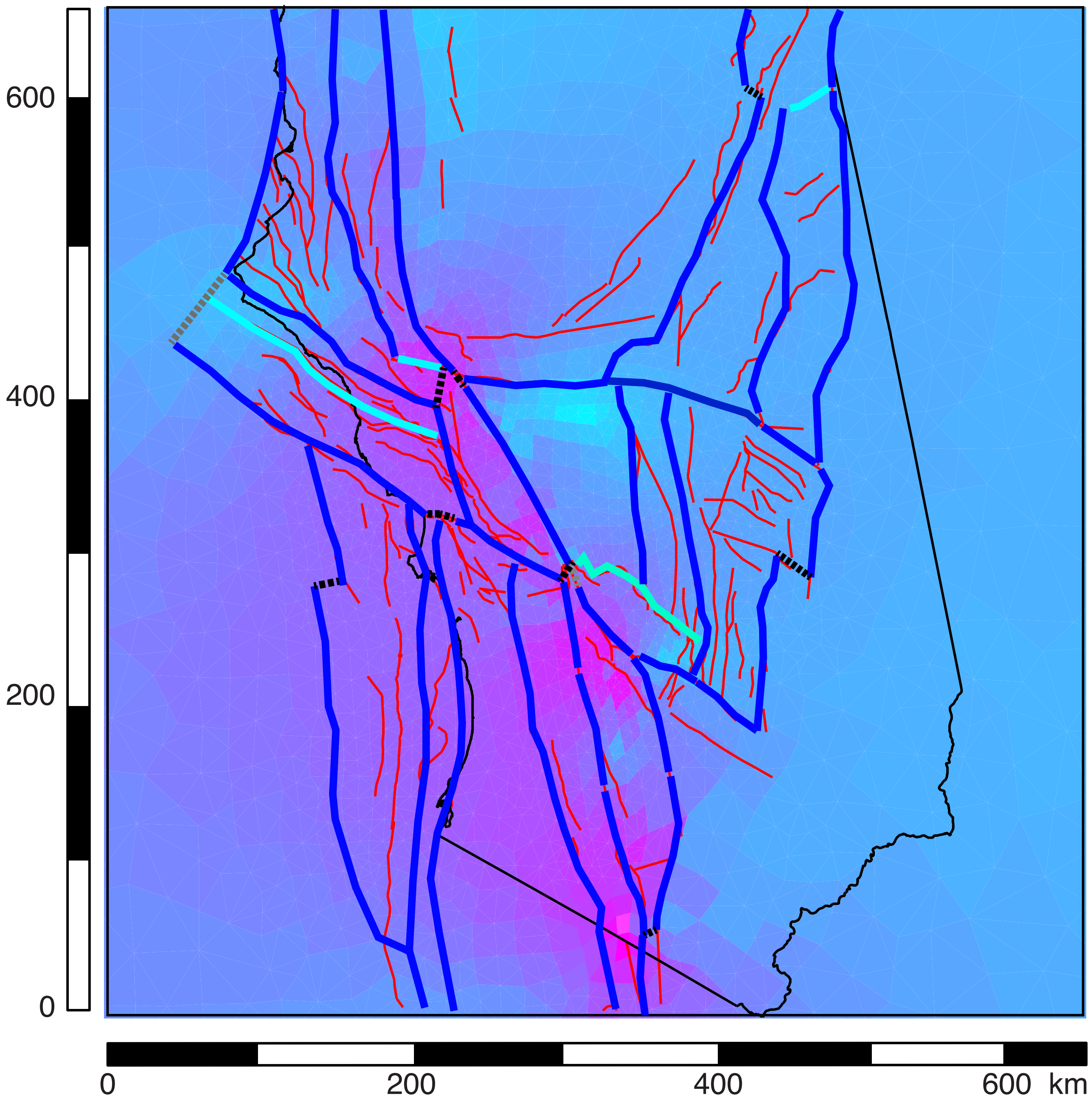
How Sensitive are Inferred Stresses and Stressing Rates to Rheology? Clues from Southern California Deformation Models

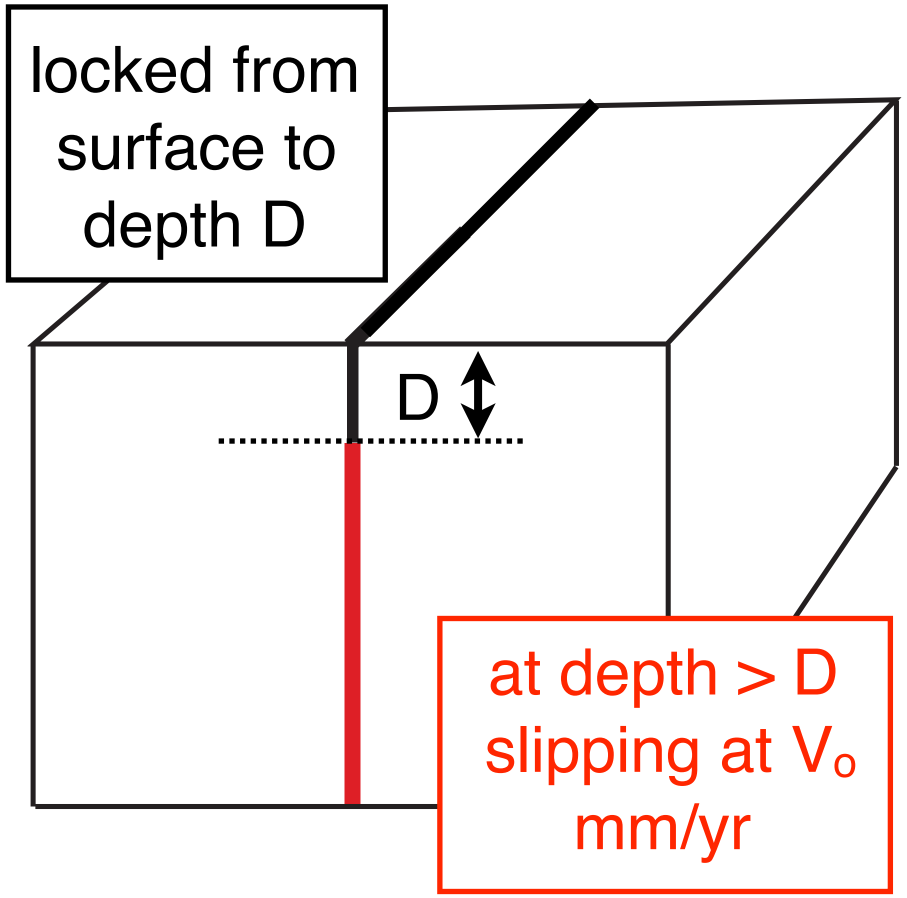
Elizabeth H. Hearn, Capstone Geophysics



SCEC5 theme: Beyond Elasticity

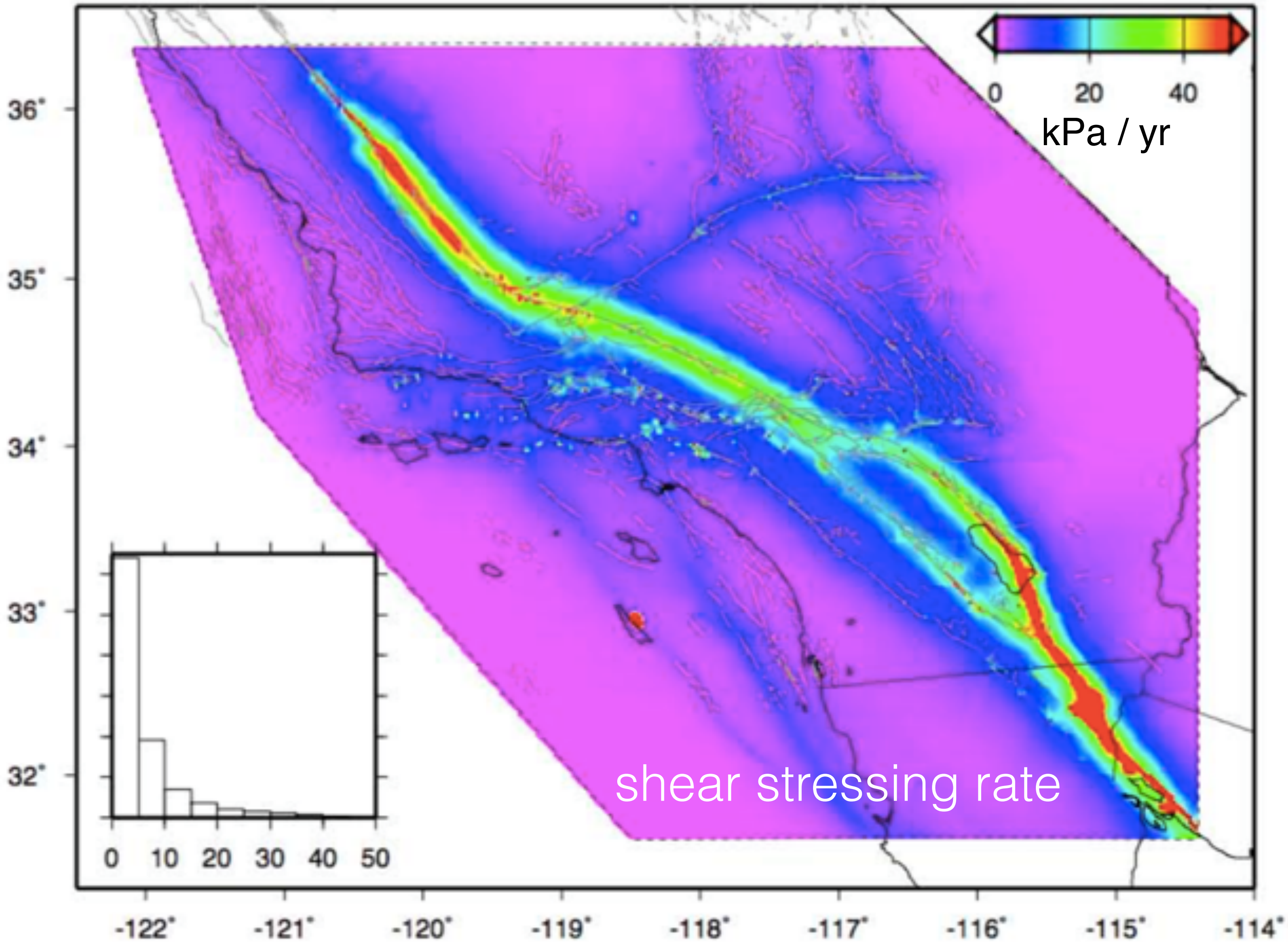
Stressing Rate

- Kinematic models of fault systems
- Slipping faults embedded in elastic volume
- Solve for slipping rates and locking depths



locked from surface to depth D

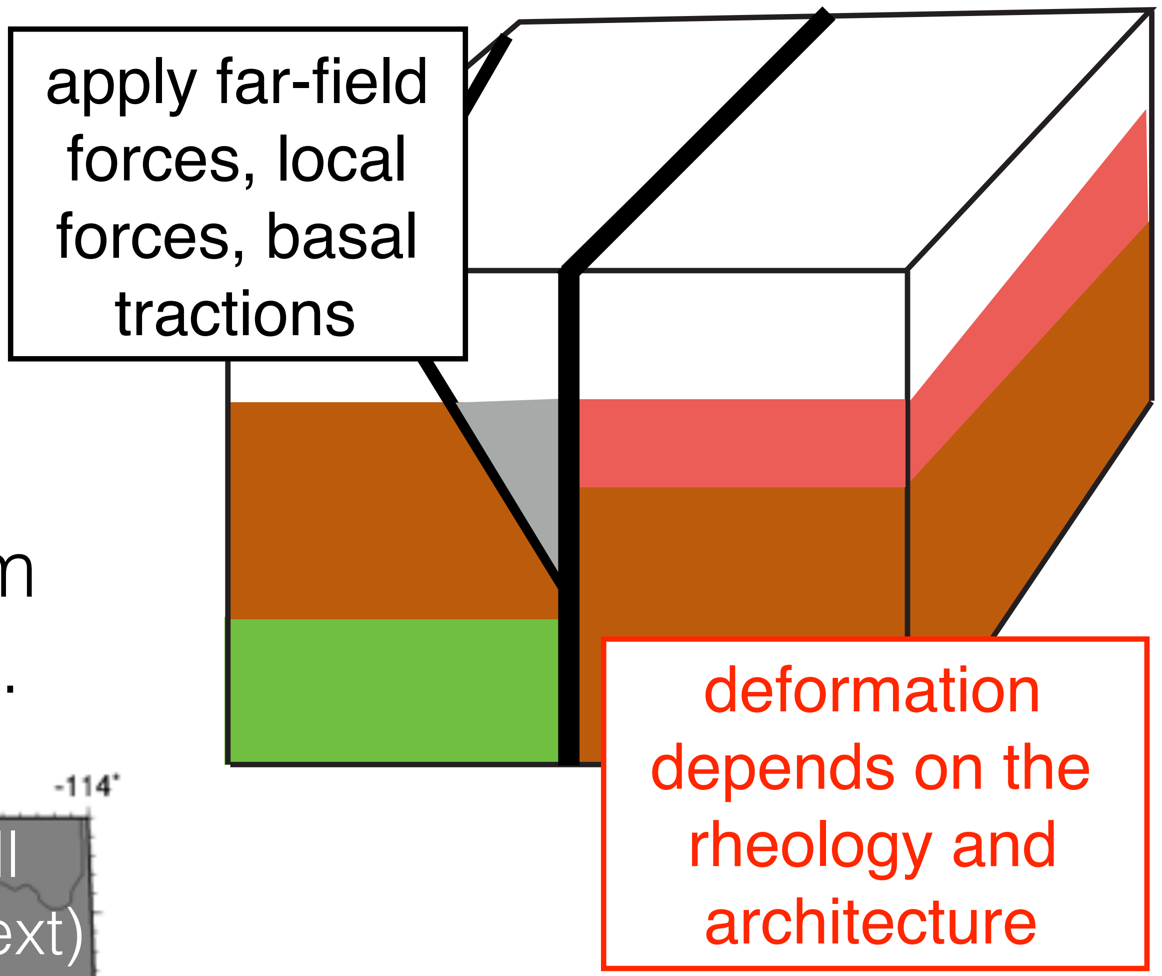
at depth > D slipping at V_o mm/yr



shear stressing rate

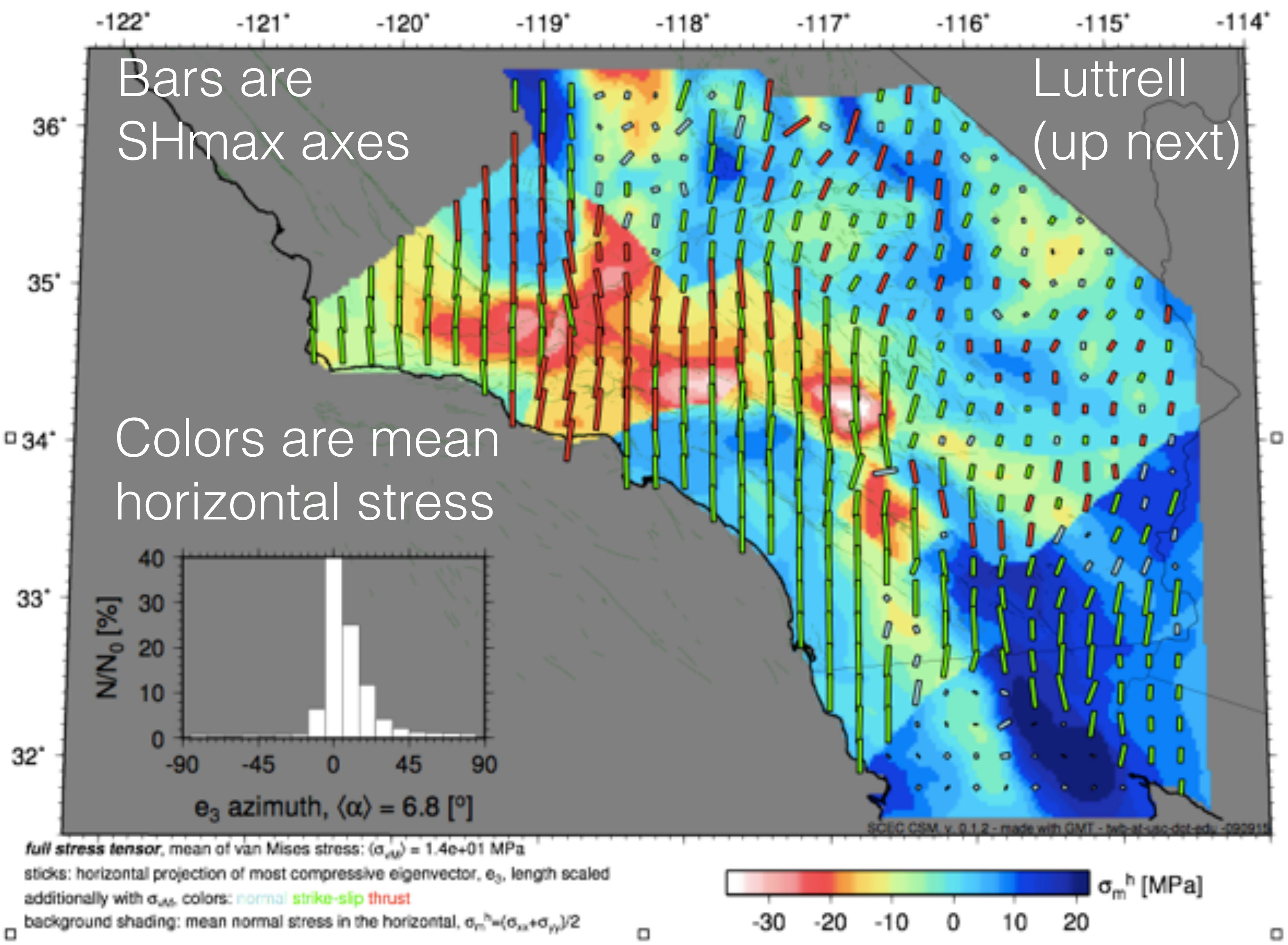
Stress

- Dynamic models of fault systems
- Balance forces driving and resisting deformation
- Tune rheology to match GPS, long-term uplift, geologic slip rates, stress data…



apply far-field forces, local forces, basal tractions

deformation depends on the rheology and architecture



Bars are SHmax axes

Luttrell (up next)

Colors are mean horizontal stress

Consistent with larger-scale geodynamics and geologic history

Consistent with *observed reaction to perturbations*.

Stress *change*

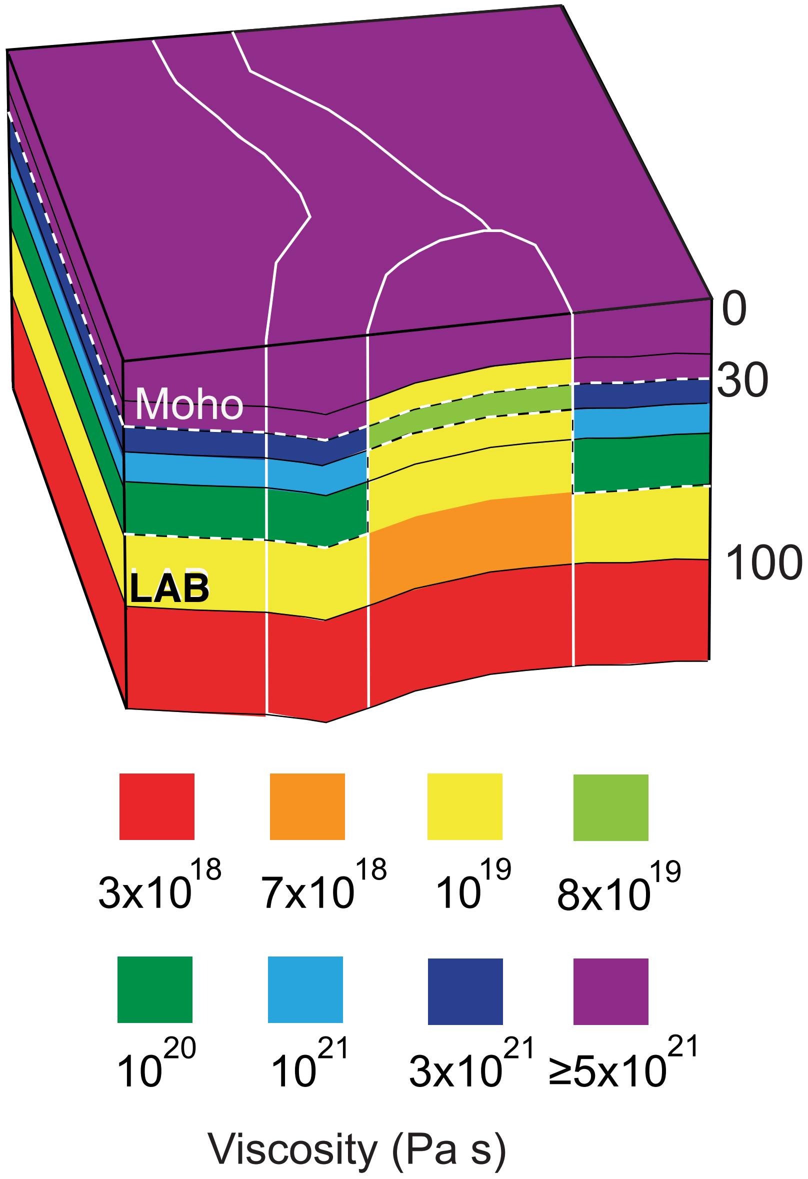
- Earthquake cycle (perturbations relative to an average)
- Coseismic, postseismic
- Loading/unloading

poster 157

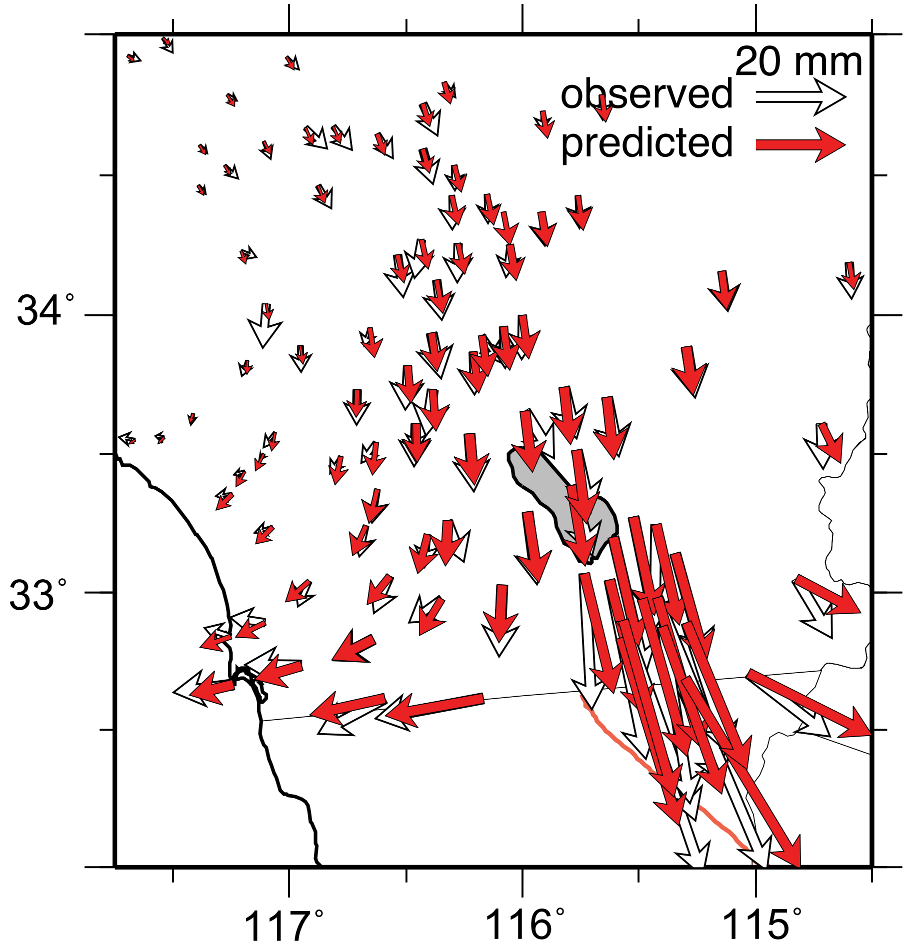
Coseismic and postseismic deformation from the 2010 Mw 7.2 El Mayor-Cucapah Earthquake in Baja California: Lithospheric structure and deformation in the Salton Trough

Huang, Dickinson, Freed, Fielding, Bürgmann, and Gonzalez-Ortega

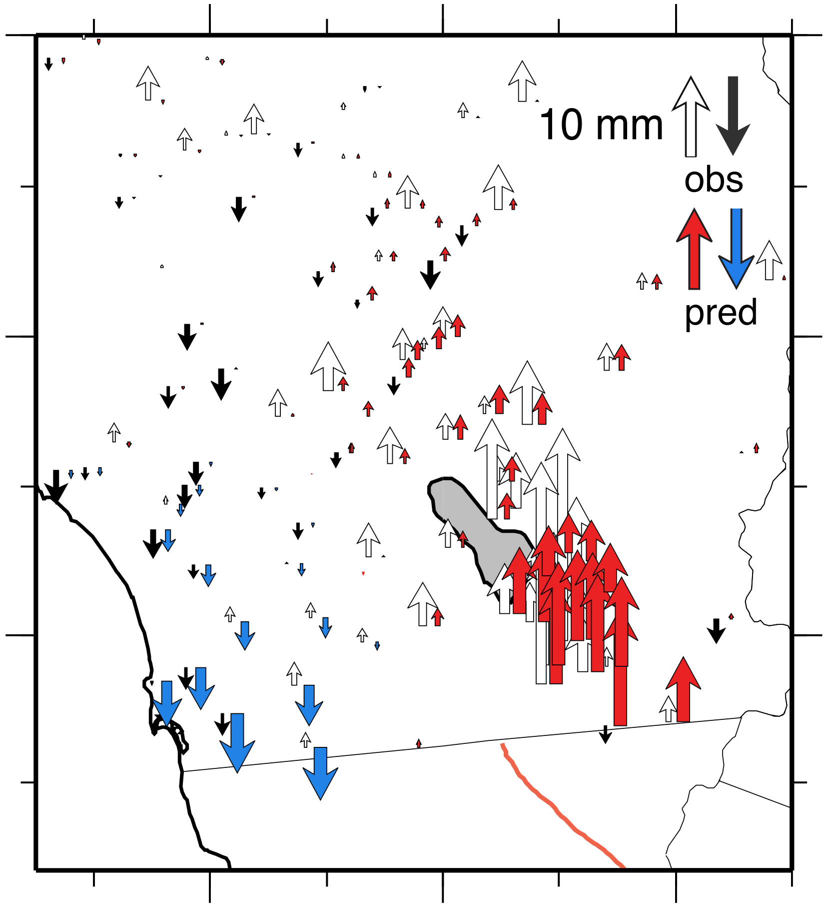
Heterogeneous 3D viscosity structure



Lateral GPS



Vertical GPS

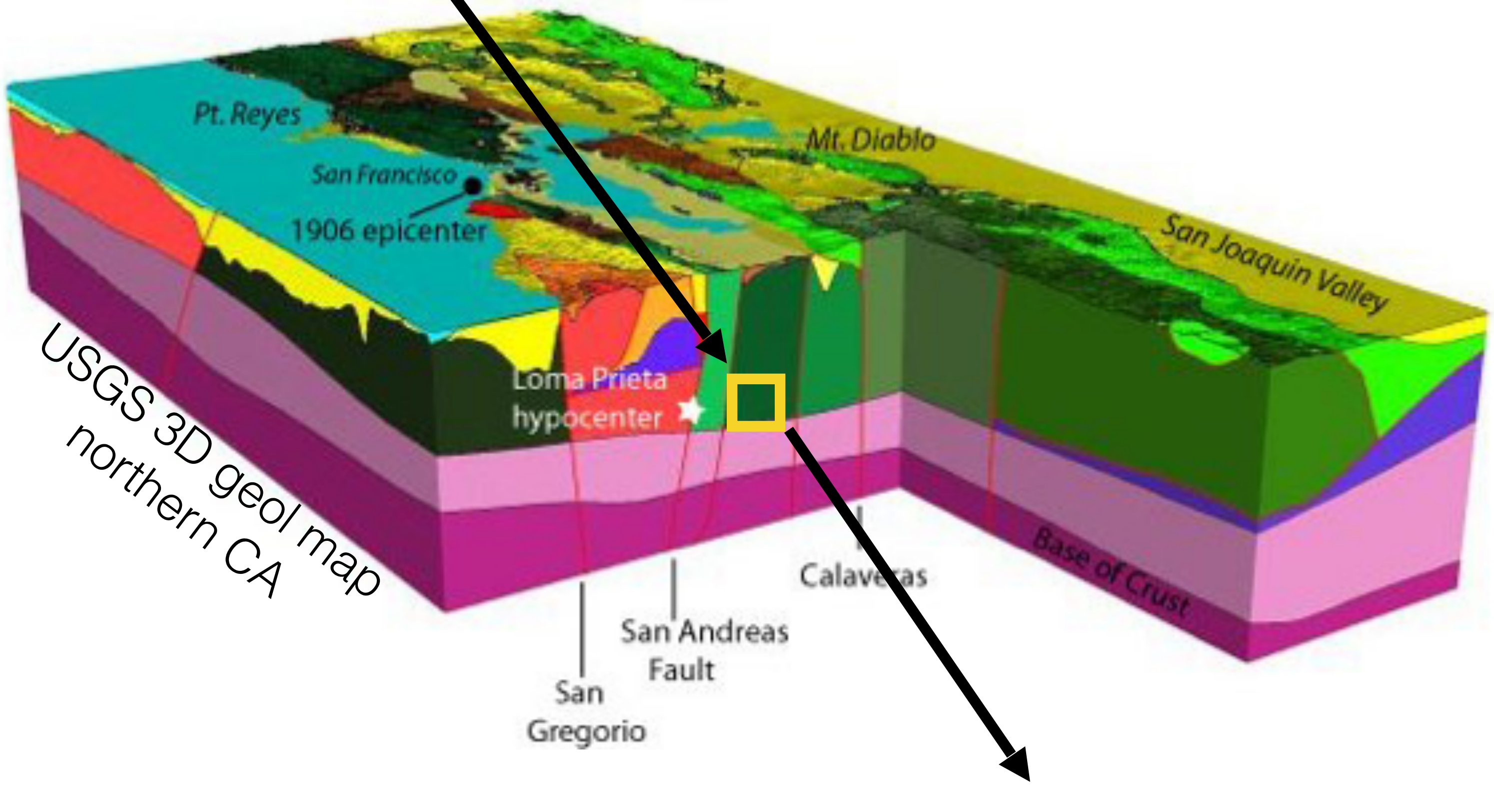


Non-unique estimates of southern CA viscosity from models

POSTSEISMIC	lower lithosphere effective viscosity Pa s, Maxwell if not otherwise indicated	references
El Mayor-Cucapah M 7.2	heterogeneous, Maxwell or power-law. 1-3 e18 Pa s mantle and (local) lower crust	Rollins et al, 2015; Gonzalez-Ortega et al., 2014; Pollitz et al., 2012
Central Nevada Quakes M 6.9 - 7.4	1e18 to 1e19 Pa s	Hammond et al., 2009
Landers and Hector Mine M 7.4 and 7.2	1e18 to 1e20 Pa s; Maxwell, power-law and/or transient flow laws with assumed T;	Pollitz (2015 and earlier refs), Fialko, Freed…
"LONG-TERM" DEFORMATION		
So Cal	From Kirby (1983) and computed T field, then perturbed to fit data	Bird and Kong, 1994
So Cal	4e19 to 1e21	Li et al., 2009
San Andreas	2e18 to 5e19 (below 70 km plate)	Smith and Sandwell, 2004
EARTHQUAKE CYCLES		
SSAF	2e19 - 1e21 layered and transient rheol. or 5e20 uniform Maxwell	Hearn et al. 2013
SoCal-wide	6e18 mantle, 2e20 lower crust	Chuang and Johnson, 2011
SSAF	0.1 - 3e20 mantle asthenosphere	Johnson and Segall, 2004
Carrizo SAF	2 - 5 e19 lower crust/upper mantle	Schmalzle et al., 2006

Rheological constraints from geology, lab experiments and temperatures: SCEC **CRM**

lat, lon, elevation
shear zone or host rock?



USGS 3D geol map northern CA

temperature (from **CTM**)
admissible rock type(s)
admissible flow law(s)
→ rheology

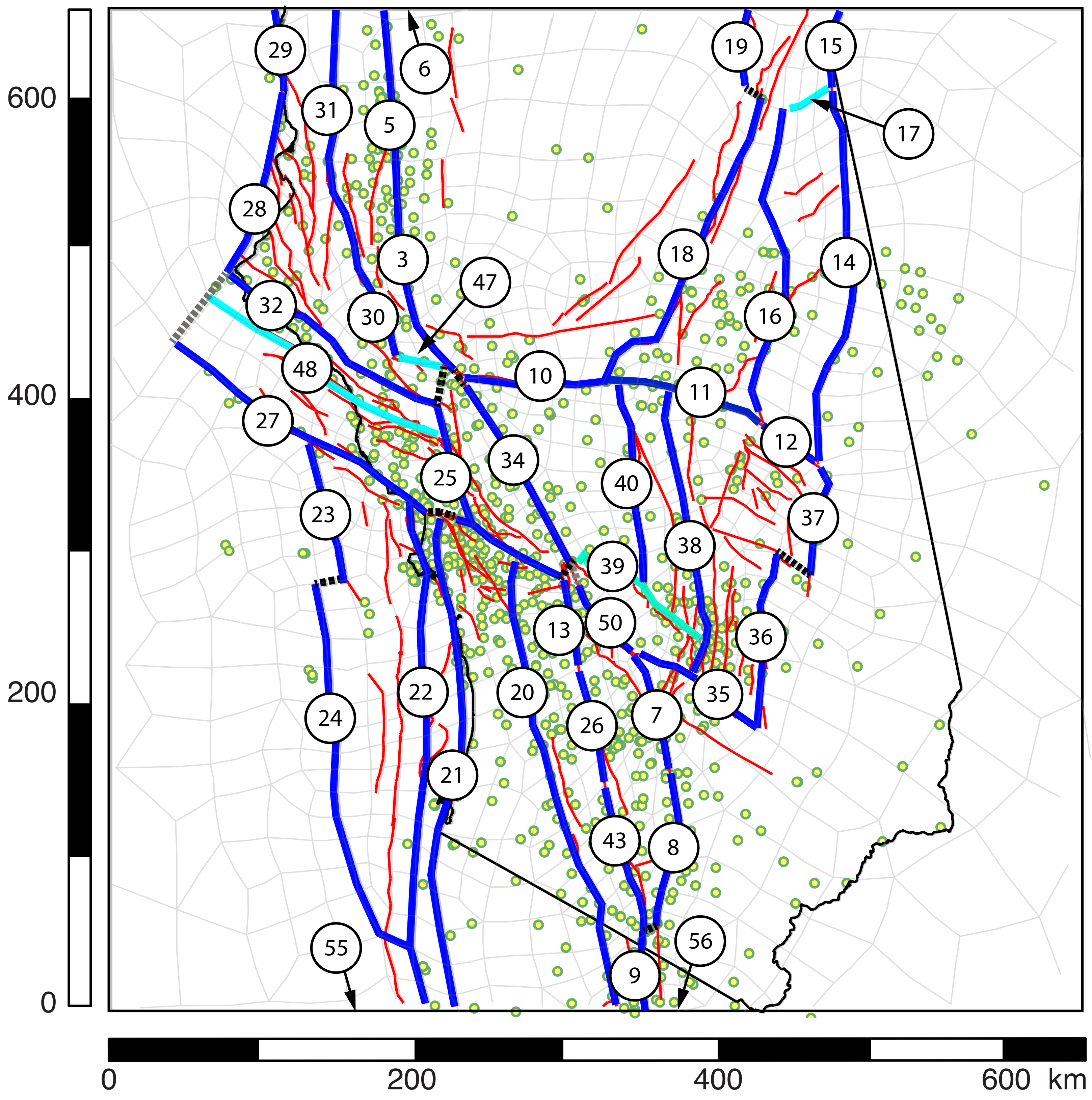
Effects of

1. Viscoelastic lower lithosphere
2. Lithosphere-scale shear zones
3. Plastic upper crust

on modeled fault system behavior and stresses

Start with a kinematic model of southern California

A southern California kinematic model (elastic FEM)

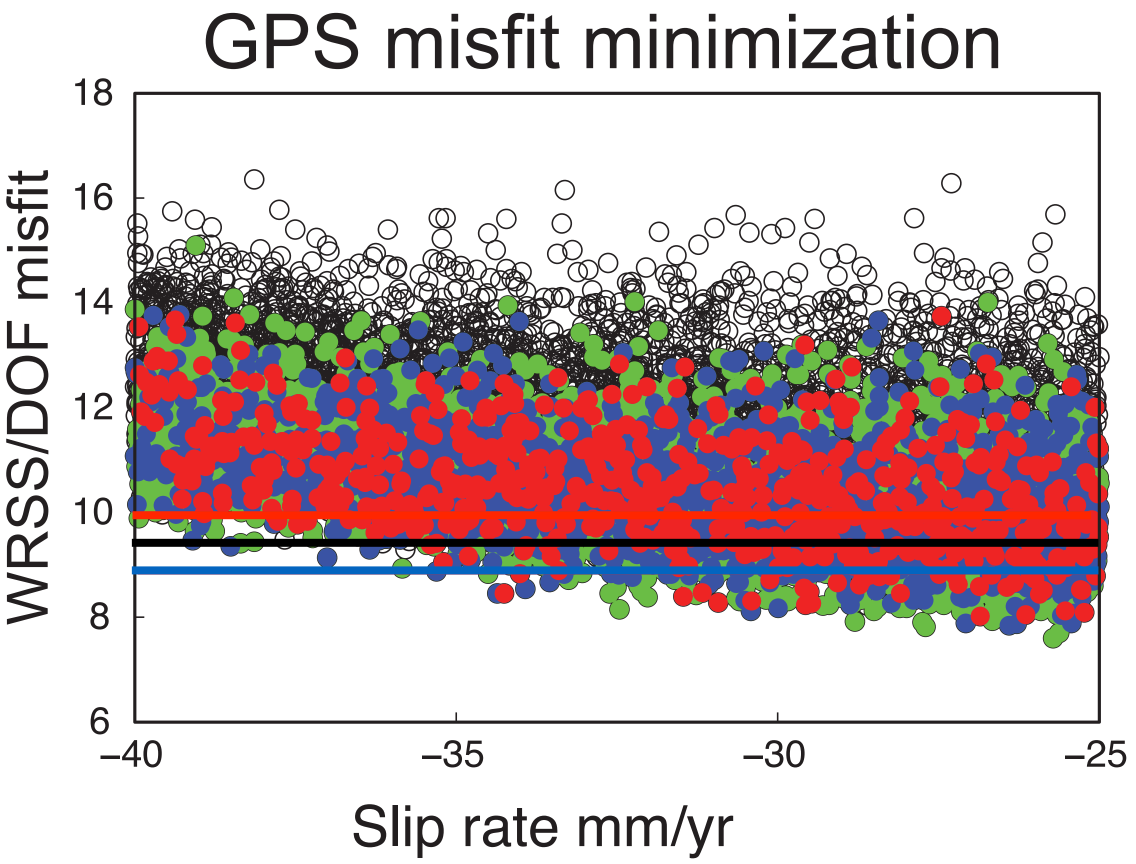


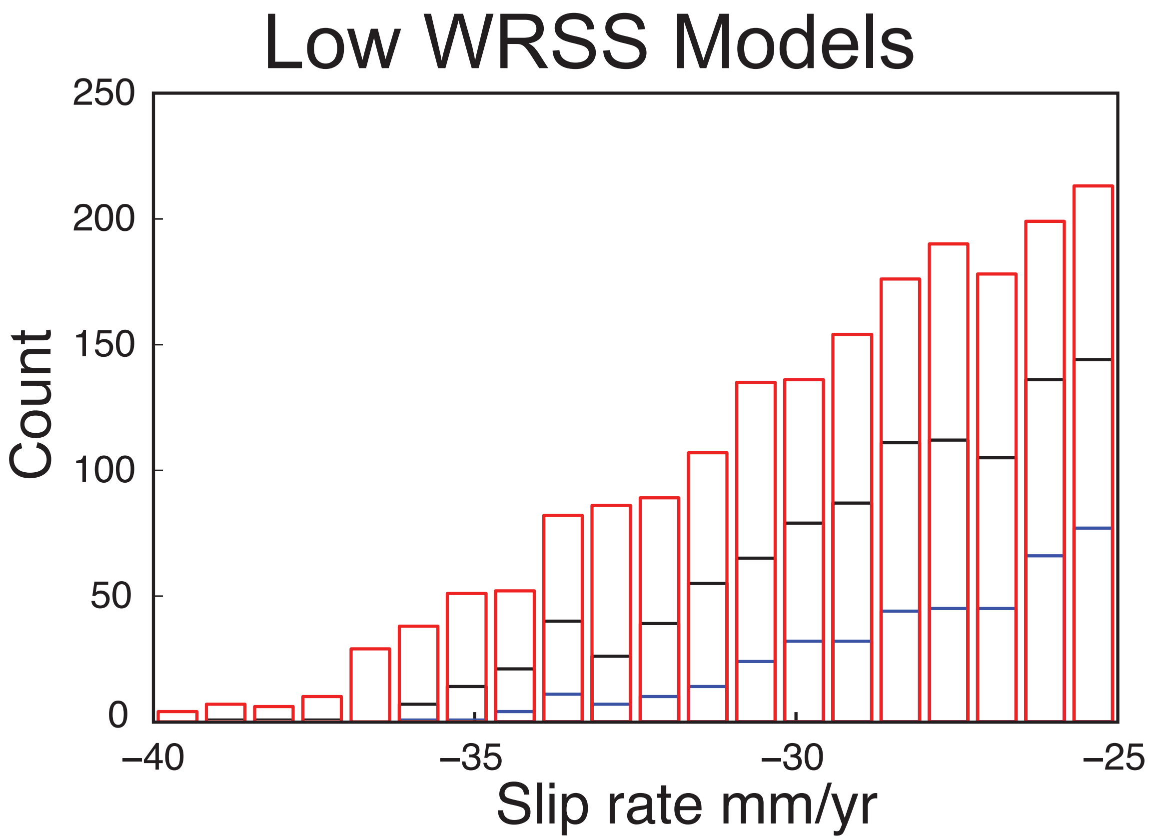
Fault geometry and slip rate ranges from UCERF3

Locking depths:
(1) 12 km
(2) from UCERF3
(3) no locking

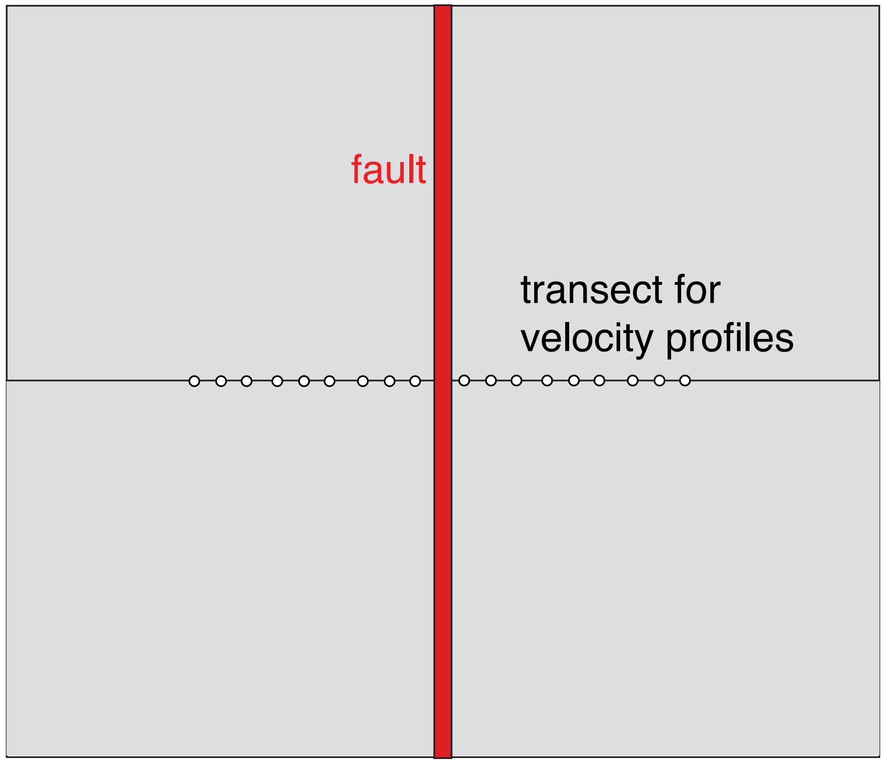
Draw slip rates from UCERF3 ranges, run 10,000 cases. Find models that fit SCEC CMM4 GPS velocity field <u>or</u> minimize strain energy

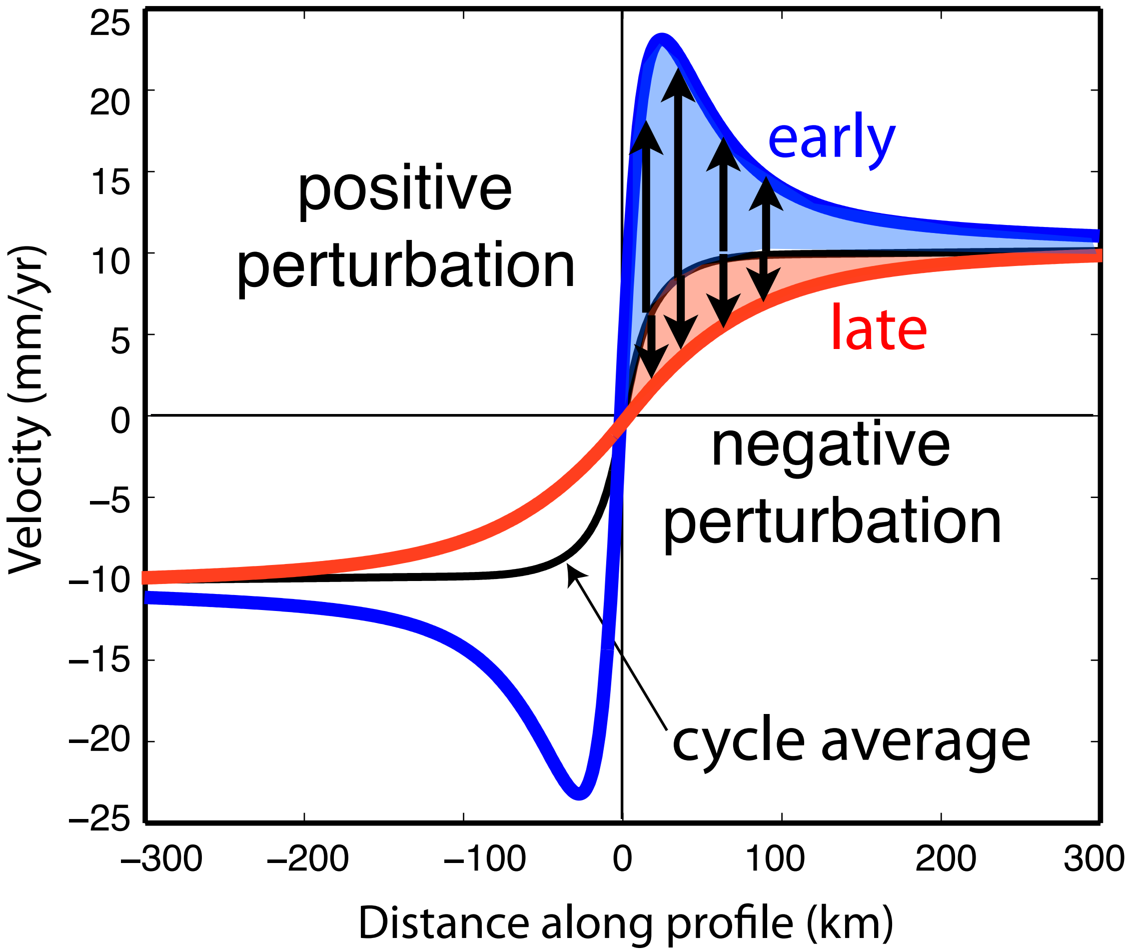
Mojave Segment slip rate



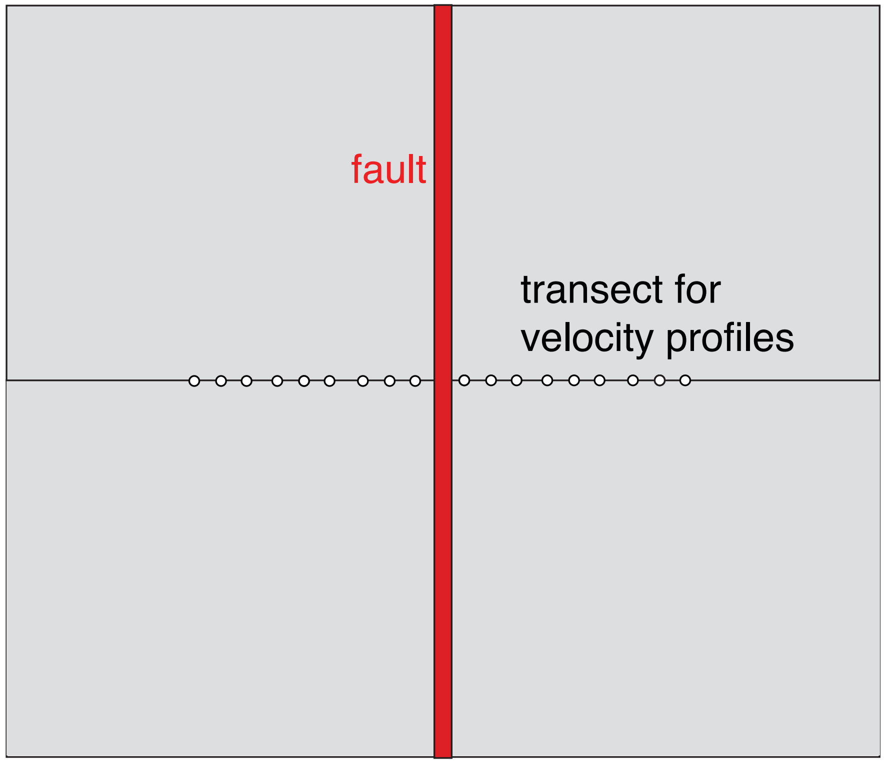


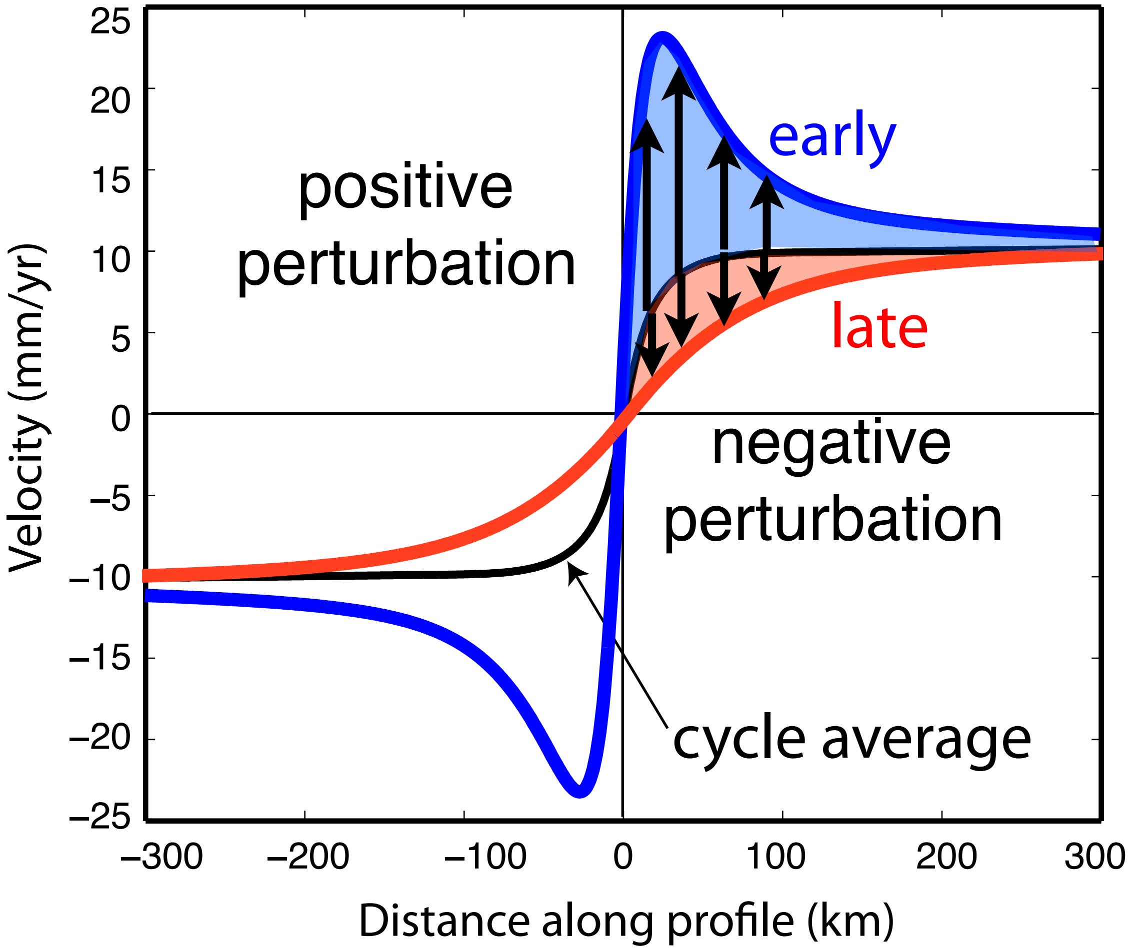
1. Effect of viscoelastic lower lithosphere



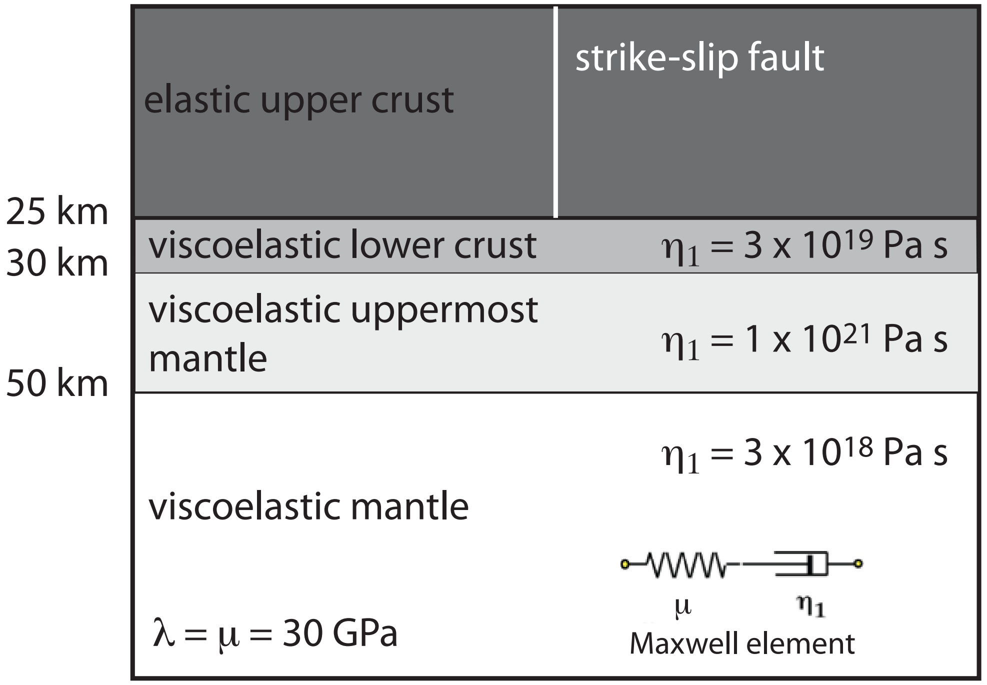


1. Effect of viscoelastic lower lithosphere





Model M1



elastic upper crust

strike-slip fault

25 km

30 km

viscoelastic lower crust $\eta_1 = 3 \times 10^{19}$ Pa s

viscoelastic uppermost mantle $\eta_1 = 1 \times 10^{21}$ Pa s

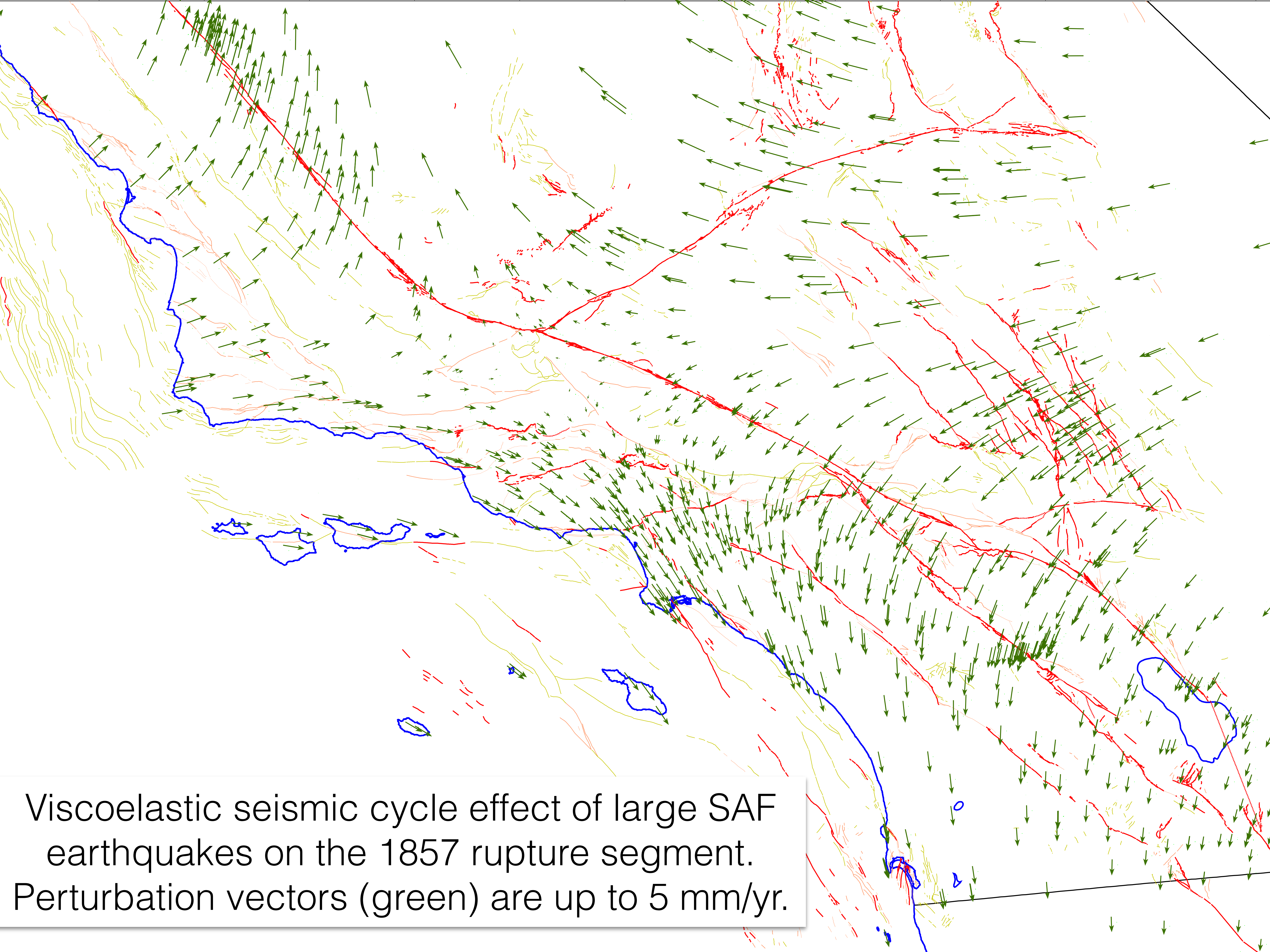
50 km

viscoelastic mantle $\eta_1 = 3 \times 10^{18}$ Pa s

$\lambda = \mu = 30$ GPa

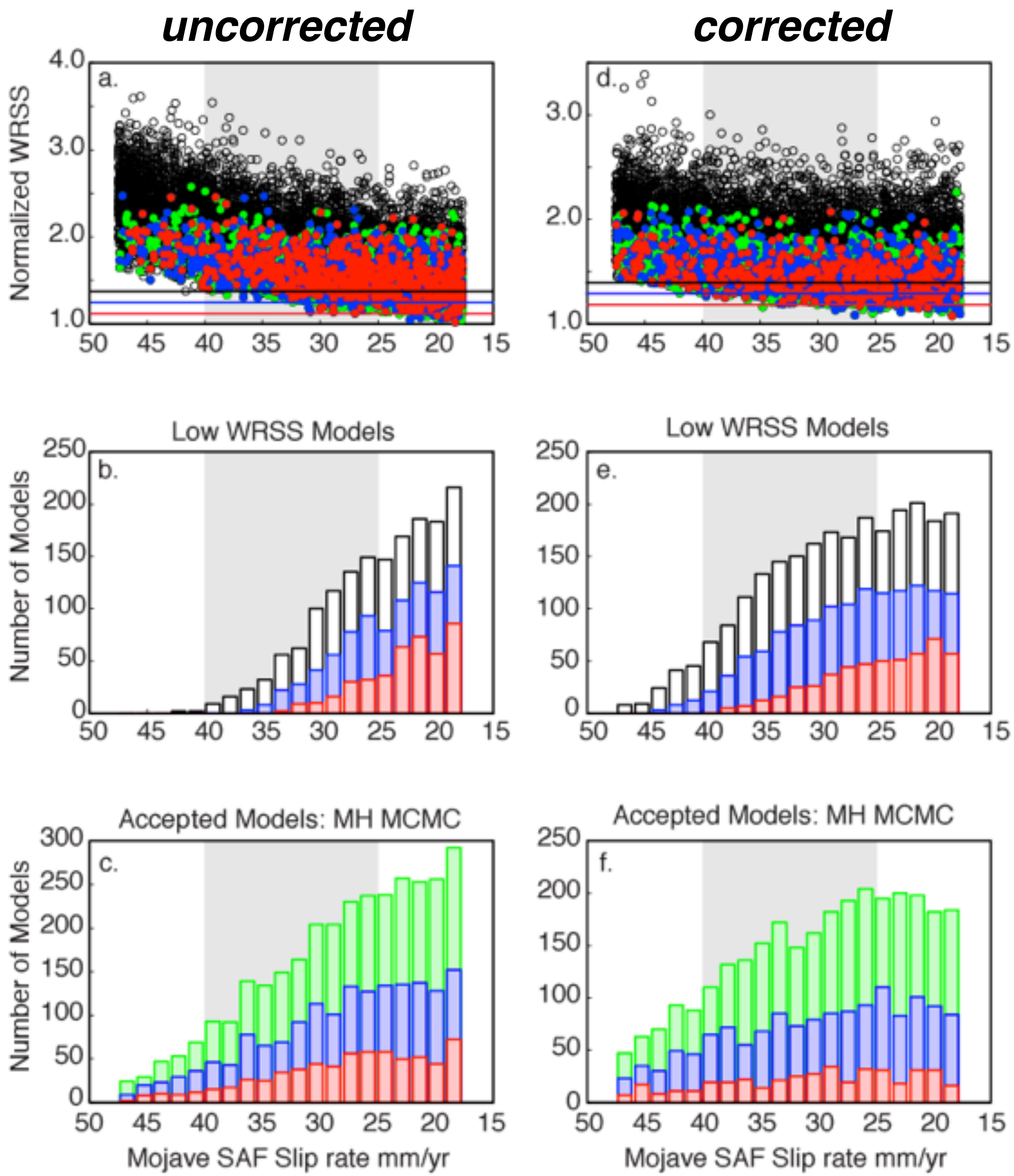
Maxwell element

- Calculate perturbation
- Correct the velocity field to get interseismic average velocities
- Infer slip rates



Viscoelastic seismic cycle effect of large SAF earthquakes on the 1857 rupture segment. Perturbation vectors (green) are up to 5 mm/yr.

Correcting for “ghost transient” affects inferred SAF Mojave slip rate.



- ○ MCMC rejected models
- ● MCMC accepted models
- ● MCMC accepted models: next to last 1000
- ● MCMC accepted models: last 500

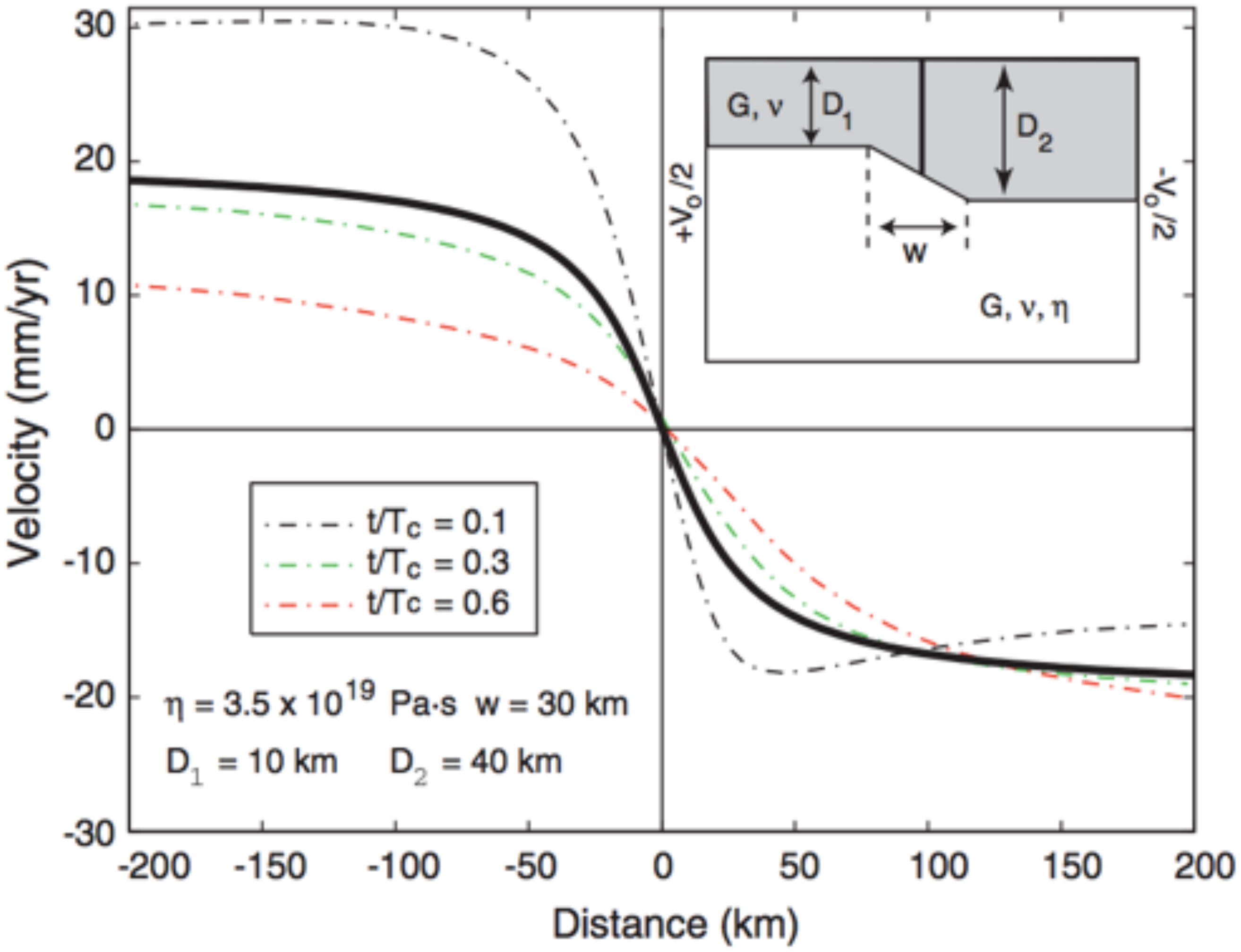
Gray: UCERF3 slip rate range

Red bars: TSE and WRSS below red line
Black bars: energy and WRSS below black line
Blue bars: energy and WRSS below blue line

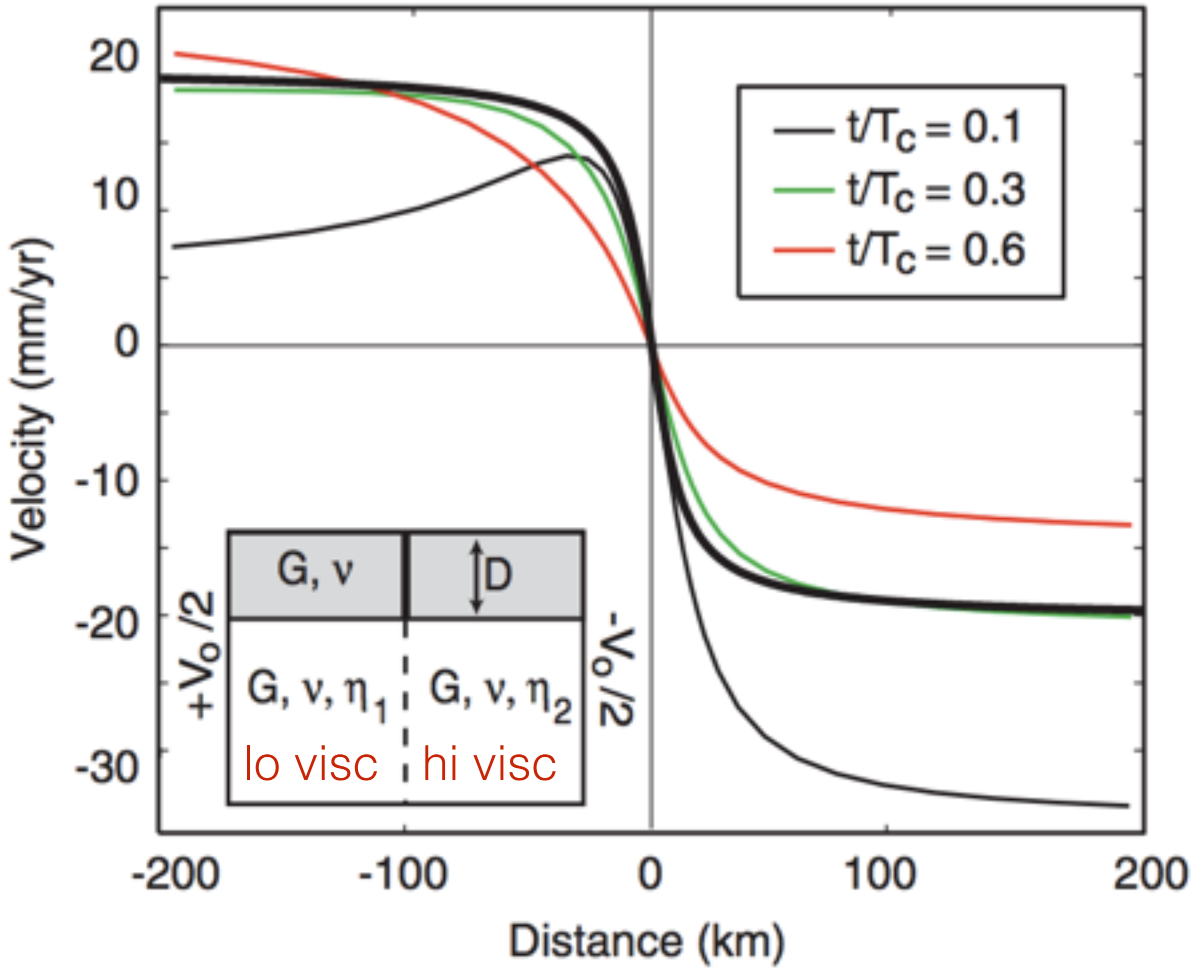
Green bars: all accepted MCMC models
Blue bars: last 1500 accepted MCMC models
Red bars: last 500 accepted MCMC models

Not a new conclusion: see also Johnson et al., 2007, Chuang and Johnson, 2011, Hearn et al., 2013

Material heterogeneity affects interseismic deformation and surface velocities



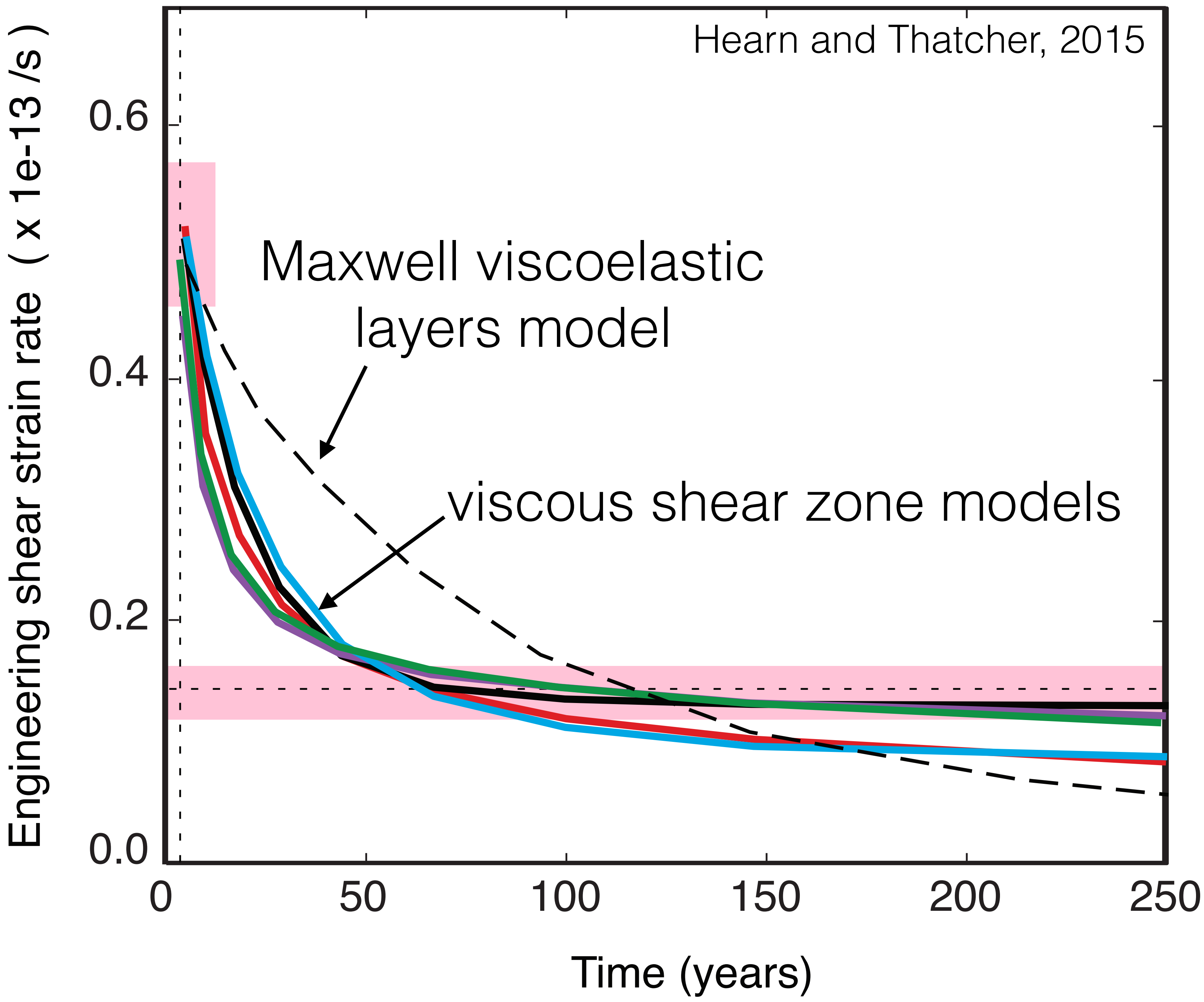
Vaghri and Hearn, 2012

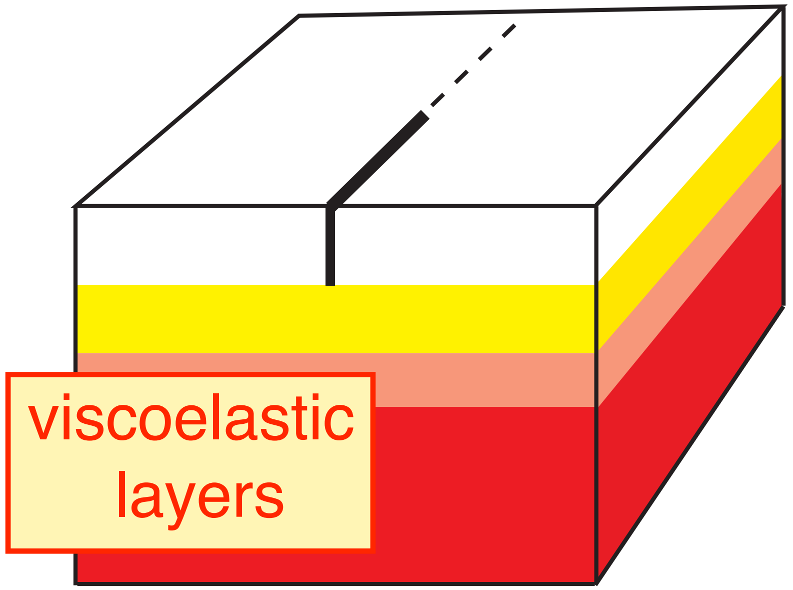


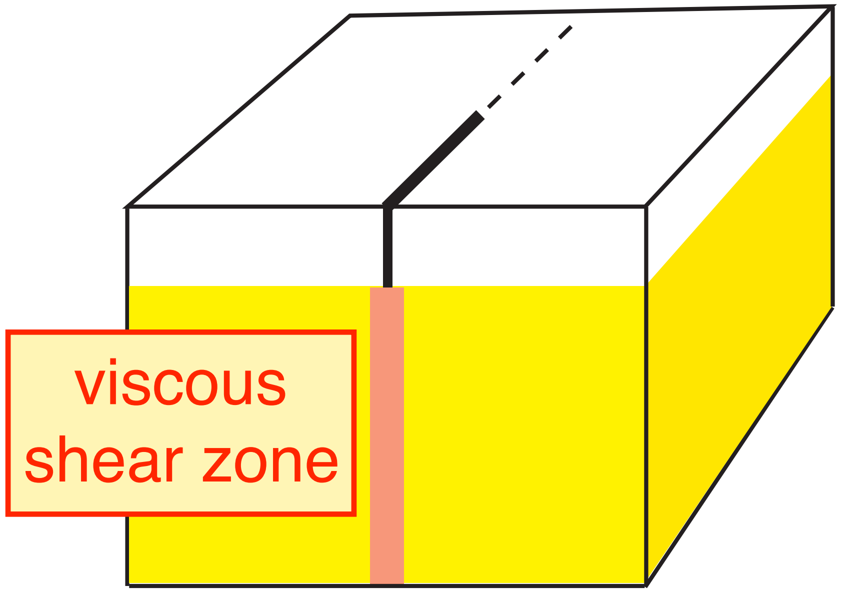
Example: asymmetry

2. Effects of lithosphere-scale shear zones

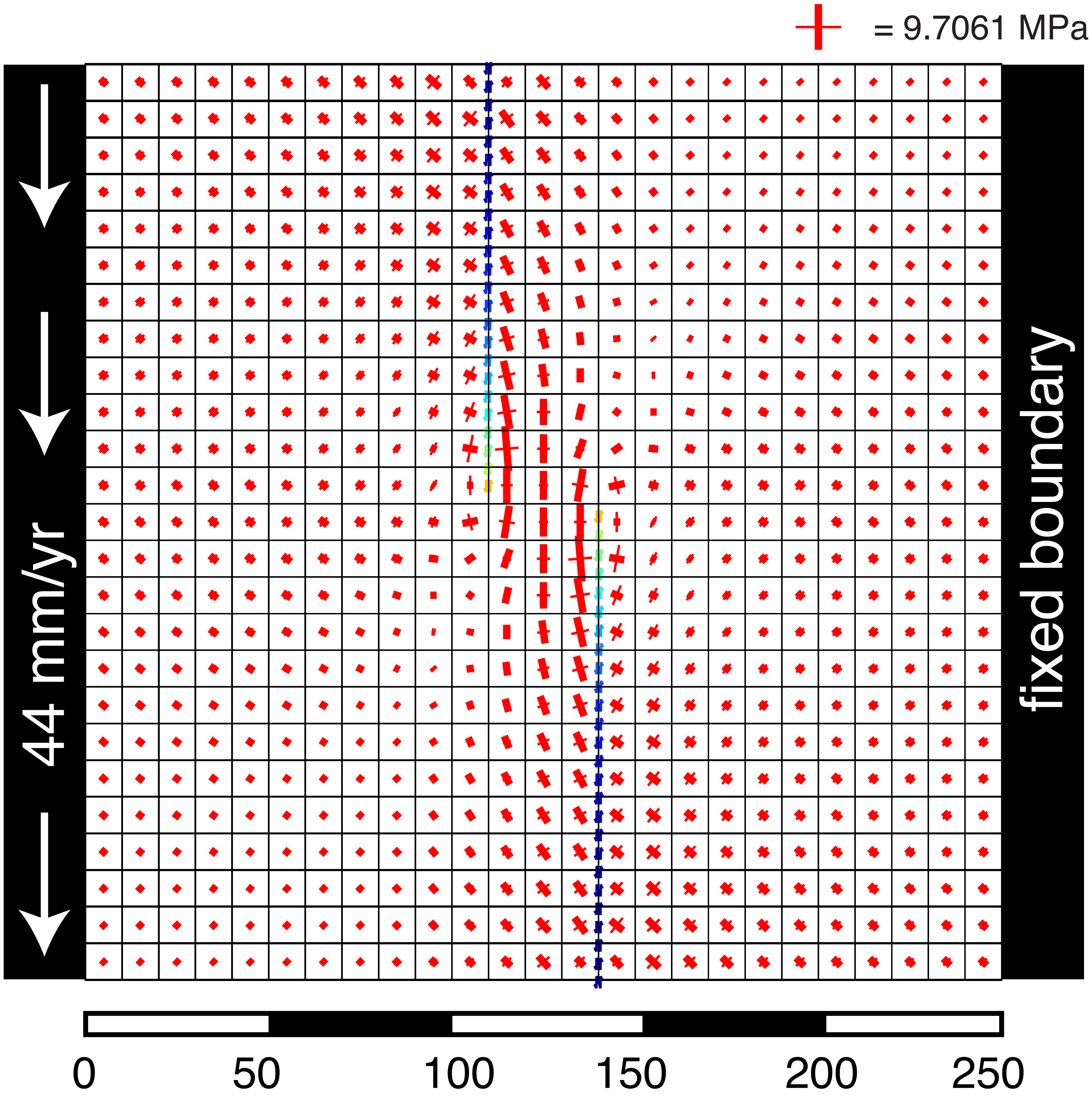
Viscous shear zones also produce interseismic stress and velocity perturbations


Hearn and Thatcher, 2015





Shear zone tractions directly influence crustal stress



Elastic model with no fault traction minus model with 5 MPa fault traction

Stresses and total fault slip are different

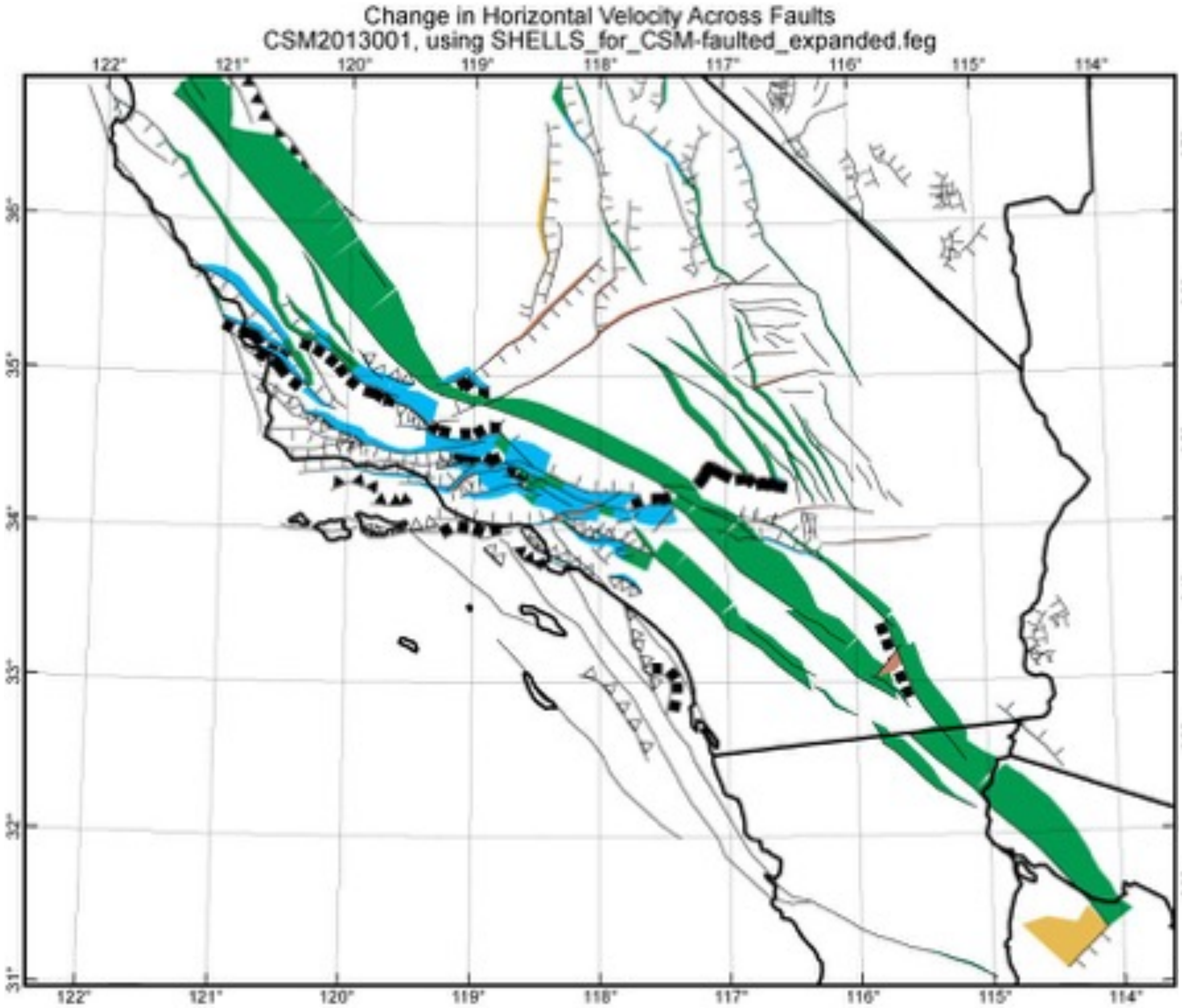
Slip rates and stress rates are identical

Poster 009

A new way to estimate shear tractions on active faults in southern California

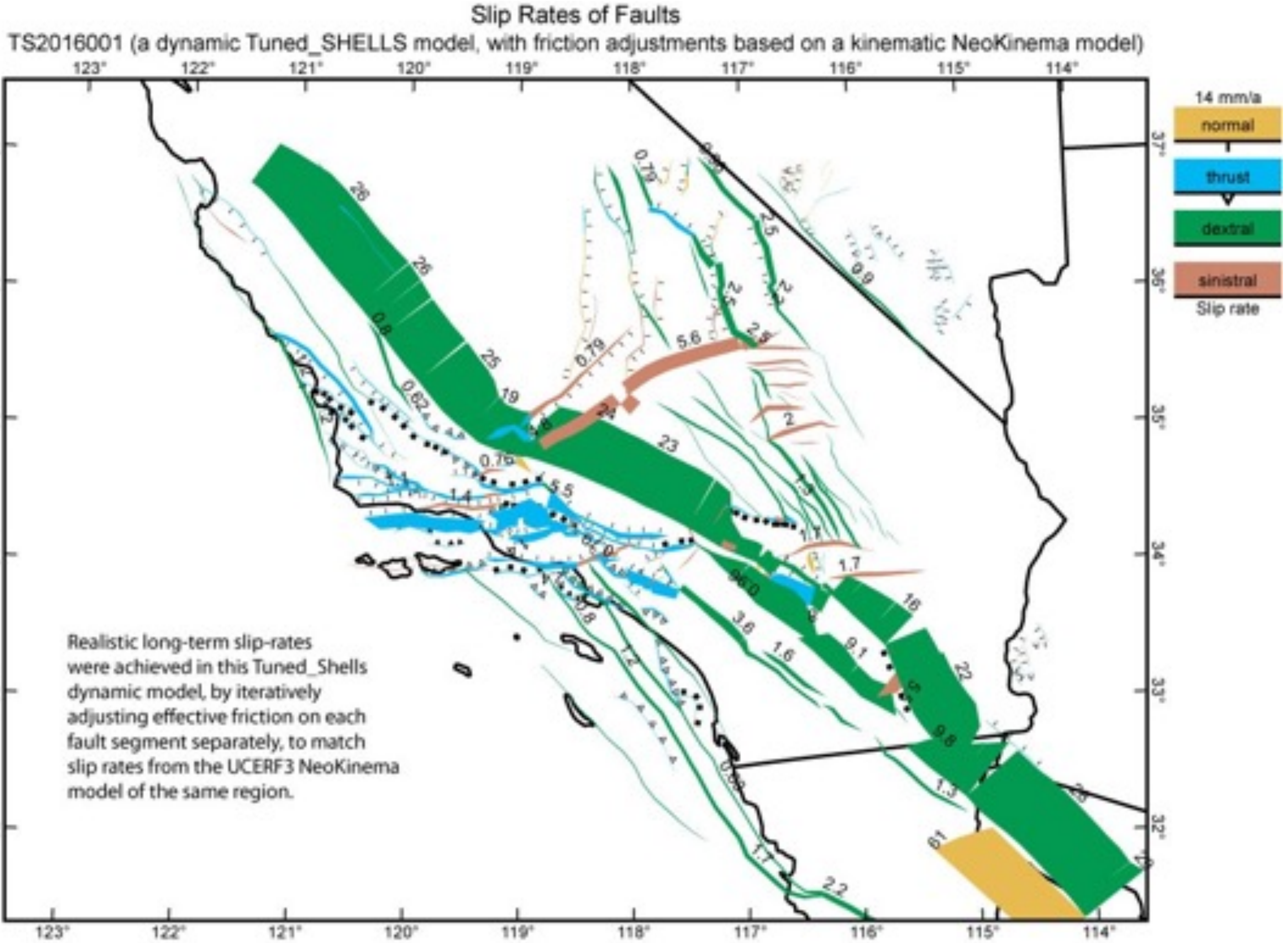
Peter Bird

Model with same effective friction on all faults



Change in Horizontal Velocity Across Faults
CSM2013001, using SHELLS_for_CSM-faulted_expanded.feg

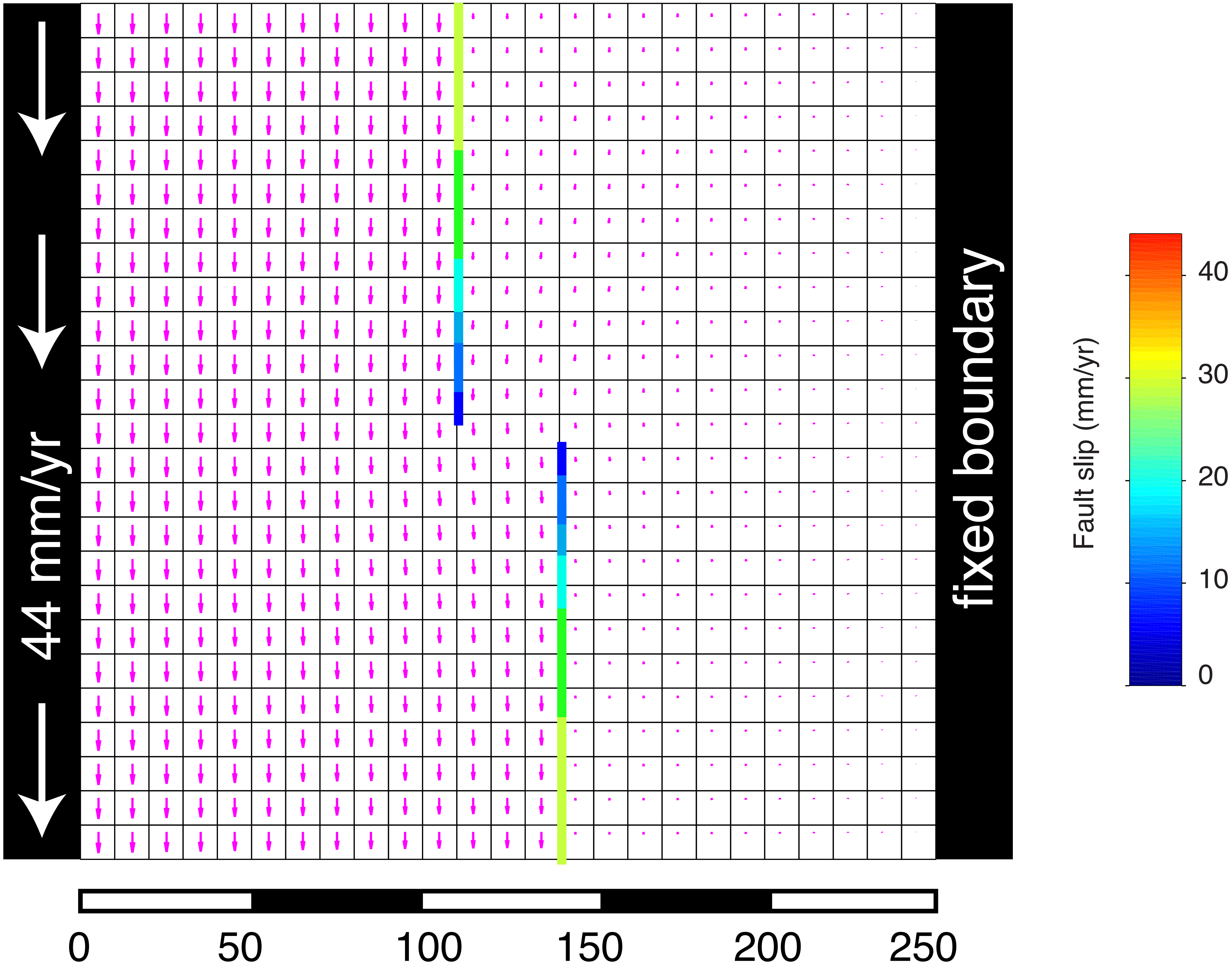
Model with effective friction adjusted for <u>each</u> fault segment to match target slip rates



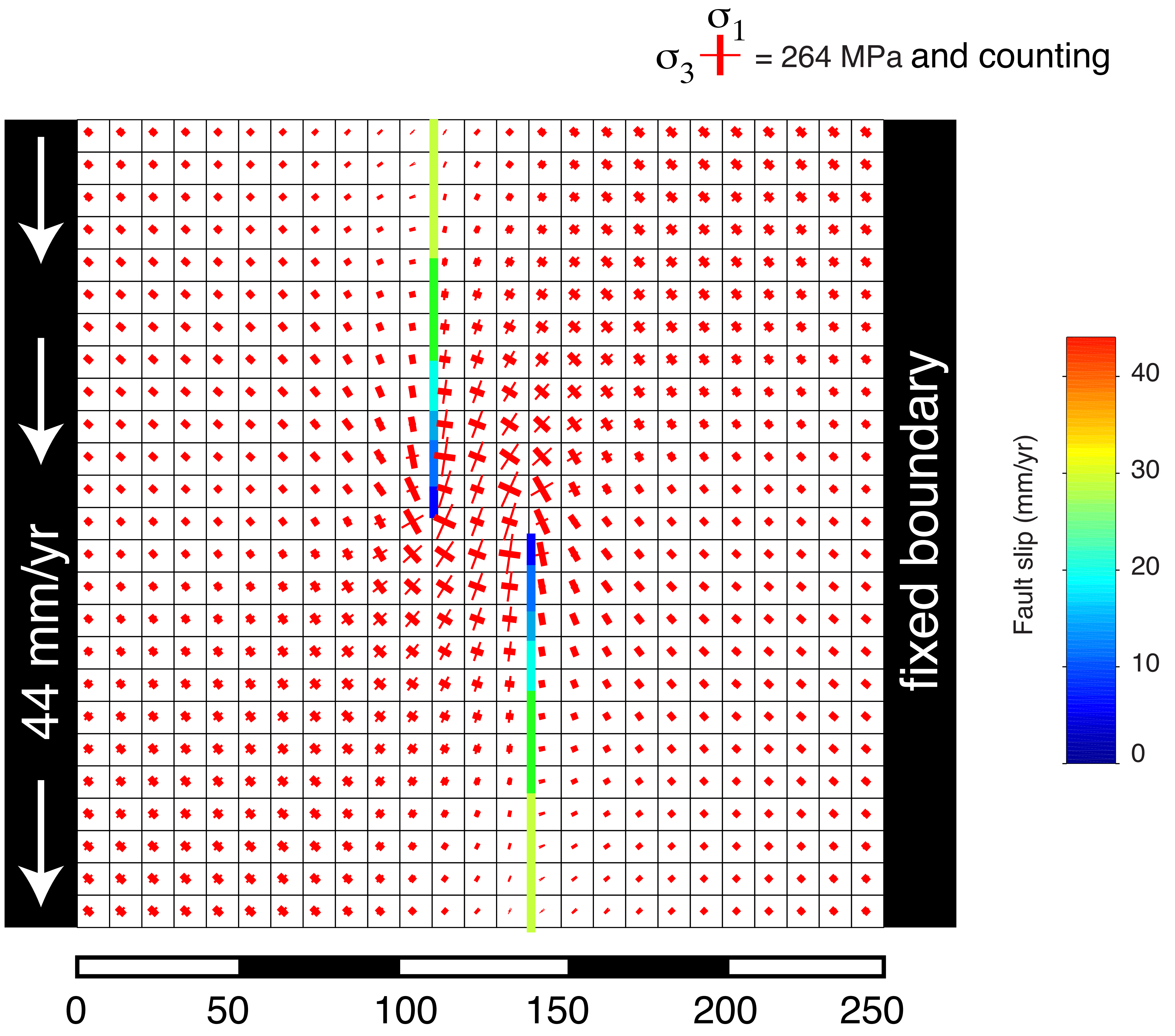
Slip Rates of Faults
TS2016001 (a dynamic Tuned_SHELLS model, with friction adjustments based on a kinematic NeoKinema model)

Realistic long-term slip-rates were achieved in this Tuned_Shells dynamic model, by iteratively adjusting effective friction on each fault segment separately, to match slip rates from the UCERF3 NeoKinema model of the same region.

3. Effect of plastic upper crust

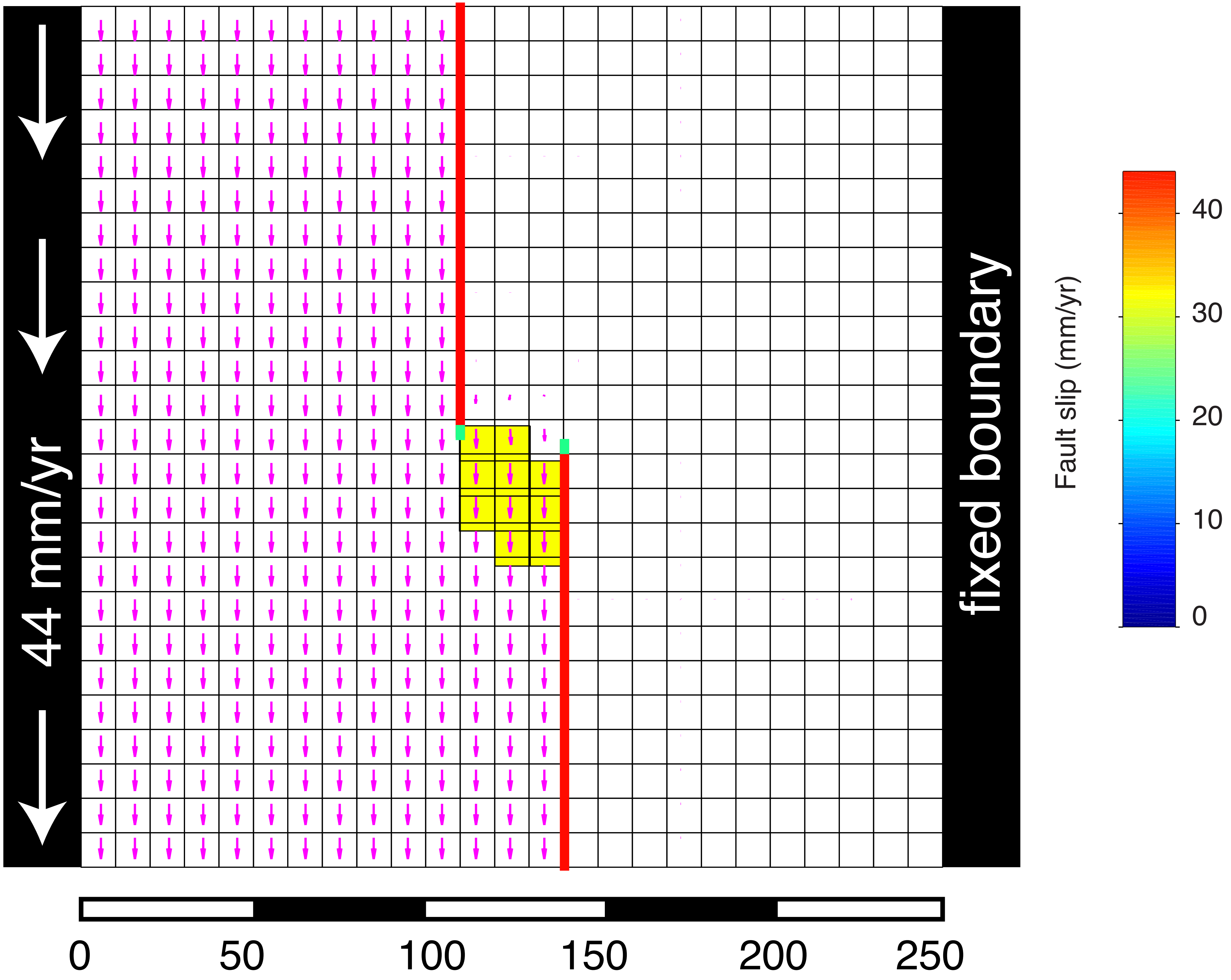


Elastic model with traction-free faults and a stepover

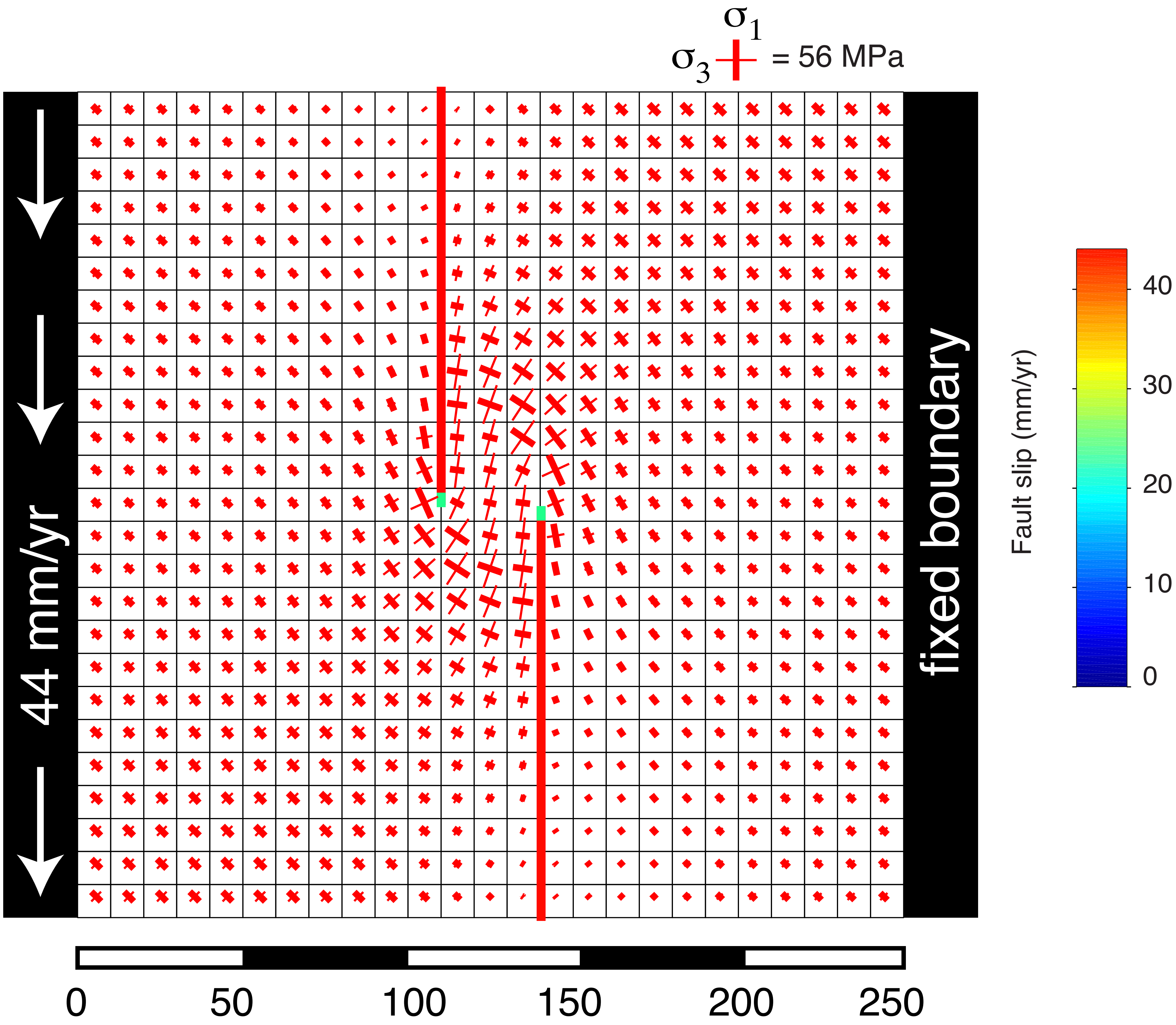


Elastic model with traction-free faults and a stepover

3. Effect of plastic upper crust

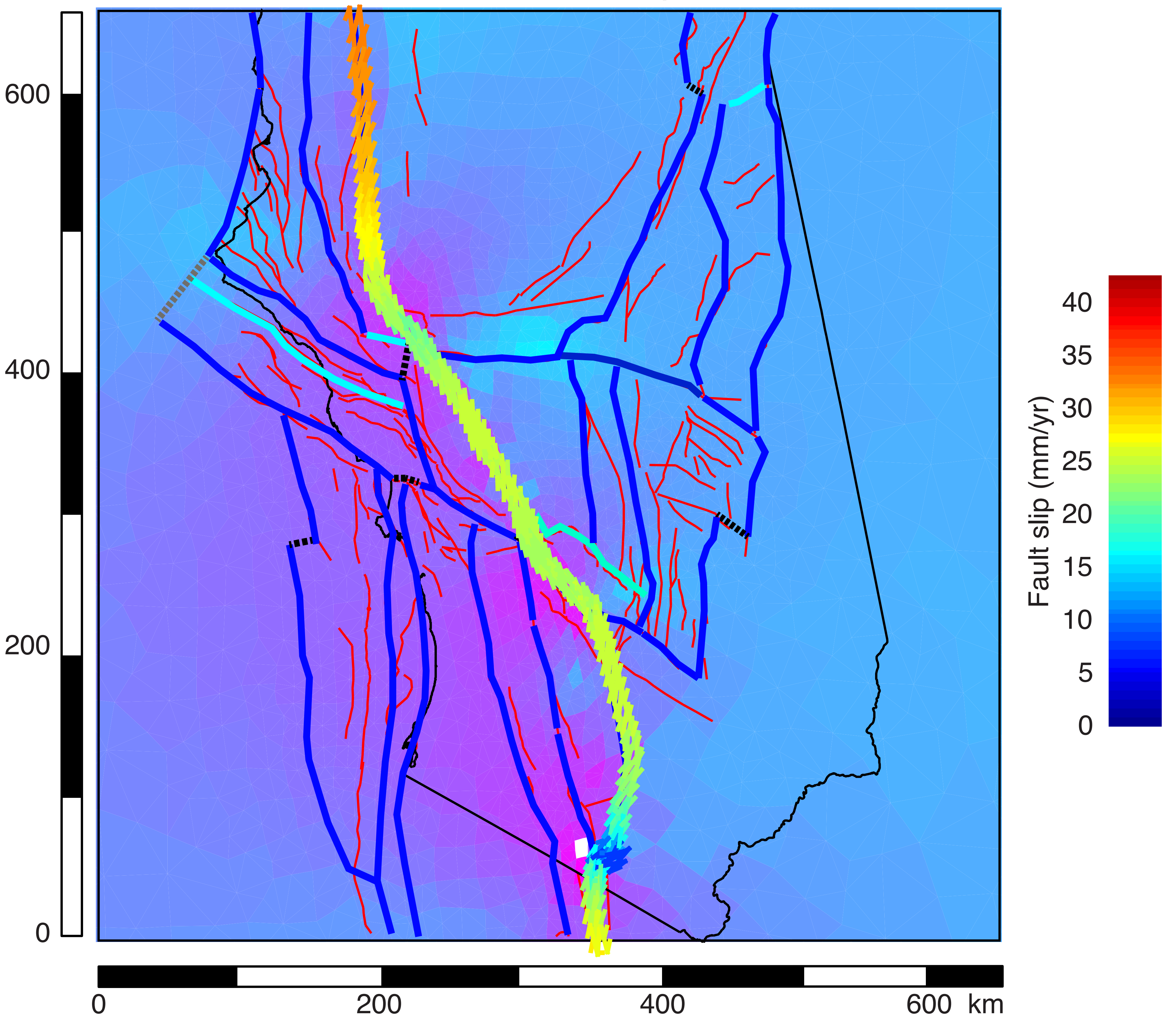


Elastic-plastic model with traction-free faults and a stepover

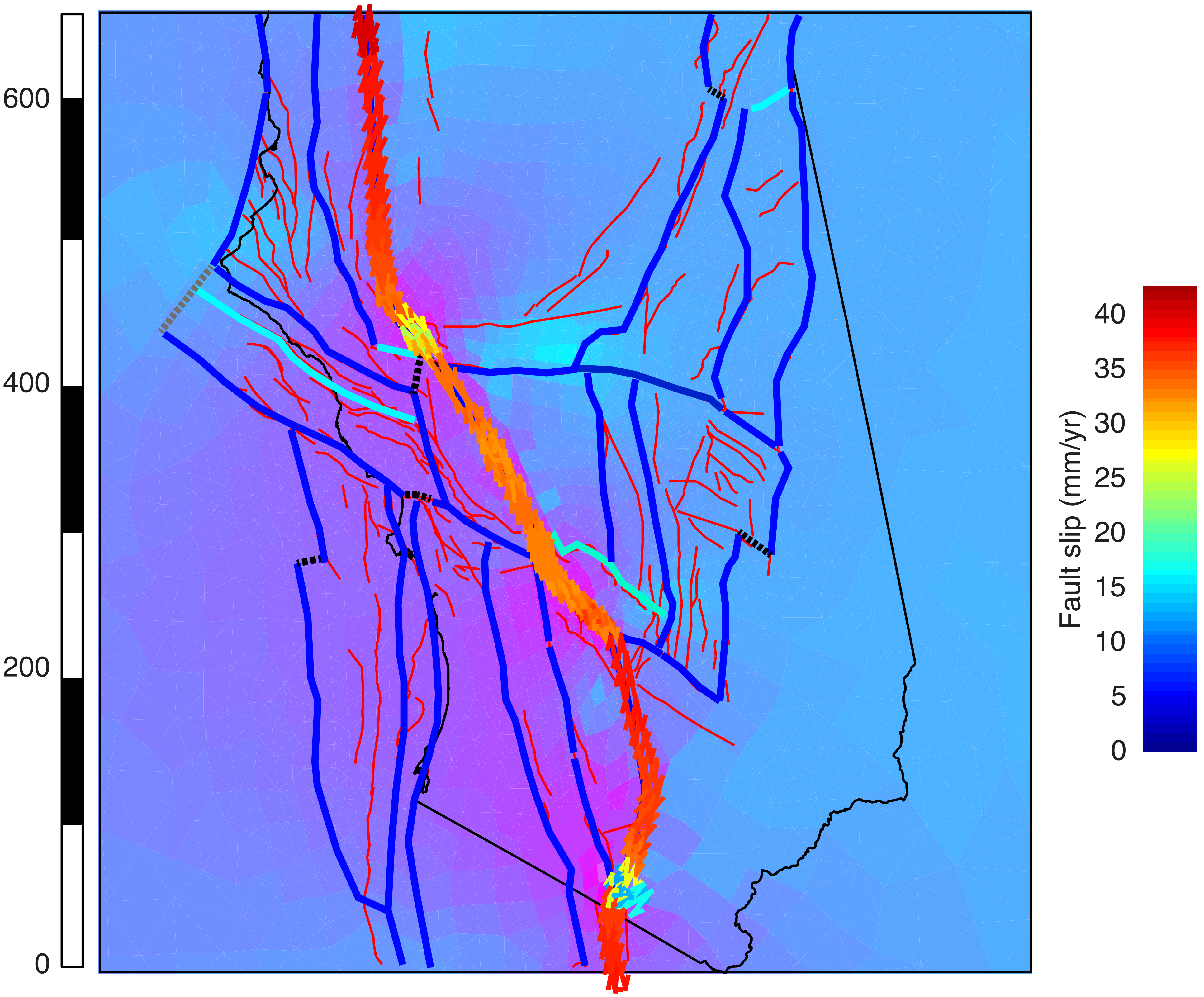


Elastic-plastic model with traction-free faults and a stepover

Elastic model with traction-free SAF: Strain energy and SAF slip rates

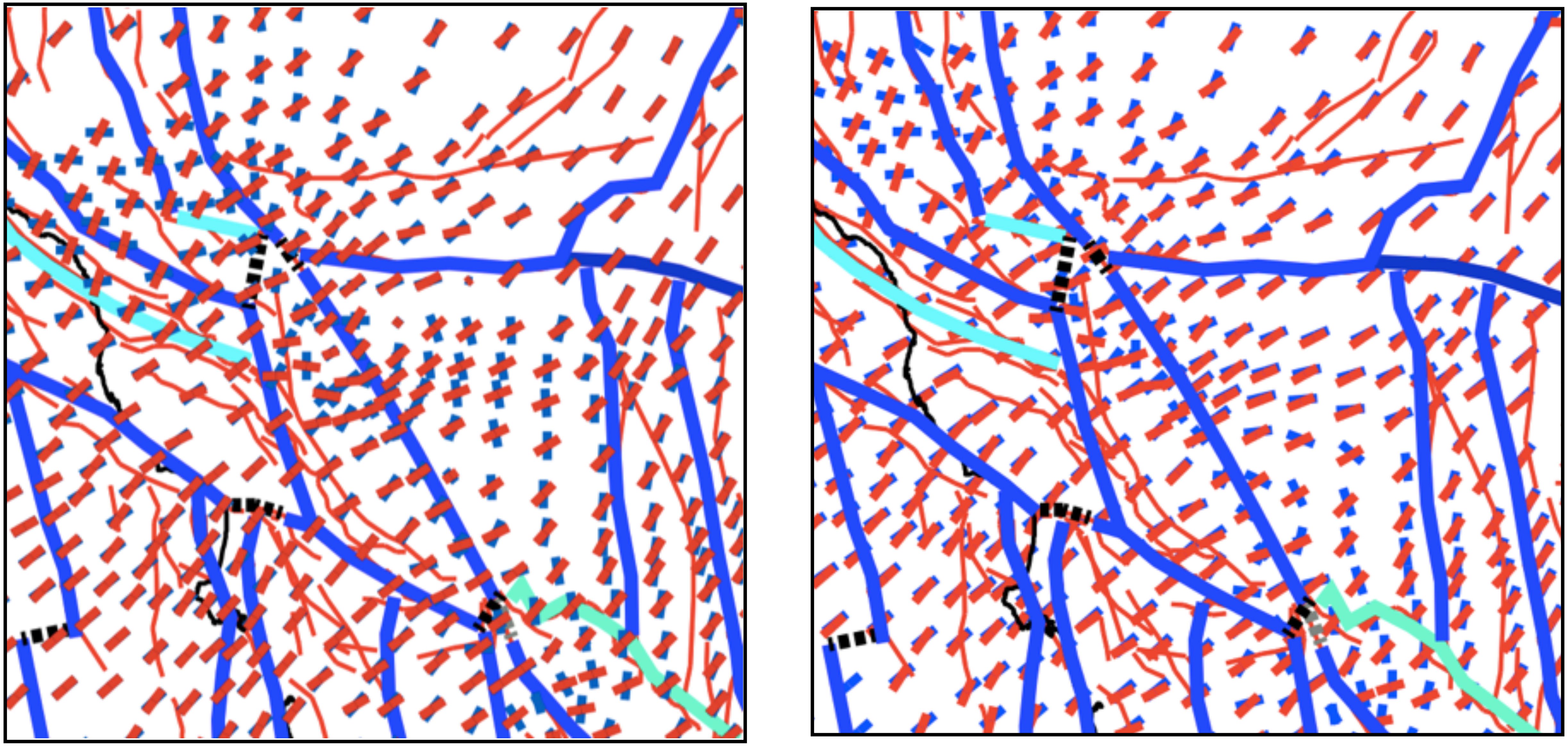


Elastic-plastic model with traction-free SAF: Strain energy and SAF slip rates



Elastic model

Elastic-plastic model



blue: from model

red: from seismicity (CSM contribution of Yang and Hauksson)

SCEC5 theme: Beyond Elasticity

Rheology influences modeled stresses, stressing rates, and fault interactions

(geologic vs. geodetic slip rates? supercycles? earthquake gates?)

1. Viscoelastic lower lithosphere
2. Lithosphere-scale shear zones
3. Plastic upper crust

today's examples