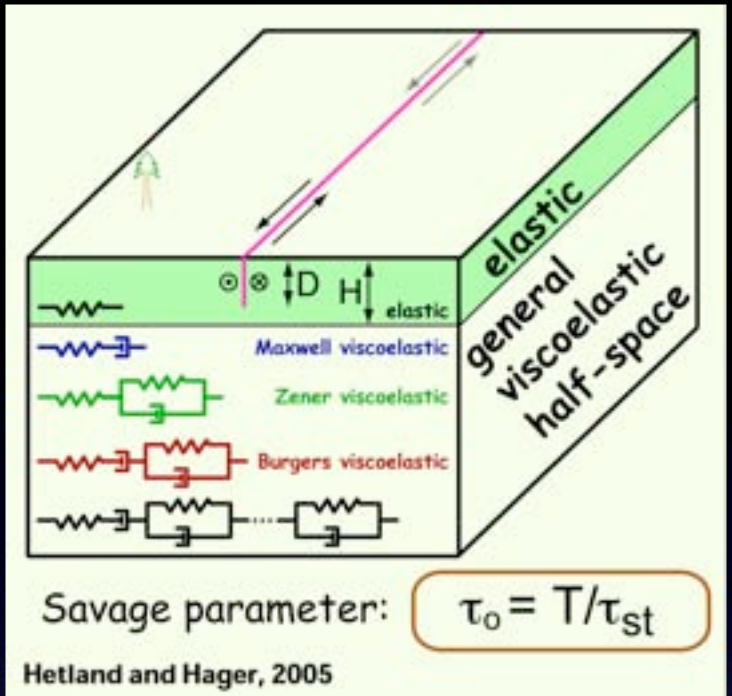
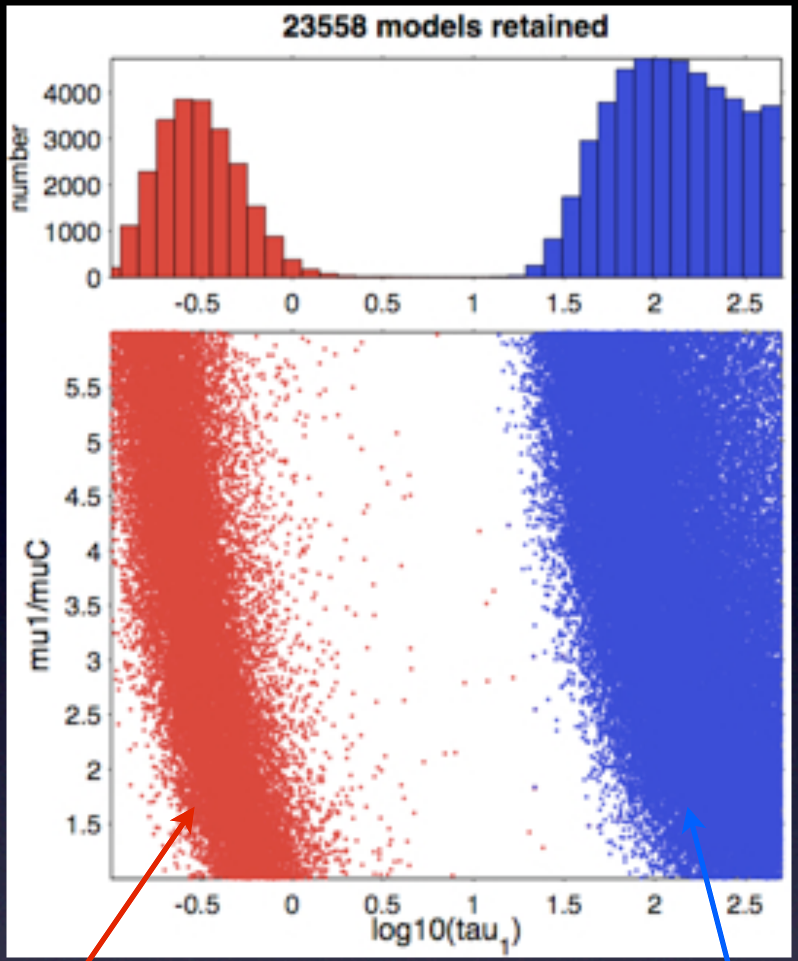


Maxwell VE



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low viscosities describe postseismic transients

high viscosities describe steady interseismic

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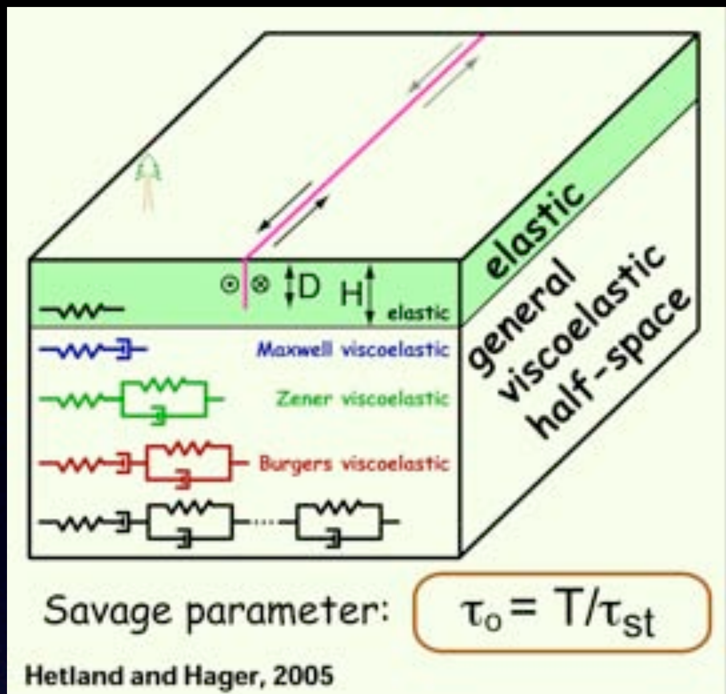

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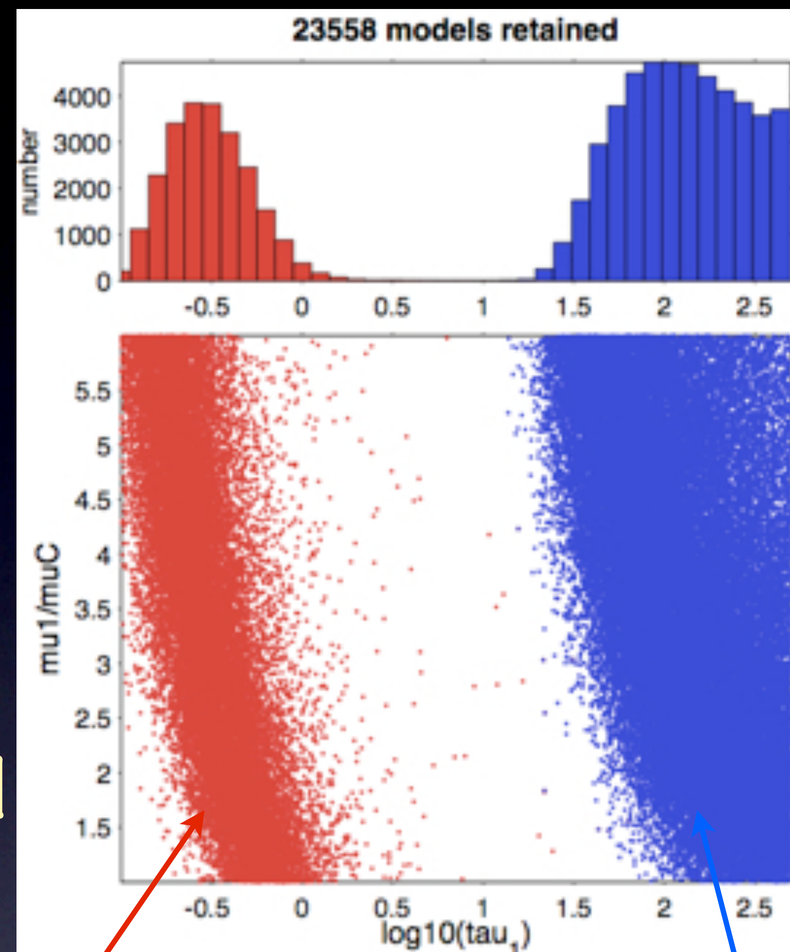
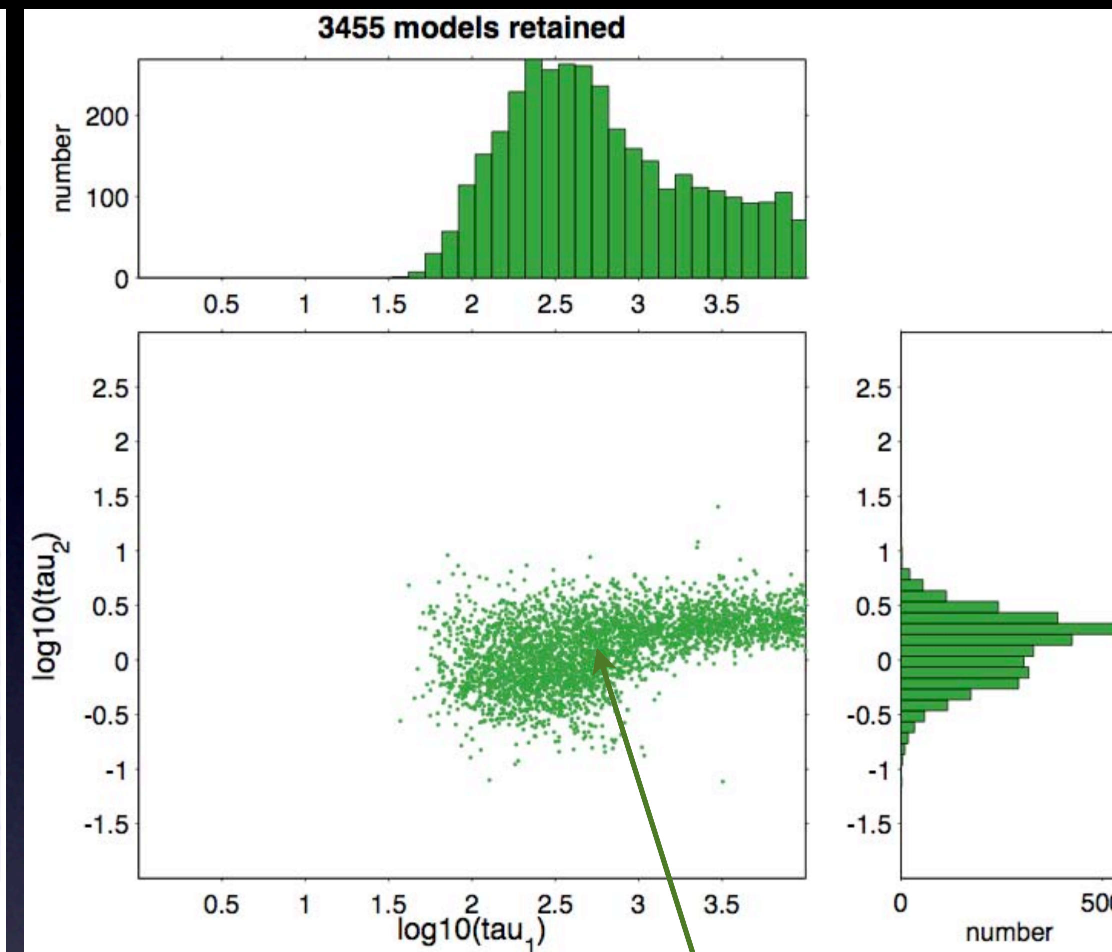


Burgers VE



earliest phase of postseismic ignored

low viscosities describe postseismic transients

high viscosities describe steady interseismic

transient + steady viscosity described both postseismic & transient in common model

τ_M > 100 years

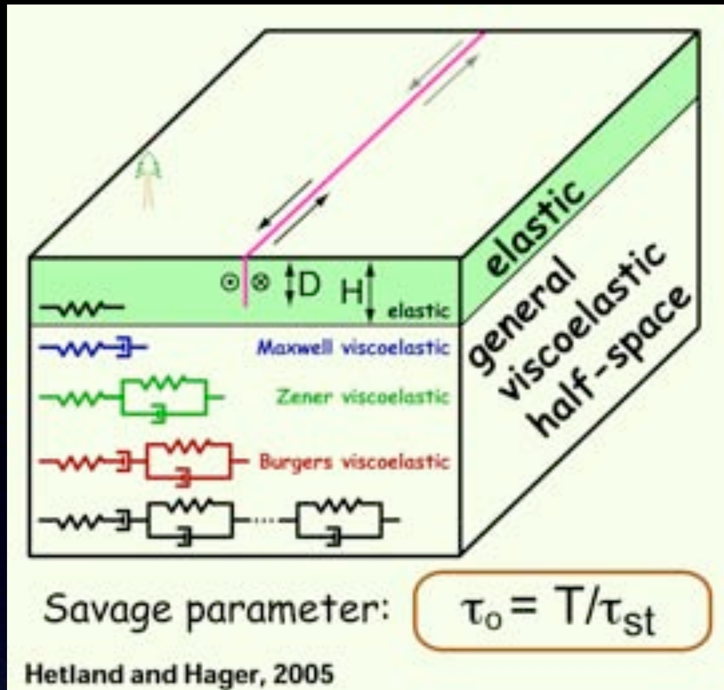
$\tau_K \approx$ 1–10 years

$\mu_M = \mu_K$ = 50 GPa

⇨ $\eta_M > 1\times10^{20}$ Pa·sec

⇨ $\eta_M \approx 1\text{–}10\times10^{18}$ Pa·sec

NAF perspective on lithosphere rheology



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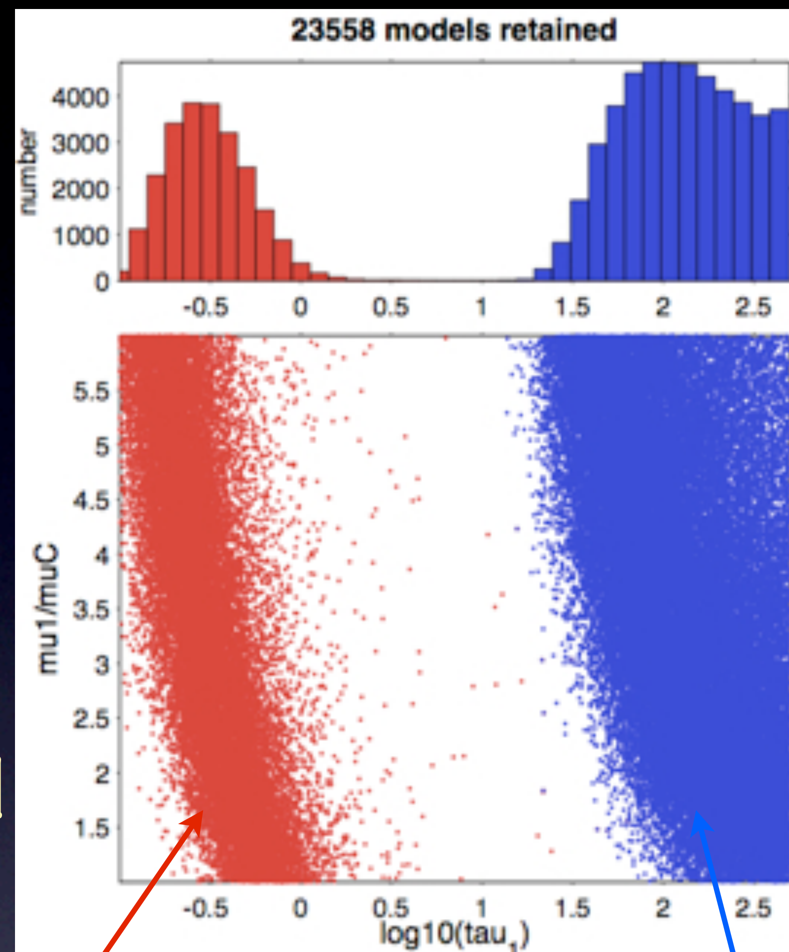

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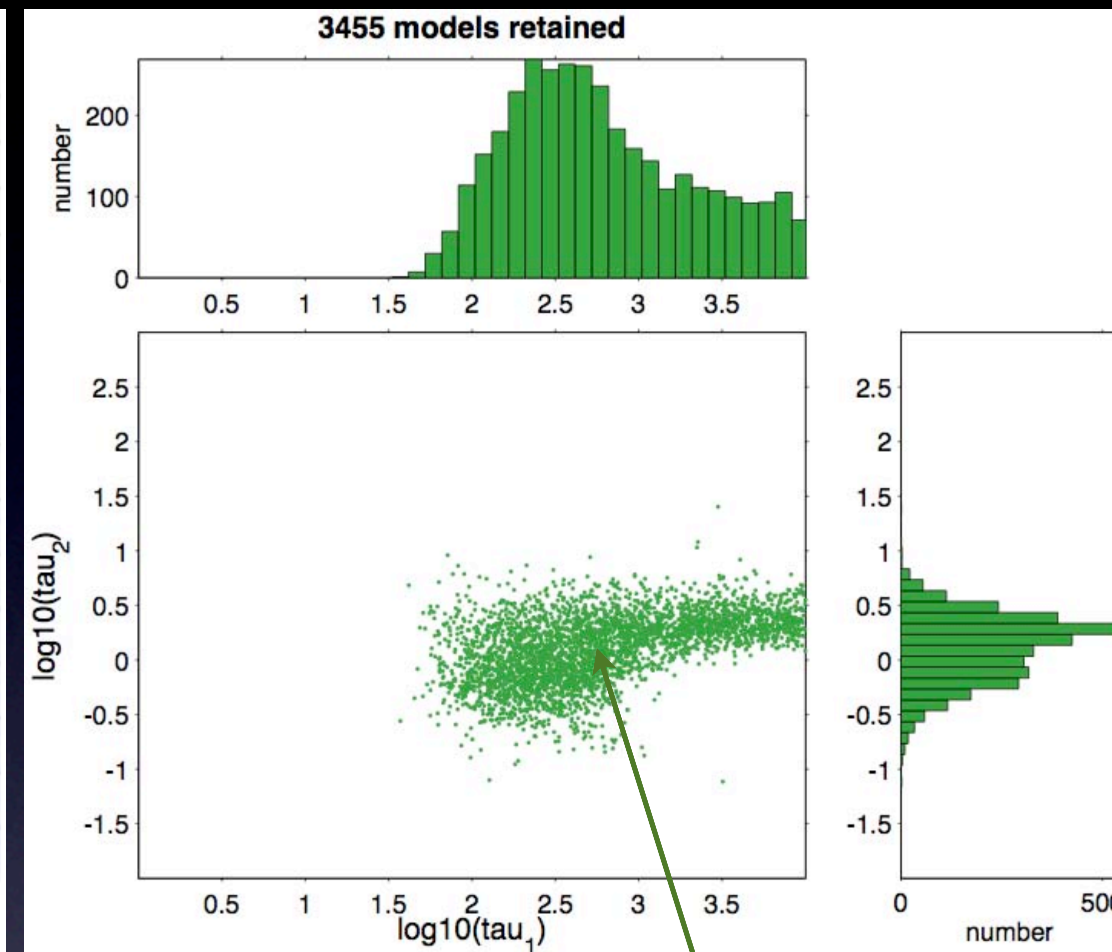

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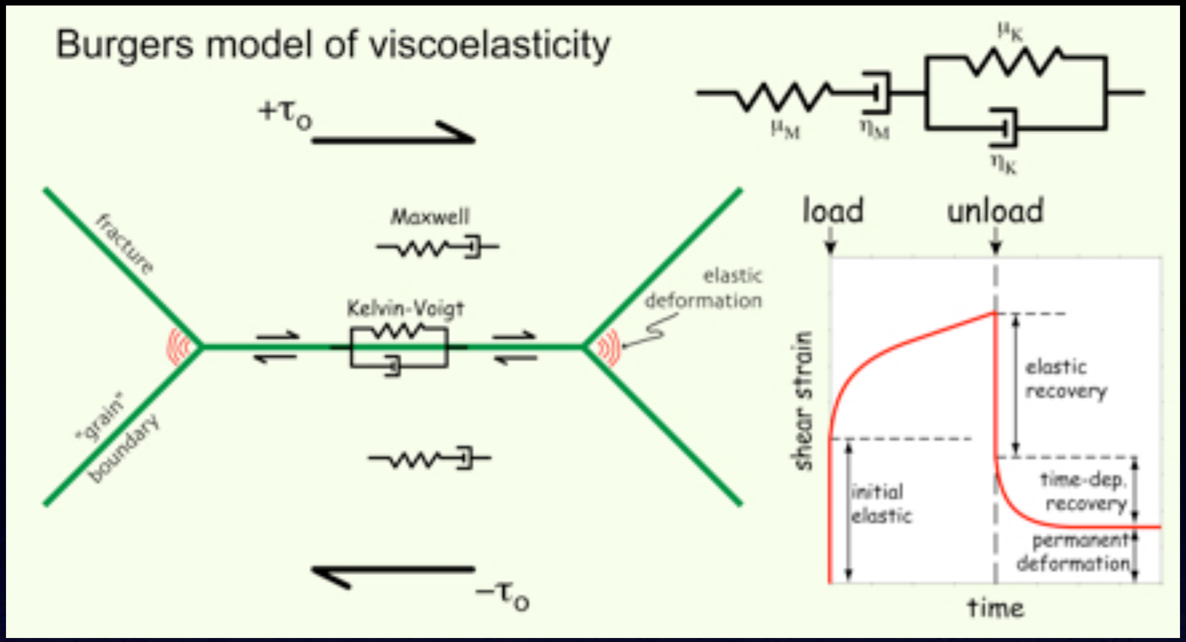
transient deformation can be confused with weak steady rheologies

Burgers vs non-linear

the transient deformation in a Burgers rheology is recoverable...
whereas the transient deformation in power-law creep is non-recoverable.



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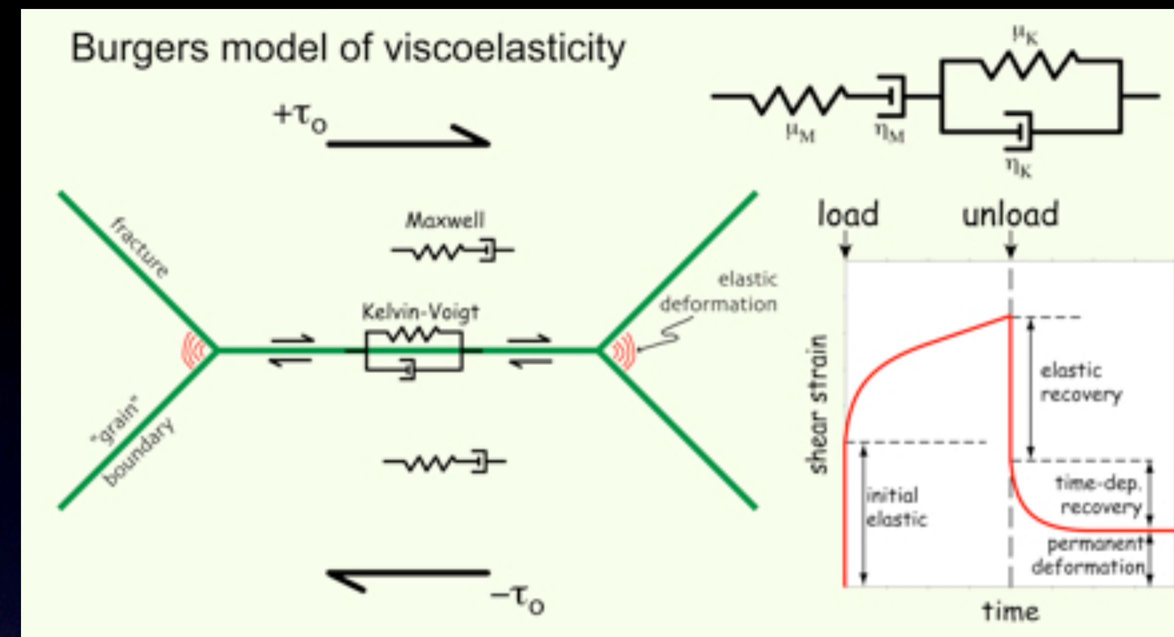
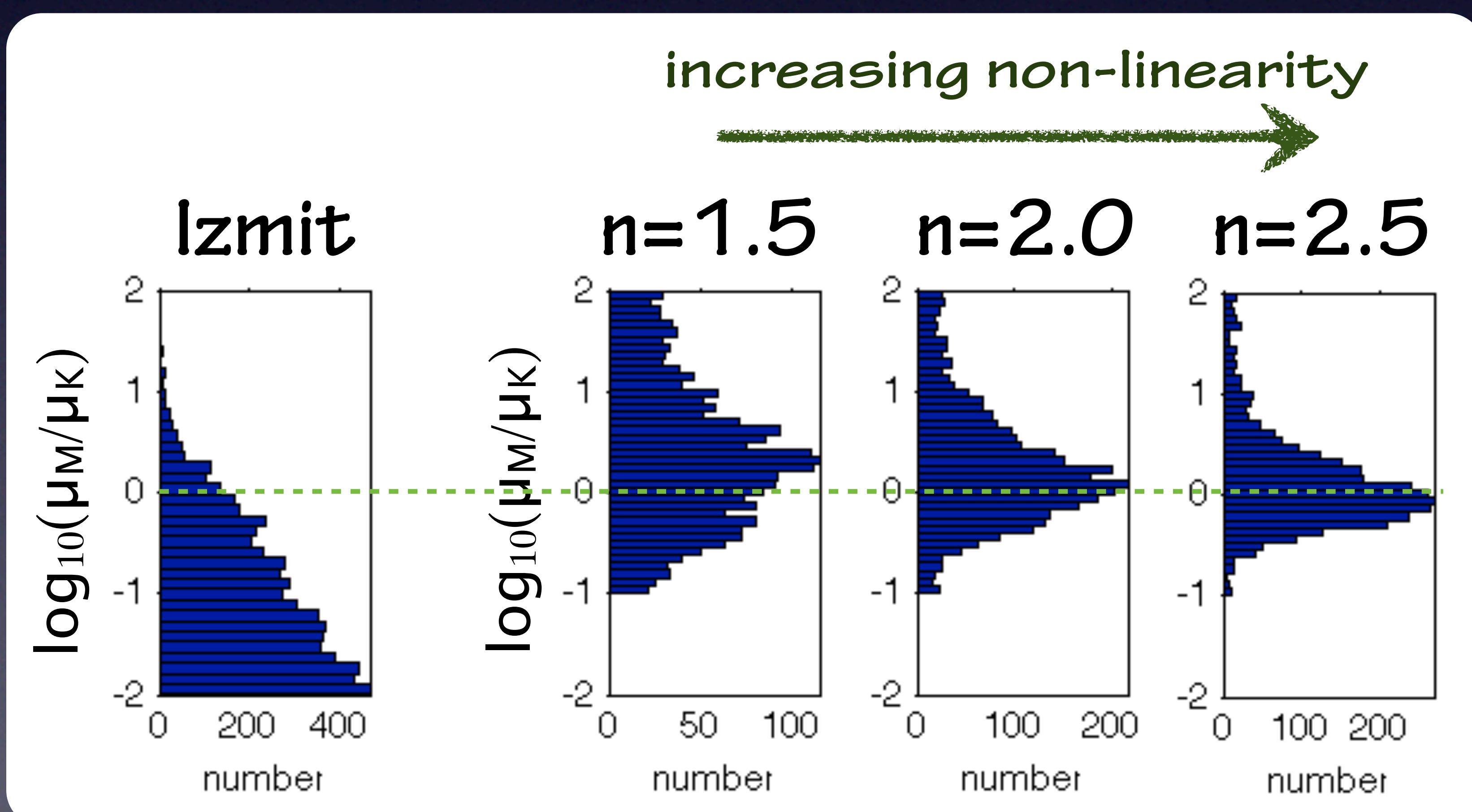




recoverability of transient phase appears to be required

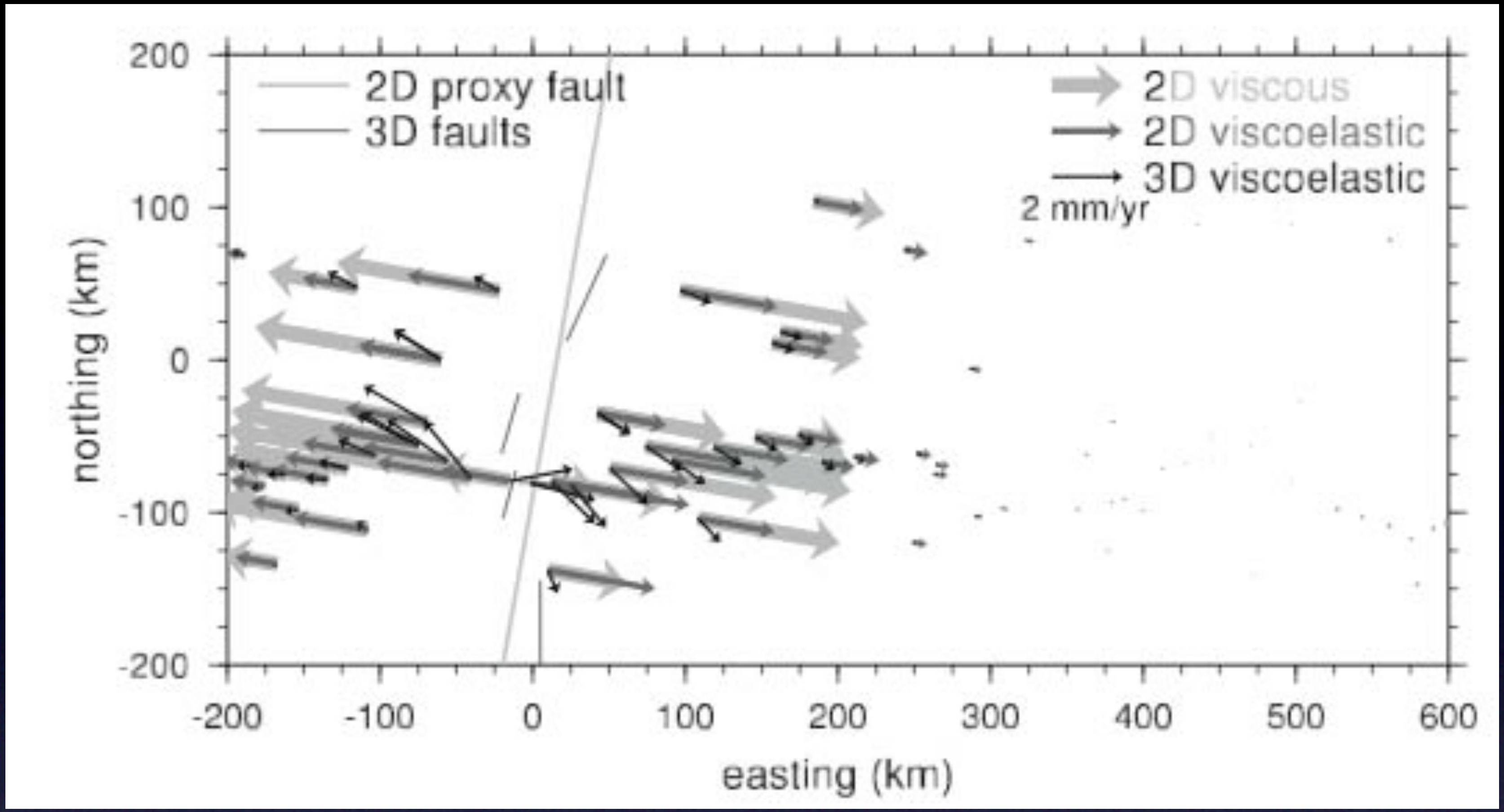
summary

- not necessarily a 1-1 mapping between models and Earth
  - some discriminants exist, most useful for complete data
  - in models with homogenous layers, estimated η (τ) is a biased estimate
    - depth dependence (biased to brittle-ductile transition)
    - transient rheologies during high stress times
- need to be better at determining suites of mechanical models consistent with data
  - large number of model permutations
  - our approach to develop equivalences between complicated (expensive) models and idealized (cheap) models

What can we do better?

Still room to develop better mechanical models, to understand the tectonic Earth, or to clean the observations (ideally both).

2d vs 3D



u1 - fault parallel displacements for an ∞ length fault

ux - fault parallel displacements for a finite fault

||ux,uy|| - magnitude of displacements for a finite fault