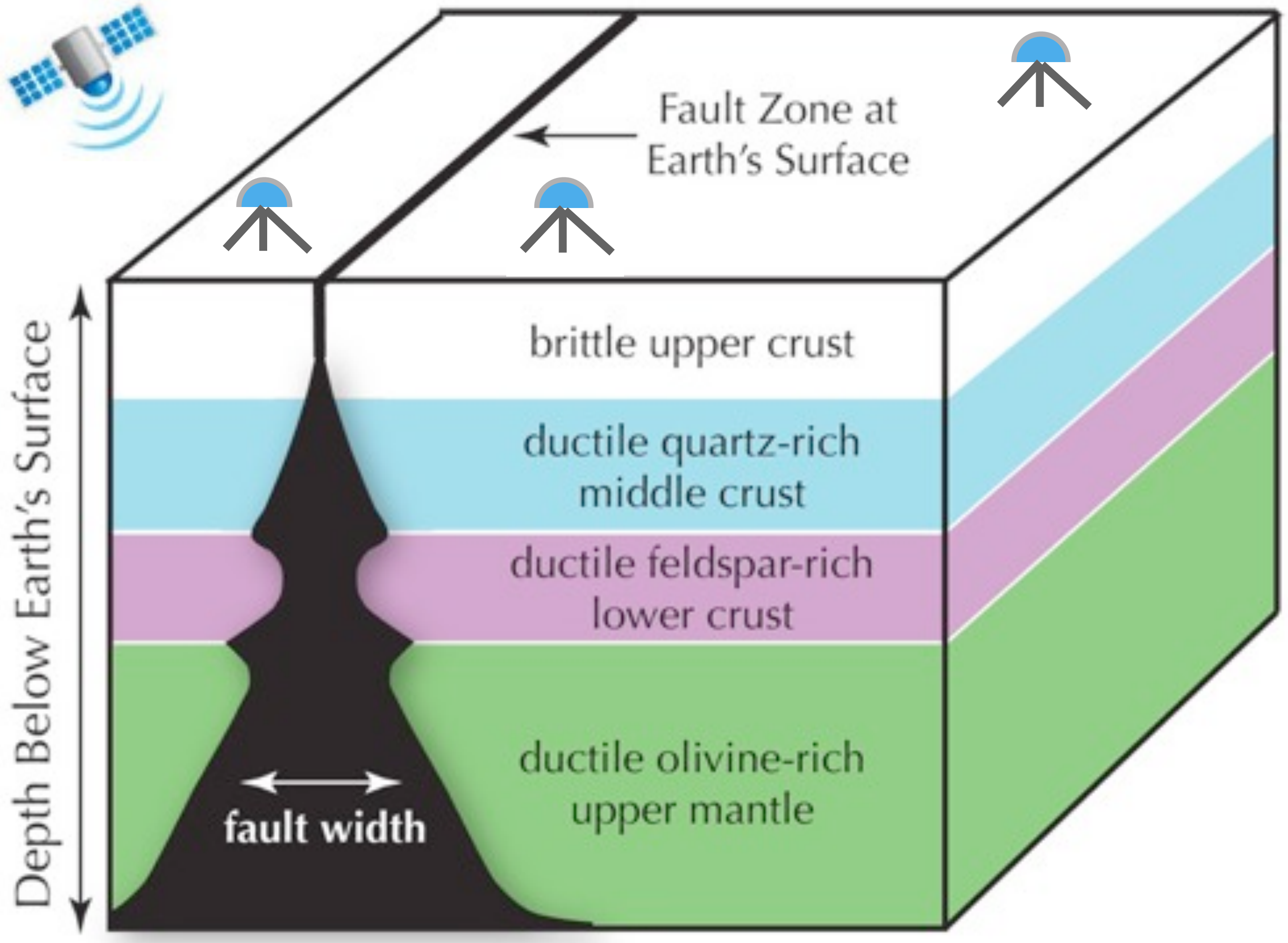
Reconciling postseismic and interseismic surface deformation around strike-slip faults: Earthquake-cycle models with finite ruptures and viscous shear zones

Elizabeth H. Hearn *hearn.liz@gmail.com*



modified from W. Behr

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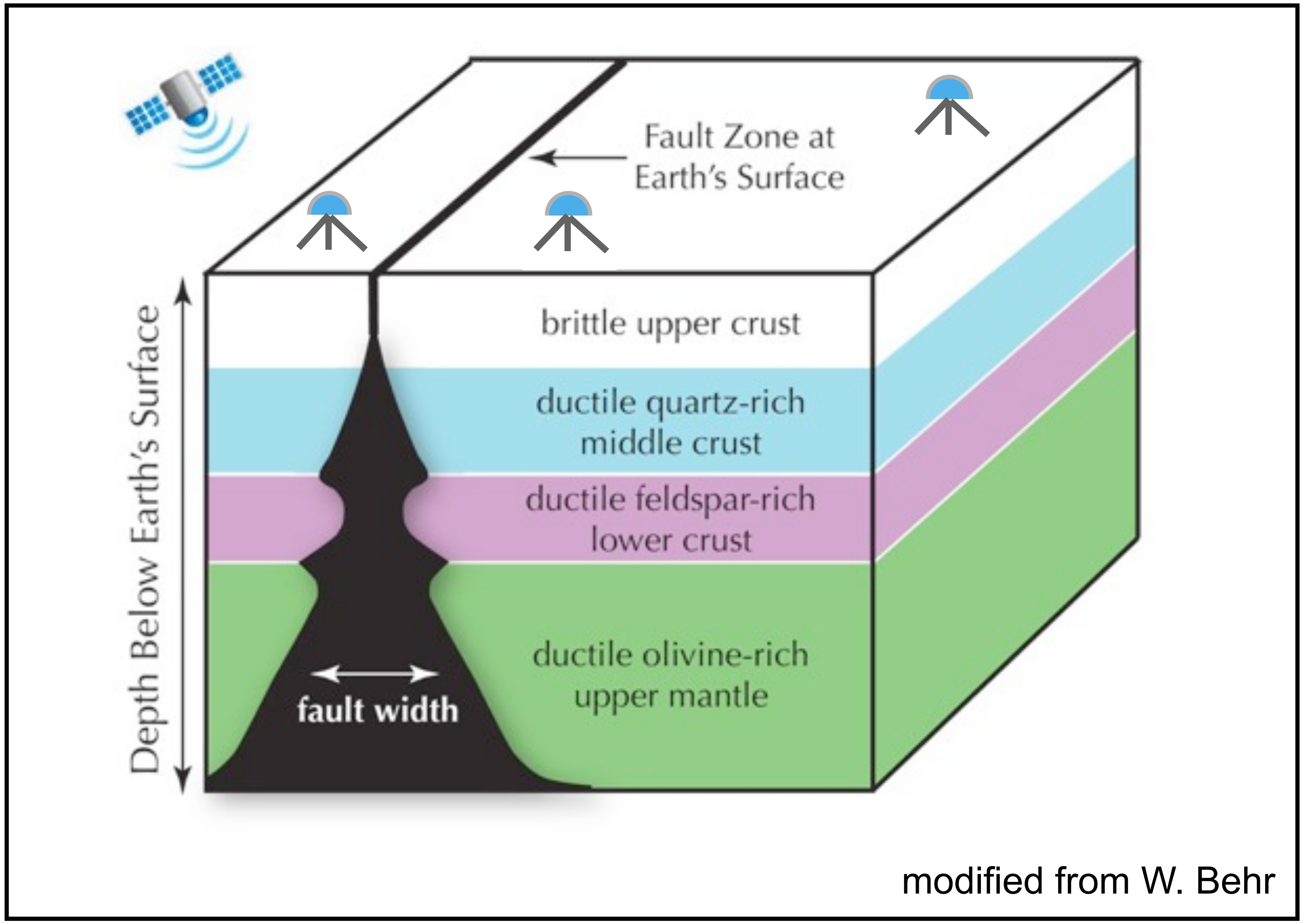


modified from W. Behr

Earthquake-cycle models incorporating viscous shear zones can resolve a longstanding conundrum: postseismic vs. interseismic deformation

Outline

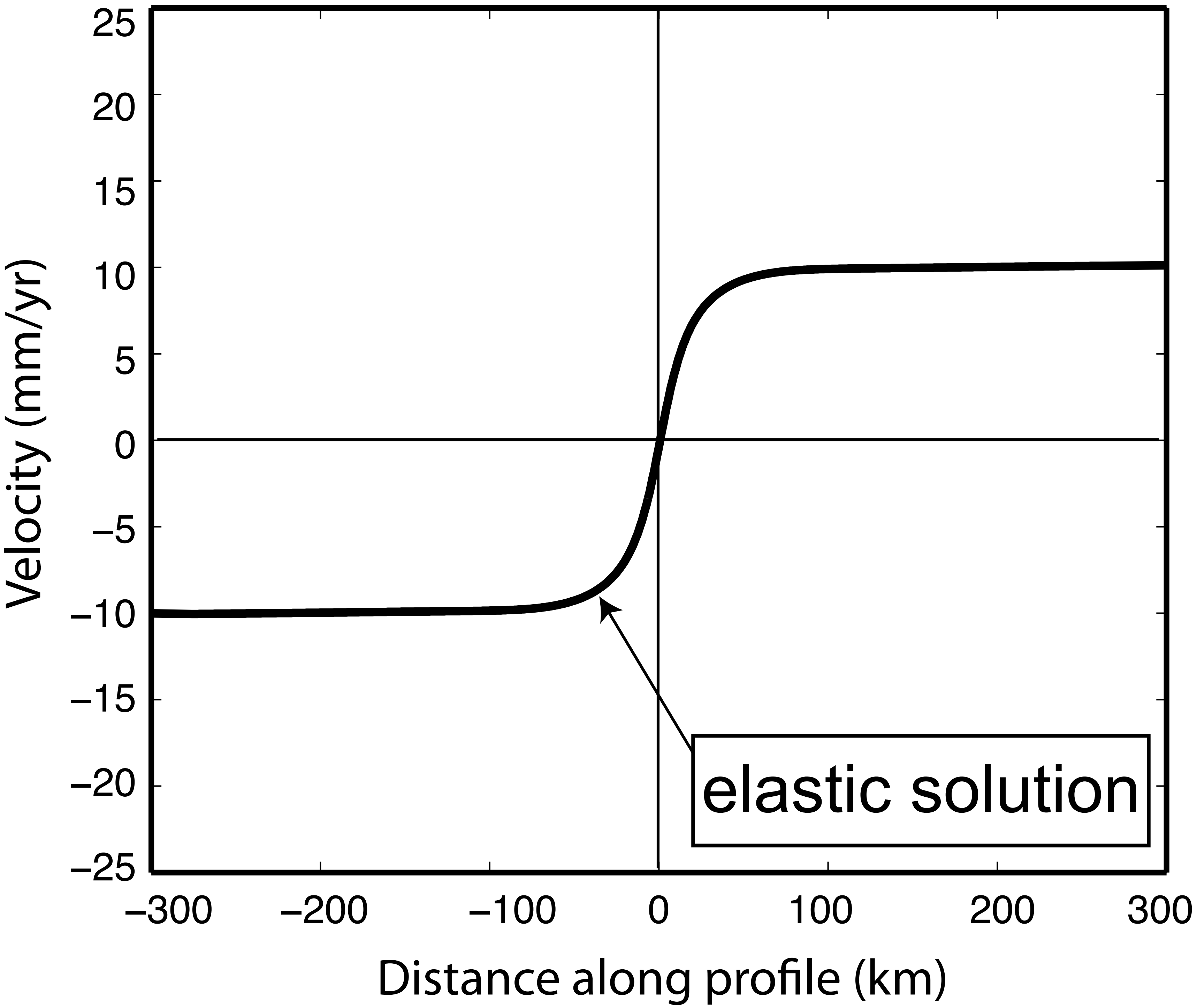
1. What am I talking about and why?

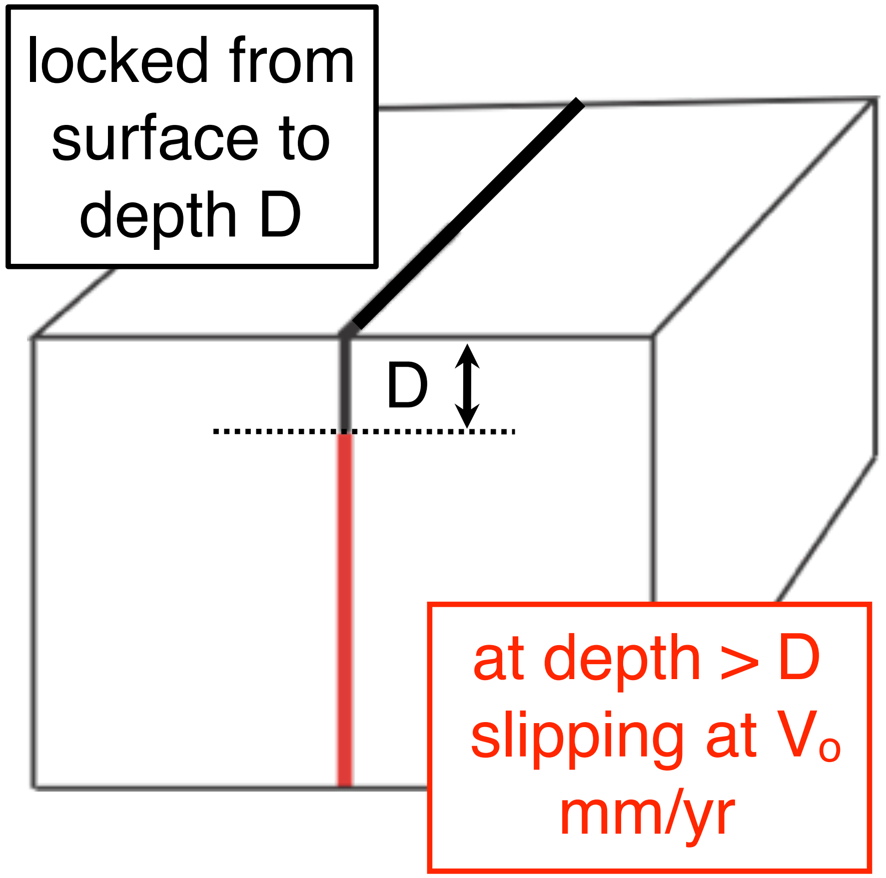
2. Modeling!

3. Interseismic velocities, stress and strain rate, and shear zone creep rate for 3 models

4. A plausible earthquake-cycle model for major strike-slip fault zones

Idealized interseismic deformation around an infinite, vertical strike-slip fault





locked from surface to depth D

at depth > D slipping at V_o mm/yr

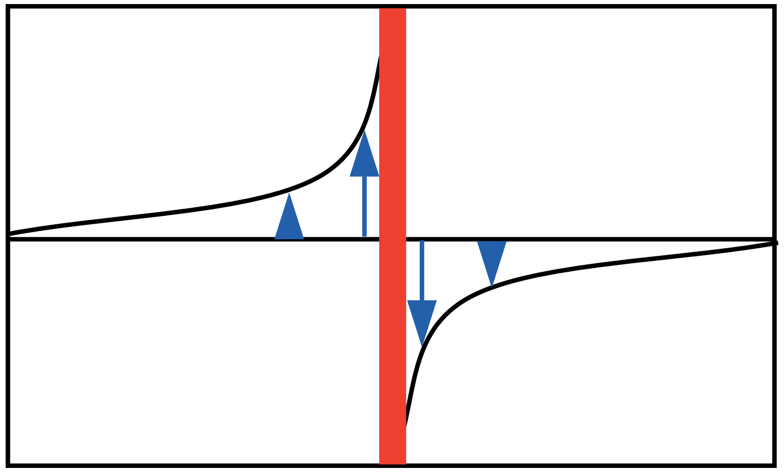
$$v = \frac{V_o}{\pi}\ atan\ \frac{x}{D}$$

Savage and Burford, 1973

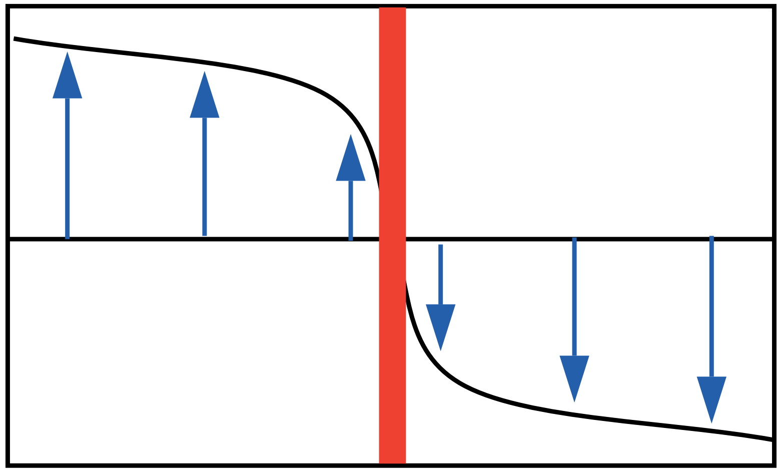
The earthquake cycle:
idealized surface deformation

earthquake! + *interseismic* = *one earthquake cycle (geologic slip rate)*

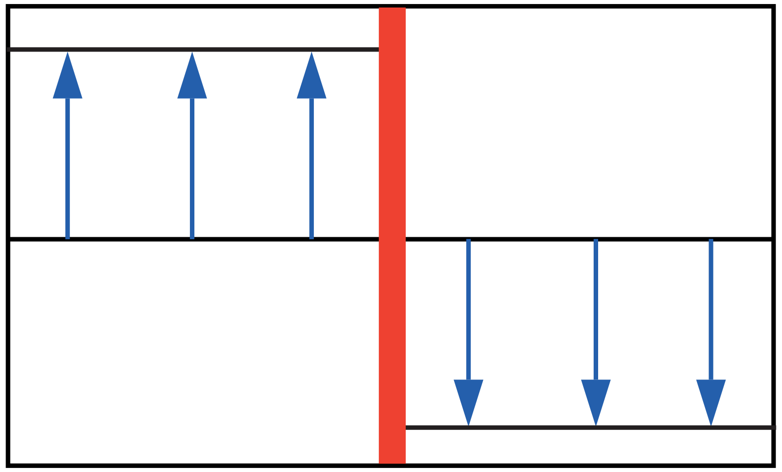
Plan view



Rapid slip!
0 to 15-20 km depth



Due to shear zone slip
below 15-20 km depth



SUM: rigid translation
of one plate past the other

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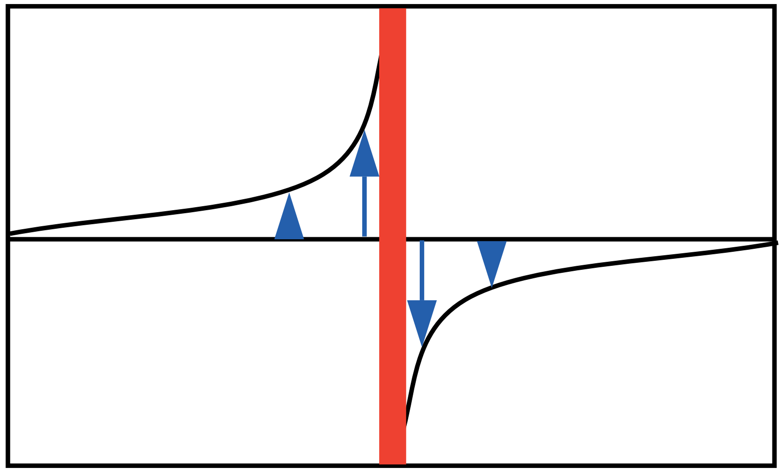
Plan view



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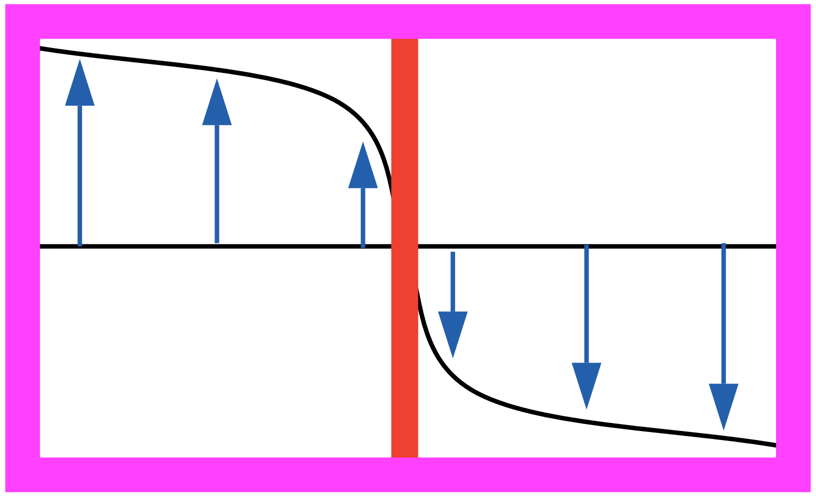

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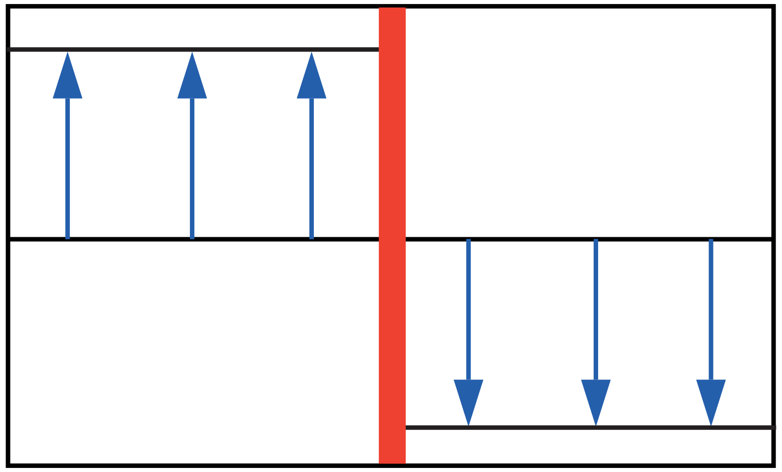

SUM: rigid translation
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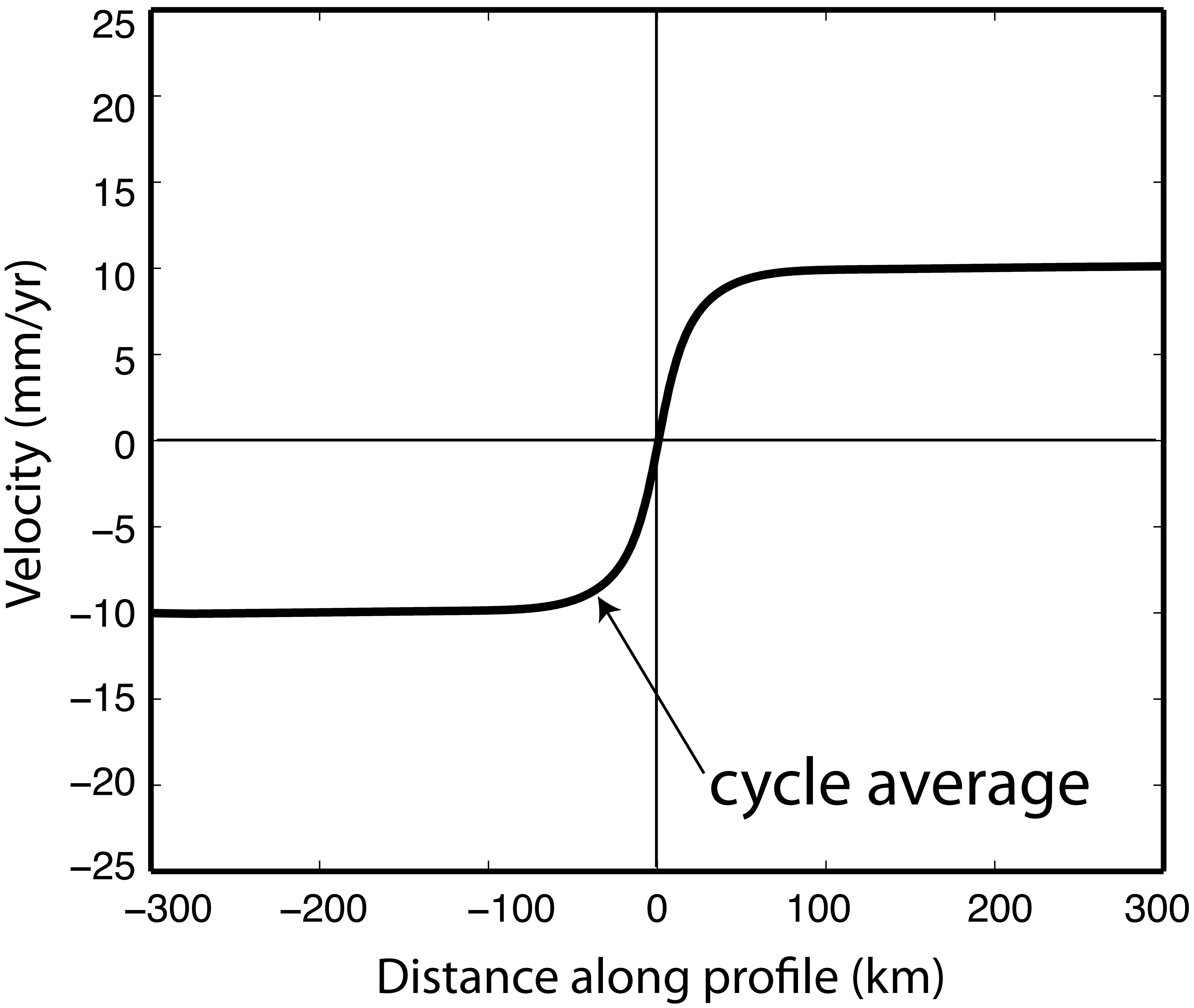
Consequence of viscoelastic material: time-varying interseismic deformation



“elastic” solution = cycle average

perturbations: see Hetland and Hager, 2006

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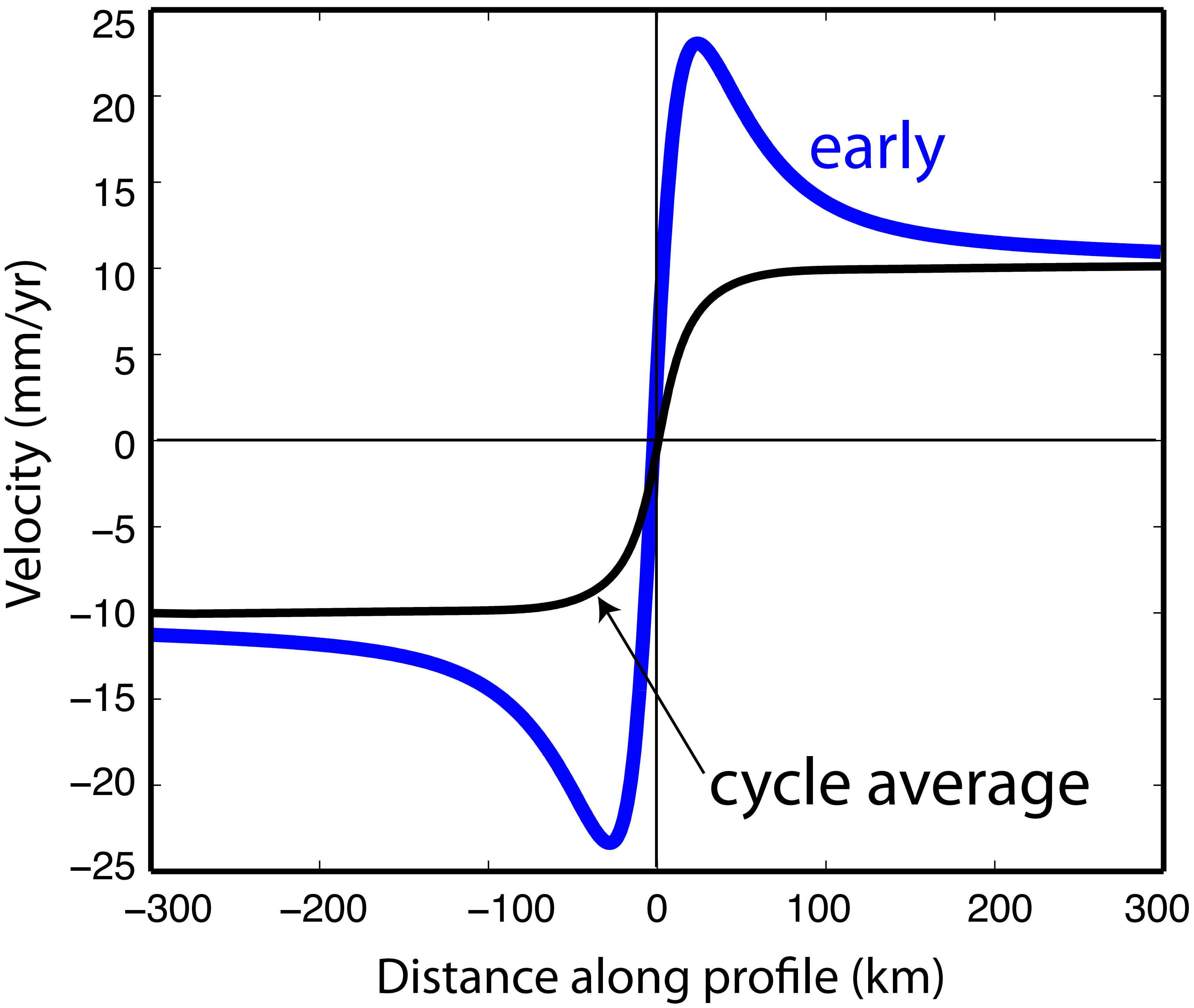

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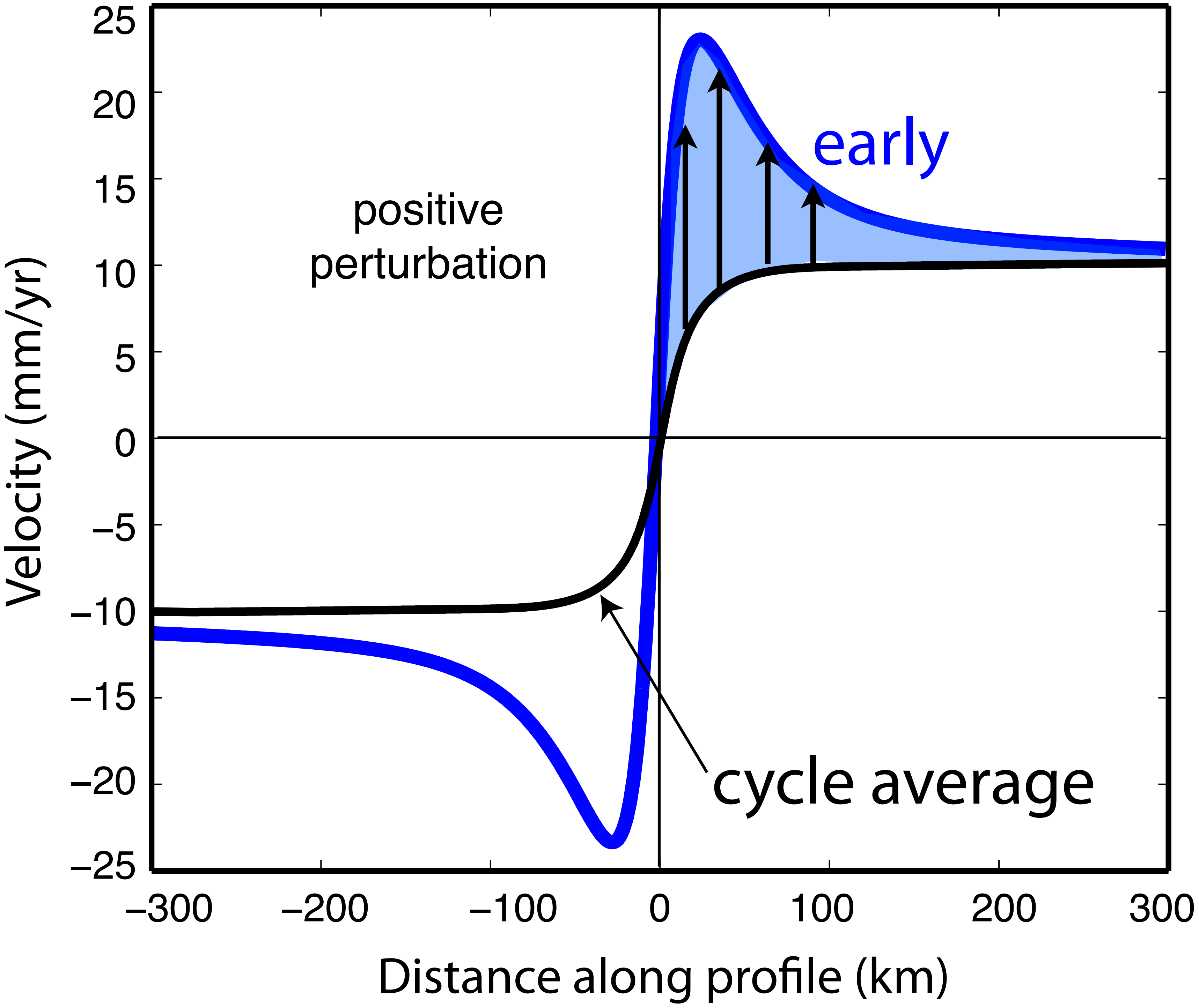

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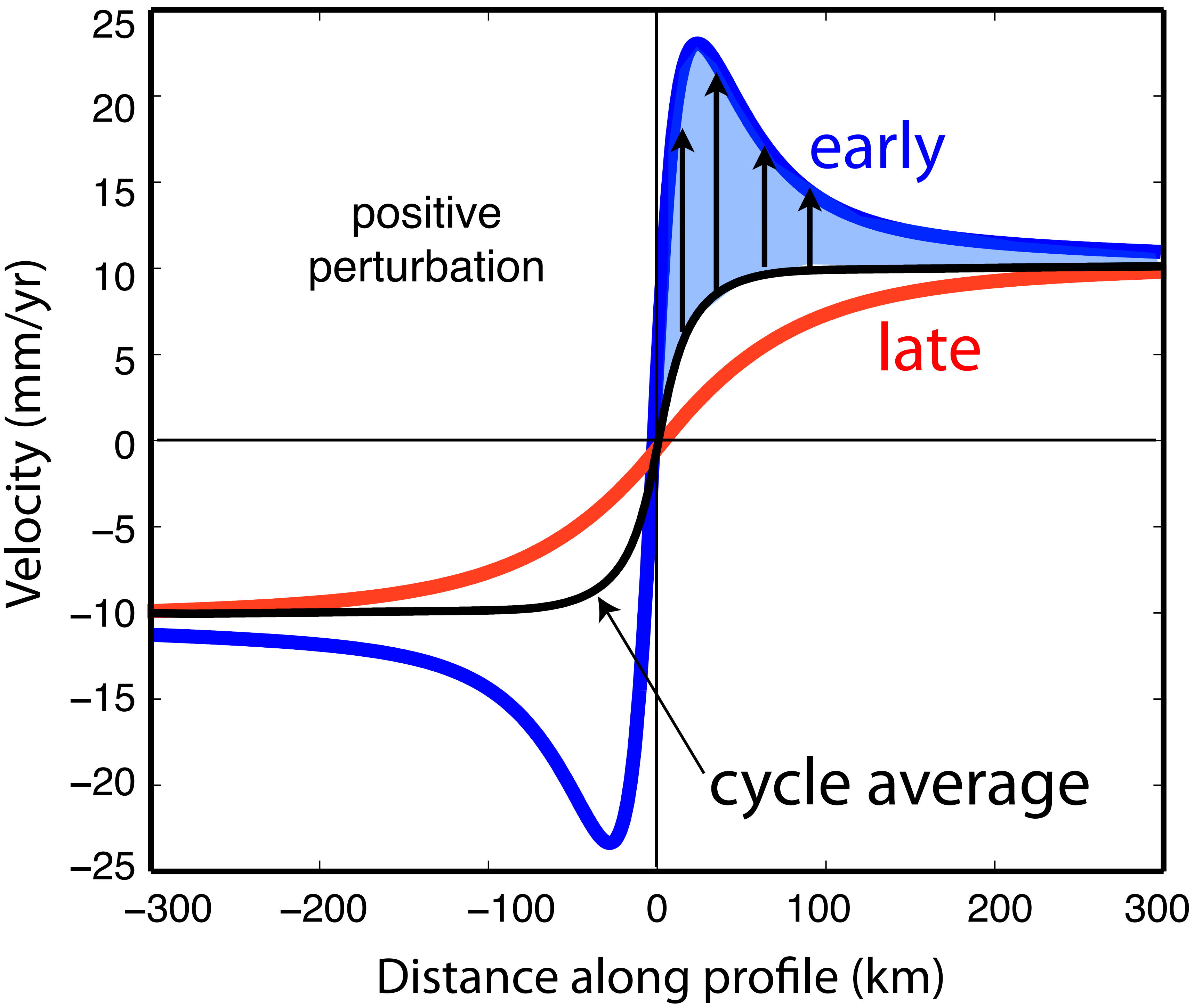

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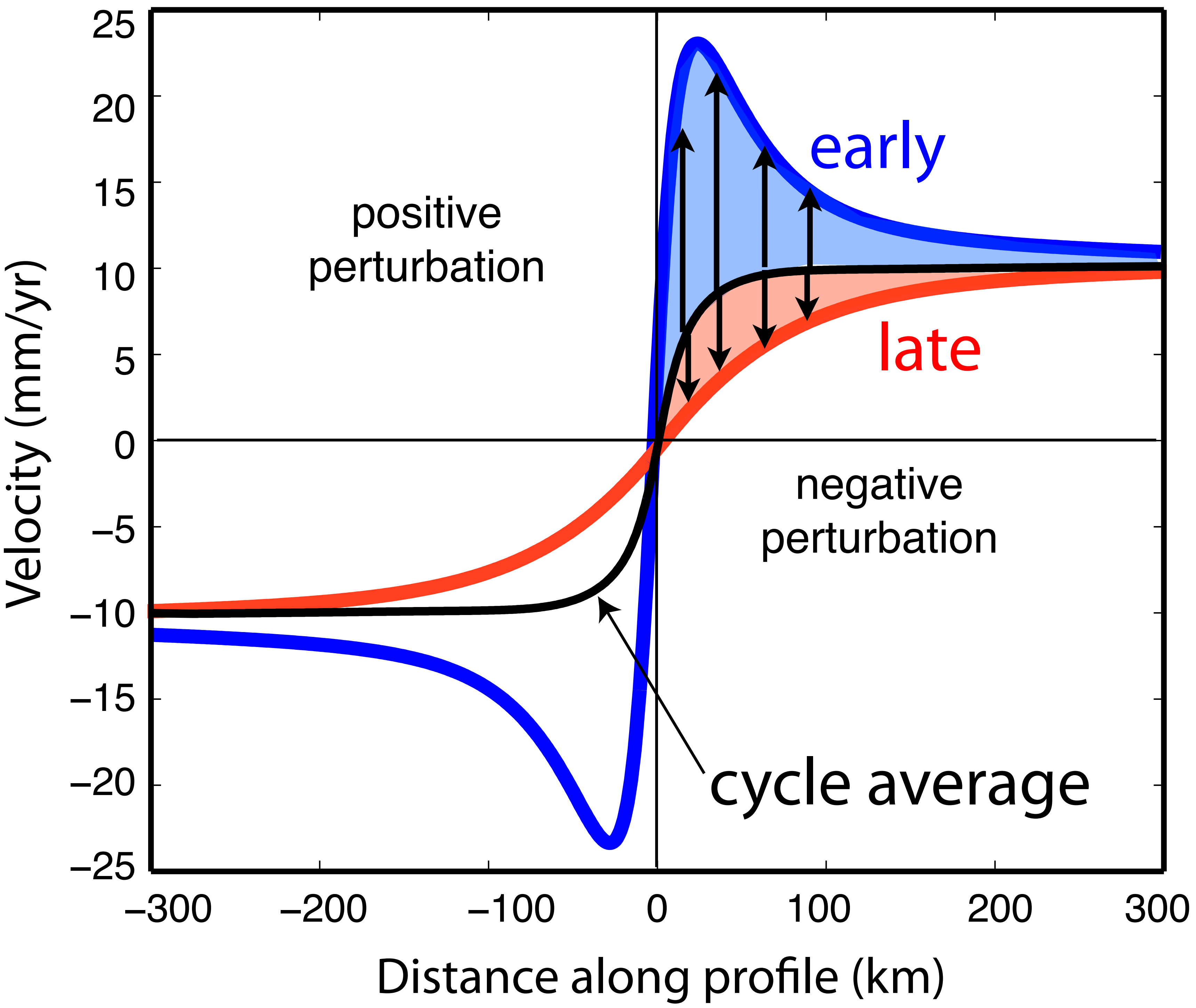

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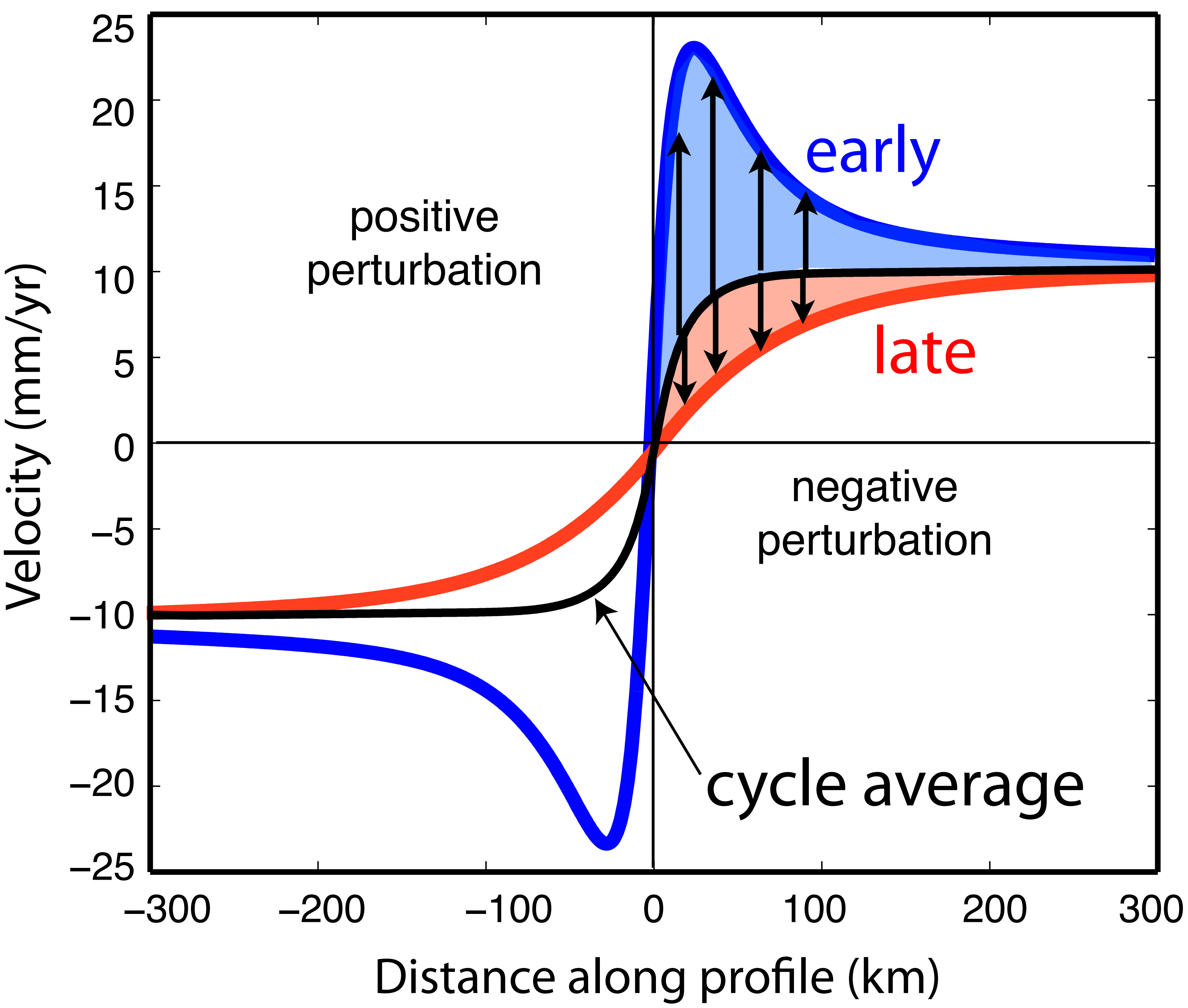


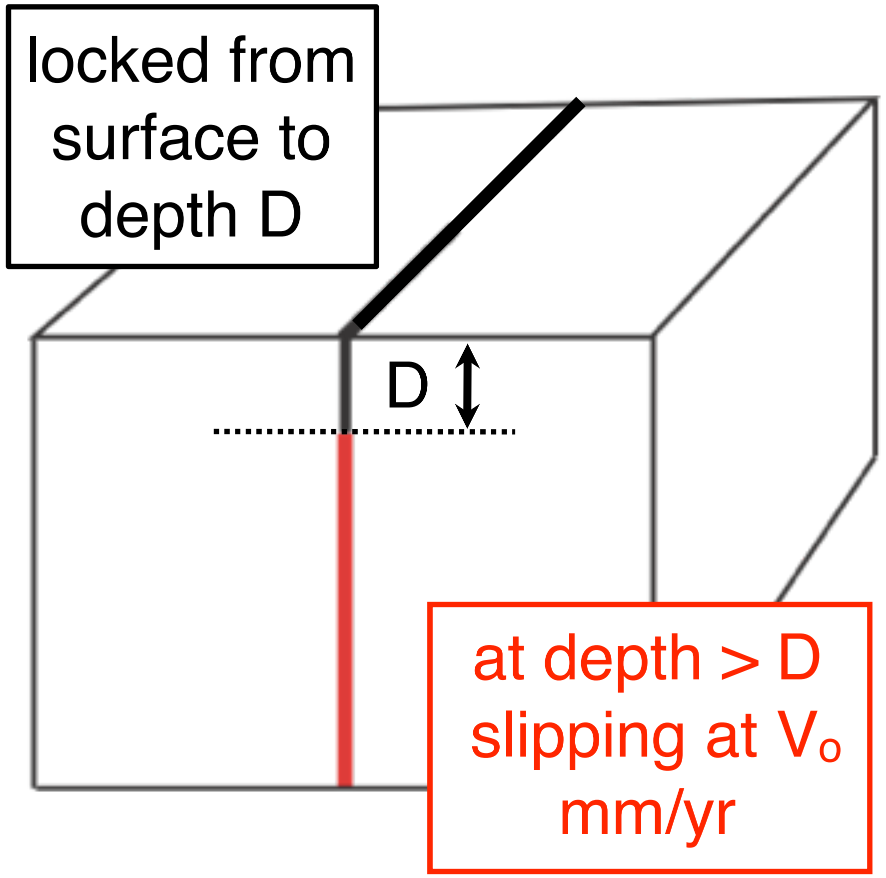
"elastic" solution = cycle average

lower viscosities cause bigger perturbations

perturbations: see Hetland and Hager, 2006

A conundrum

Observed interseismic deformation: velocity profiles look like cycle-average



locked from surface to depth D

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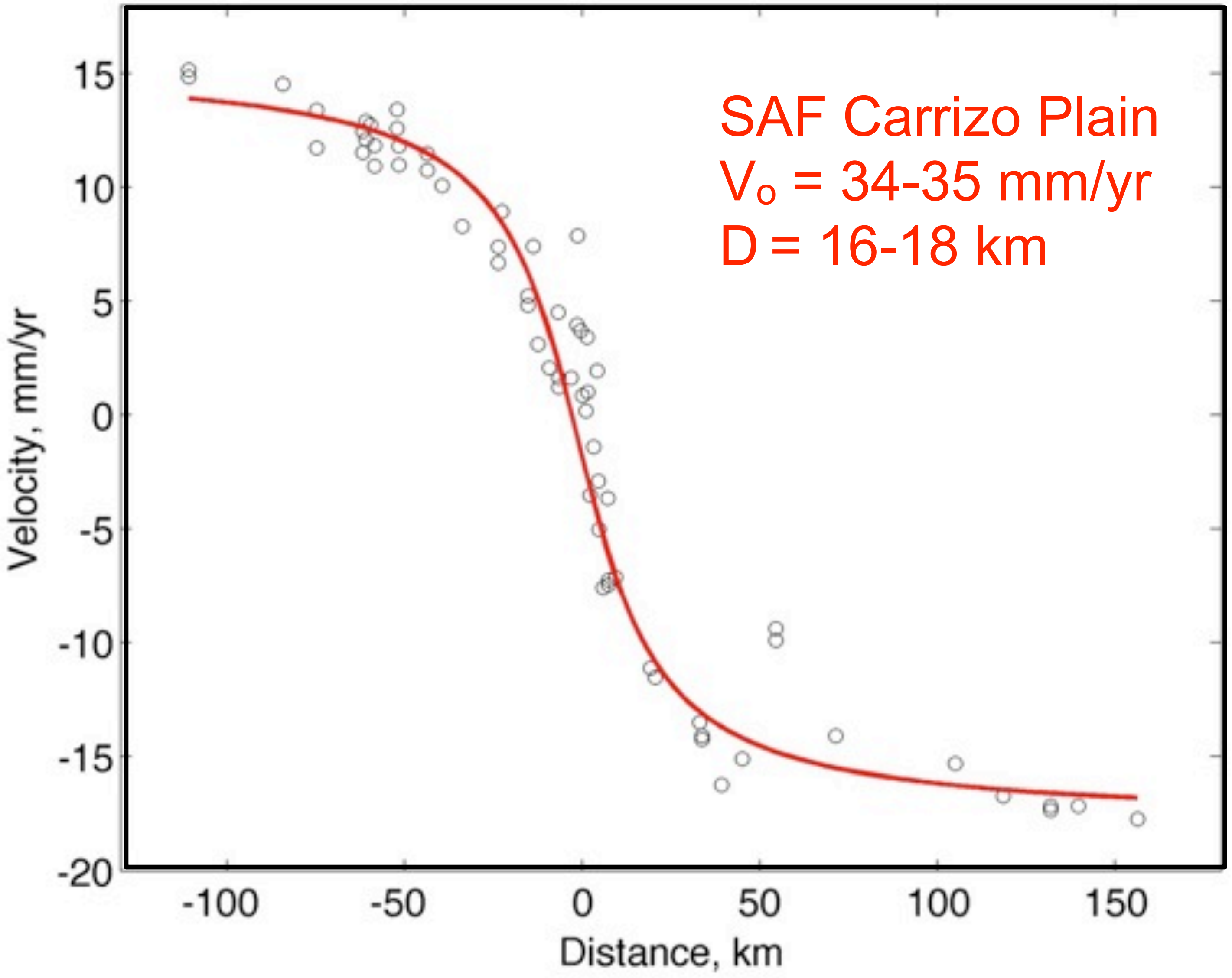
$$v = \frac{V_o}{\pi}\, atan\, \frac{x}{D}$$

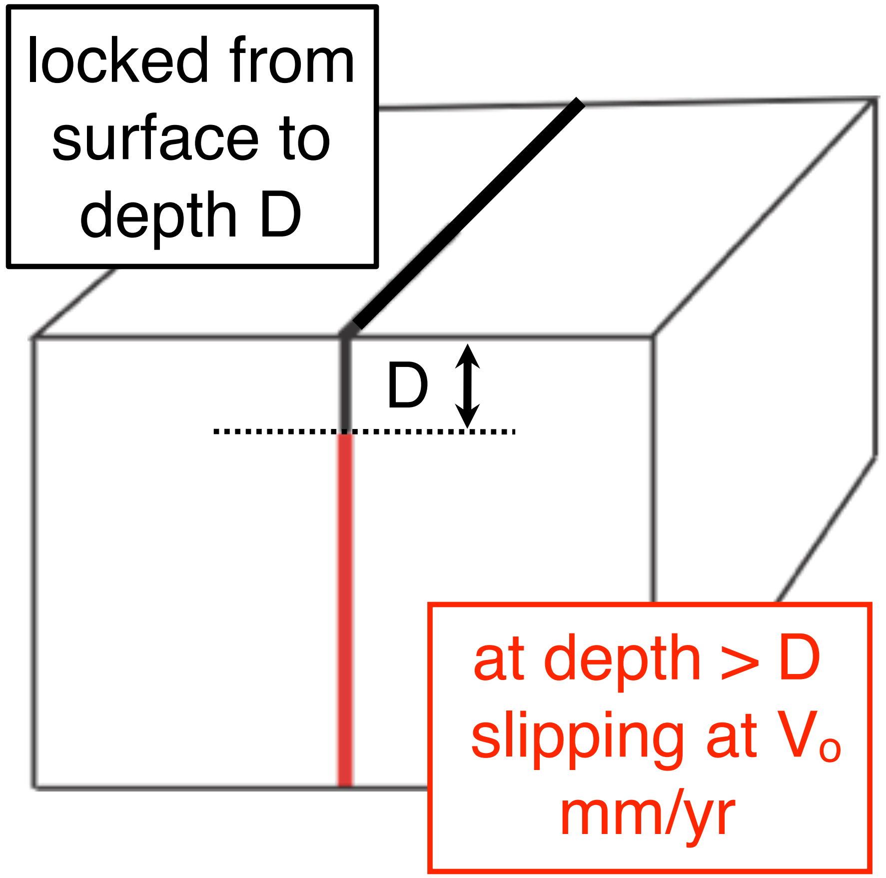


SAF Carrizo Plain

V_o = 34-35 mm/yr

D = 16-18 km

Observed interseismic deformation: velocity profiles look like cycle-average



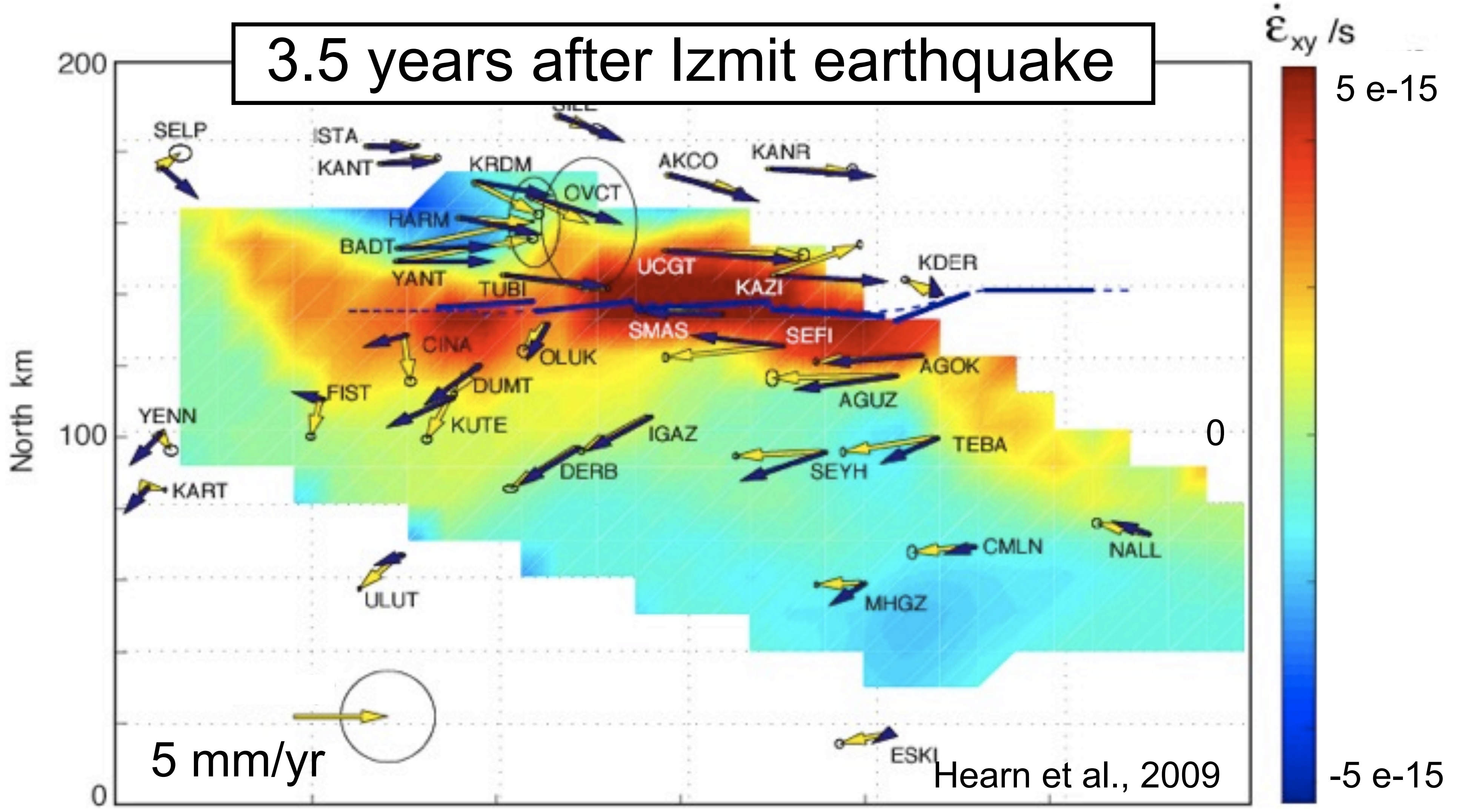
$$v = \frac{V_o}{\pi}\ atan\ \frac{x}{D}$$

From GPS and InSAR:
D = maximum coseismic rupture depth,
V_o = Holocene slip rate, *regardless of time in the seismic cycle*.

(Wright et al., 2013, Meade et al., 2013)

Of course, there are exceptions.

Observed "late" postseismic deformation: large perturbation



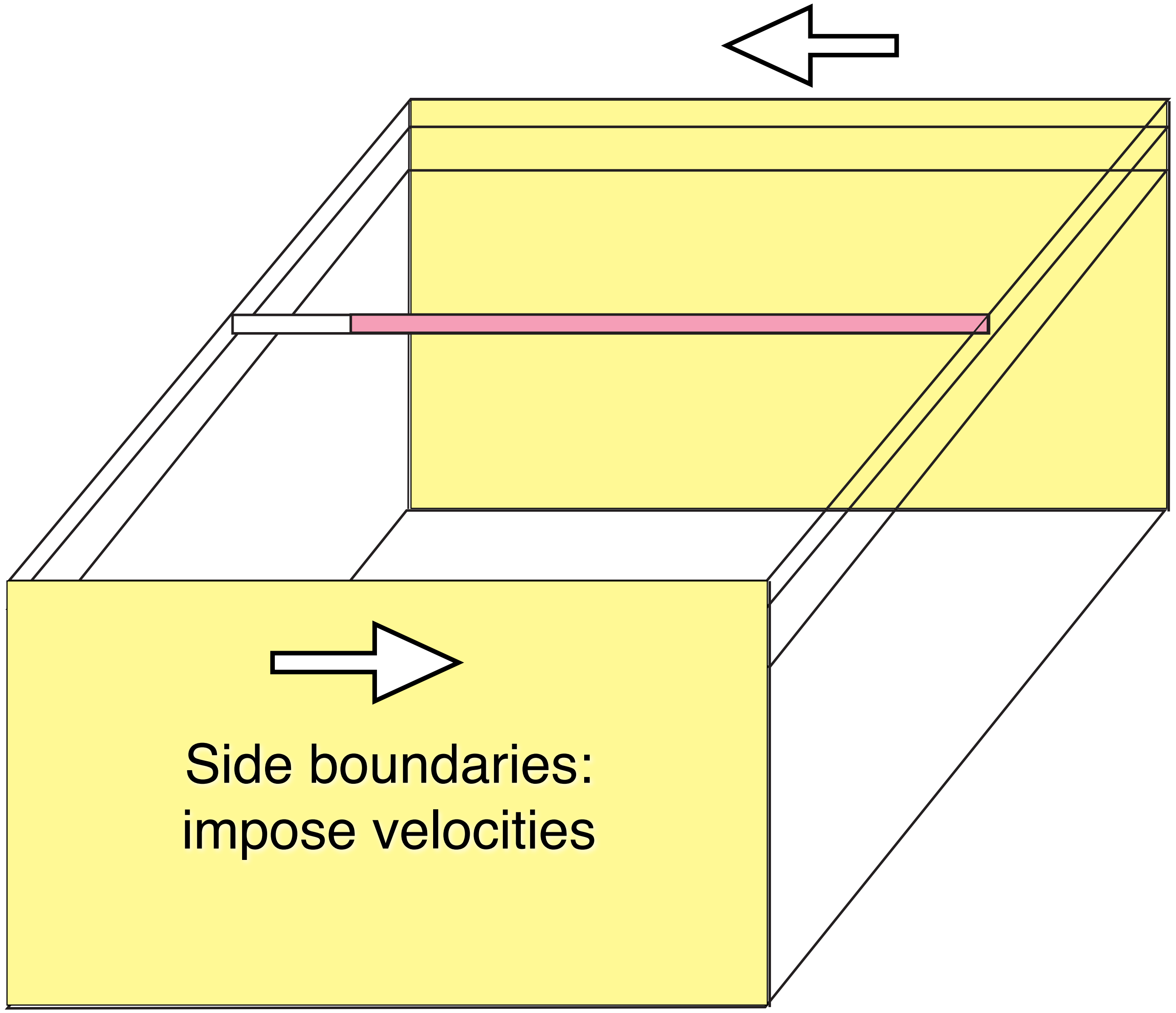
Hearn et al., 2009

Quake	postseis. / pre-quake rel. rate	When	Distance to maximum	Reference
M 7.5 Izmit	2	4 years	20 km	Ergintav et al., 2009
M 7.8 Kokoxili	2 to 4	2 to 6 years	15 km	Wen et al., 2012
M 7.9 Denali	~5	4 to 7 years	20-50 km	Freymueller et al, 2009 (AGU)

Postseismic deformation seems to require low viscosity material

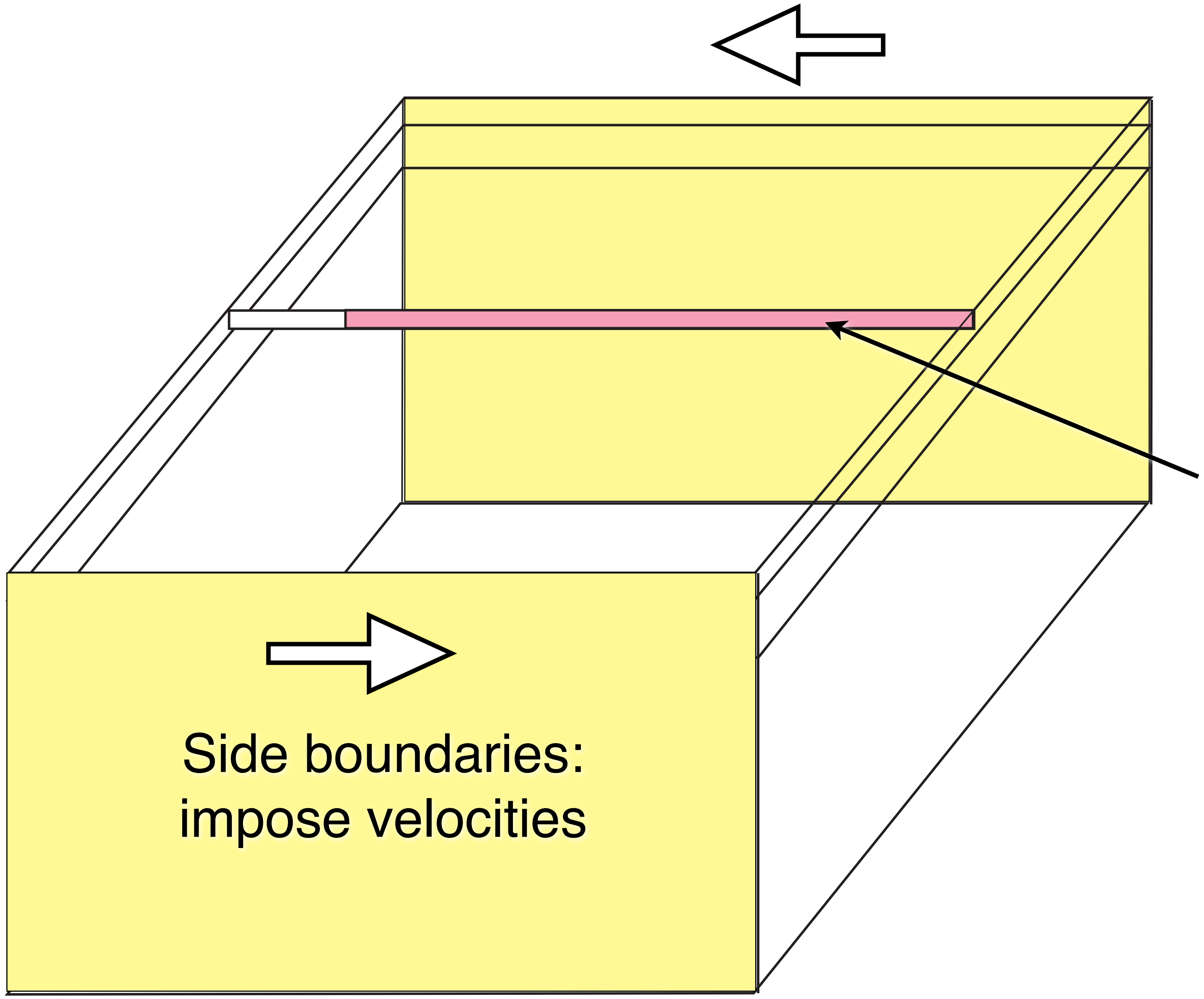
Interseismic deformation seems to require high viscosity material

Earthquake-cycle modeling



Side boundaries:
impose velocities

Earthquake-cycle modeling



Side boundaries:
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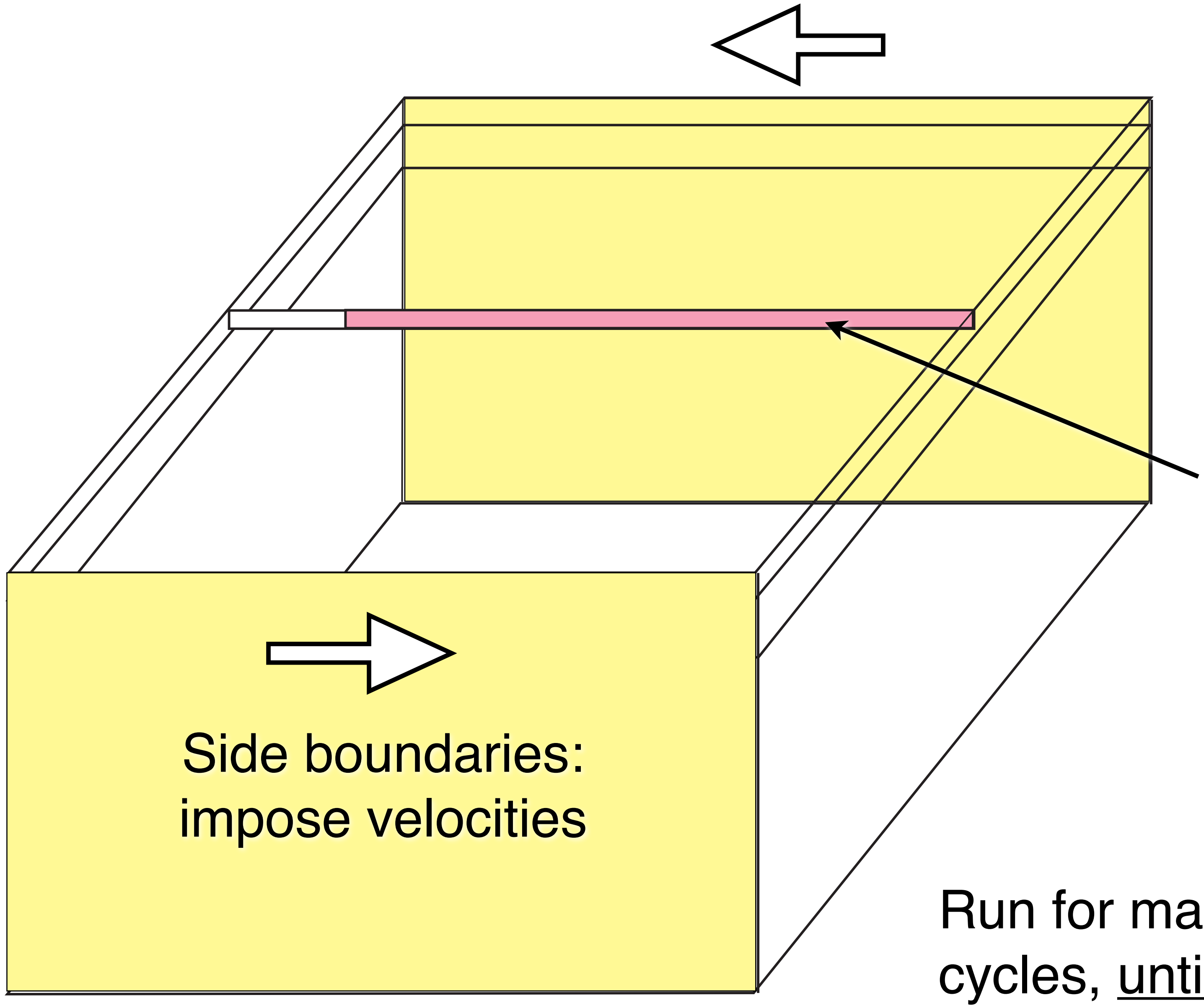
Fault:
impose episodic
coseismic slip or
steady creep

Earthquake-cycle modeling



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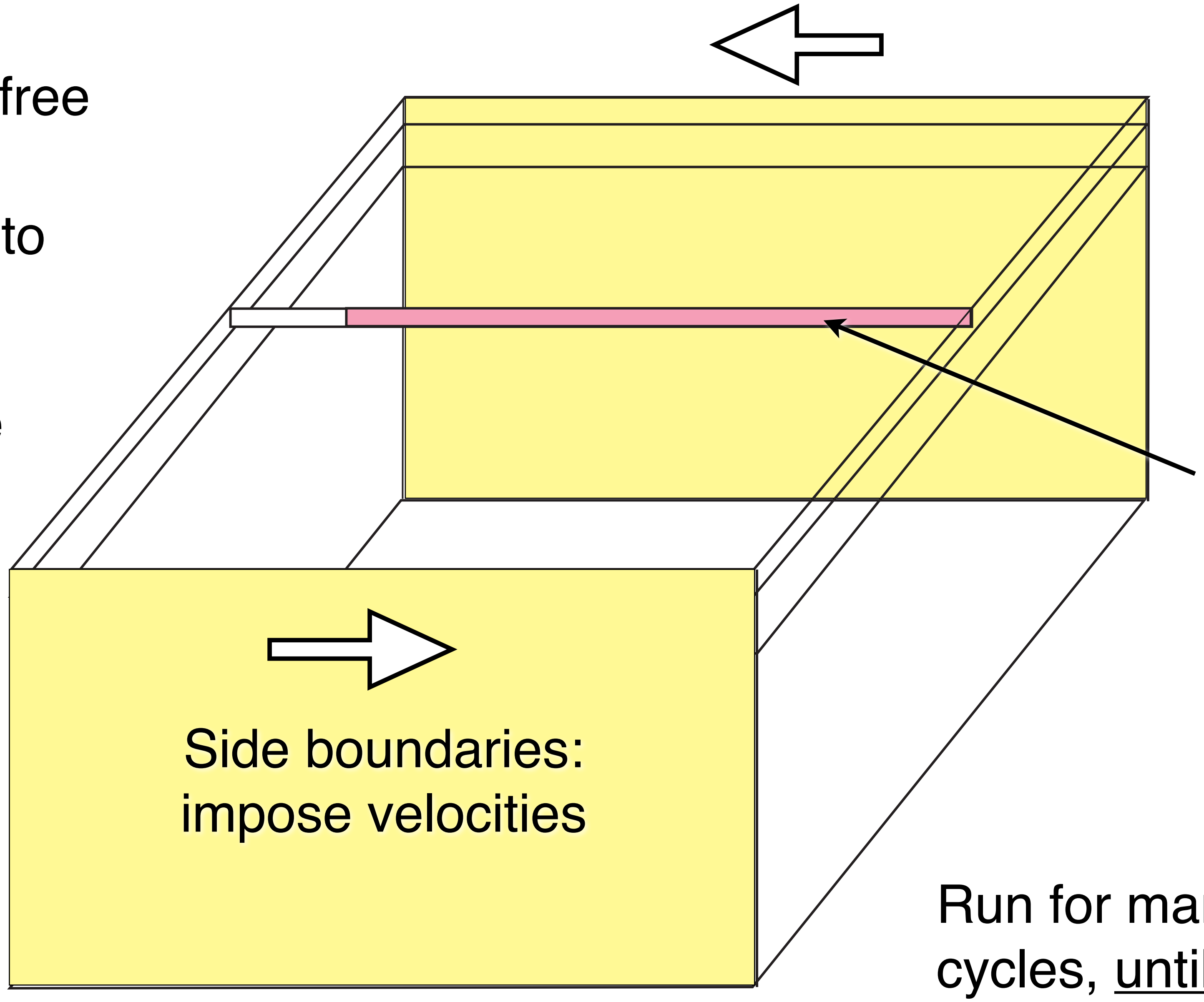
Run for many earthquake cycles, until cycle-invariant status is attained

Earthquake-cycle modeling

top surface: traction-free

bottom surface: free to displace horizontally

end boundaries: free to displace parallel to the fault



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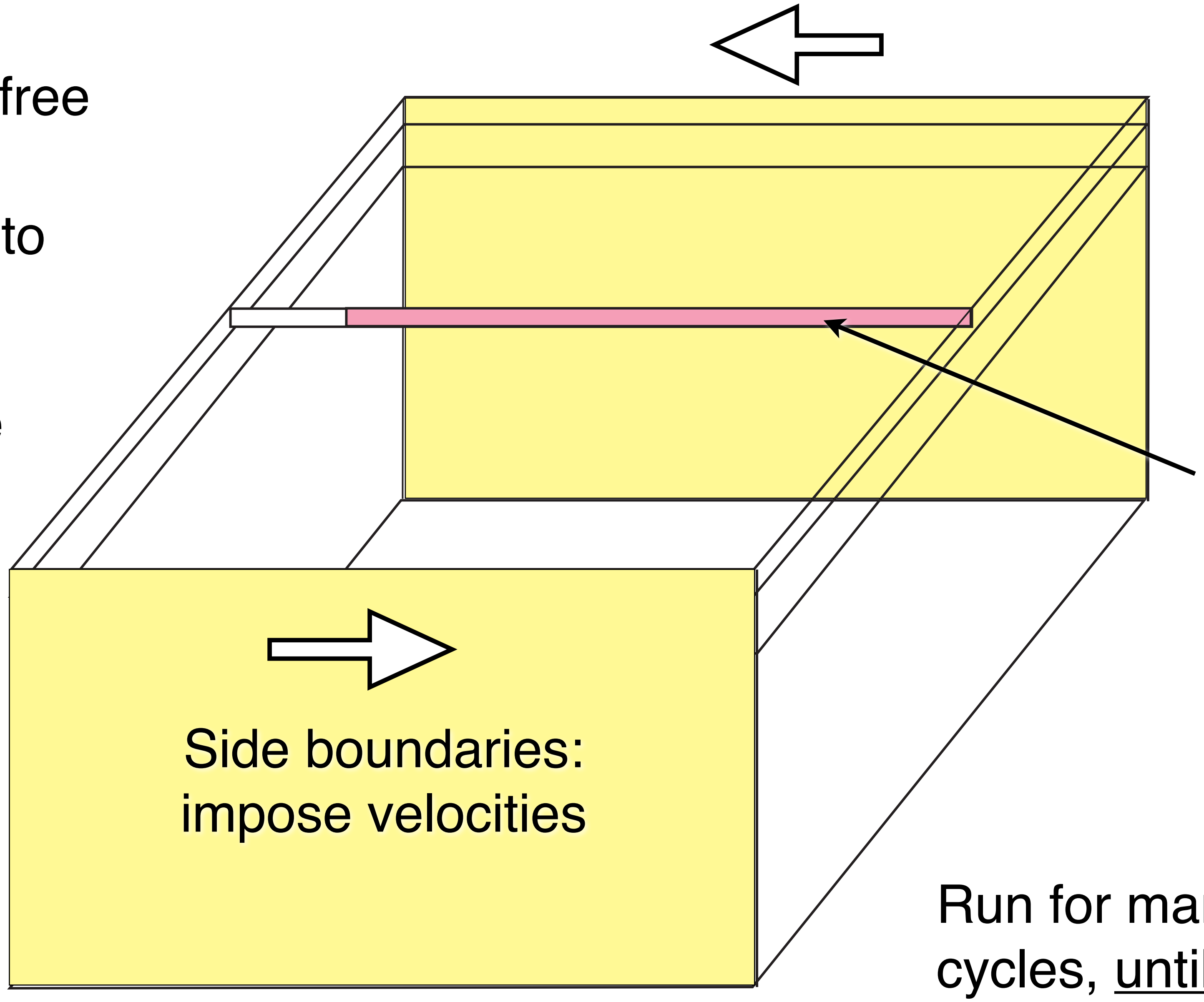

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Side boundaries: impose velocities

Fault:
impose episodic coseismic slip or steady creep

Run for many earthquake cycles, until cycle-invariant status is attained

Result: Velocities, strain rates, shear zone creep rates and (below the brittle upper crust) stresses

Solving the conundrum

- Non-Maxwell viscoelastic material? (e.g. Freed et al., 2013, Hearn et al., 2009, Takeuchi and Fialko, 2012 and 2013, Pollitz, 2005, Hetland and Hager, 2006, Ryder et al., 2010)
  - Burgers
  - Power law
  - Both, composite....

Solving the conundrum

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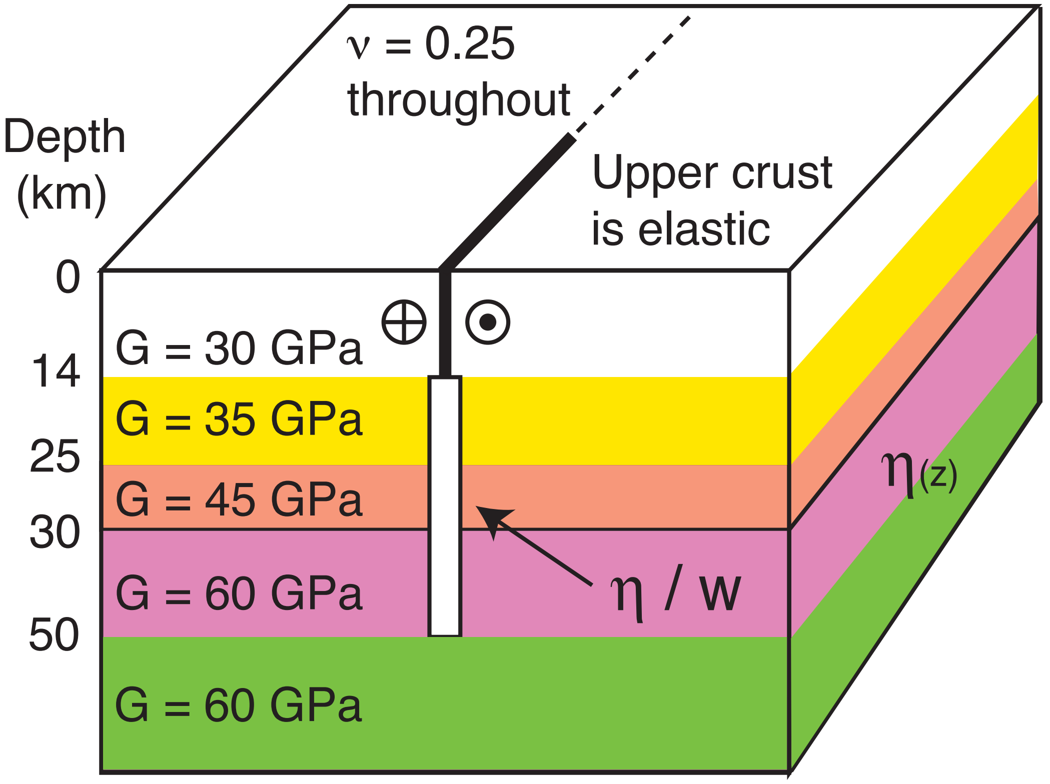
  - Burgers
  - Power law
  - Both, composite....
- Thin low-viscosity layer? Stratified? (e.g., DeVries and Meade, 2013,Yamasaki and Houseman, 2012, Hetland and Hager, 2006, Cohen and Kramer, 1984)
- Viscous shear zone? (e.g., Kenner and Segall, 2003; Johnson and Segall, 2004; Yamasaki et al., 2014; Takeuchi and Fialko, 2012 and 2013, Pollitz, 2001 [wide SZ])

My earthquake-cycle models

- Viscous shear zones and relaxing layers
- Non-Maxwell viscoelastic material



My earthquake-cycle models

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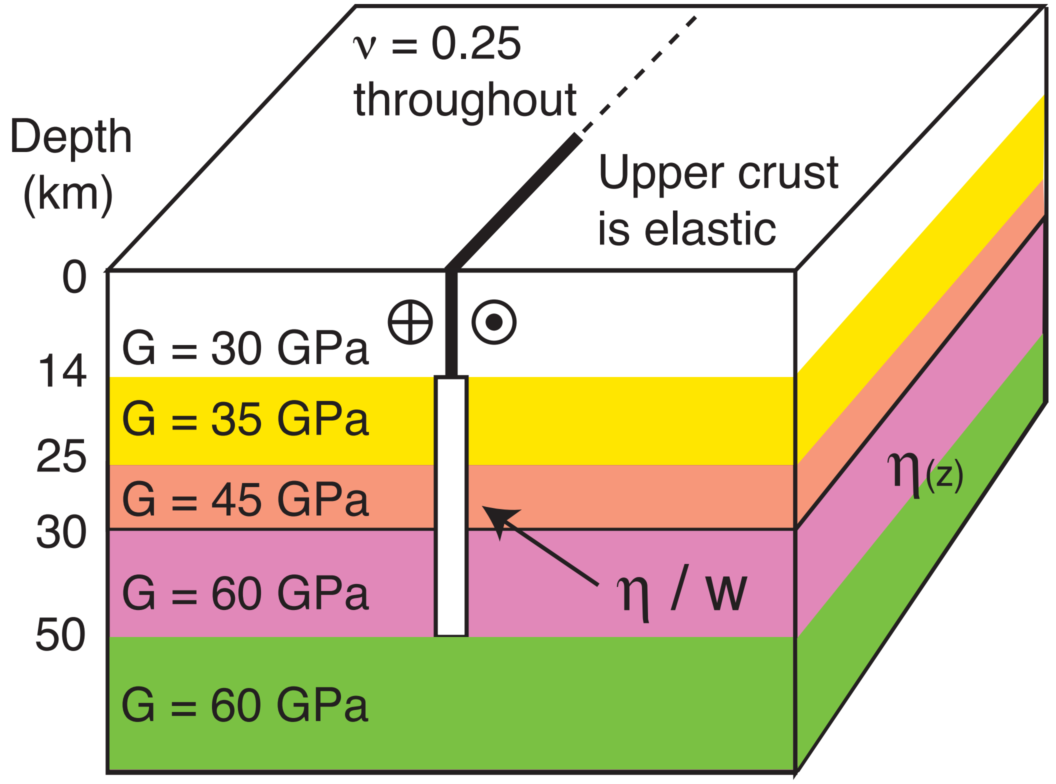


- Non-Maxwell viscoelastic material

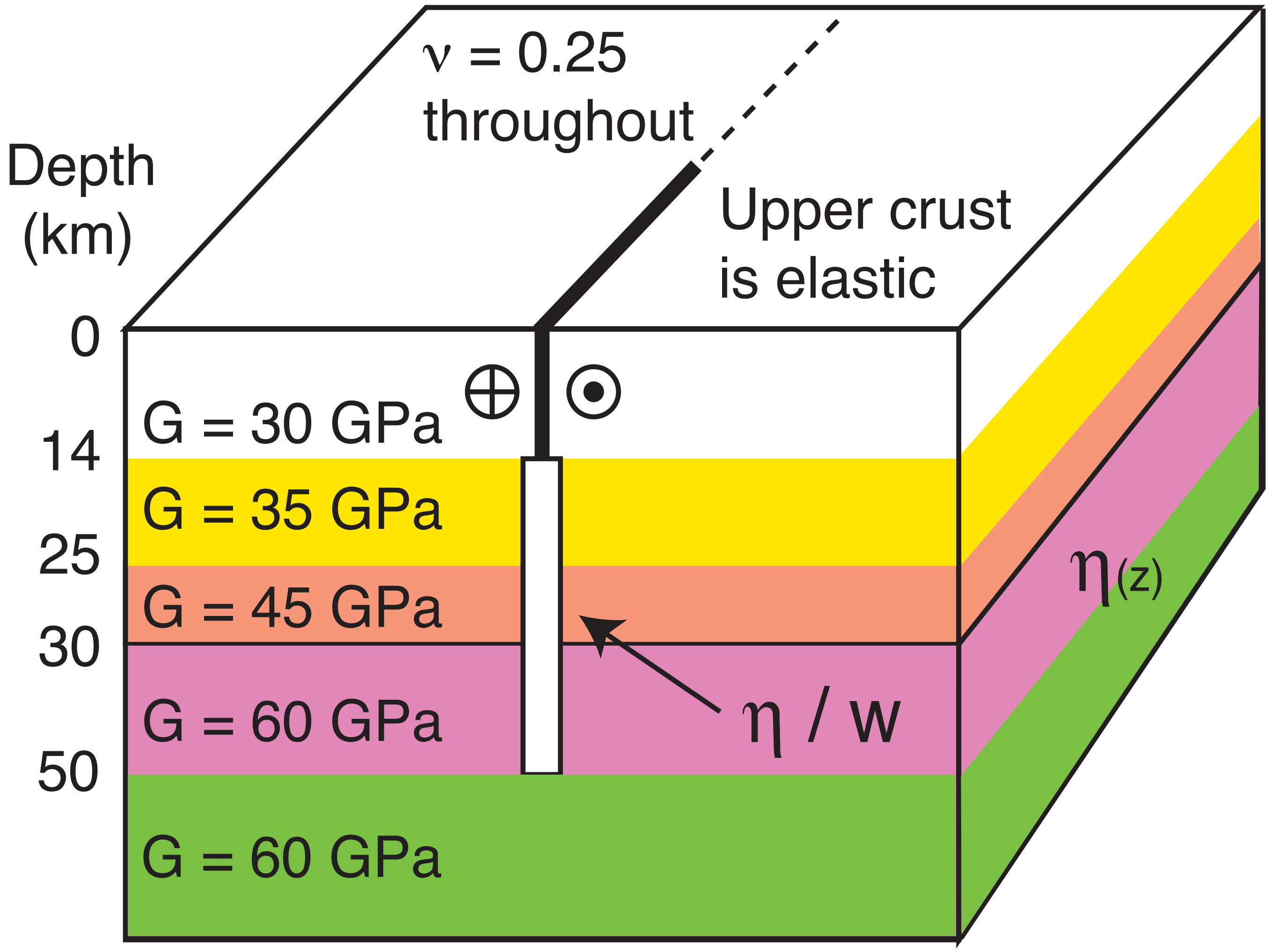
- Finite ruptures

Tc	coseis slip	slip rate	Mw	L	W
300 y	6 m	20 mm/y	7.8	200 km	14 km

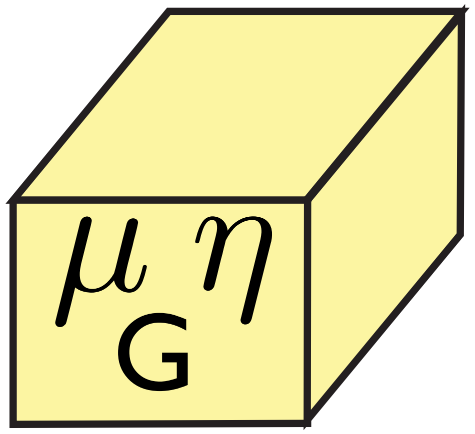
Shorter and infinite-length ruptures, and different slip per event were also modeled, not discussed today.

FEM code: GAEA (Saucier and Humphreys, 1992; Palmer, Hearn)

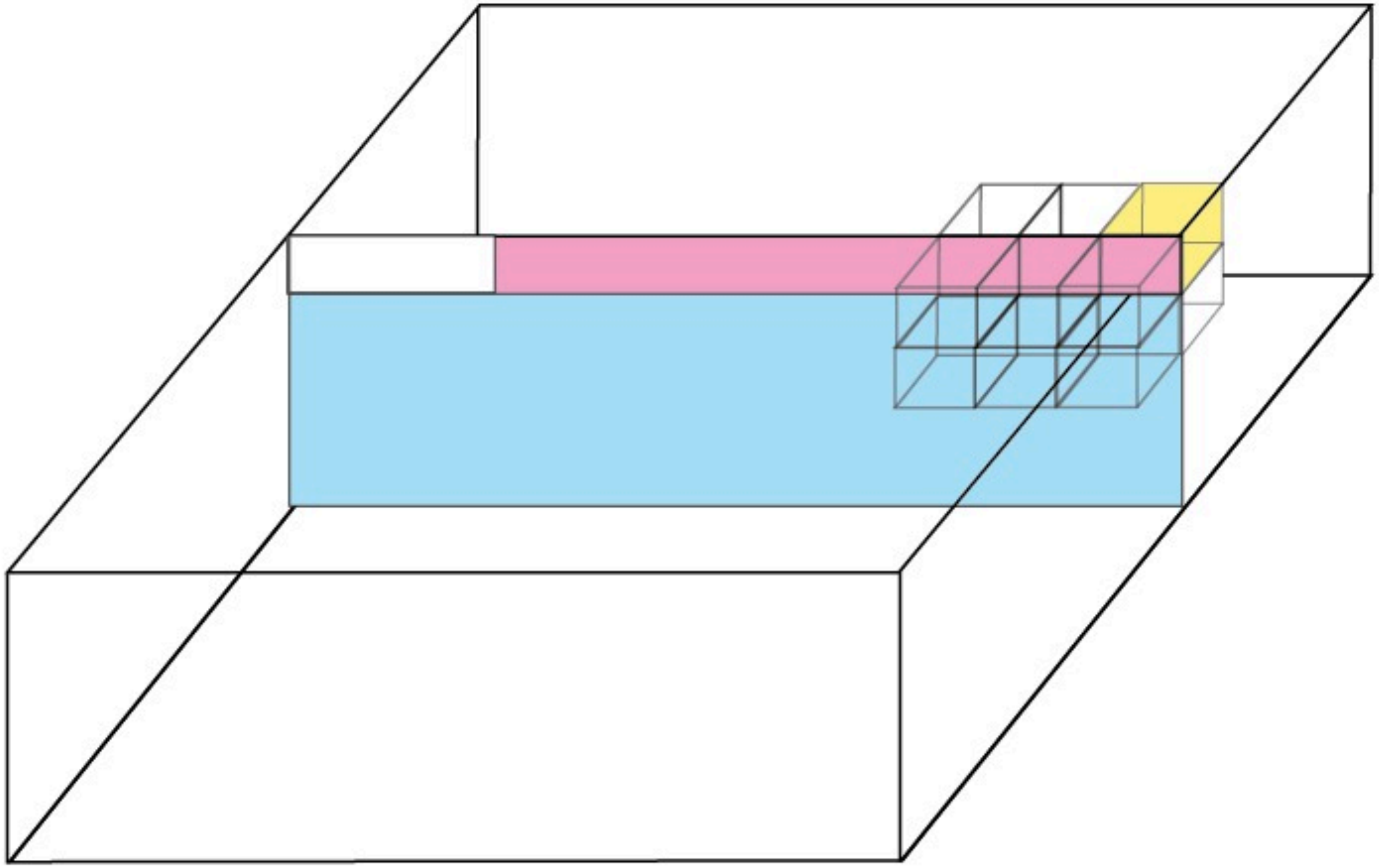
What's in the box?



material properties are assigned to each element and may evolve



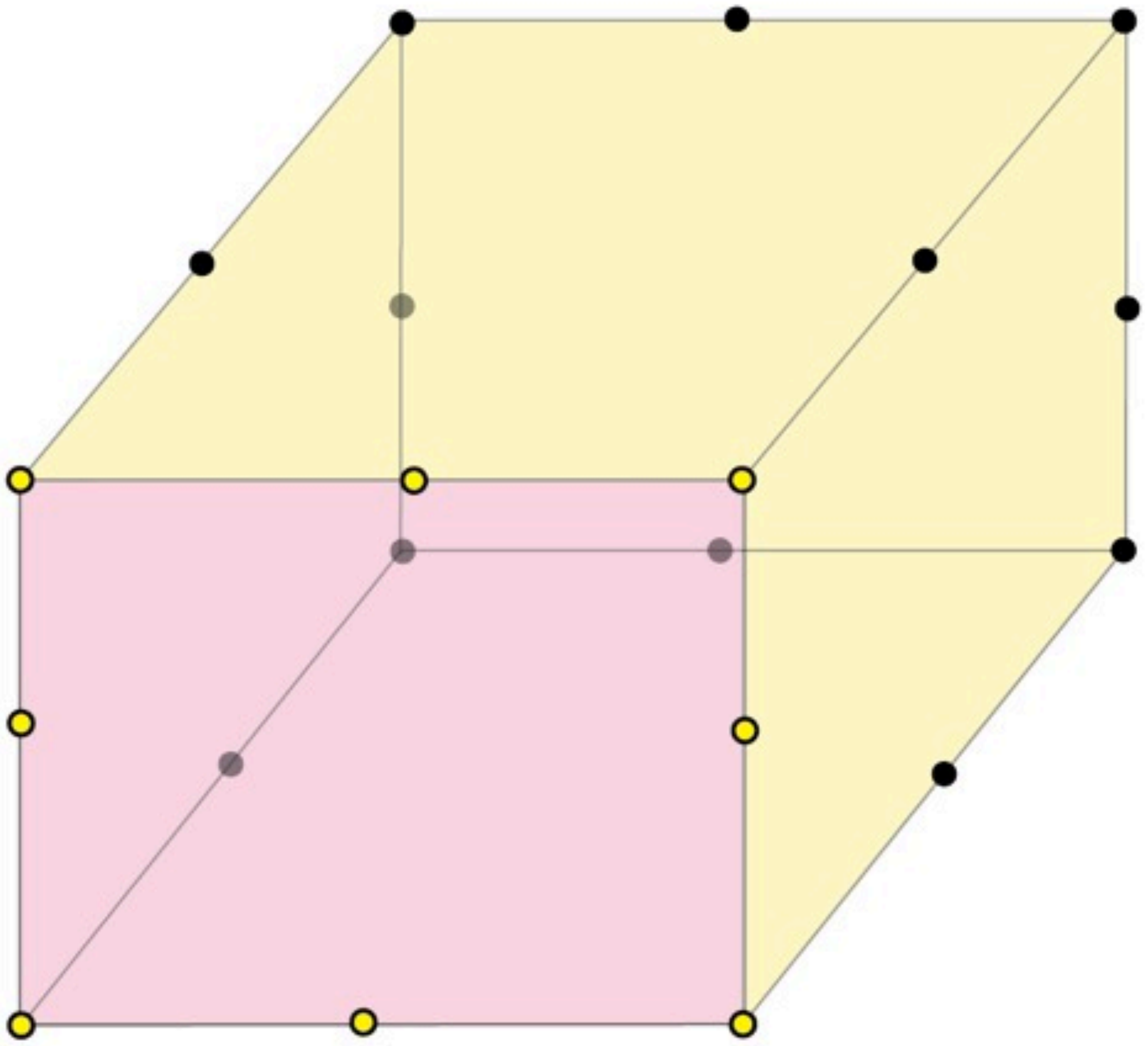
Faults are defined at nodes forming element faces



Assign slip, slip rate or compute stress-driven slip rate each time step. Use split nodes*.

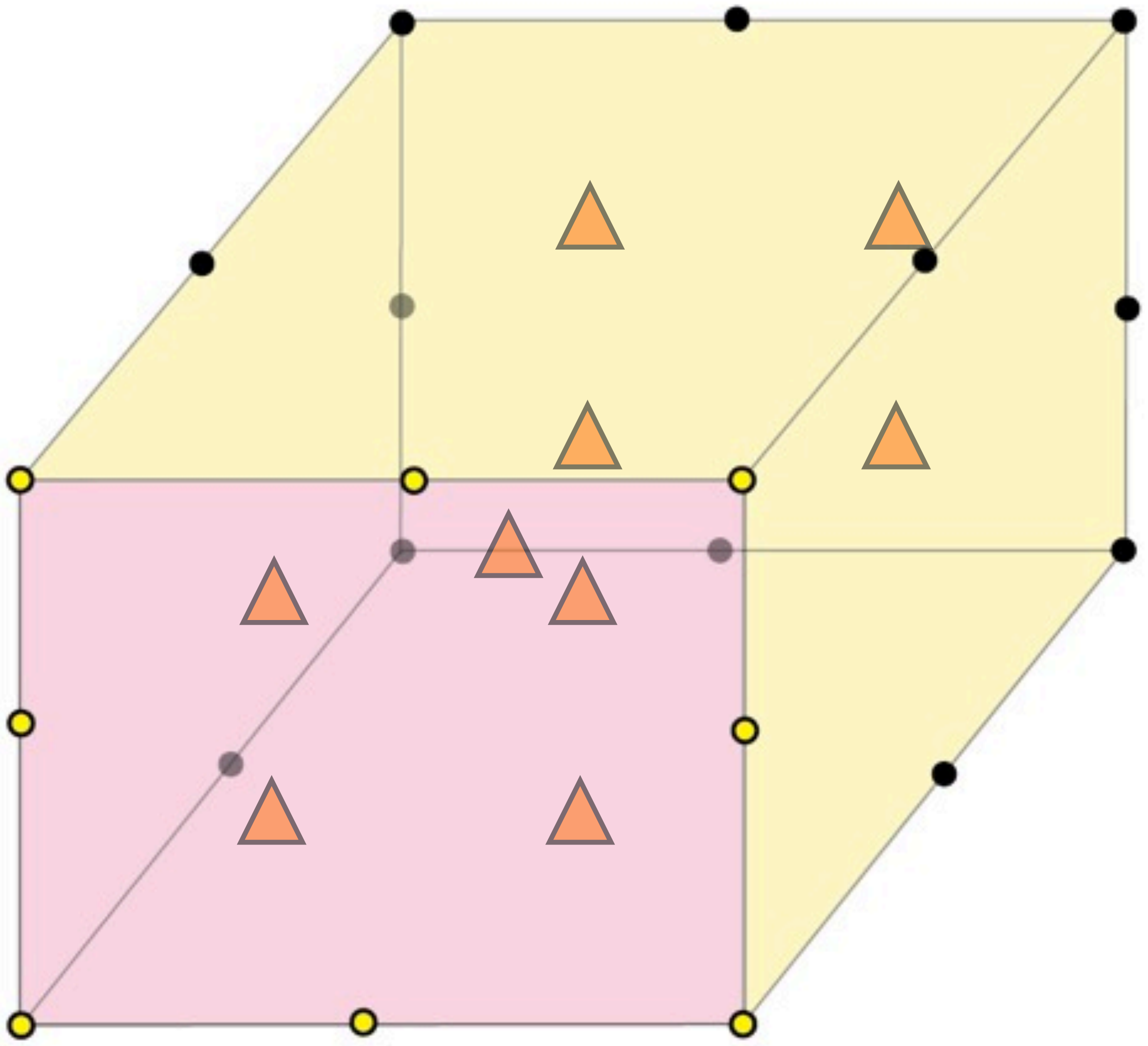
*Melosh and Raefsky, 1981

Modeling stress-driven fault creep



- Compute horizontal shear stress on fault-parallel plane at Gauss point (or points)

Modeling stress-driven fault creep



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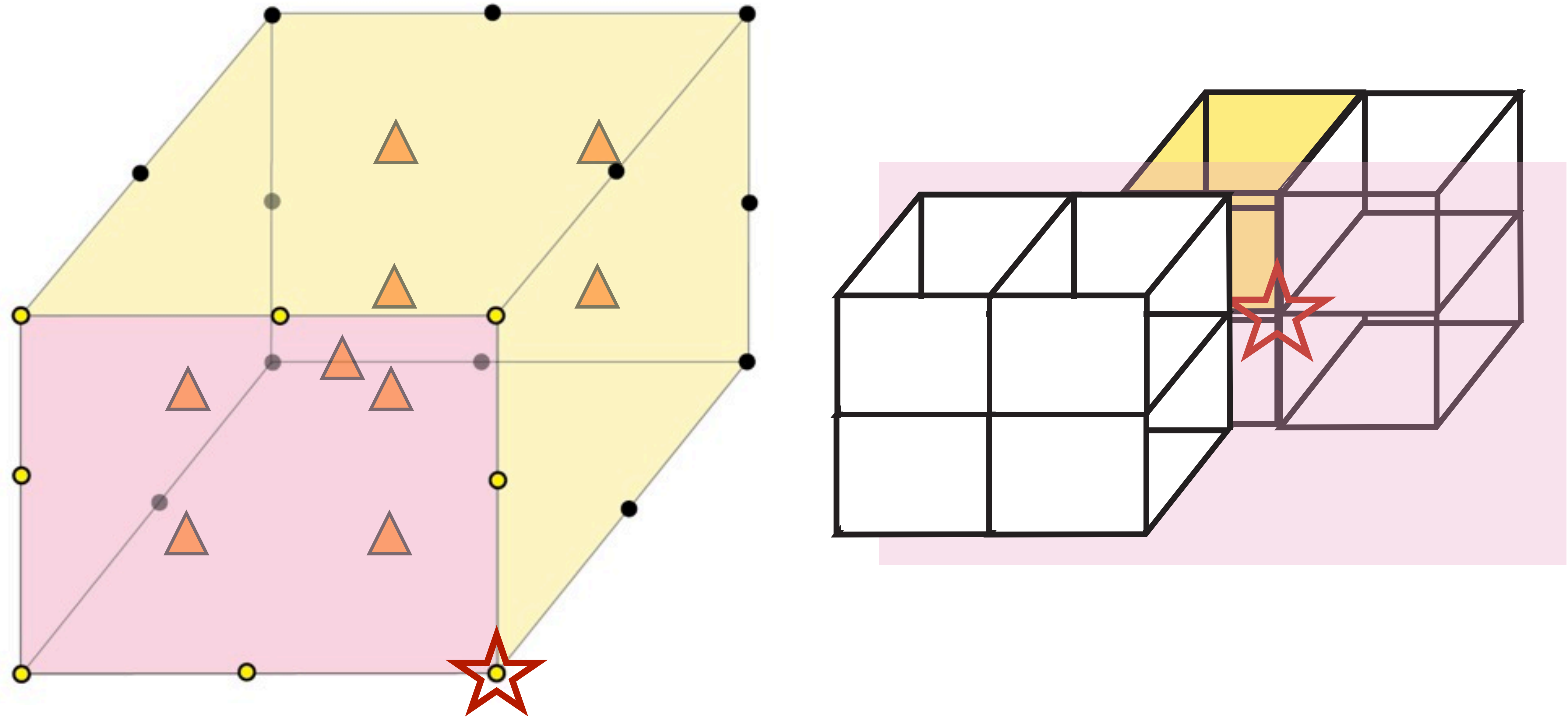
Modeling stress-driven fault creep



- Compute horizontal shear stress on fault-parallel plane at Gauss point (or points)
- Take average for all elements containing the fault node

Modeling stress-driven viscous fault creep

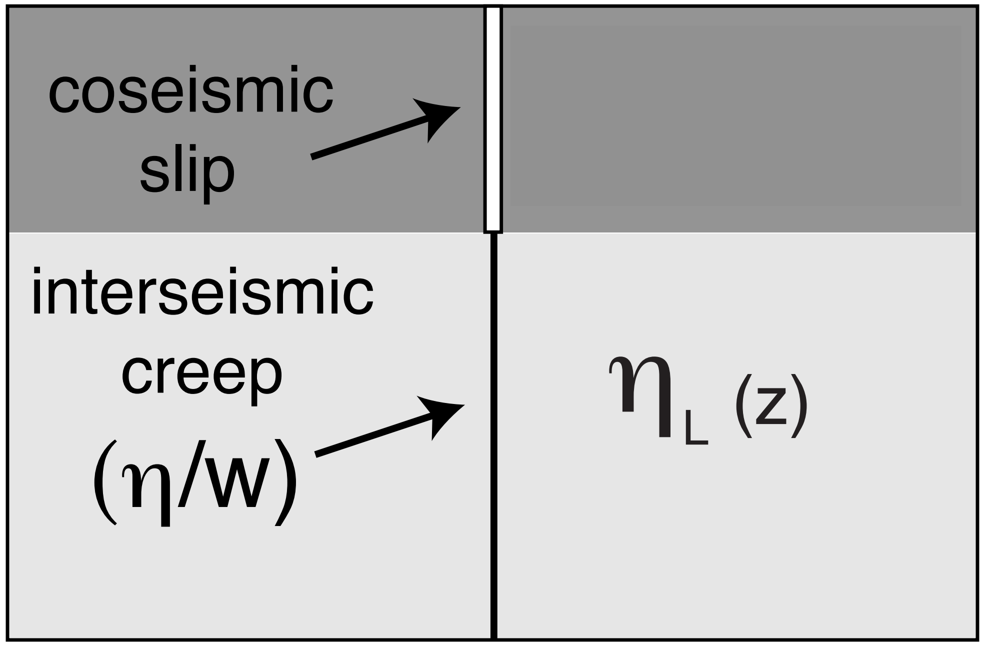
Finite width shear zone is represented as a surface in the mesh.

Offset rate at each fault node is calculated from shear stress at each time step.

$$v = \tau(\frac{w}{\eta})$$

$\frac{\eta}{w}$ can vary with stress, position or time.

Today: Results from three models



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For a large suite of 2D and 3D models, see Hearn and Thatcher, 2014

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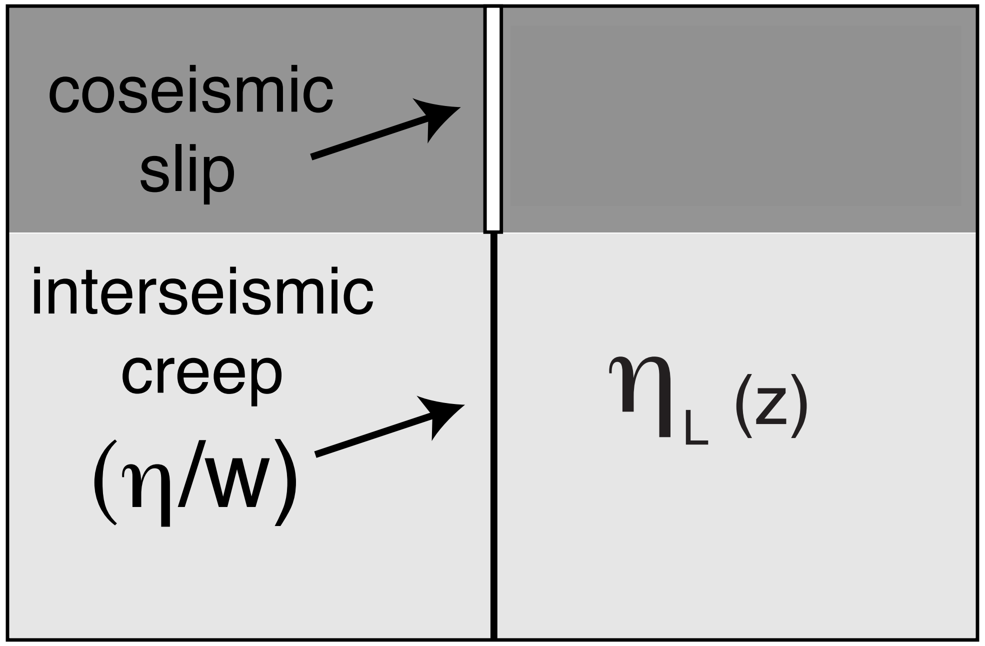

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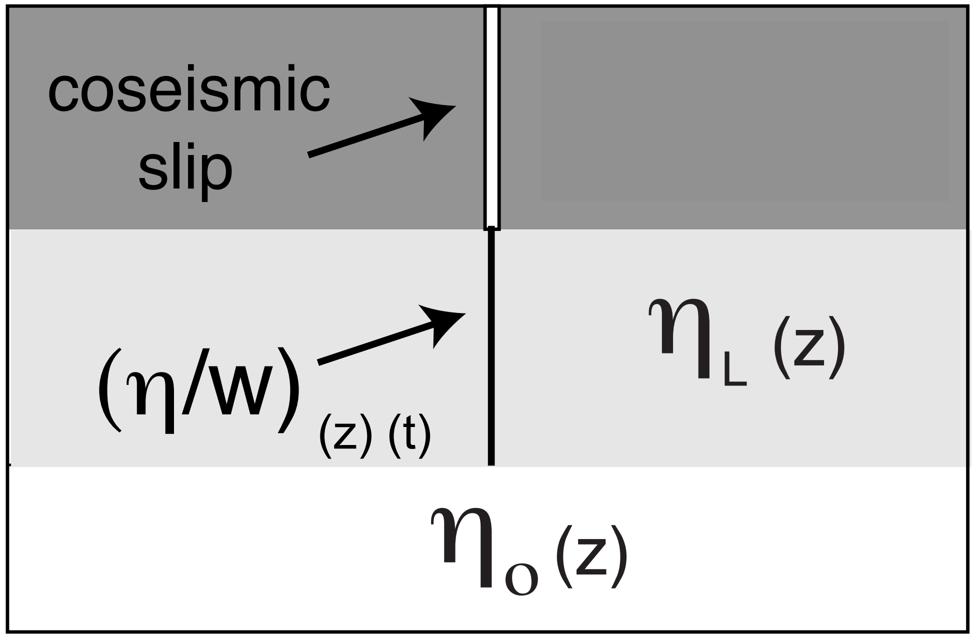

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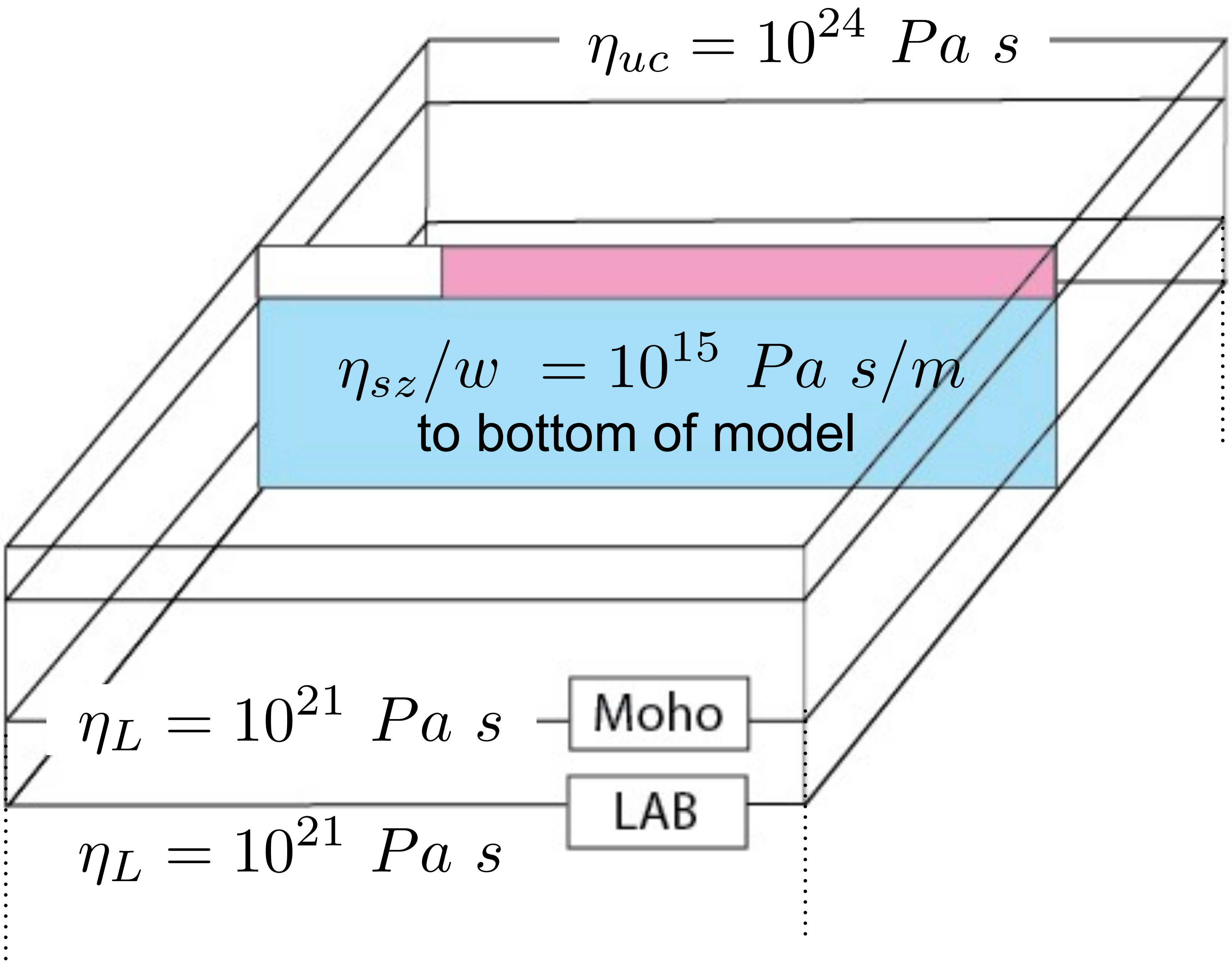

$\eta_{uc} = 10^{24}\ Pa\ s$

$\eta_{sz}/w = 10^{15}\ Pa\ s/m$

to bottom of model

$\eta_L = 10^{21}\ Pa\ s$

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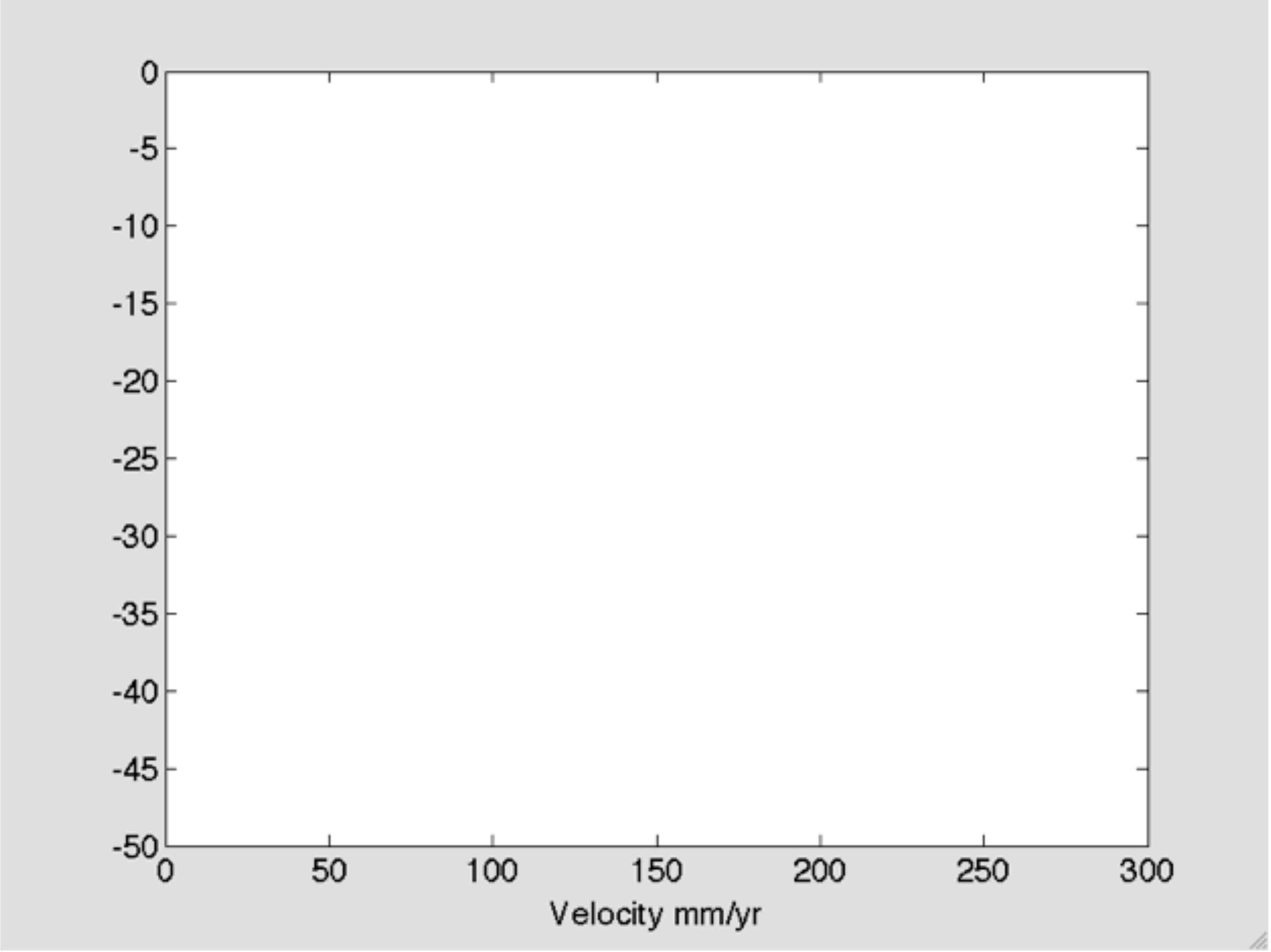
Slip velocity below coseismic rupture as a function of depth and time

①

Slip velocity below coseismic rupture as a function of depth and time



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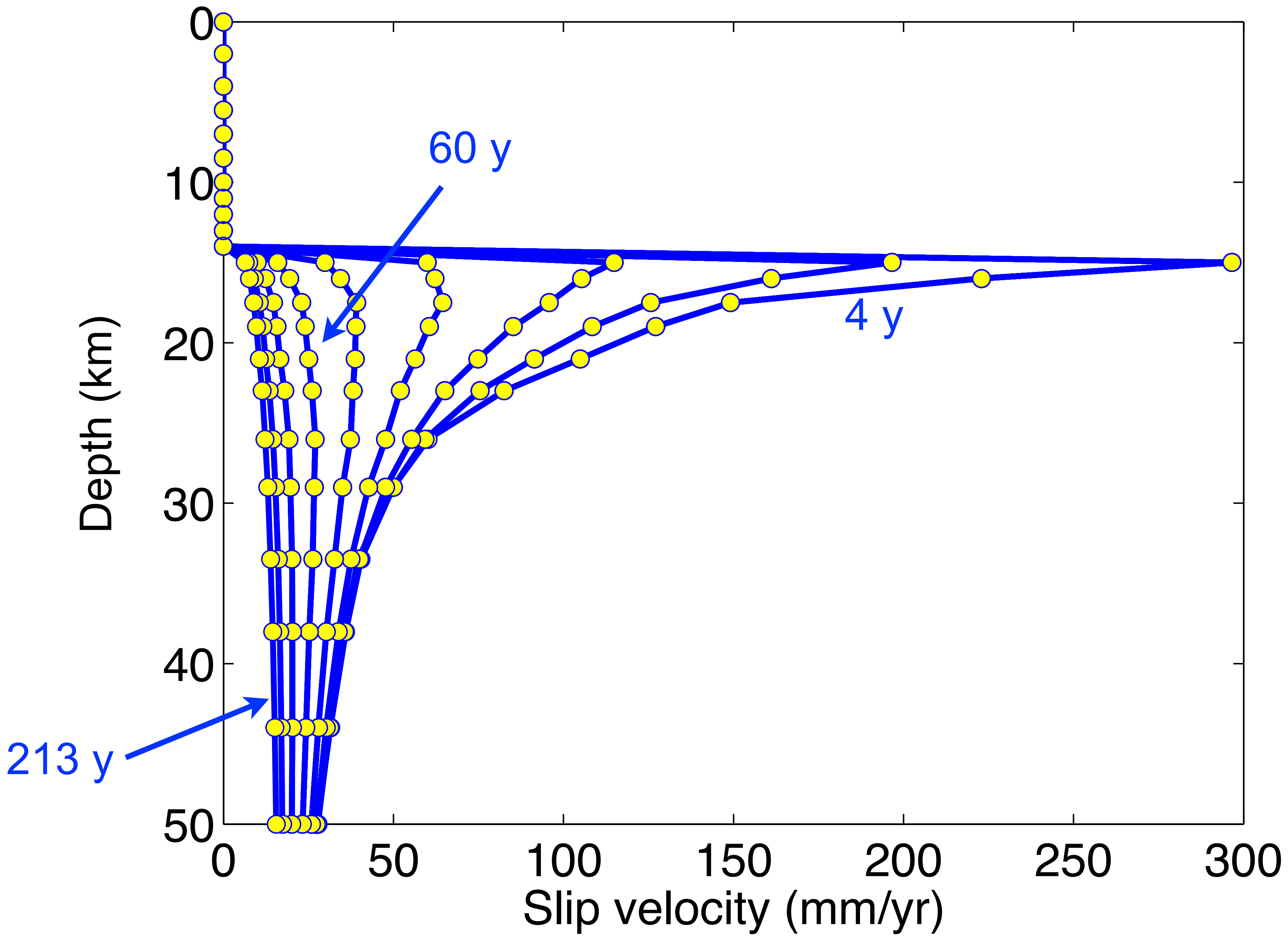

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Slip velocity below coseismic rupture as a function of position and time

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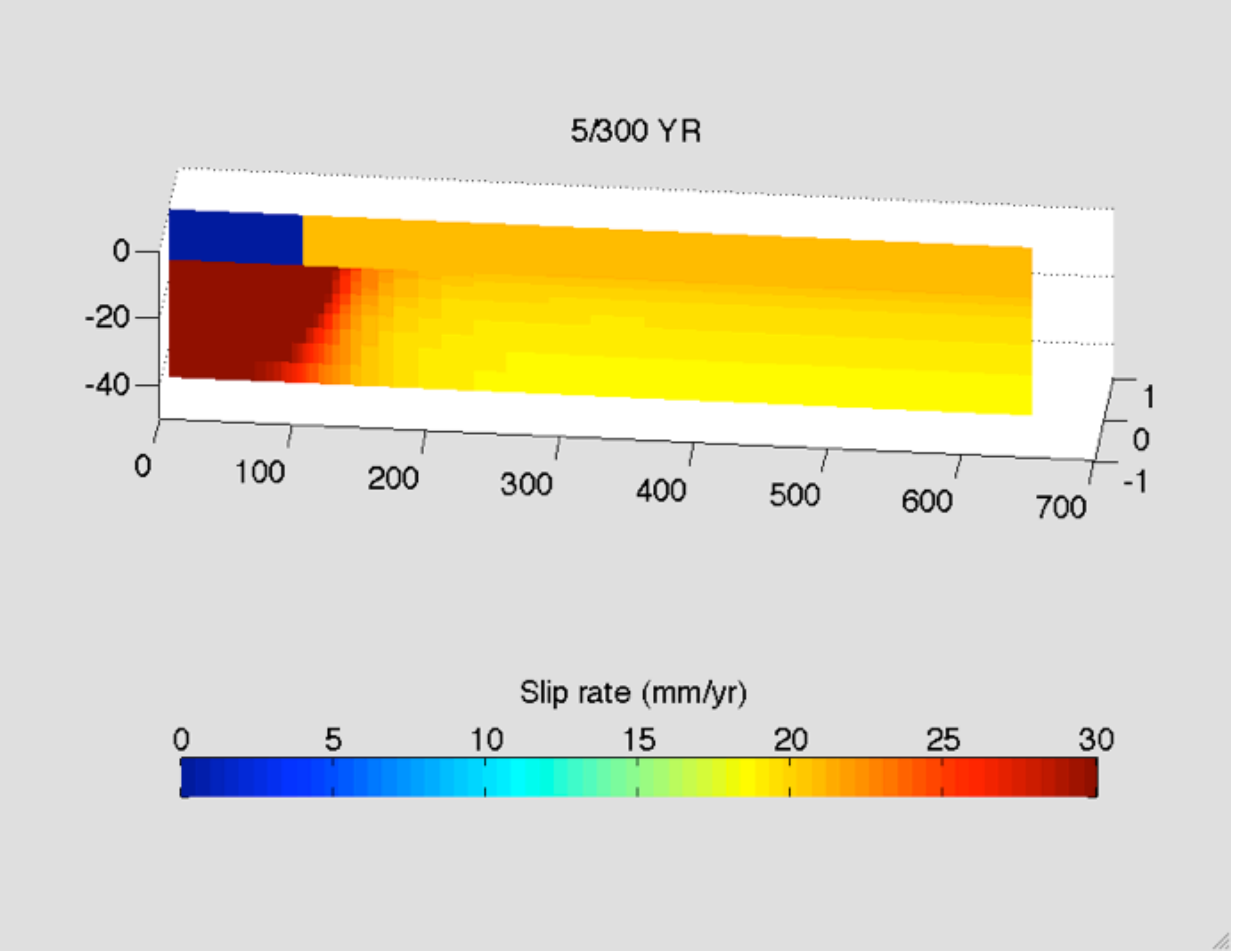

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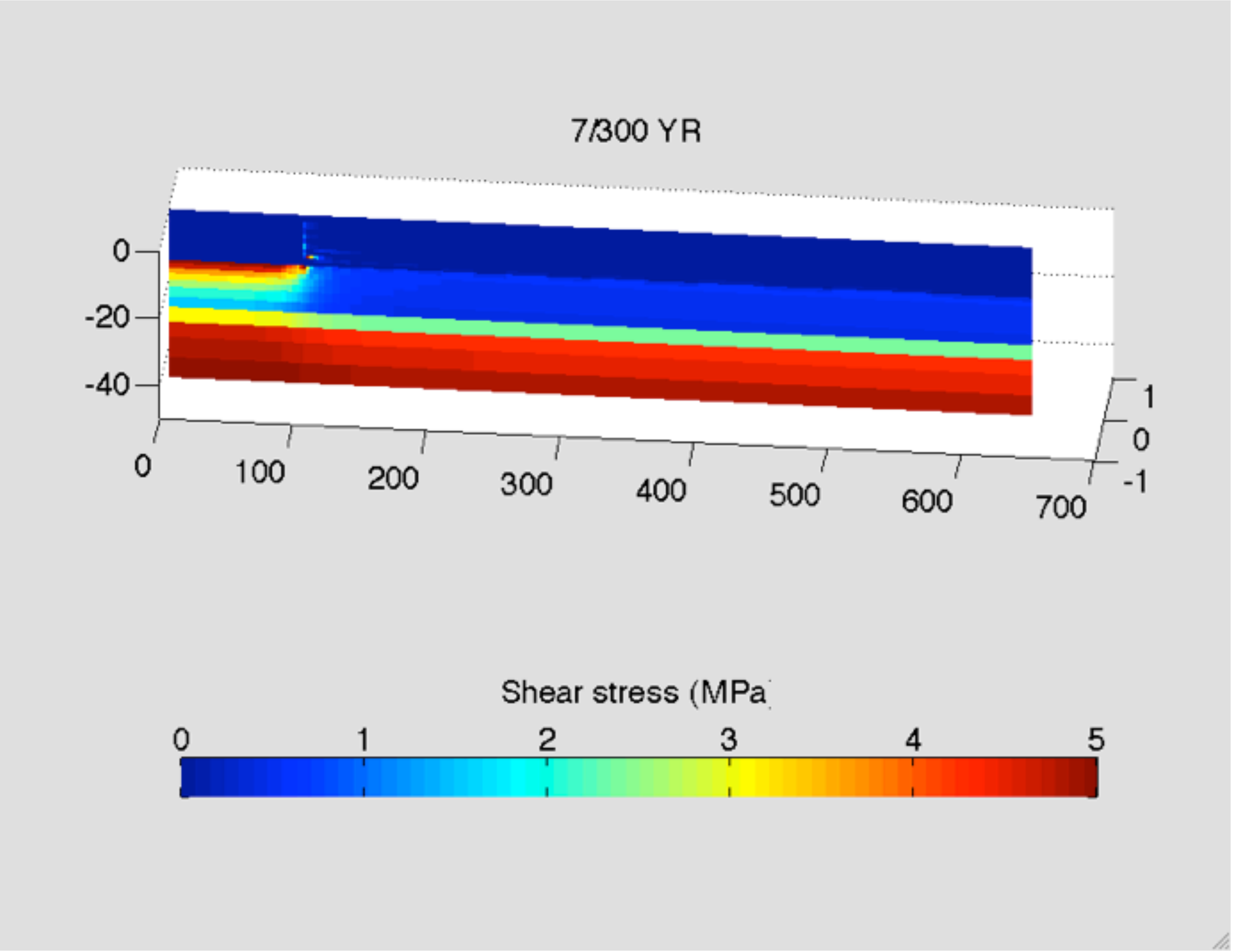
Shear stress below coseismic rupture as a function of position and time

①

Shear stress below coseismic rupture as a function of position and time



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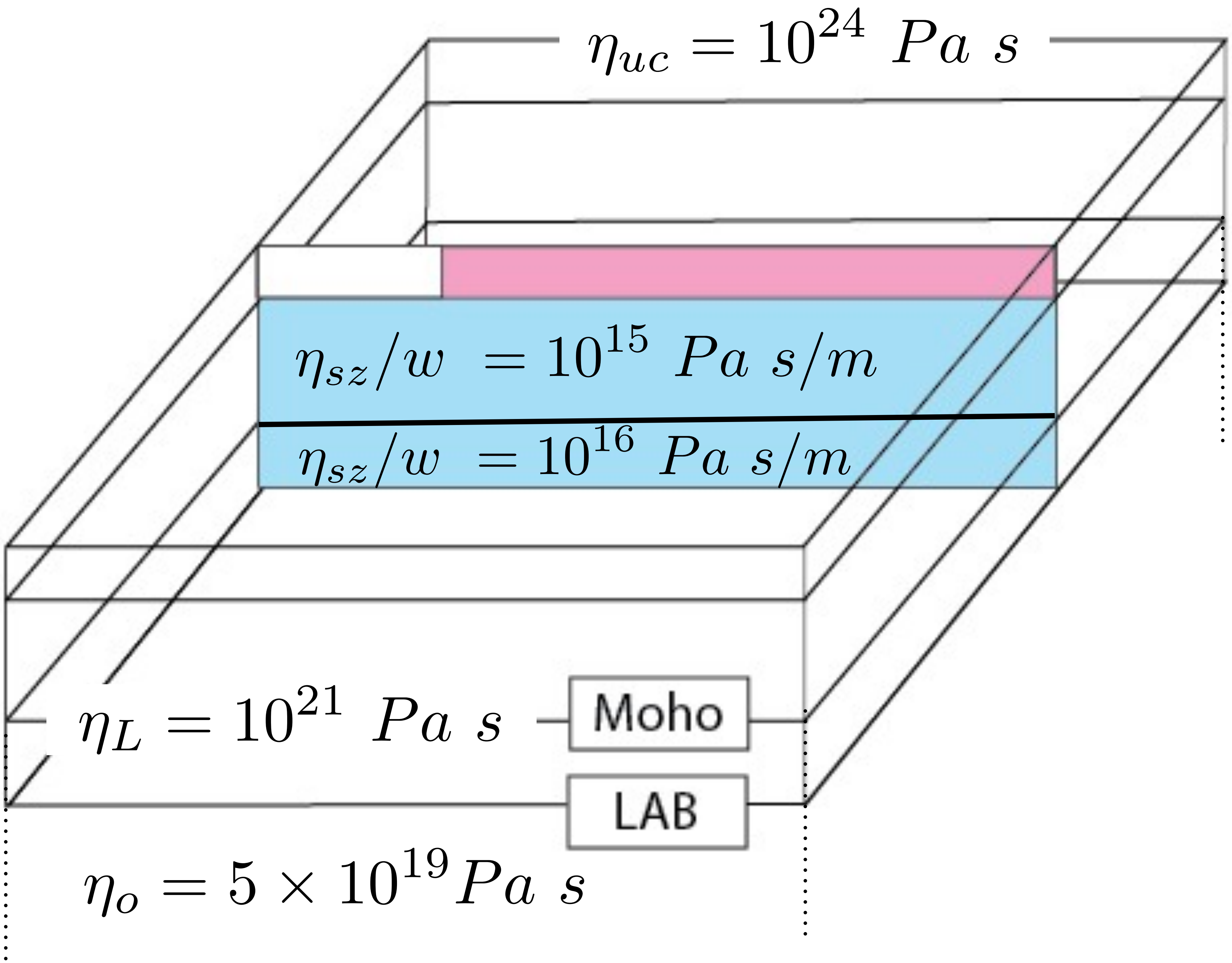
$\eta_{uc} = 10^{24}\ Pa\ s$

$\eta_{sz}/w\ = 10^{15}\ Pa\ s/m$

$\eta_{sz}/w\ = 10^{16}\ Pa\ s/m$

$\eta_L = 10^{21}\ Pa\ s$

$\eta_o = 5 \times 10^{19} Pa\ s$

Slip velocity below coseismic rupture as a function of position and time

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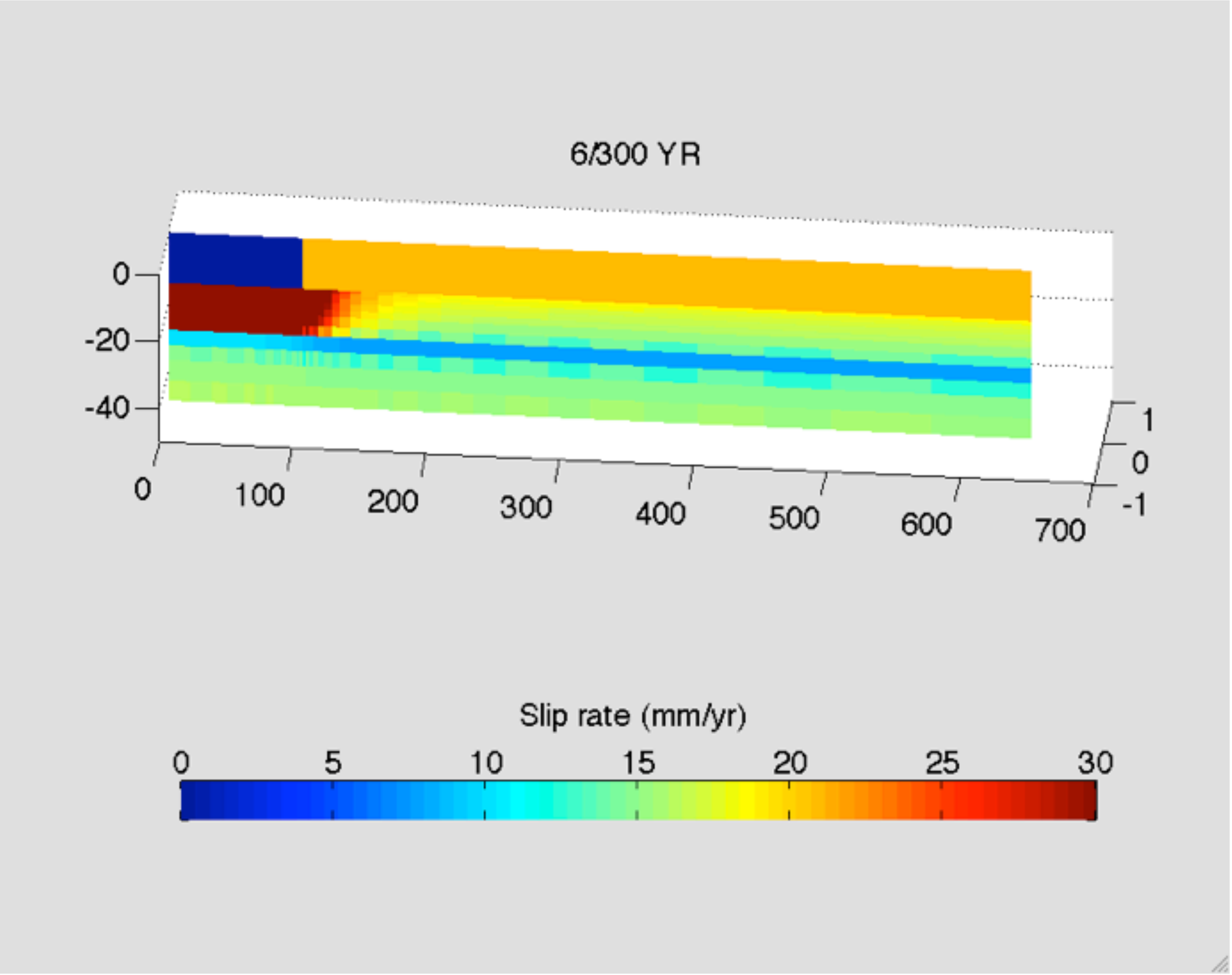
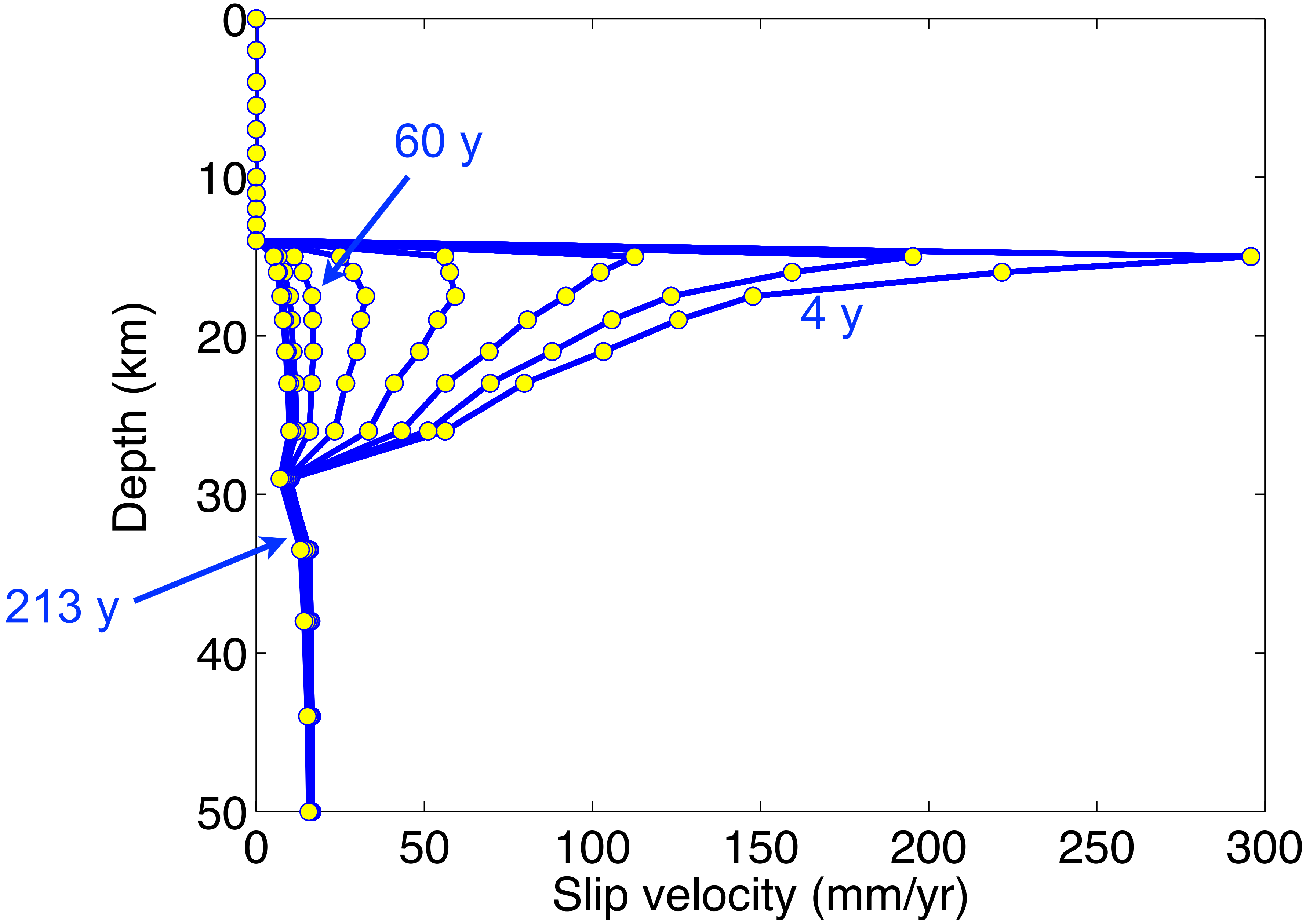
Slip velocity below coseismic rupture as a function of position and time



Slip velocity below coseismic rupture as a function of depth and time



Shear stress below coseismic rupture as a function of position and time

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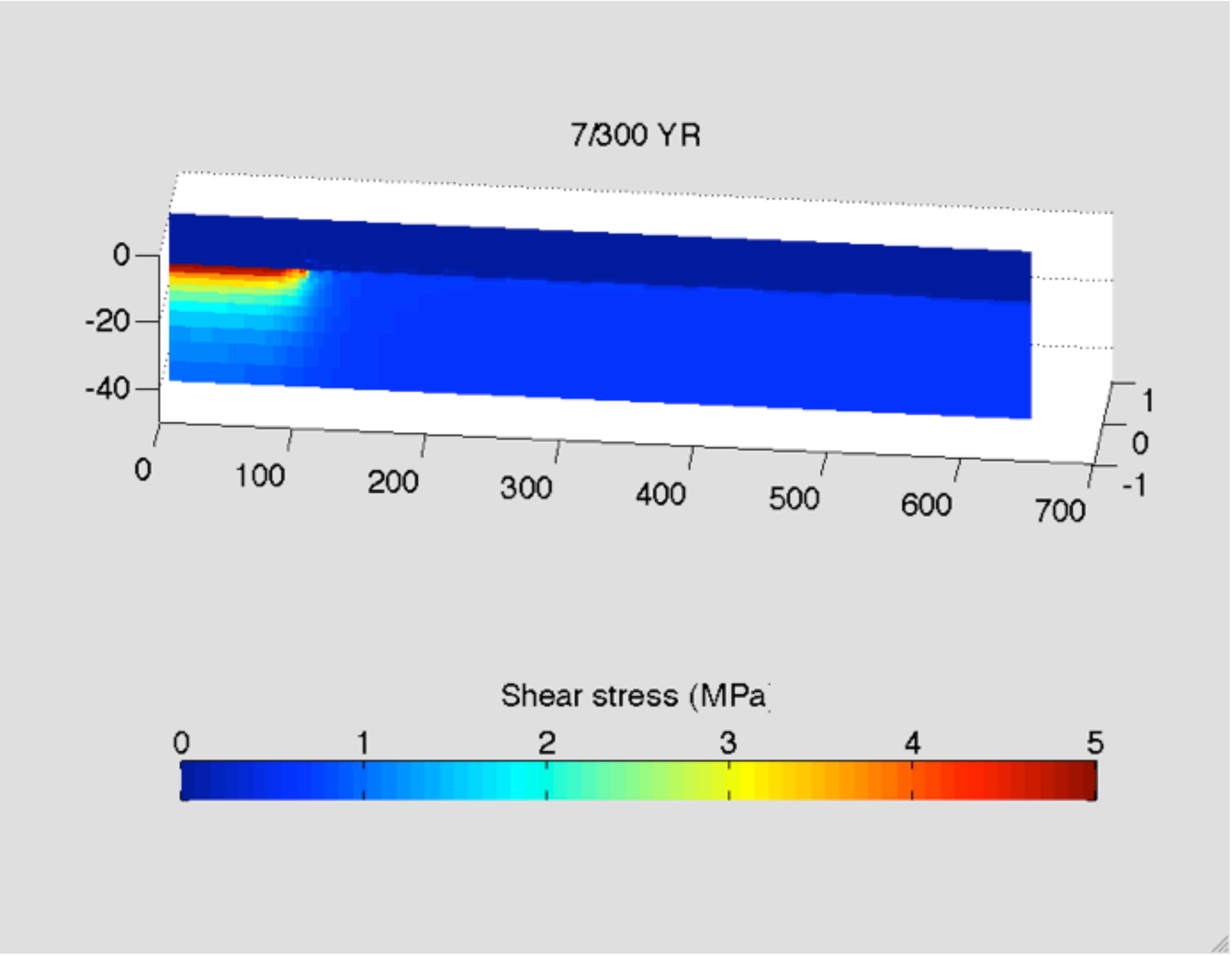

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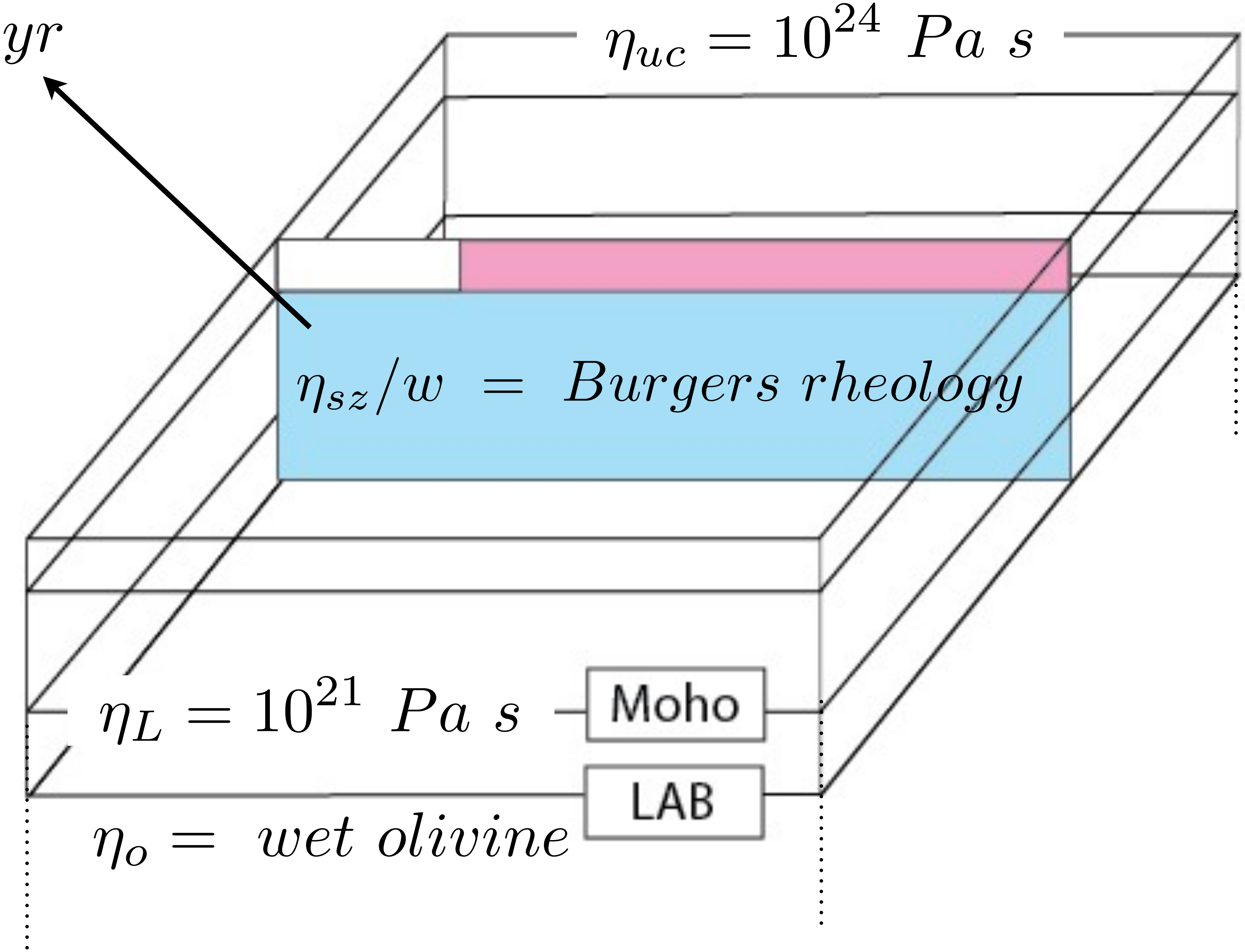
$10^{15}\ Pa\ s$ to $5 \times 10^{15}\ Pa\ s$

$t_c = 10\ yr$



$\eta_{uc} = 10^{24}\ Pa\ s$

$\eta_{sz}/w\ =$ *Burgers rheology*

$\eta_L = 10^{21}\ Pa\ s$

Moho

LAB

$\eta_o =$ *wet olivine*

Slip velocity below coseismic rupture as a function of position and time

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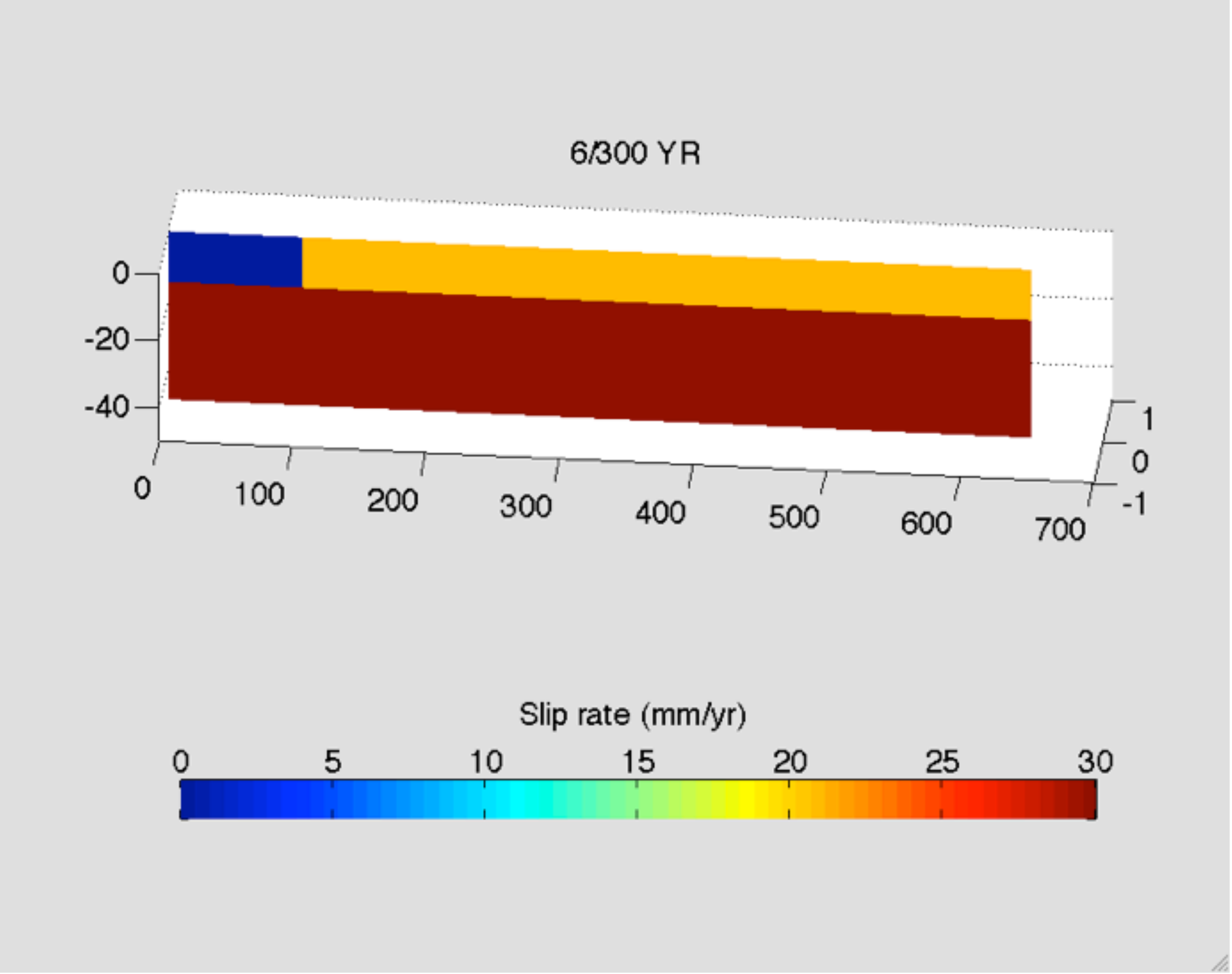
Slip velocity below coseismic rupture as a function of position and time



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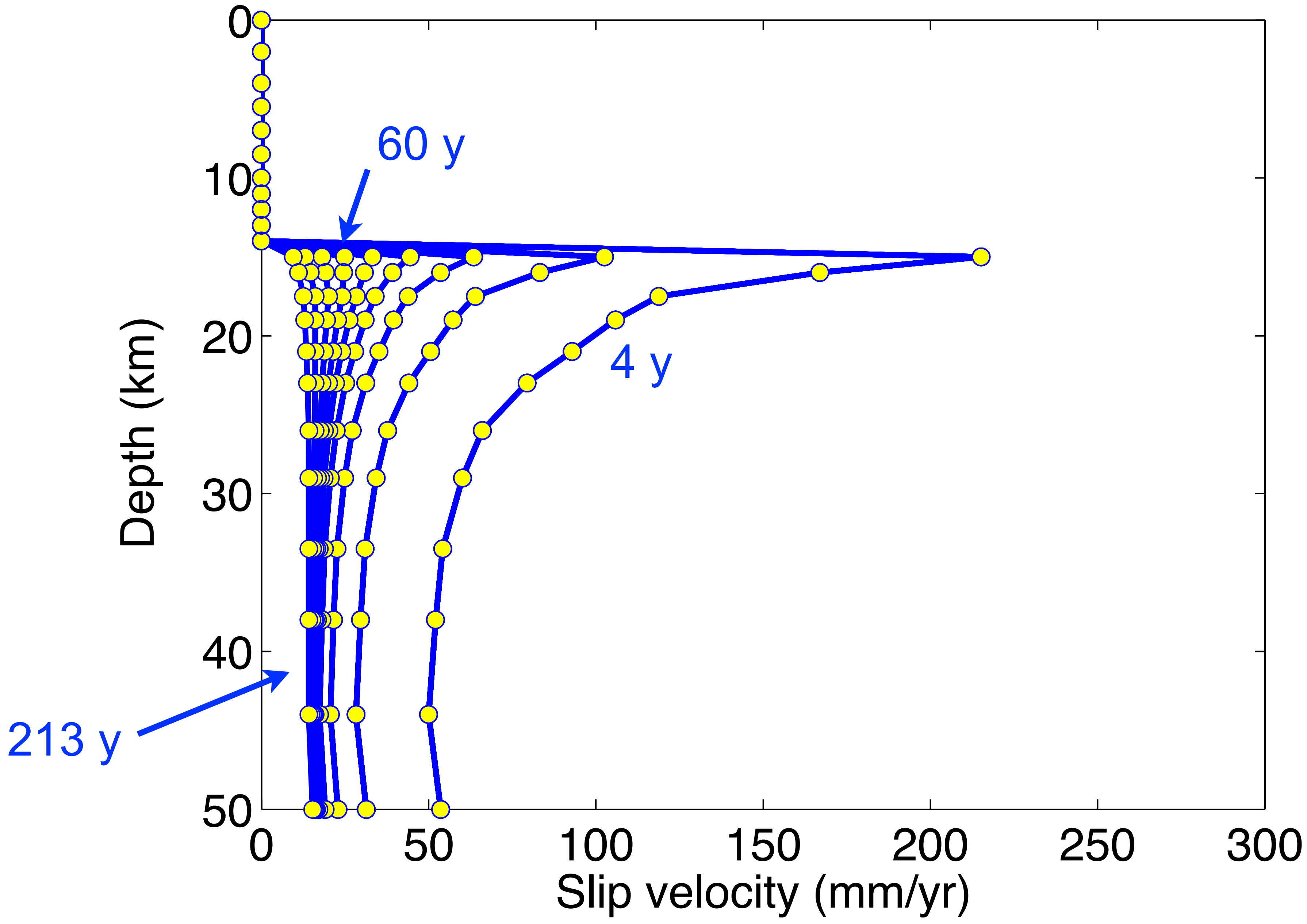

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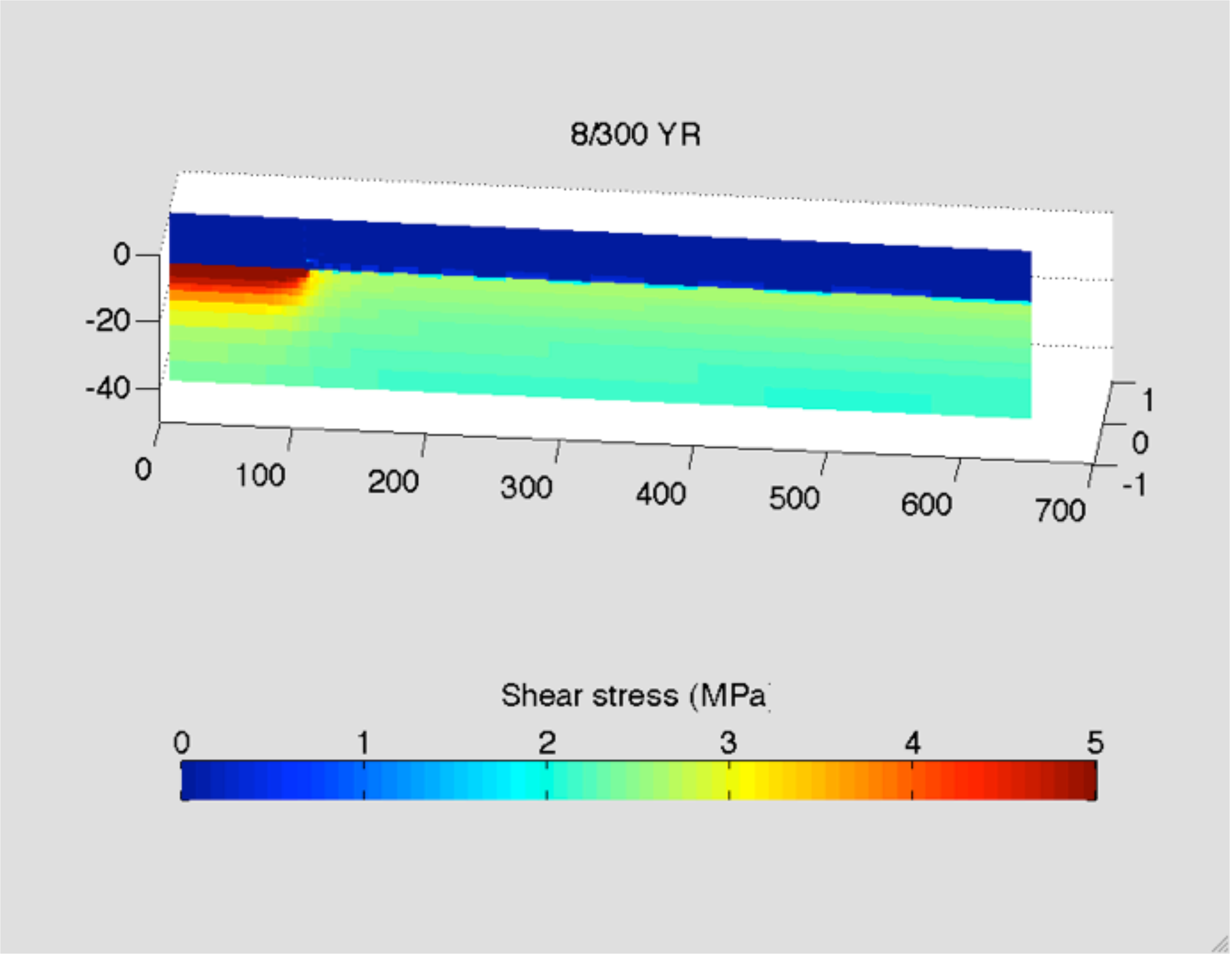
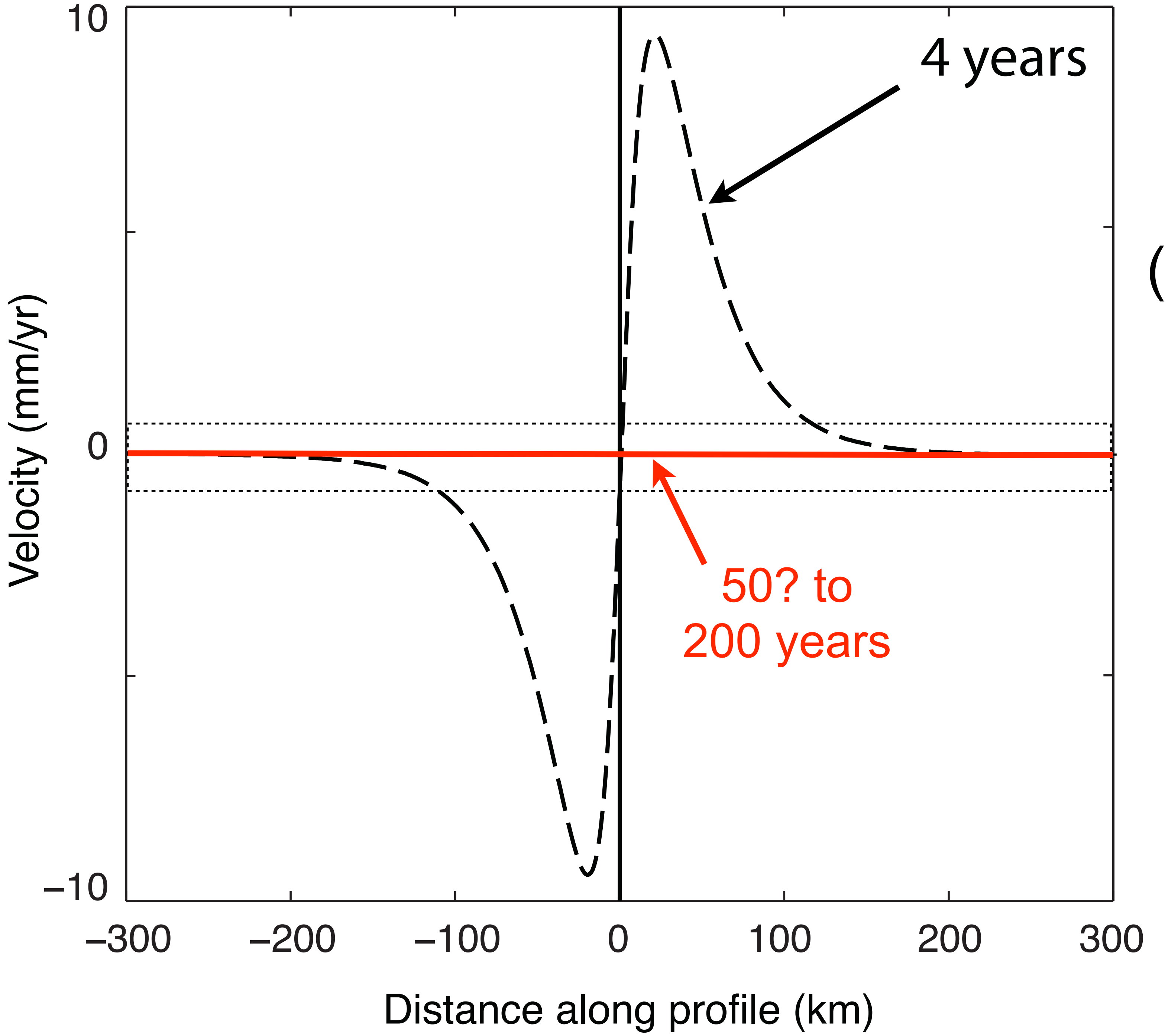


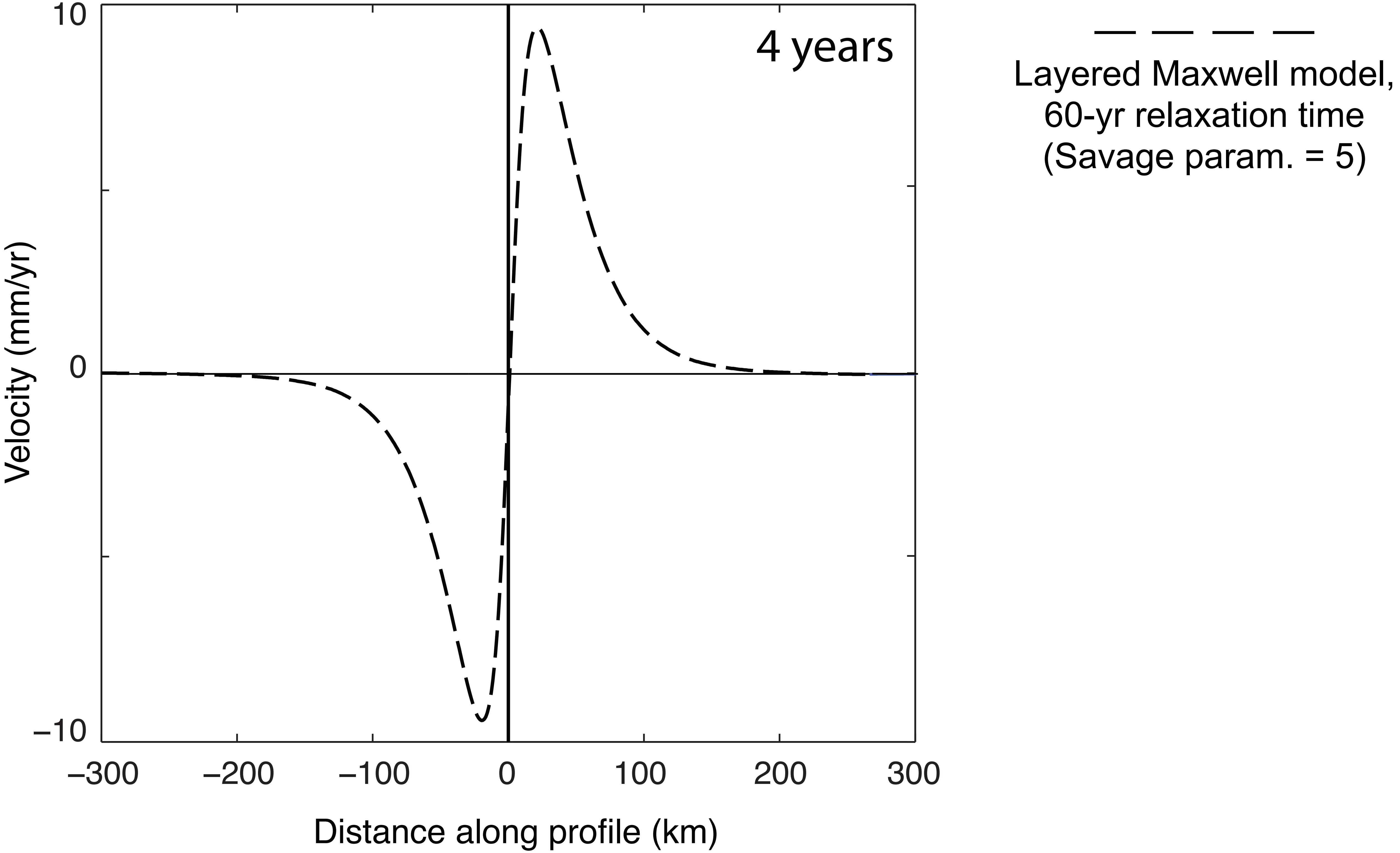
Velocity perturbations throughout the earthquake cycle: reference models



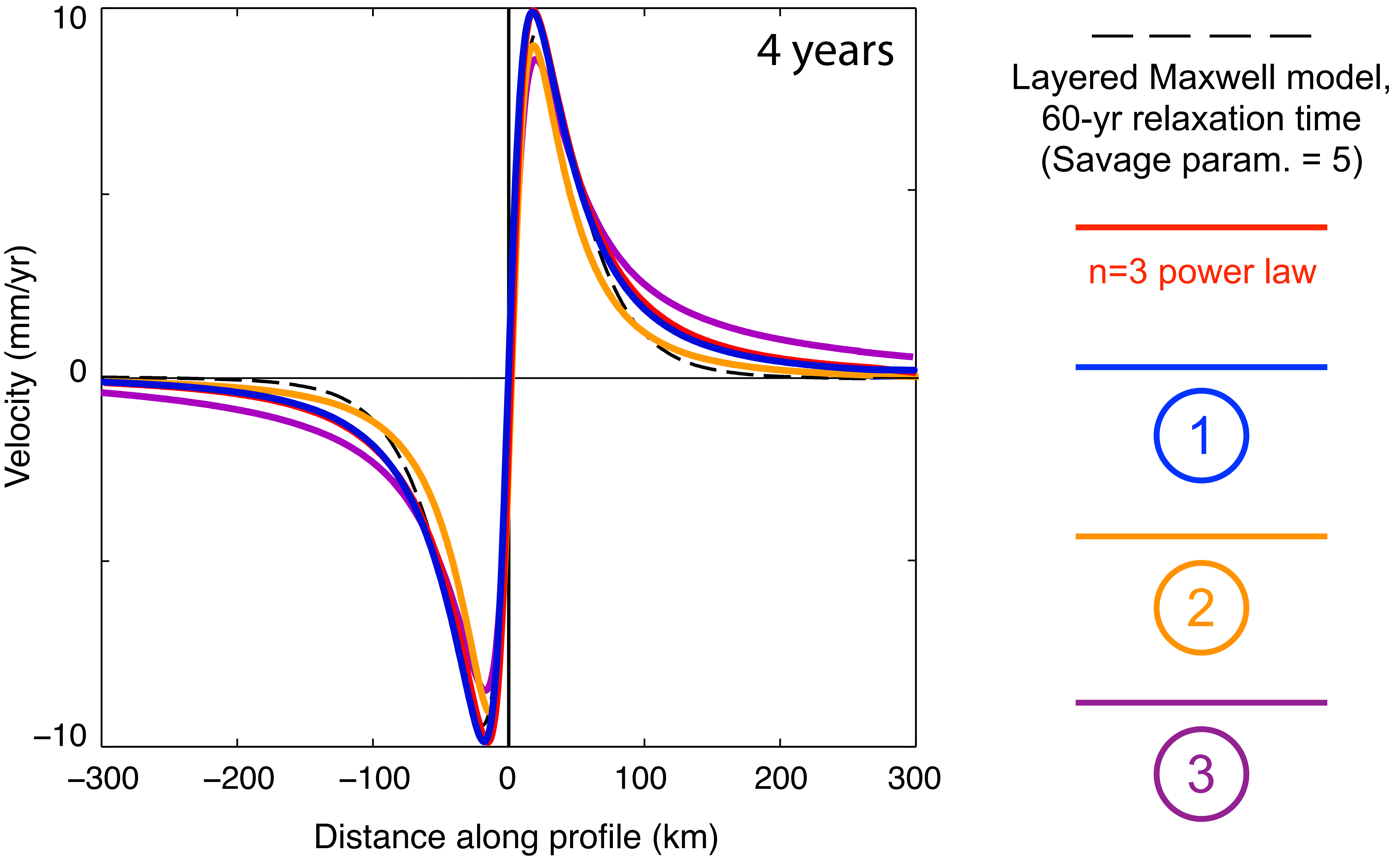
Postseismic deformation (perturbation relative to the cycle average)

Interseismic: we want the profile to look like the cycle average, so negligible perturbation

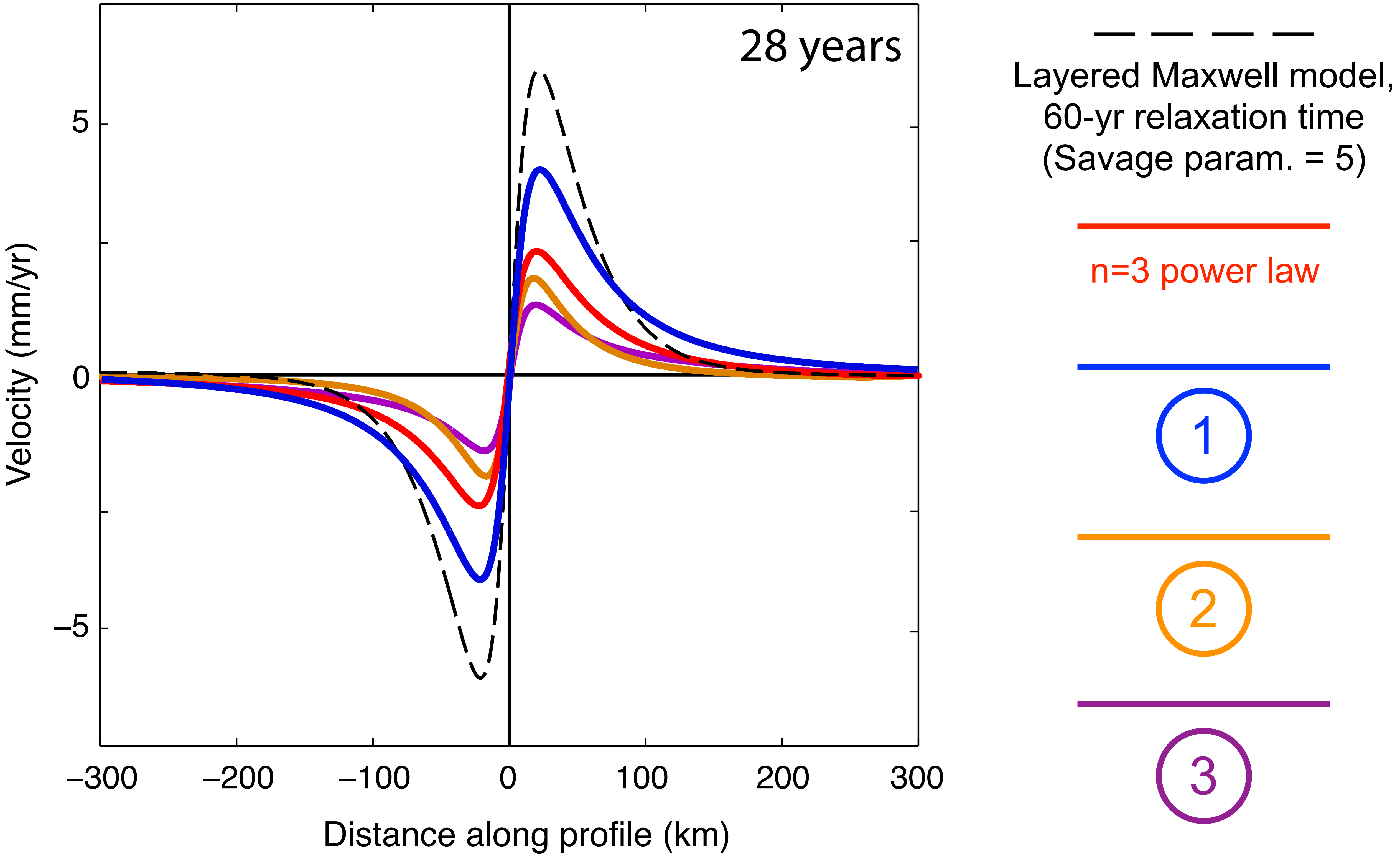
Several models can generally represent postseismic deformation



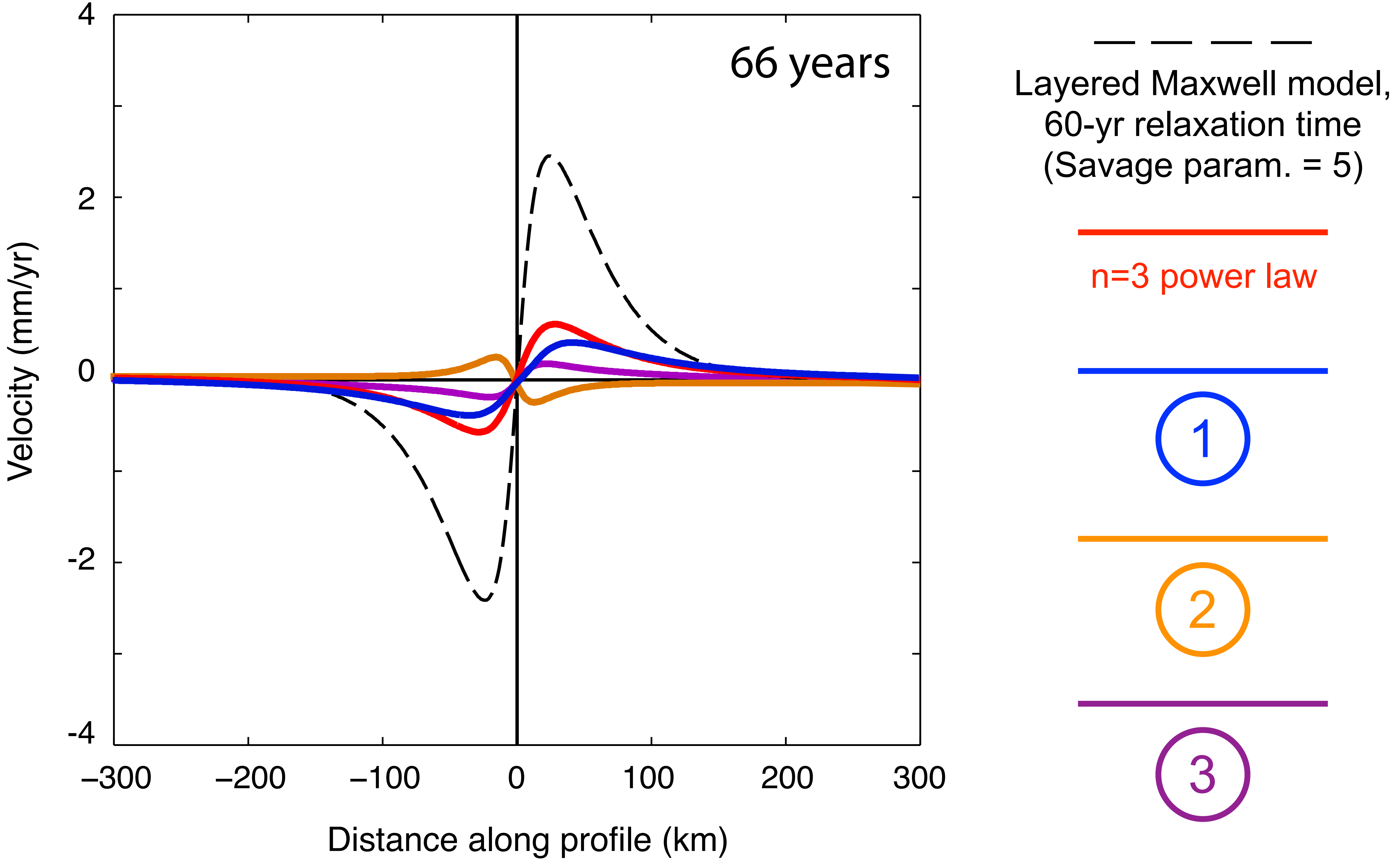
Several models can generally represent postseismic deformation



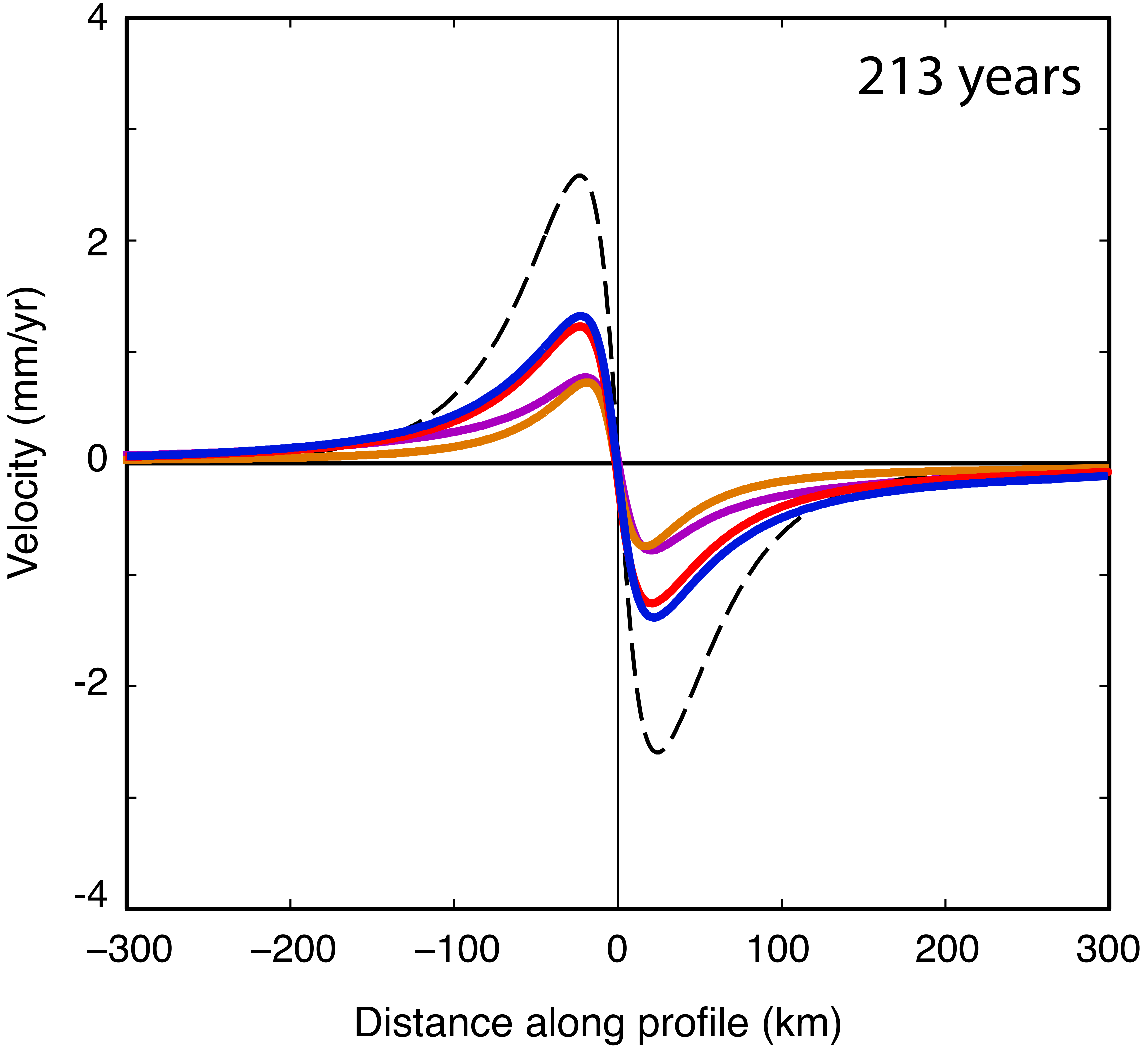
Interseismic velocity perturbations relative to cycle average



Interseismic velocity perturbations relative to cycle average



Interseismic velocity perturbations relative to cycle average



— — — —

Layered Maxwell model, 60-yr relaxation time (Savage param. = 5)

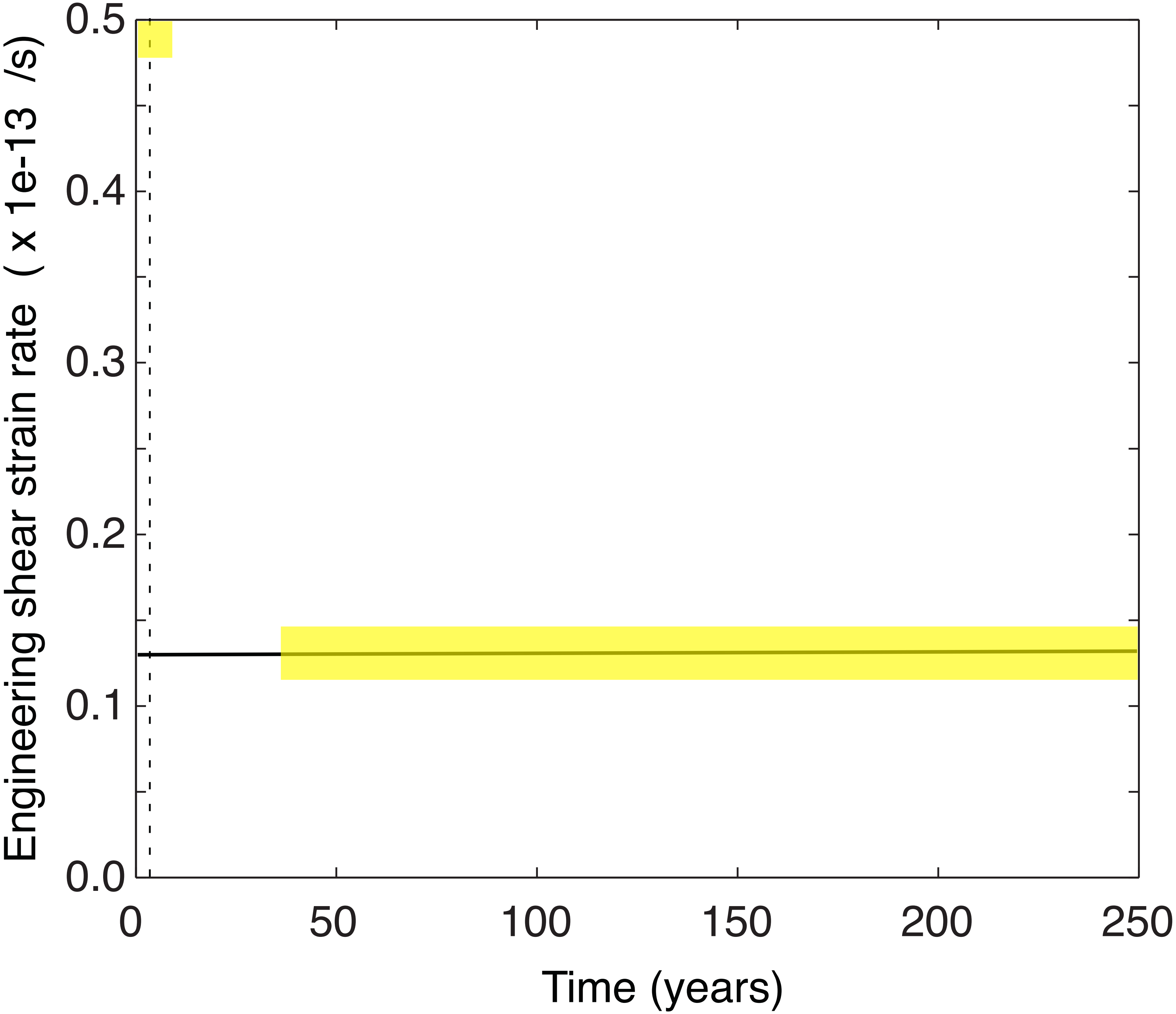
n=3 power law

①

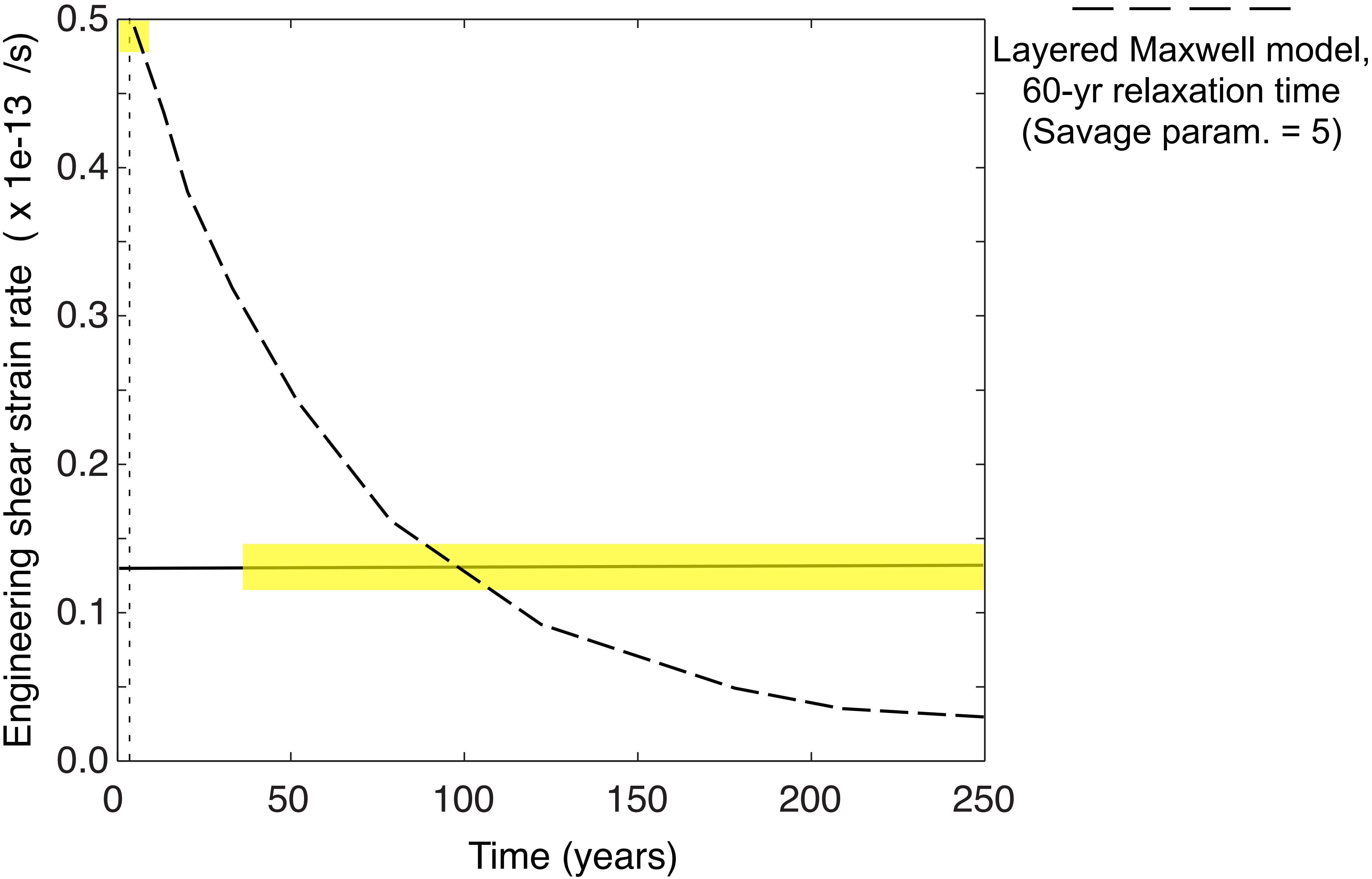
②

③

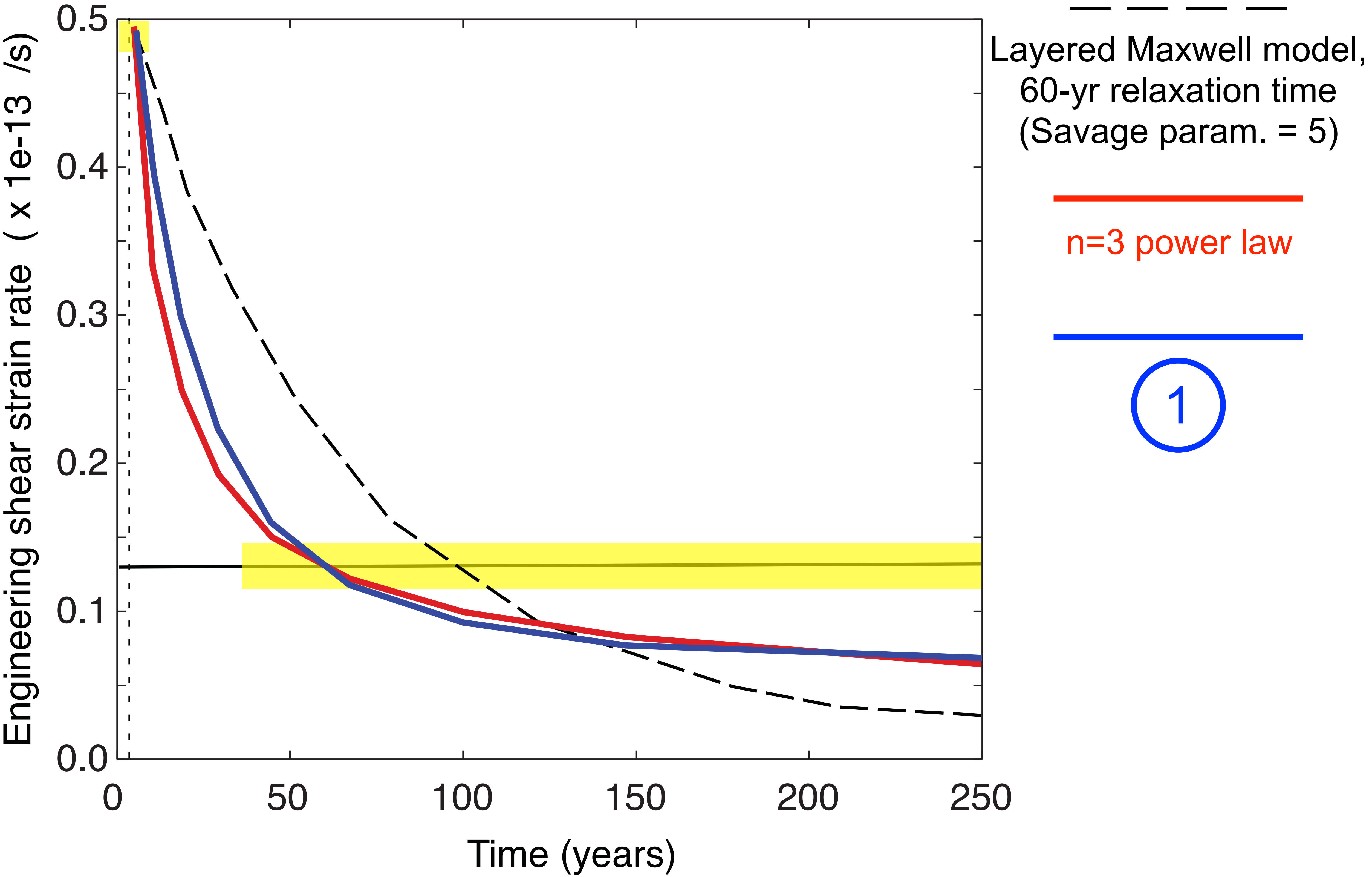
Shear strain rate at the fault as a function of time



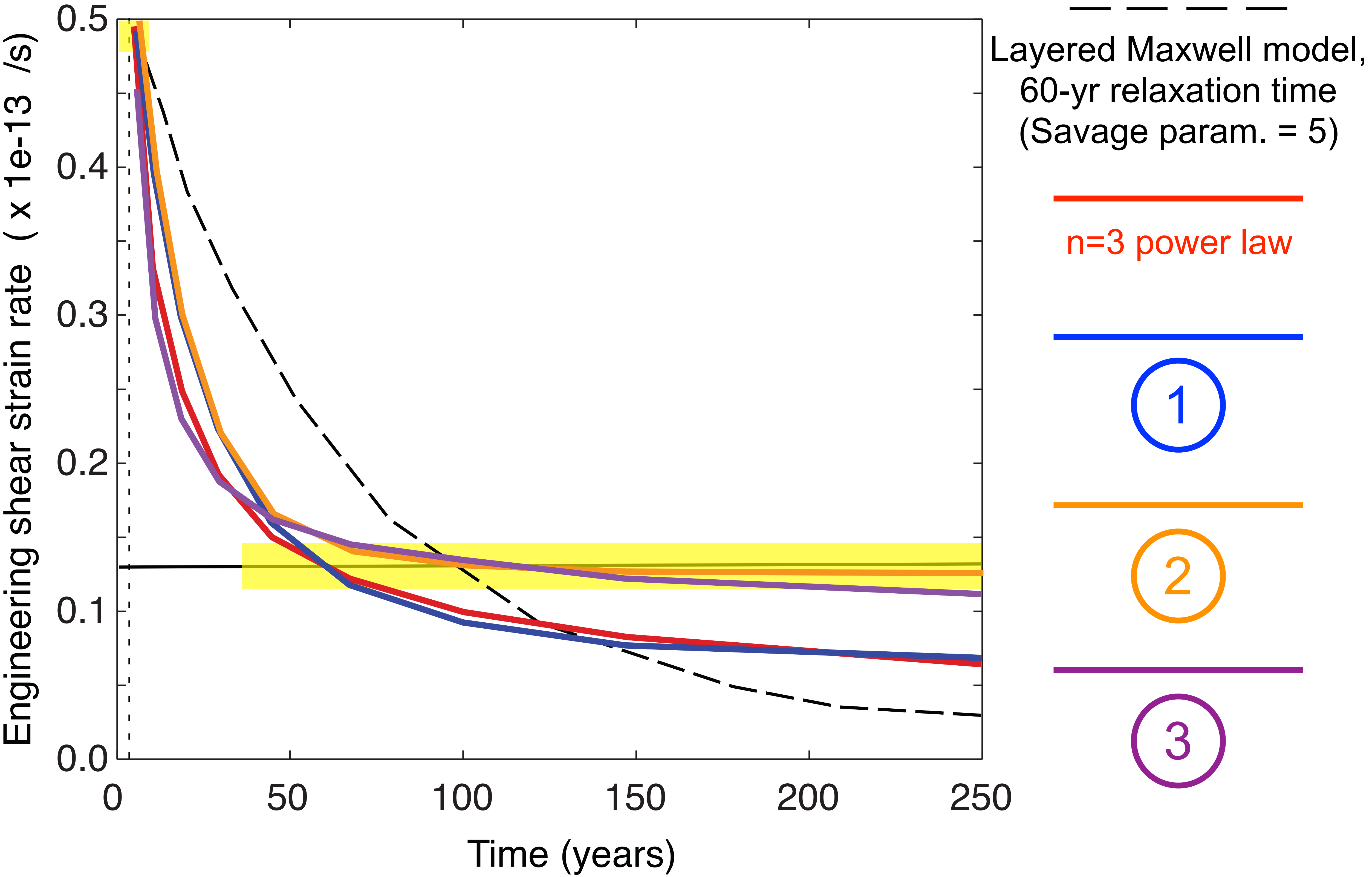
Shear strain rate at the fault as a function of time



Shear strain rate at the fault as a function of time

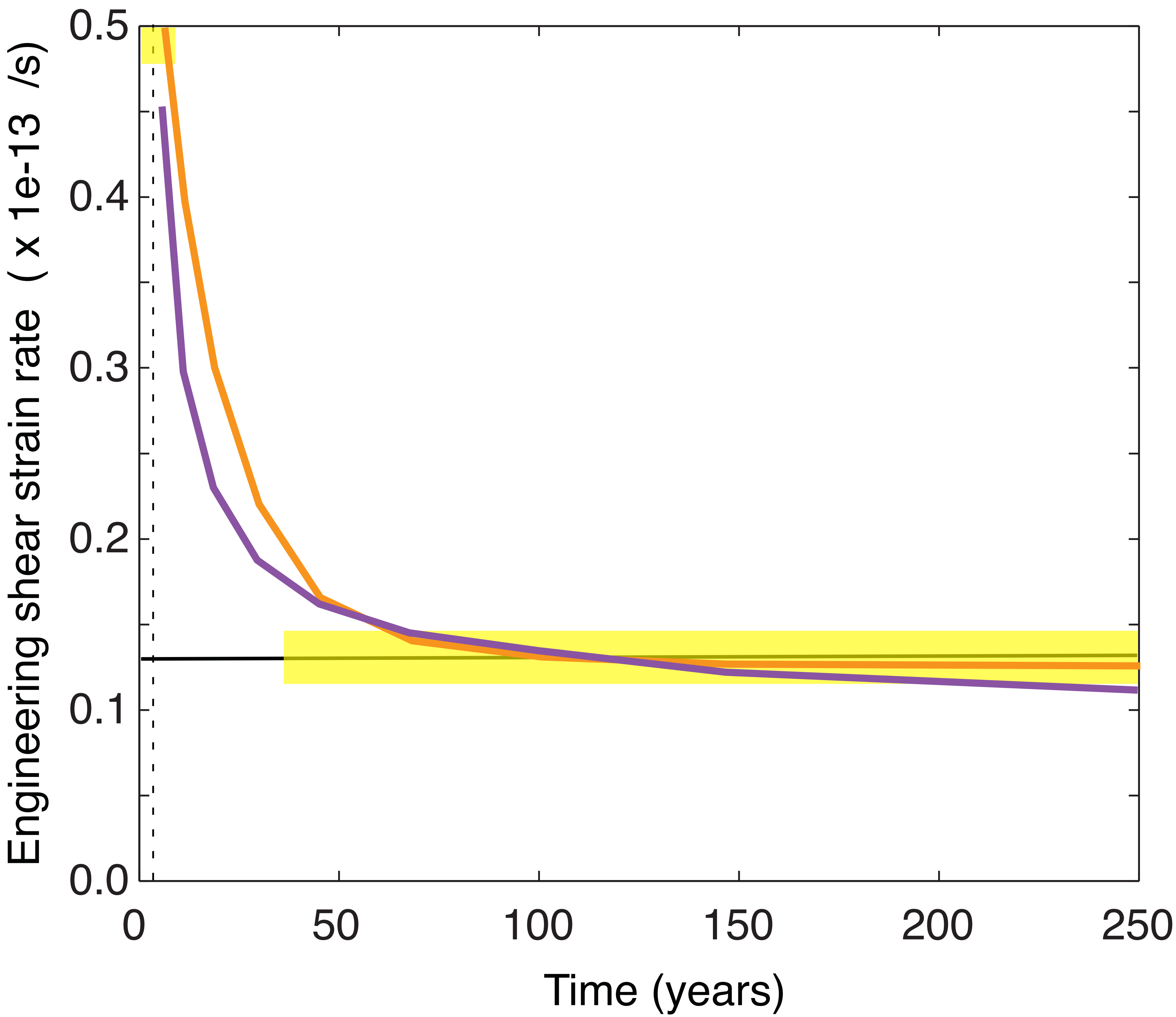


Shear strain rate at the fault as a function of time



Two pretty good models

(non-unique)



②

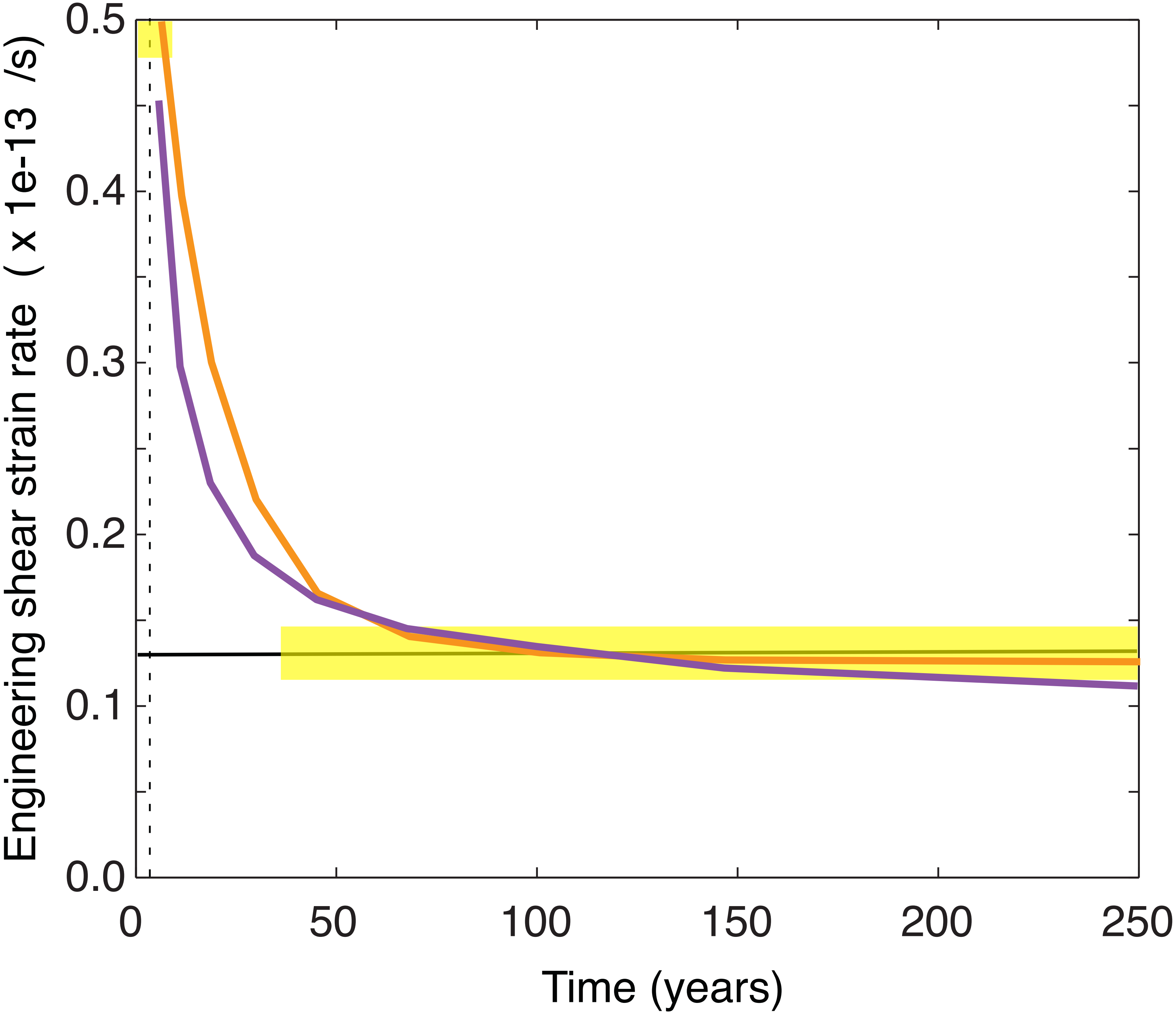
η/w increases from 10^{15} Pa s /m to 10^{16} Pa s /m at the Moho. Shear zone width is not constrained by this model.

③

Effective η/w increases from 10^{15} Pa s /m to 5 x 10^{15} Pa s /m with a characteristic evolution time of 10 years. Shear zone transient viscosity is 5×10^{18} Pa s and a width of 5 km (assuming μ = 30 GPa).

Two pretty good models

(non-unique)



②

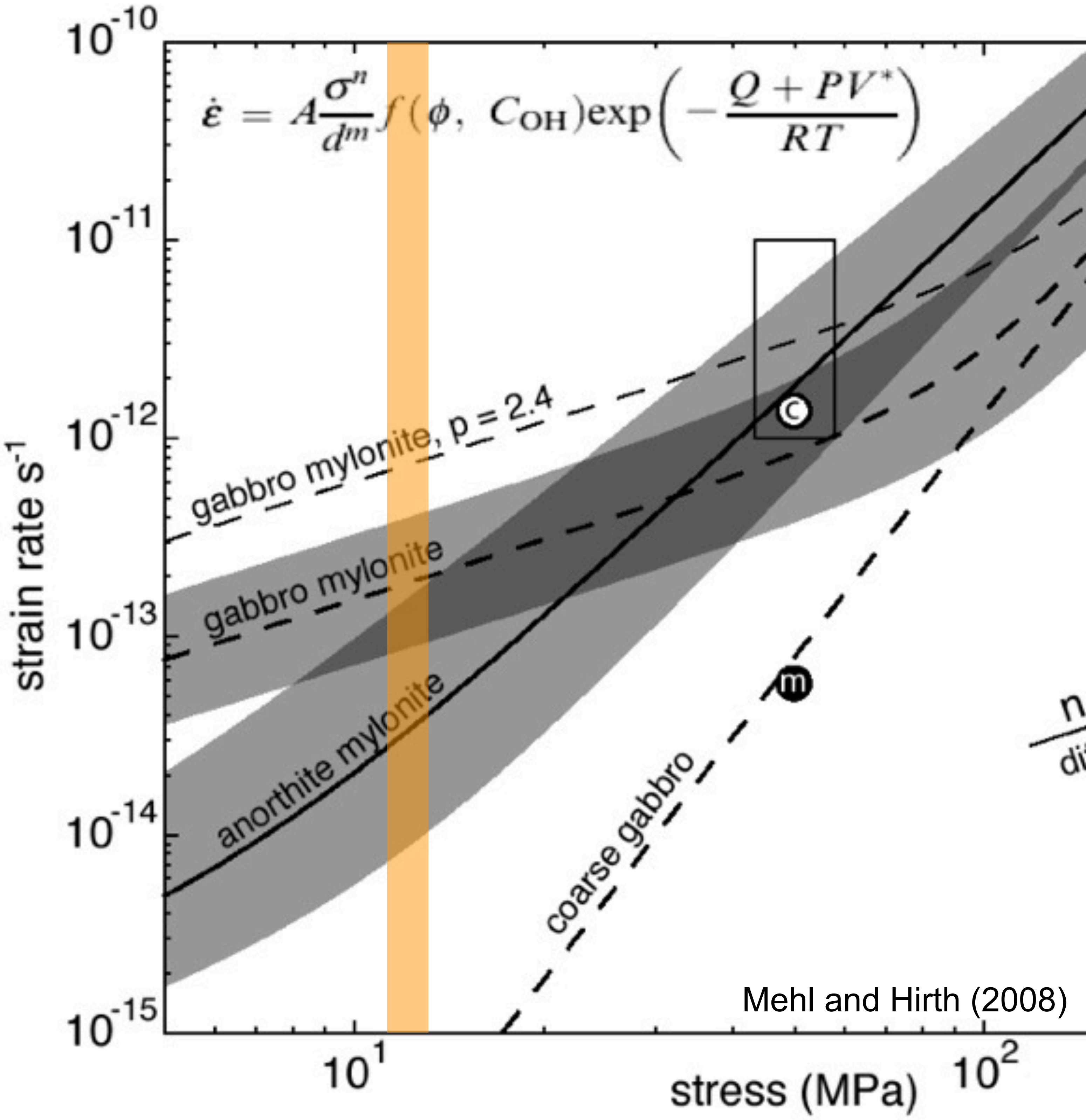
η/w increases from 10^{15} Pa s /m to 10^{16} Pa s /m at the Moho. Shear zone width is not constrained by this model.

Does the model make sense geologically?

Look at the lower crust...

②

$$\frac{\eta}{w} = 10^{15}\ Pa\ s\ /m$$
$$\sigma_{diff} = 2\tau = 1.2\ MPa$$



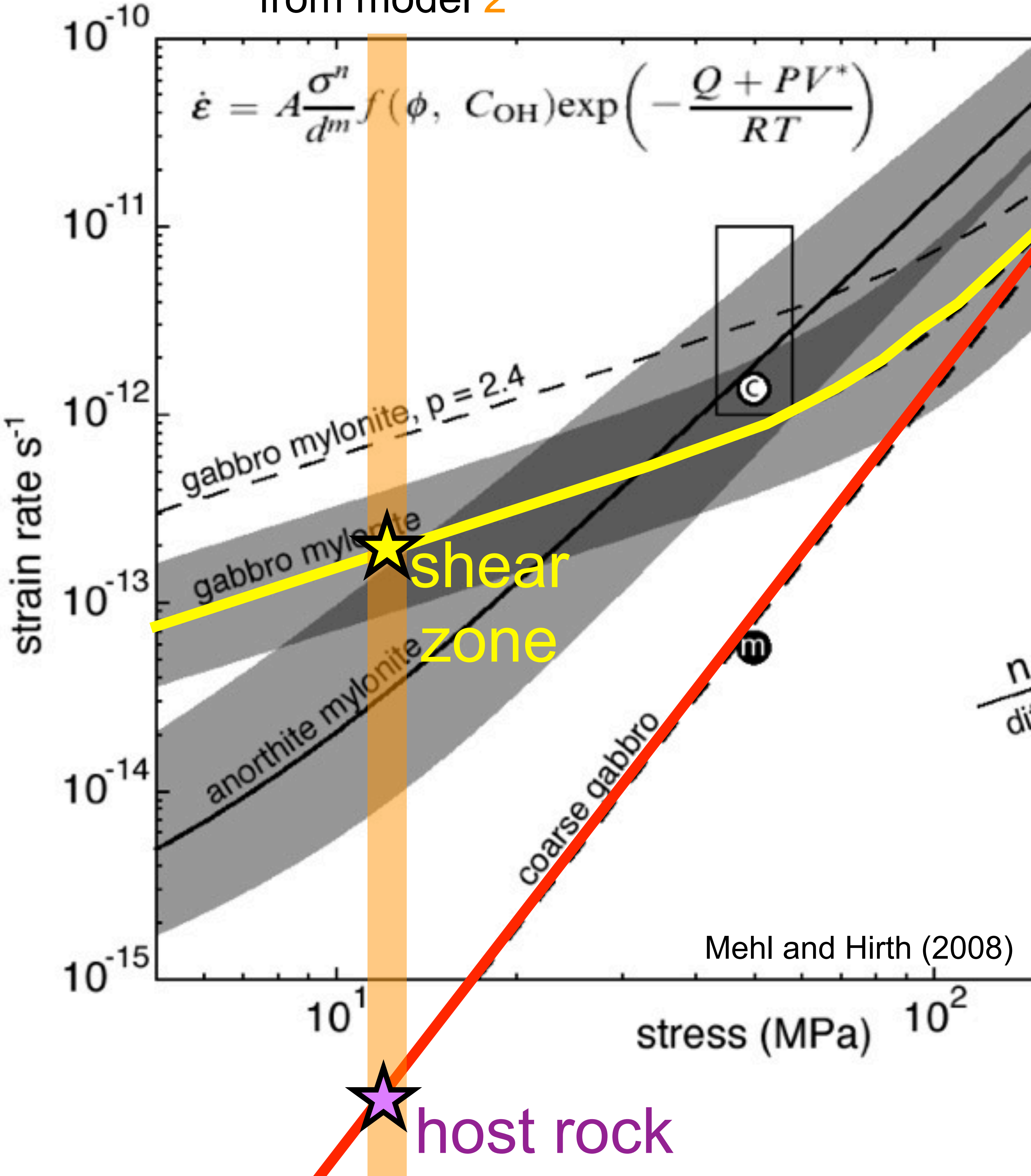
Mehl and Hirth (2008)

from the rock physics lab:

$$\dot{\epsilon} = 1.5 \times 10^{-13}\ /s$$

$$\eta = 4 \times 10^{18} Pa\ s$$

$\sigma_{diff} =$
differential stress
from model 2



Mehl and Hirth (2008)

from the rock physics lab:

$$\dot{\epsilon} = 1.5 \times 10^{-13}\ /s$$

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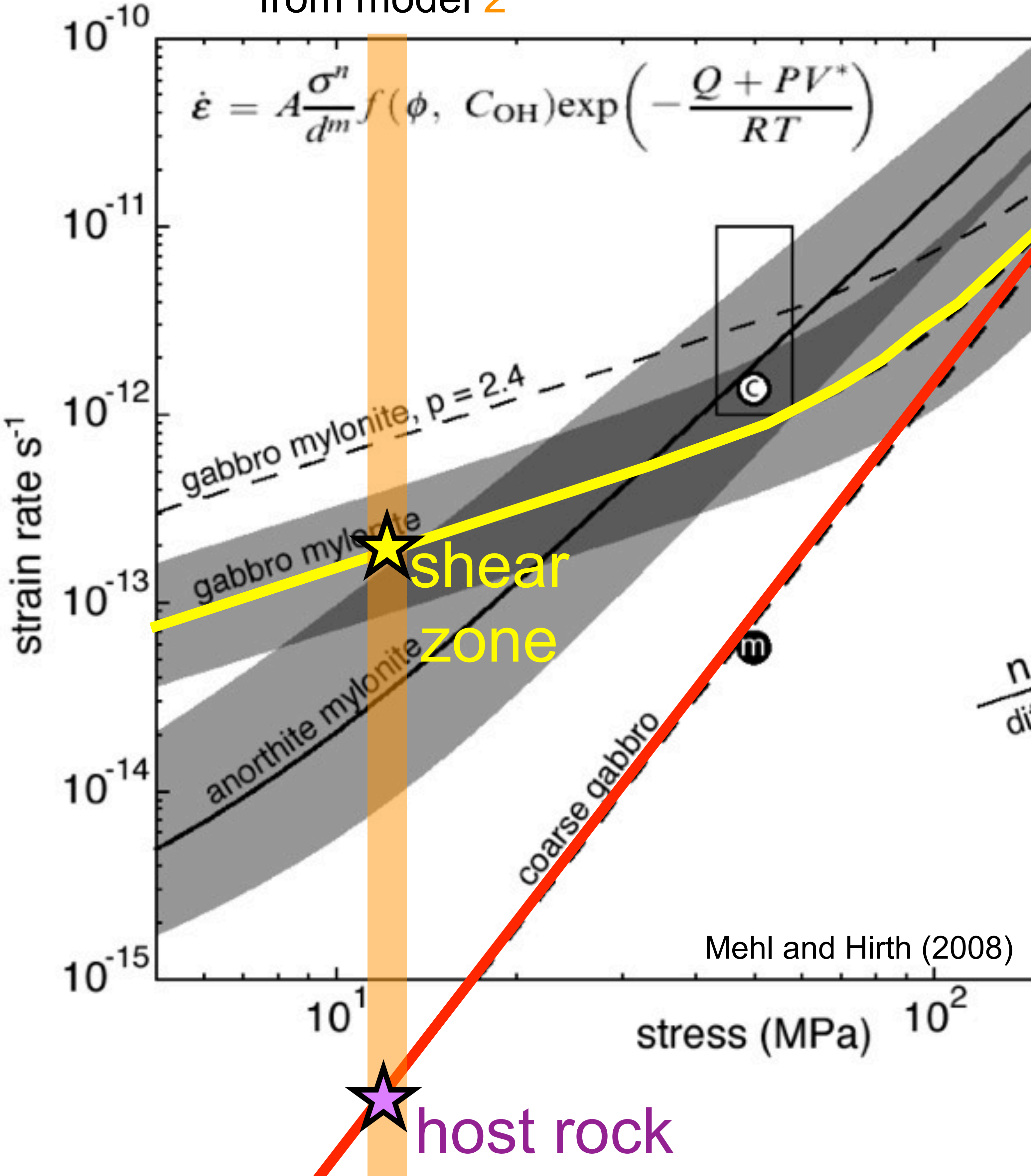
therefore w must be 4 km.

does this check out?

$\sigma_{diff} =$

differential stress from model 2



Mehl and Hirth (2008)

from the rock physics lab:

$\dot{\epsilon} = 1.5 \times 10^{-13}\ /s$

$\eta = 4 \times 10^{18} Pa\ s$

therefore w must be 4 km.

does this check out?

SZ creep rate *v* = 6×10^{-10} m/s

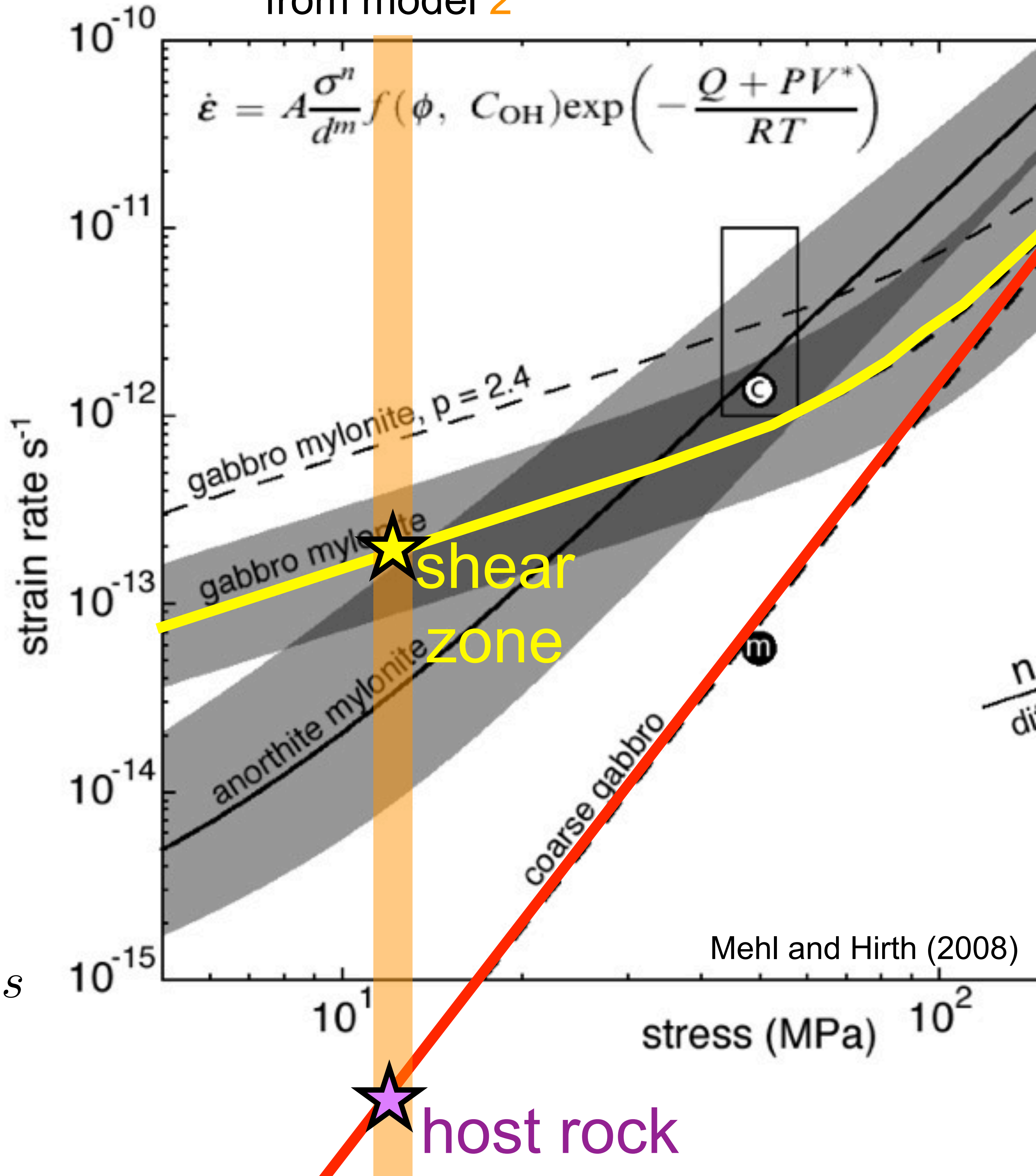
$$\dot{\epsilon} = \frac{v}{2w} \quad = 0.8 \times 10^{-13}\ /s$$

Model 2 seems roughly consistent with this rheology

also, host rock η_o is $10^{21}\ Pa\ s$

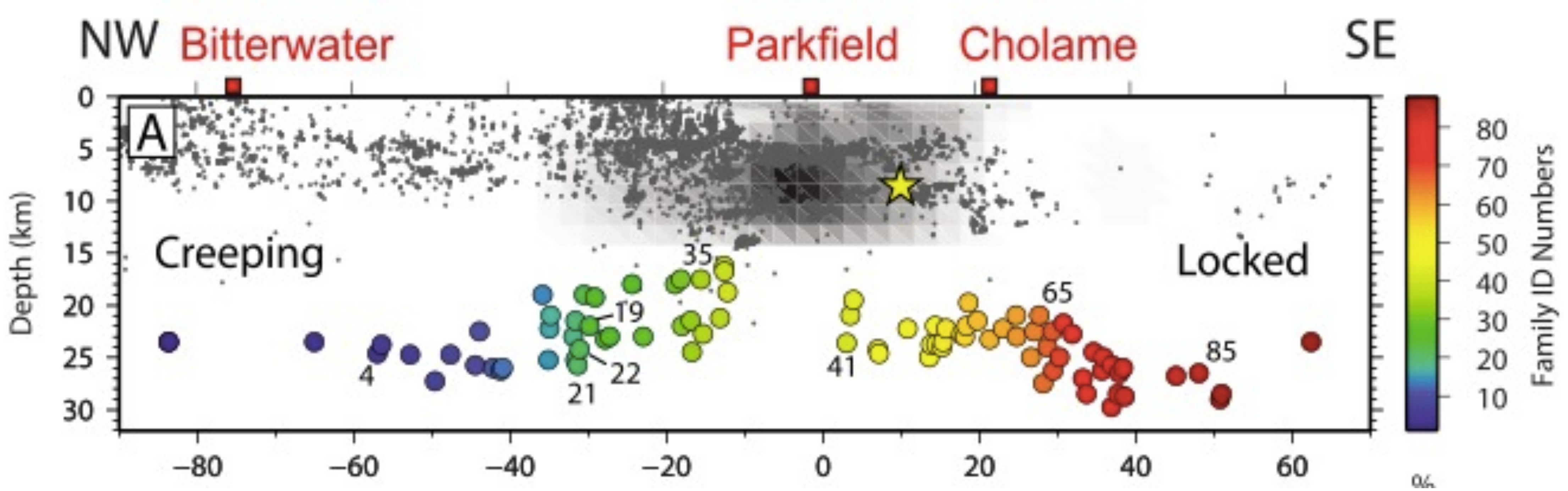
Problem: figure is for 875°C.

$\sigma_{diff} =$
differential stress
from model 2



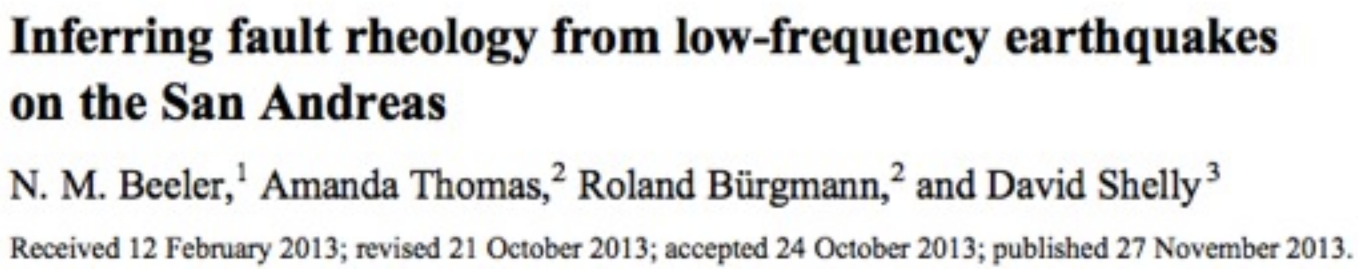
Mehl and Hirth (2008)

SAF low-frequency earthquakes



Thomas et al., 2012

- shear stress less than 1000 Pa (0.001 MPa)
- lithostatic pore pressure

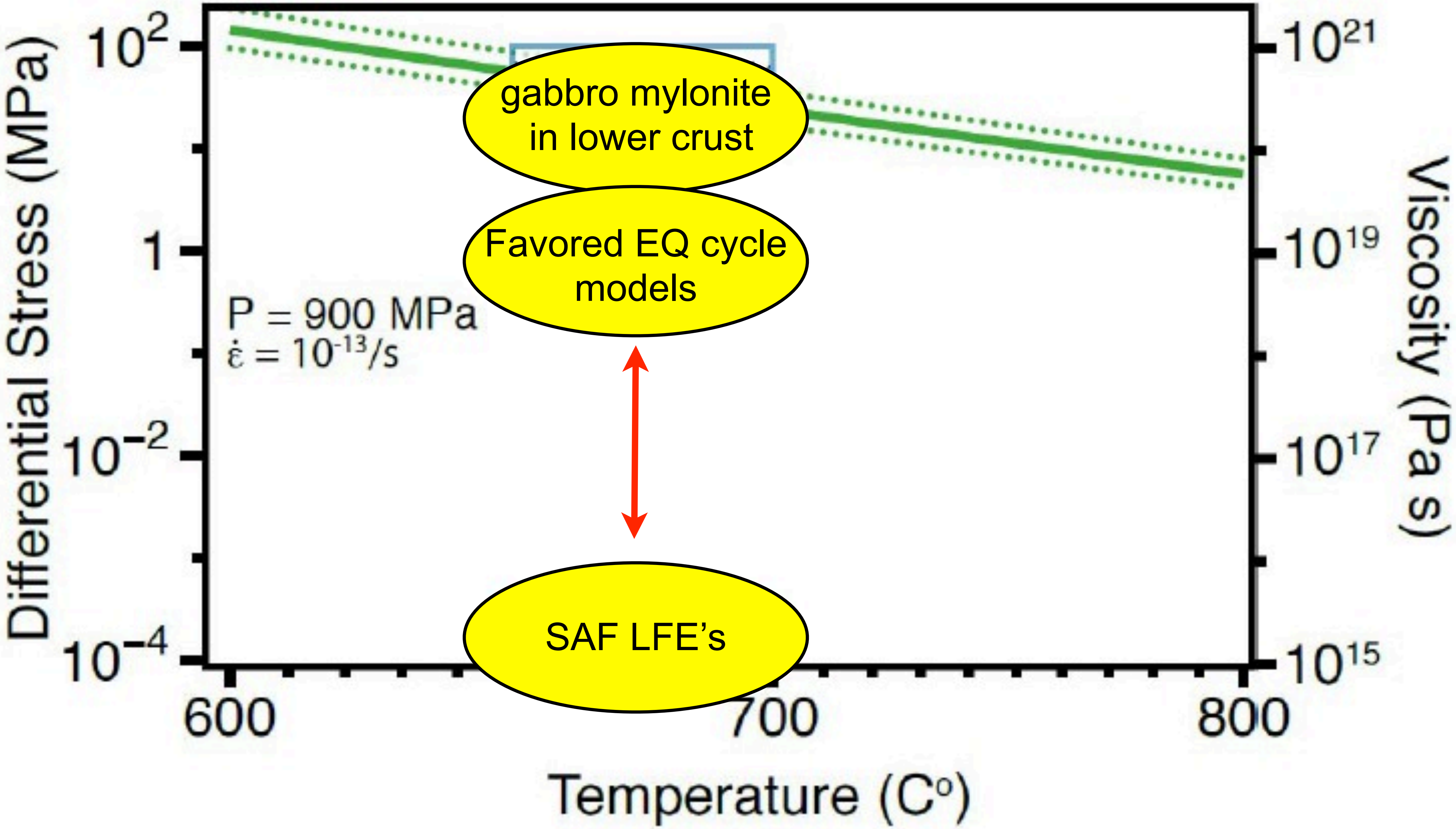


Inferring fault rheology from low-frequency earthquakes on the San Andreas

N. M. Beeler,[1] Amanda Thomas,[2] Roland Bürgmann,[2] and David Shelly[3]

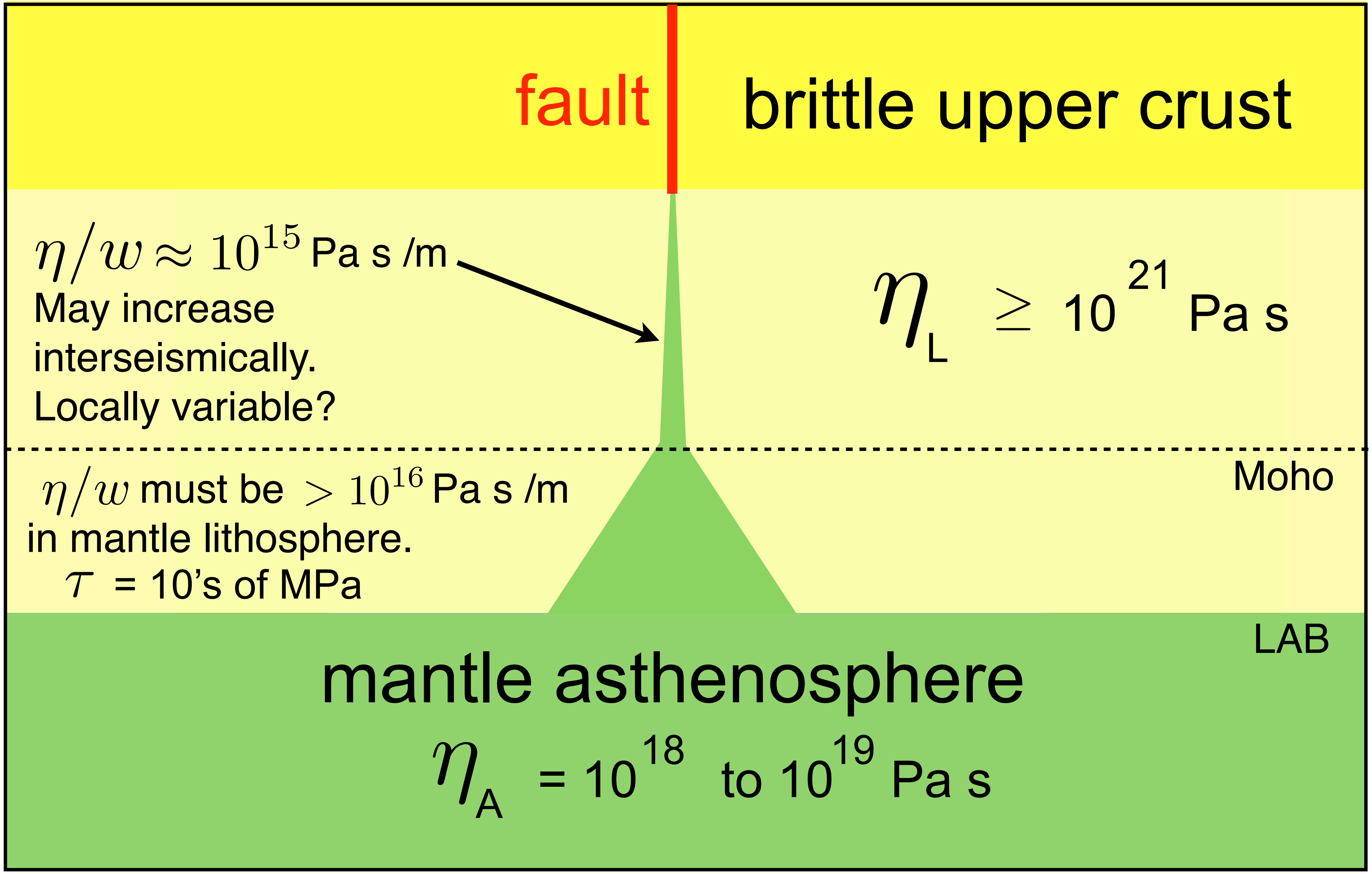
Received 12 February 2013; revised 21 October 2013; accepted 24 October 2013; published 27 November 2013.

A new conundrum



Modified from
Getsinger et al., 2013

Plausible model for major continental strike-slip faults



Not unlike results of Segall, Johnson and others, based on infinite fault models.