Vertical Motions and the Earthquake Cycle in Southern California

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in collaboration with

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U. Nevada Reno

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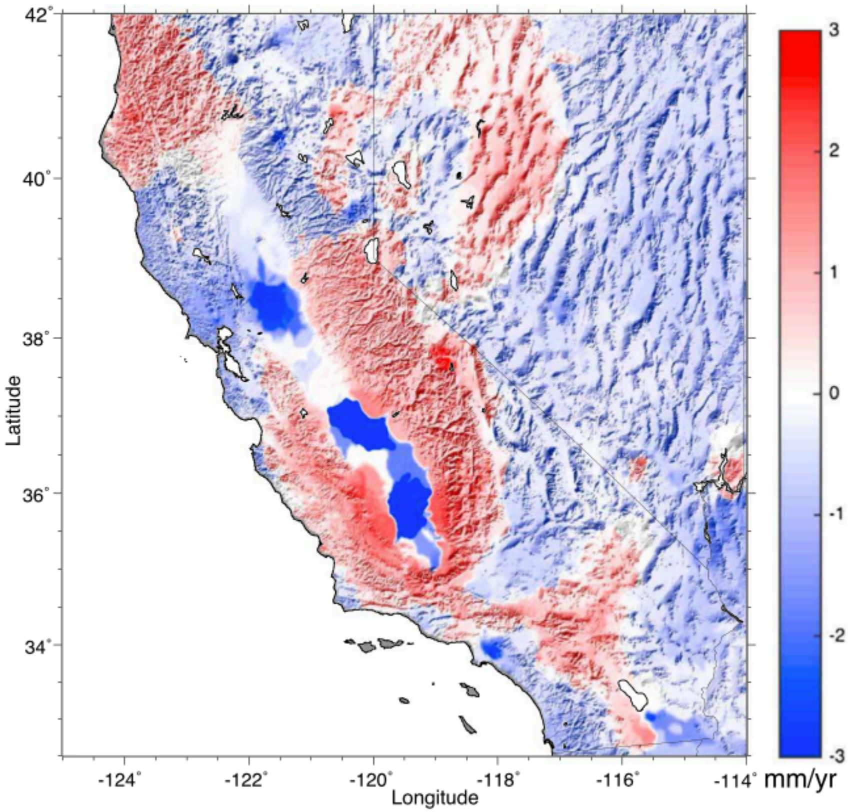
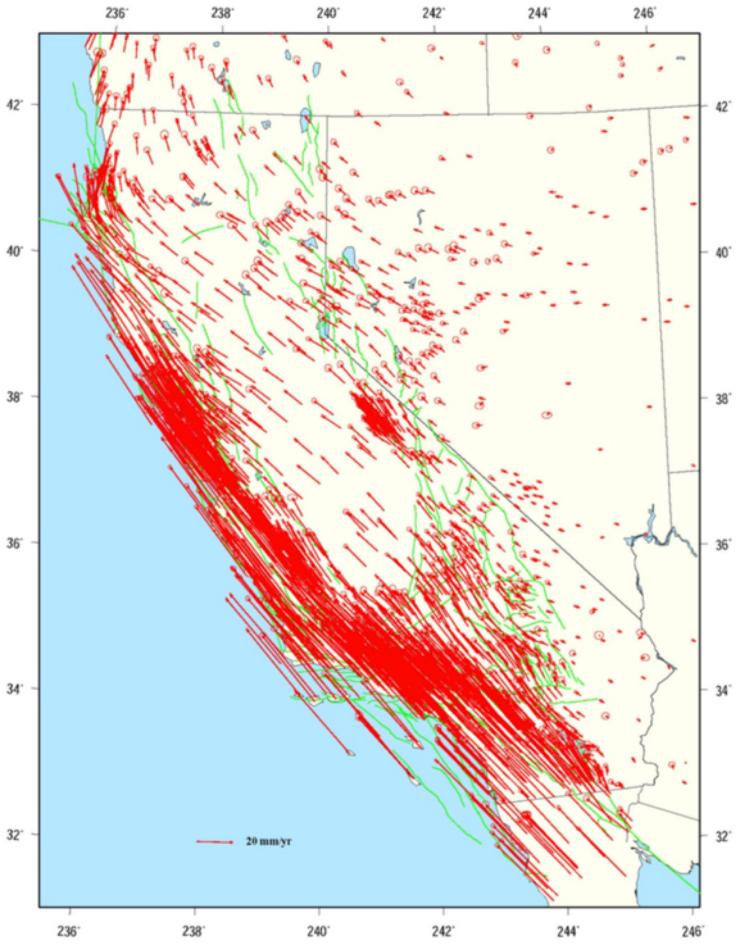


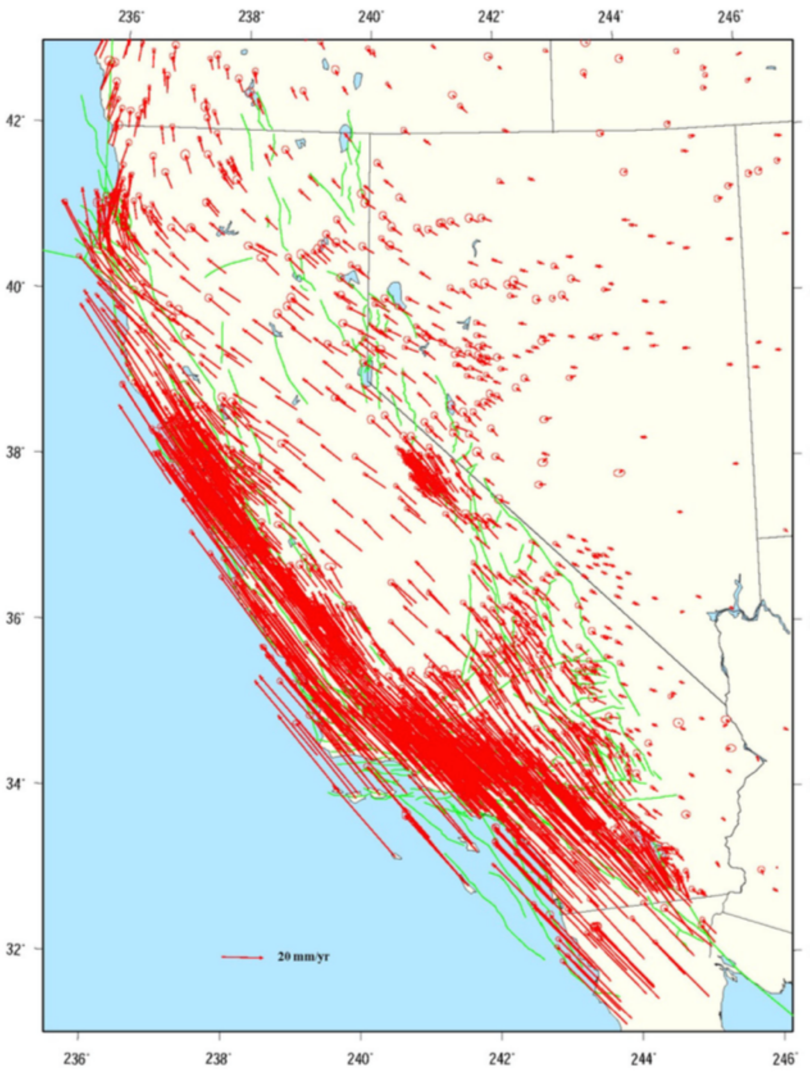
Hammond et al. 2016

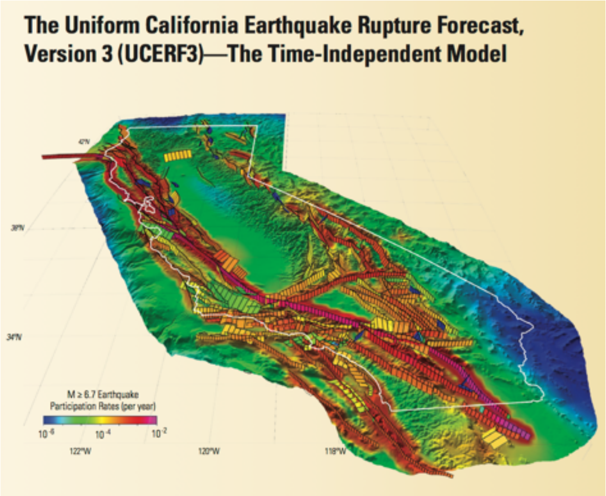


UCERF3, 2013

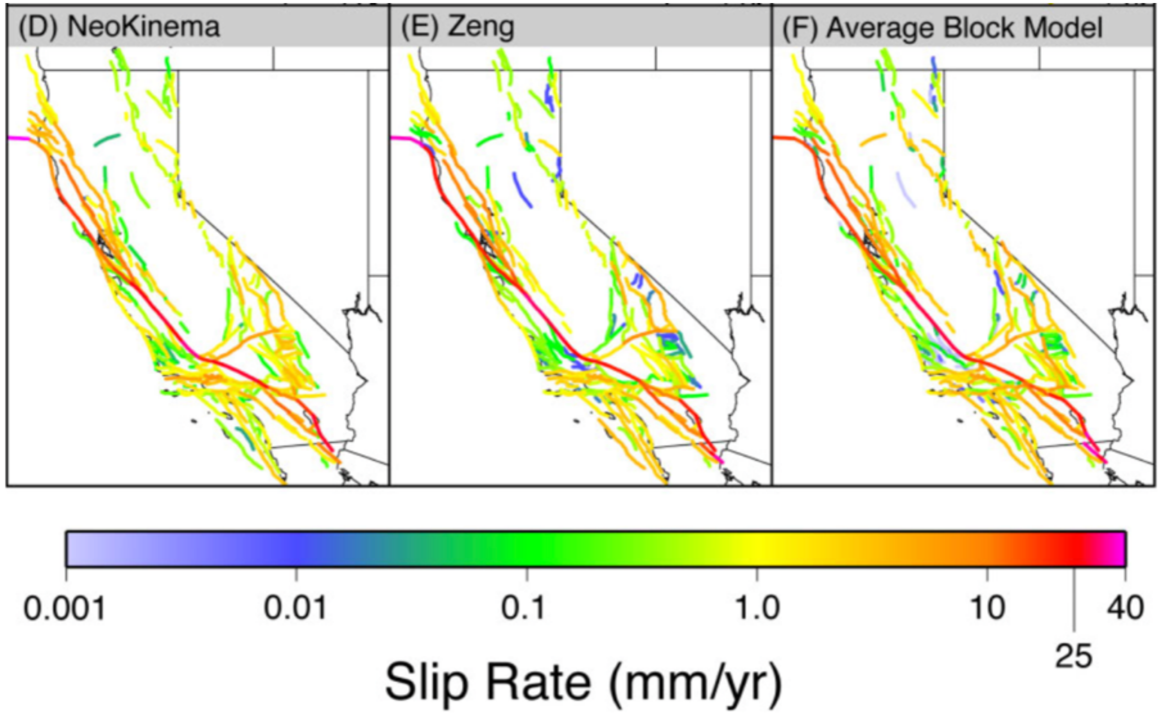
A Motivation: Earthquake Hazards

UCERF3, 2013



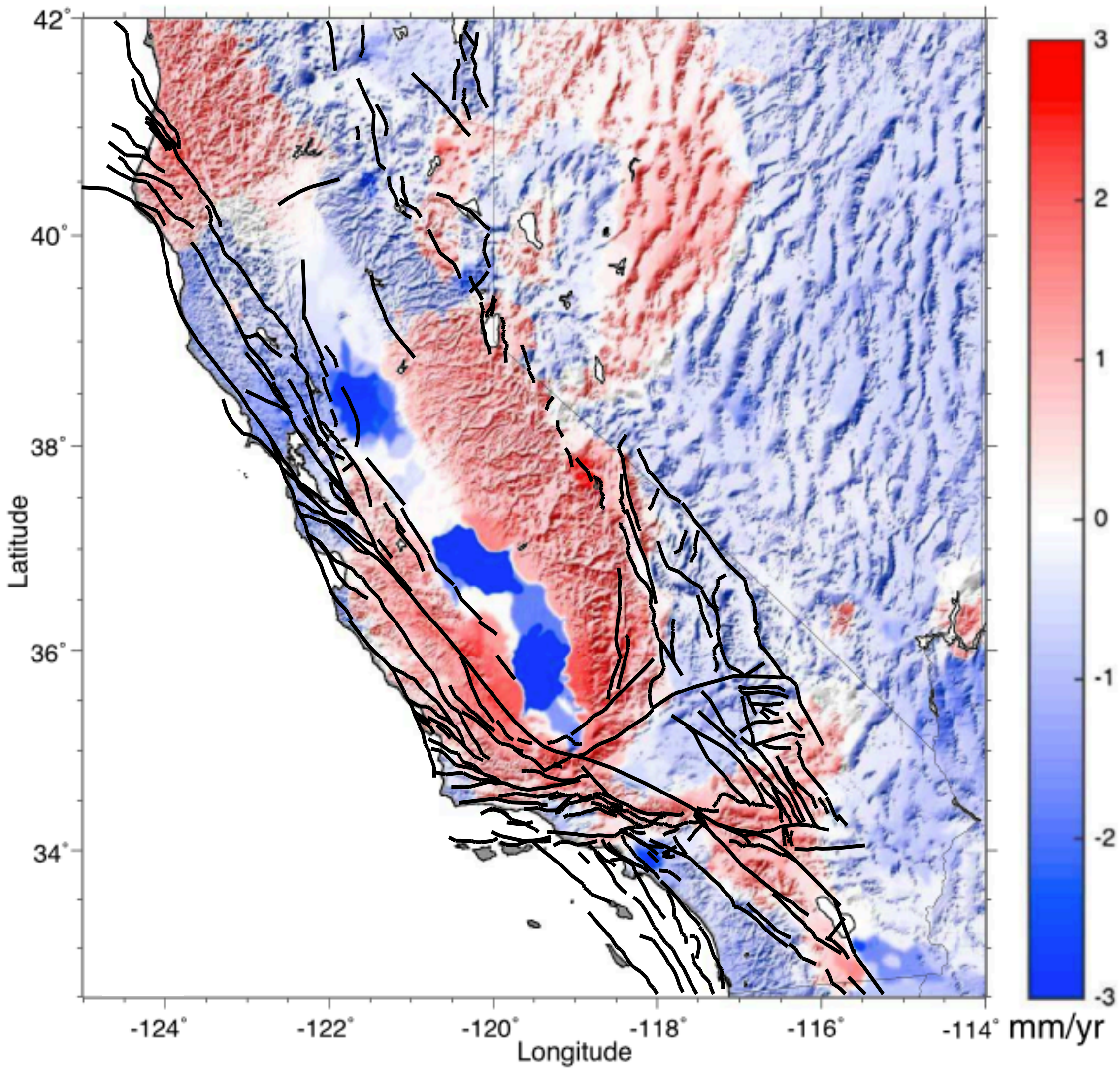


- Kinematic models
- Assume steady deformation
- Incorporate recoverable elastic strain accumulation
- Invert GPS horizontal velocity field for fault slip rates

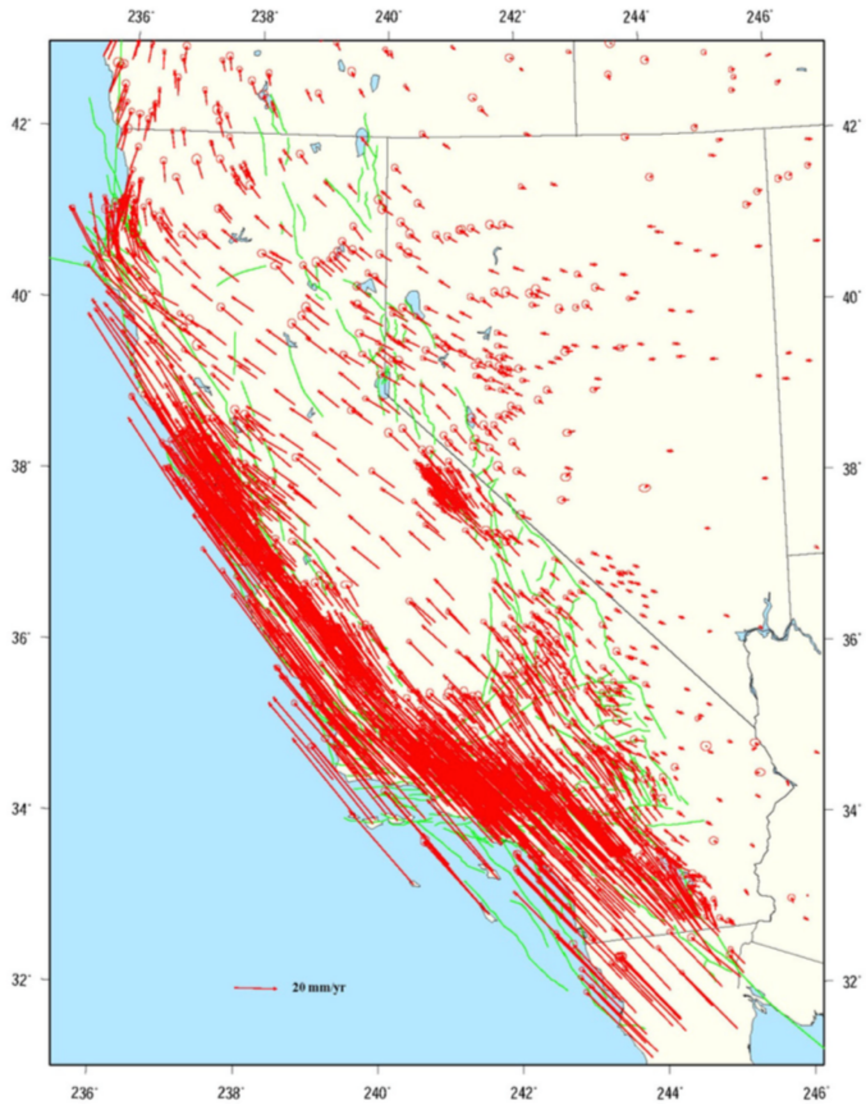


A snapshot of time-varying processes

Hammond et al. 2016



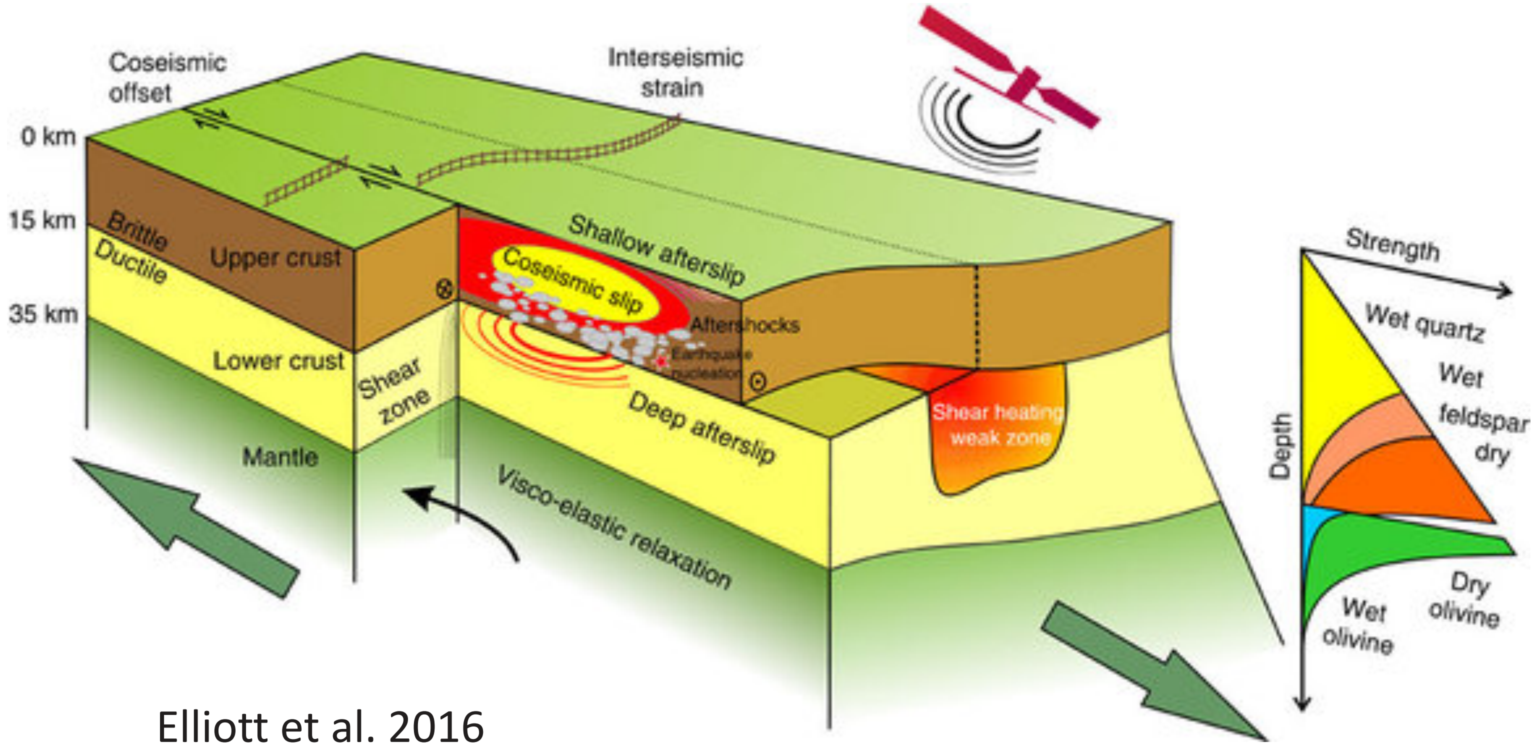
UCERF3, 2013



Deformation is Transient

- Recoverable elastic strain – fault coupling

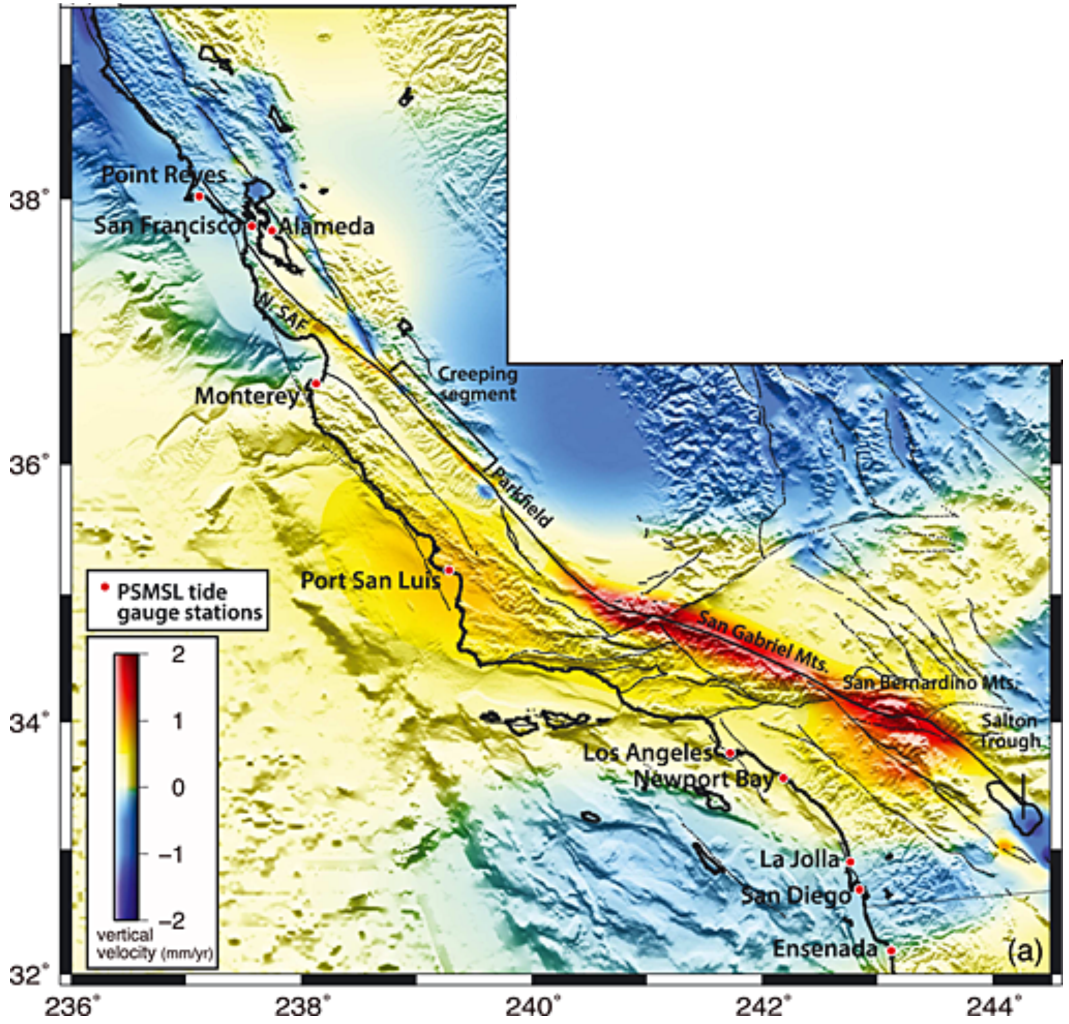
- Time-dependent deep fault creep
- Time-dependent lower crust and mantle flow

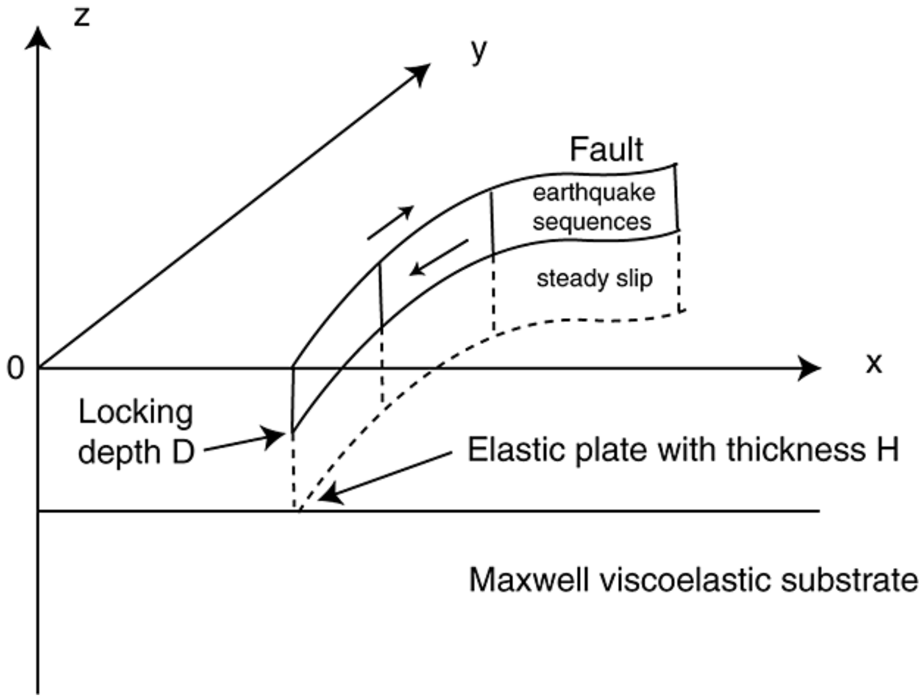


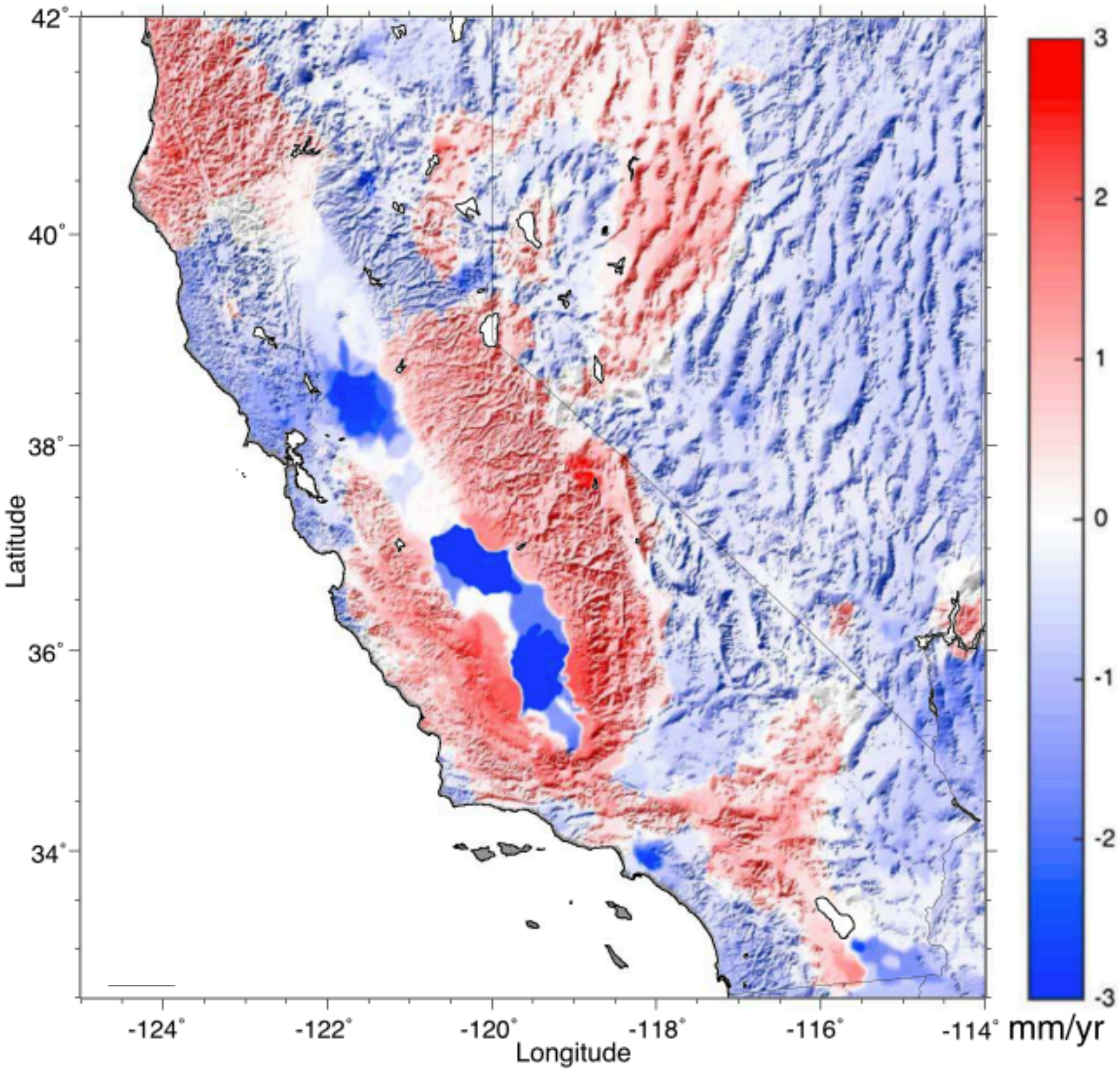
Elliott et al. 2016

Vertical Motions Associated with the Earthquake Cycle are Predicted

e.g., Konter-Smith et al., 2014







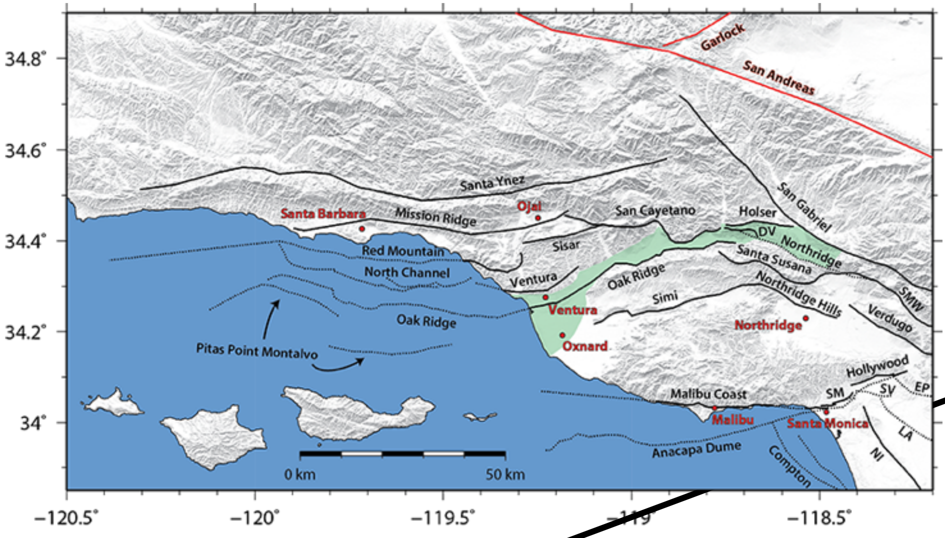
Questions Regarding Vertical Motions:

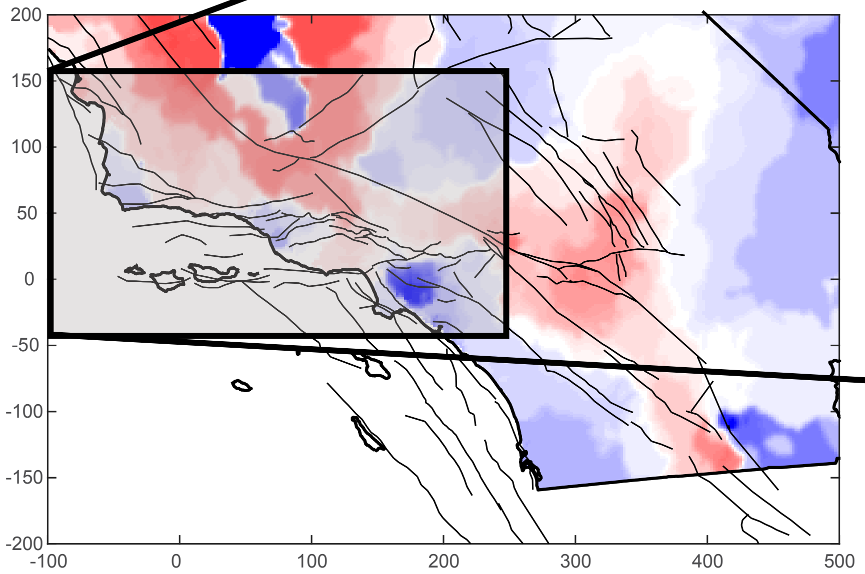
- Can we separate out tectonic signal from other sources?
  - Hydrologic loading
  - Sediment compaction
  - GIA
- Tectonic uplift across faults?
- Fingerprint of “ghost” transients due to mantle flow and past earthquakes?

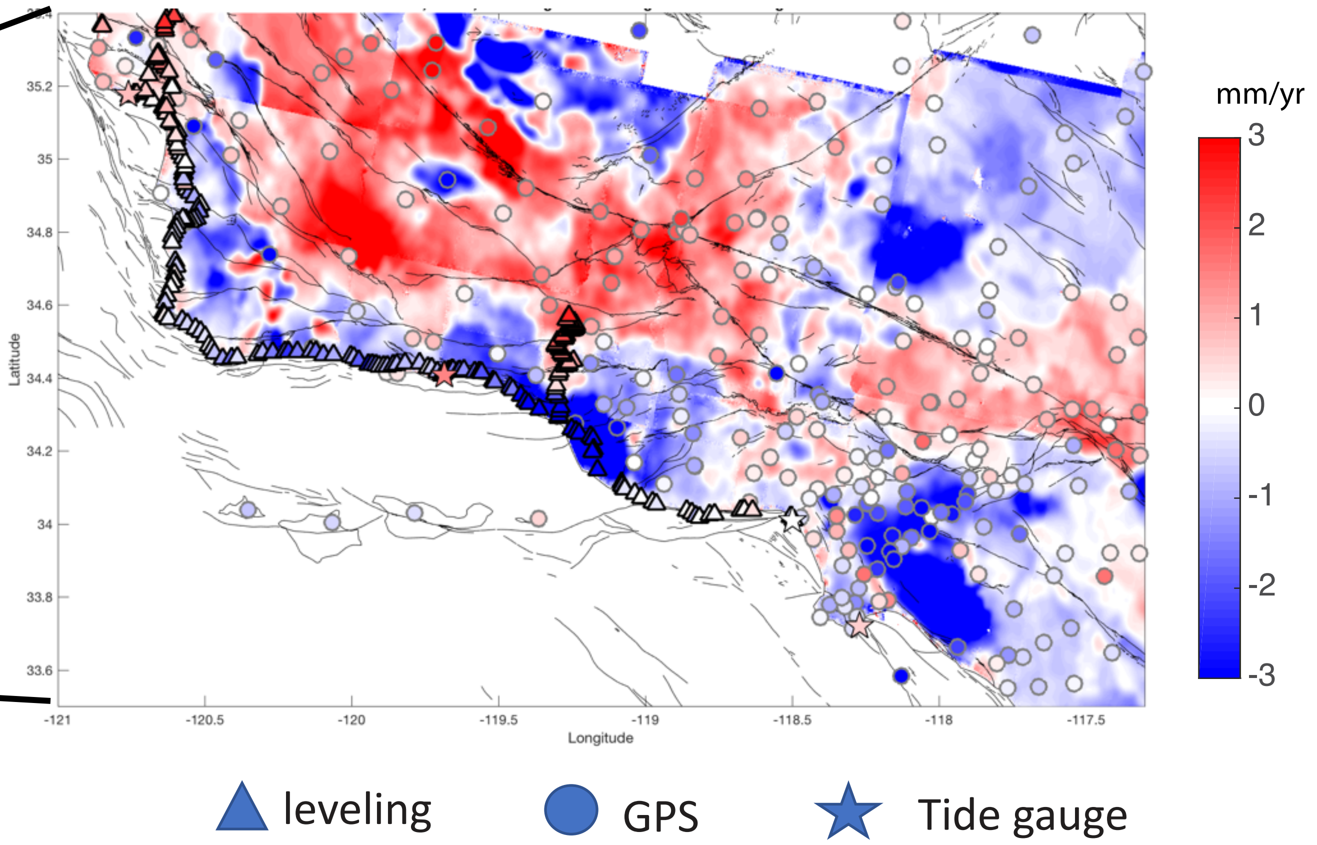
Western Transverse Ranges

Four-Technique Geodetic Study: GPS, InSAR, Leveling and Tide Gauges

Bill Hammond and Reed Burgette



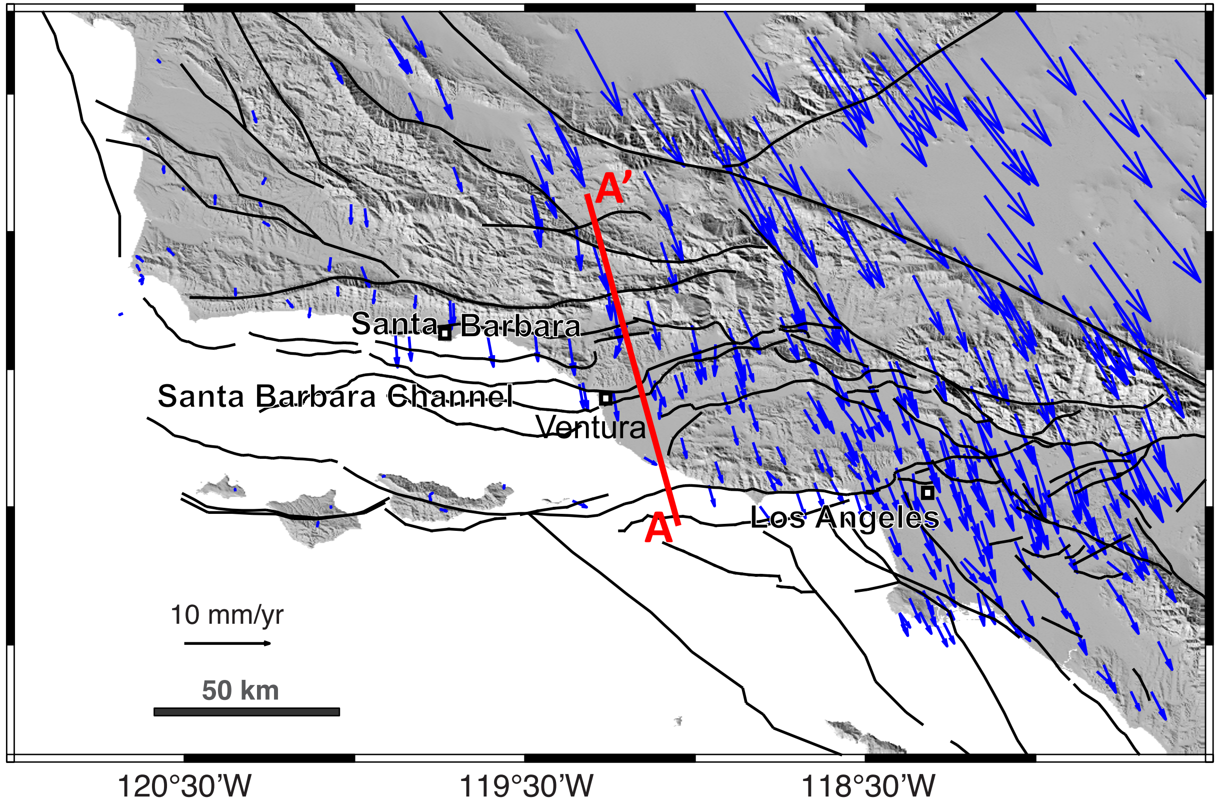


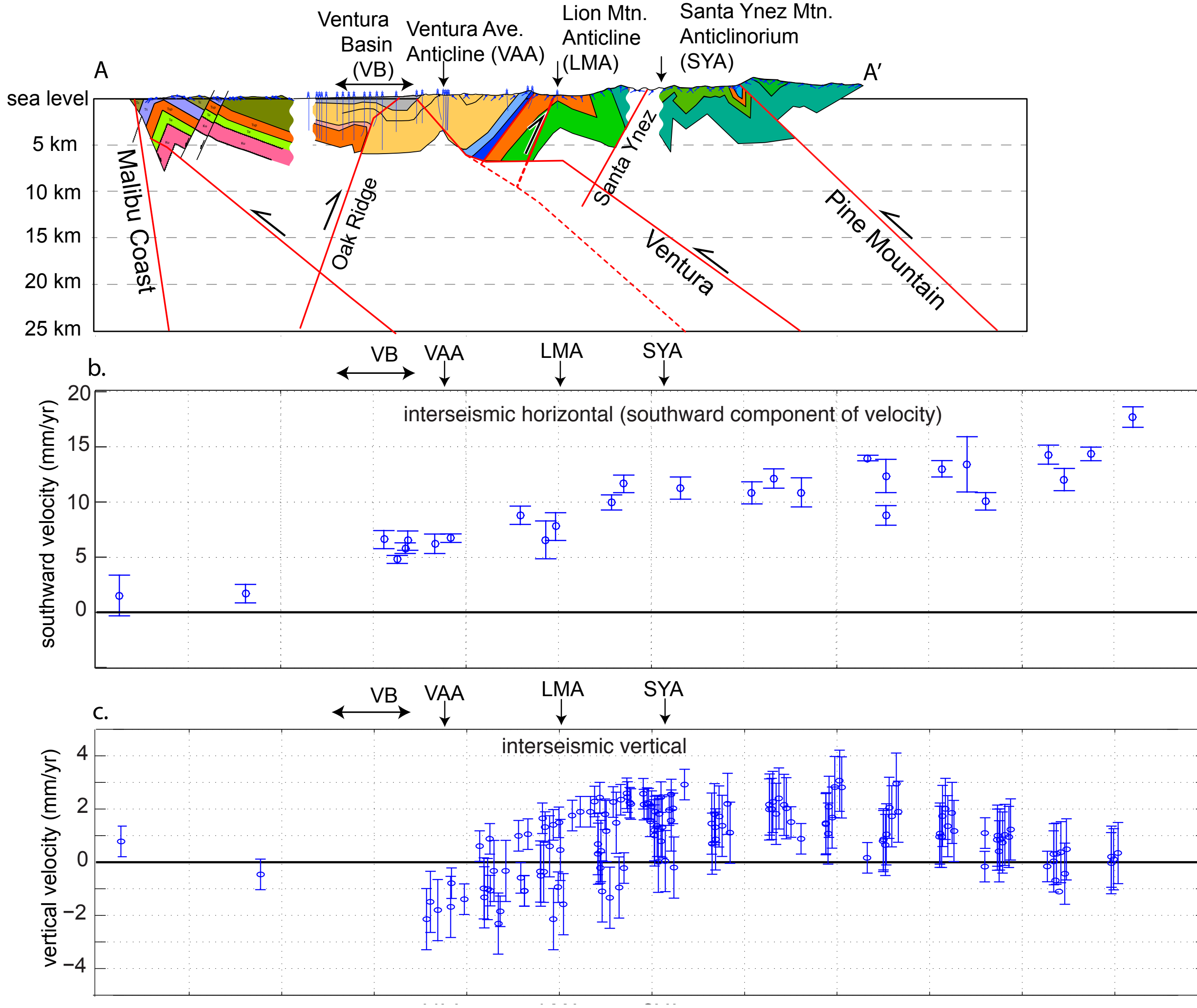


Rapid Shortening and Uplift

Active Fold and thrust Belt

horizontal GPS-derived velocities (SCEC CMM)

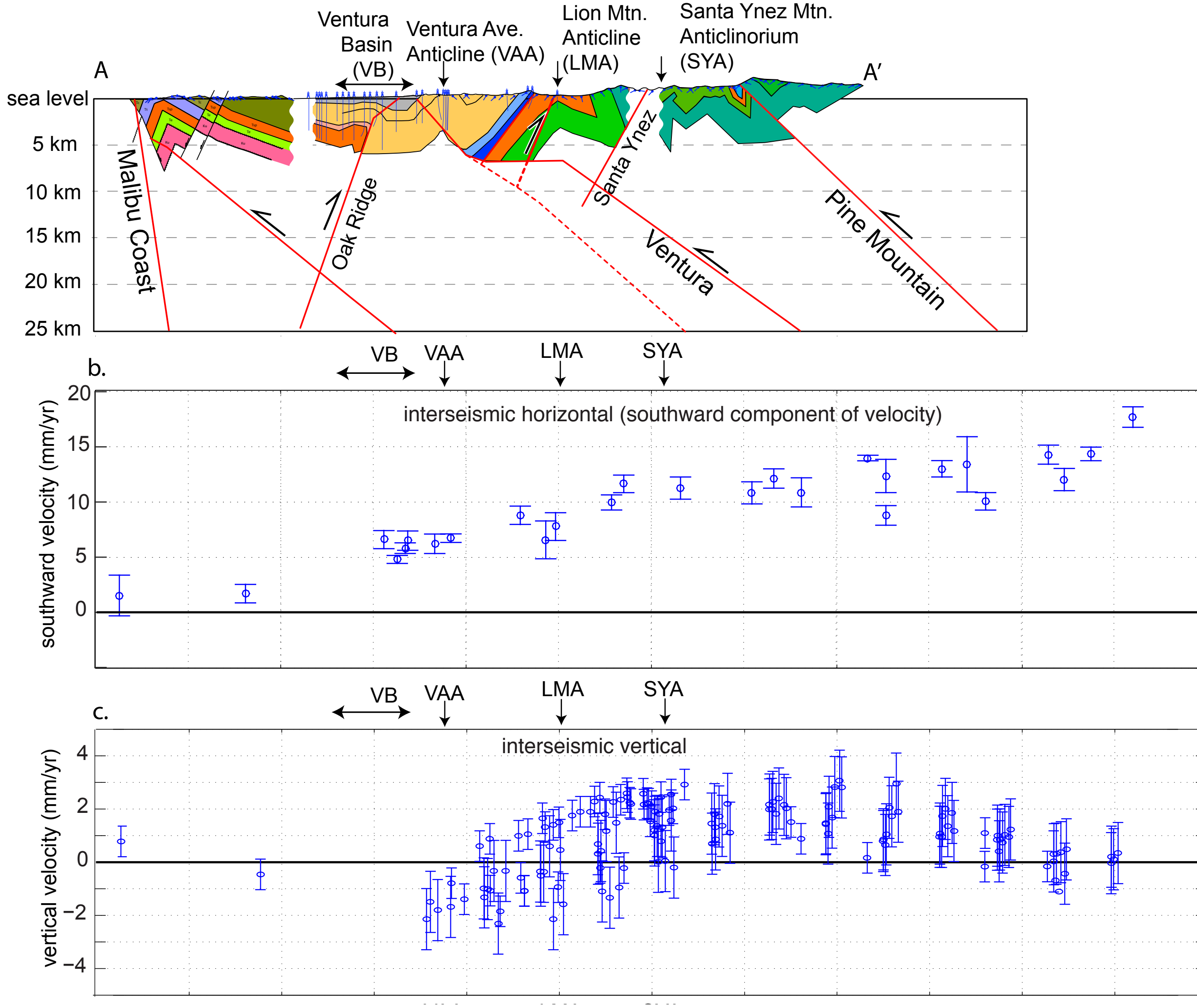




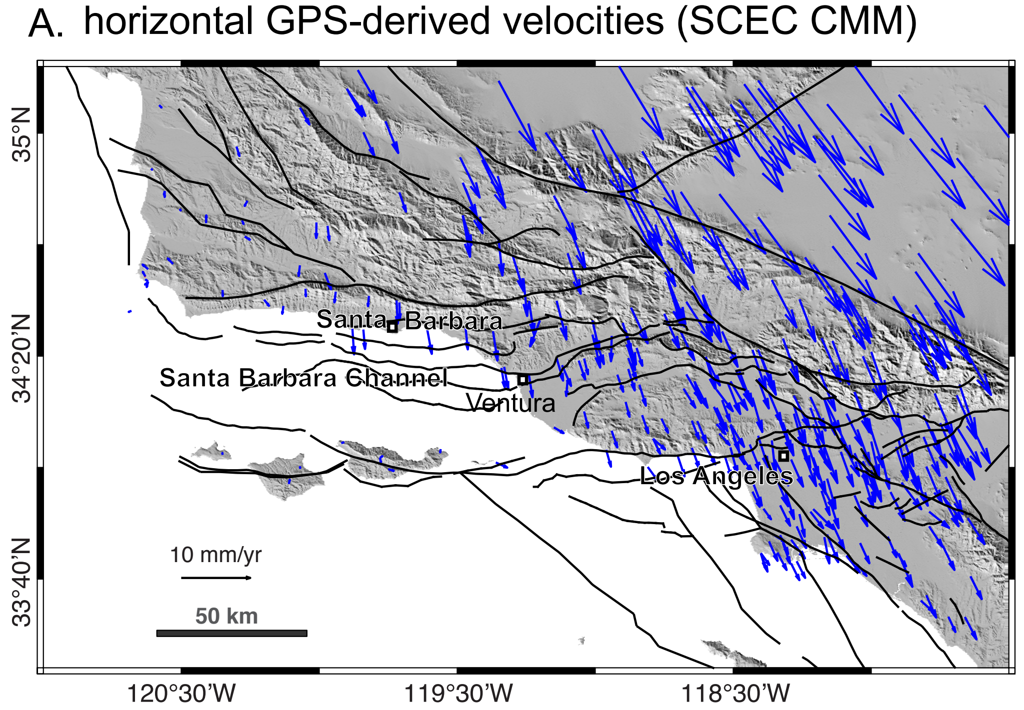
Rapid Shortening and Uplift

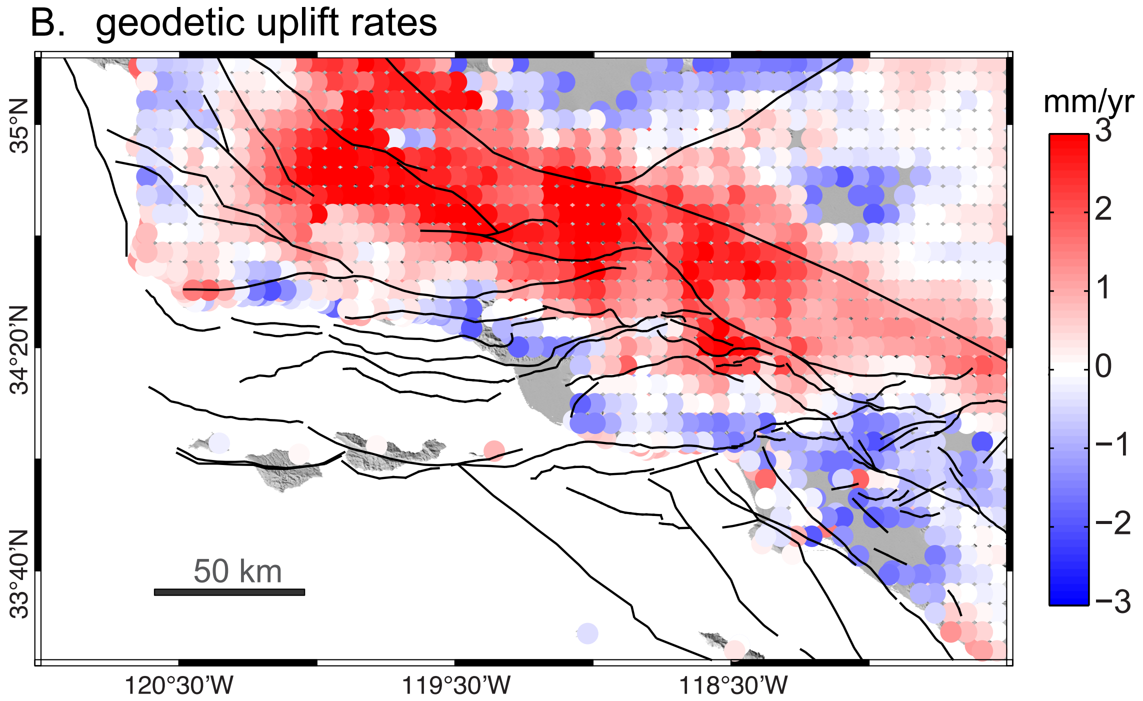
Active Fold and thrust Belt

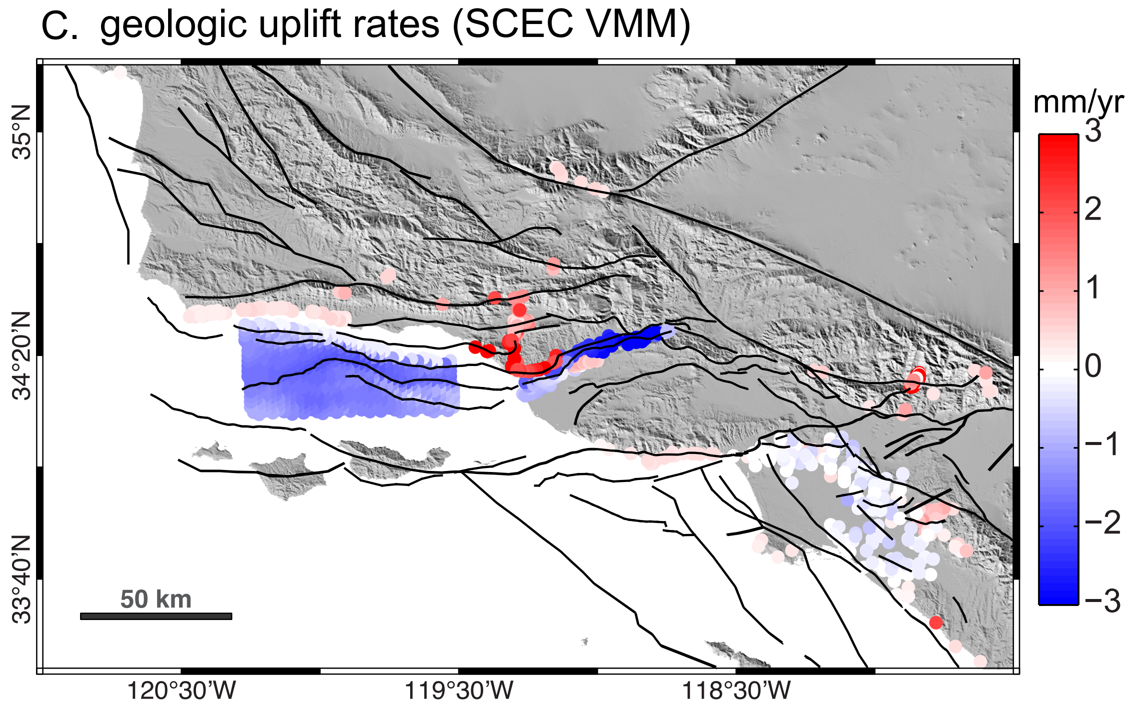
- How is shortening accommodated across fault system? What are the slip rates?
- Is the broad warping across Transverse Ranges tectonic uplift? How much is permanent? Recoverable?



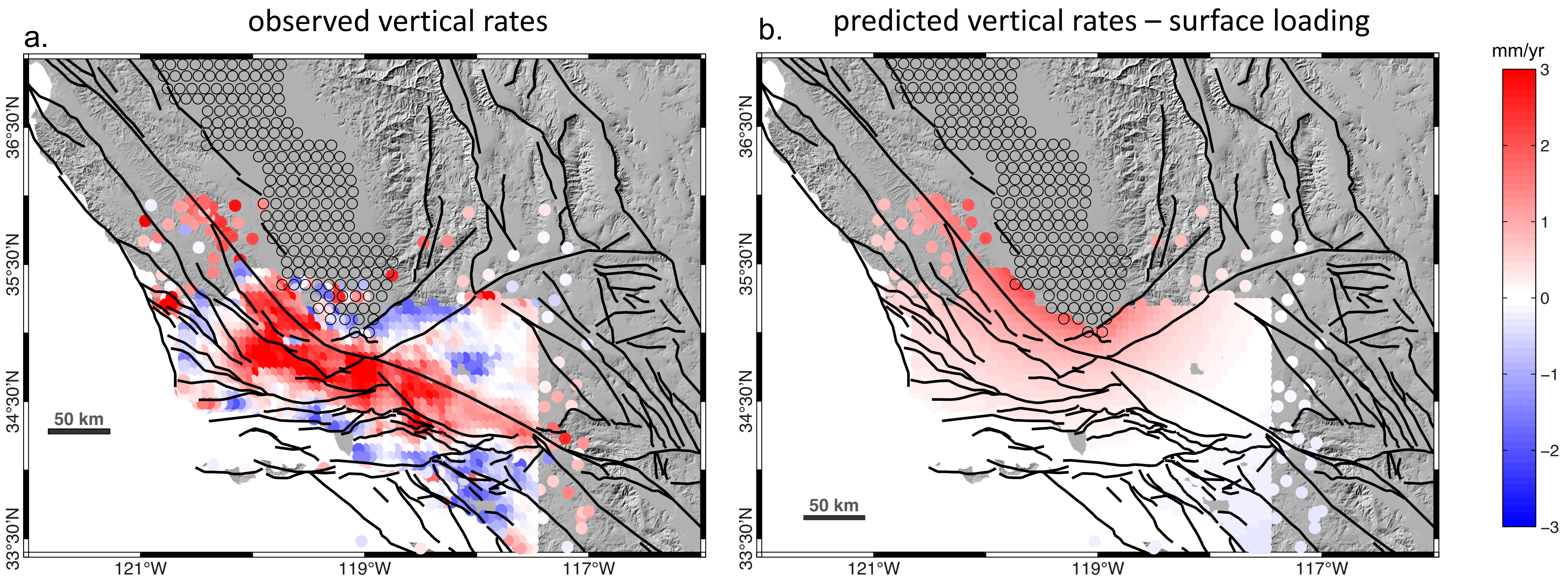
Data Constraints





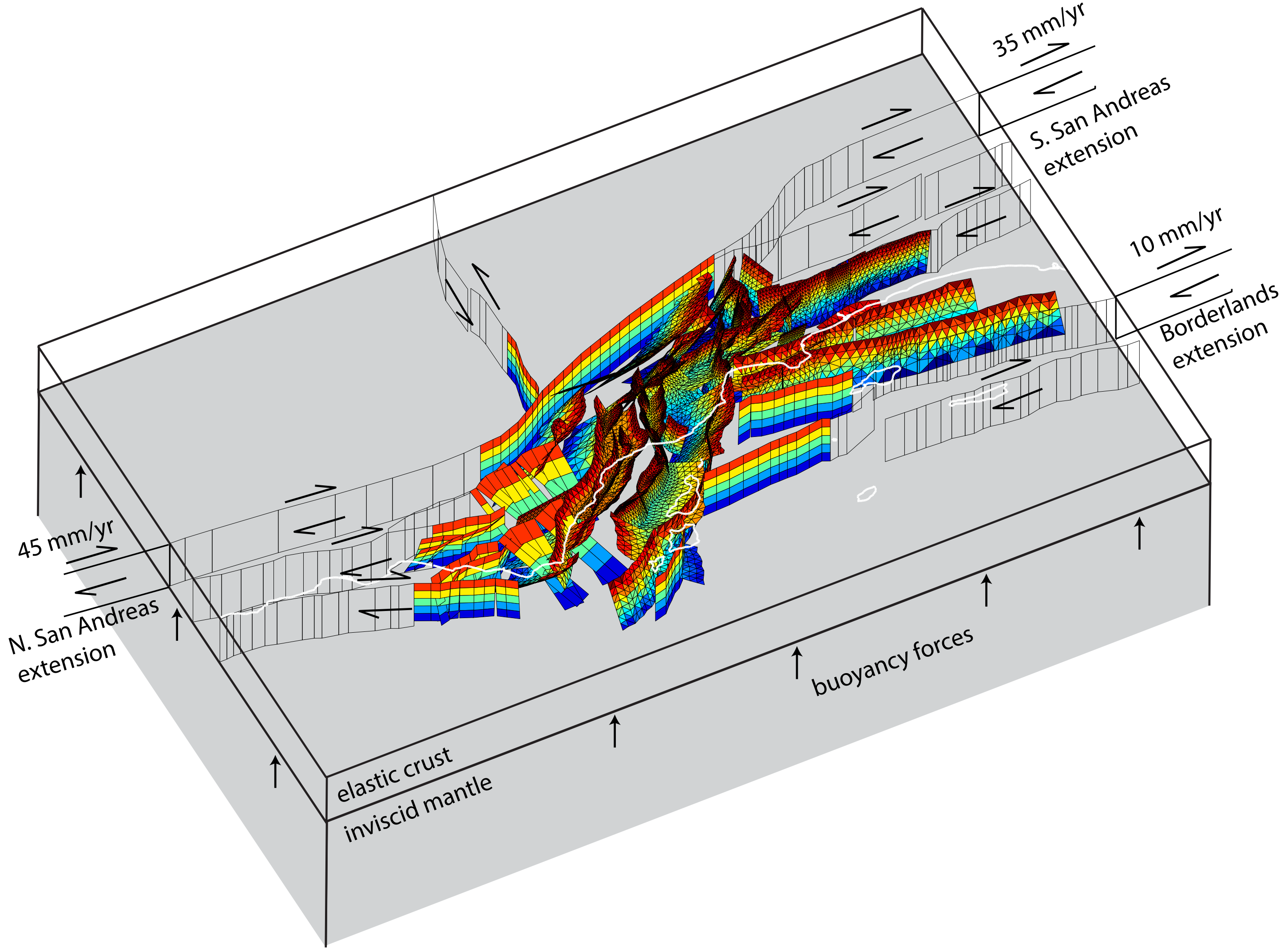


San Joaquin Valley Groundwater Withdrawal



Deformation Model

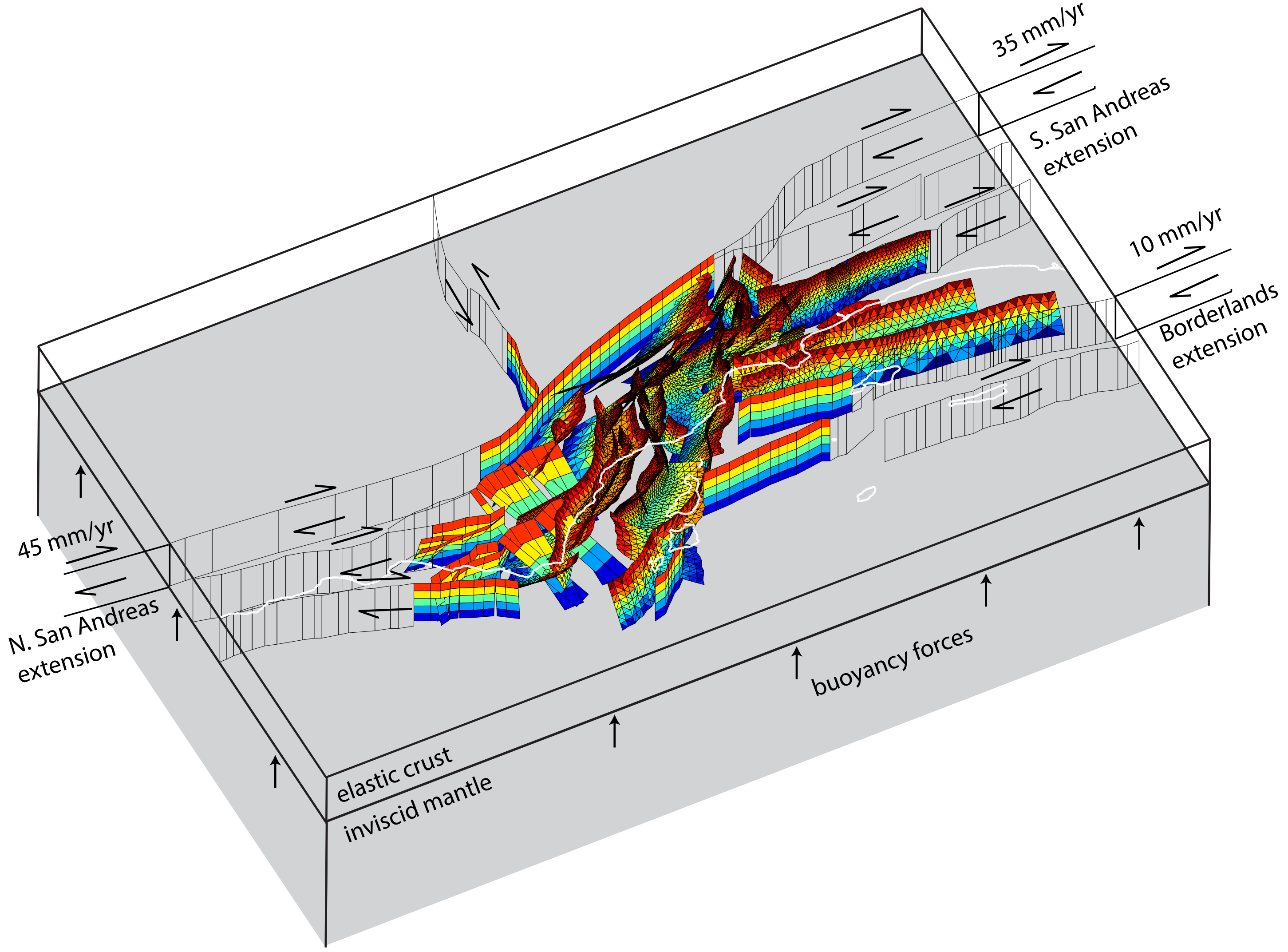
- Elastic plate over inviscid substrate (gravitational restoring forces)
- Populate plate with 3D fault surfaces (SCEC CFM)
- Impose long-term fault slip rates (permanent deformation)
- Impose backslip in elastic halfspace above locking depth (recoverable elastic deformation)



Inverse Methods

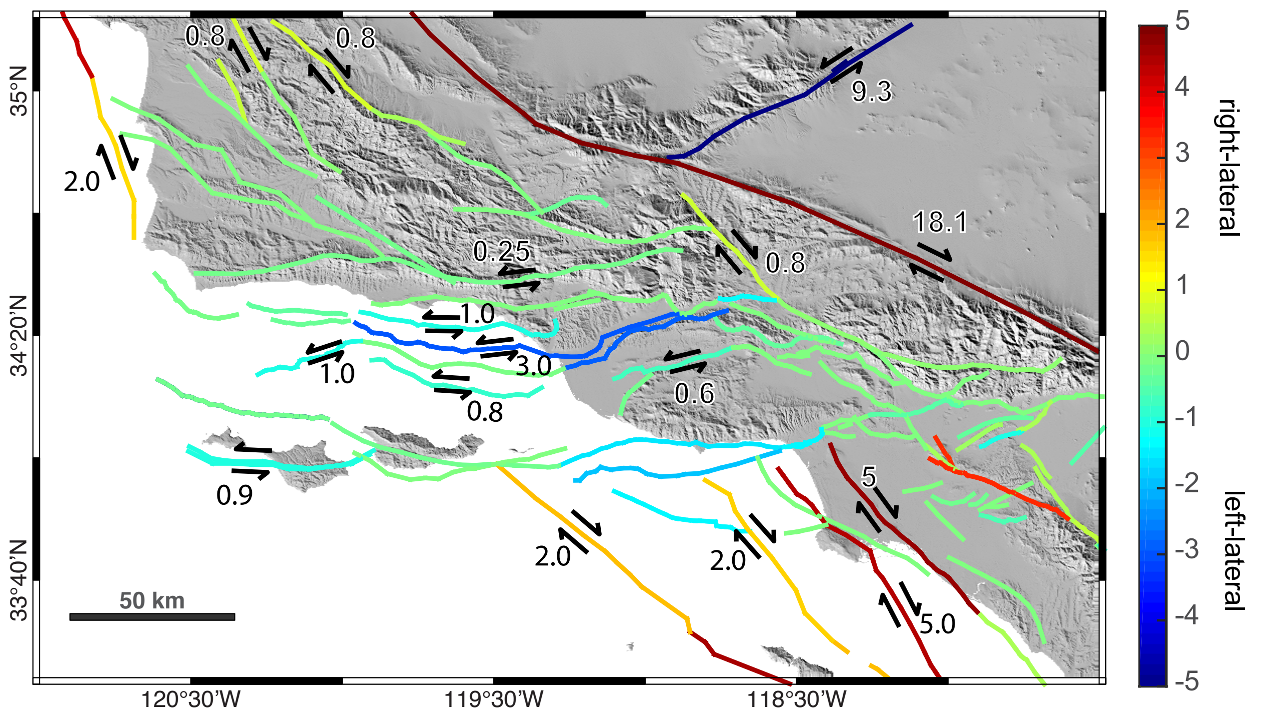
- Bayesian Inversion (MCMC)

- Solve for:
    - fault slip rates
    - locking depth
    - data weights

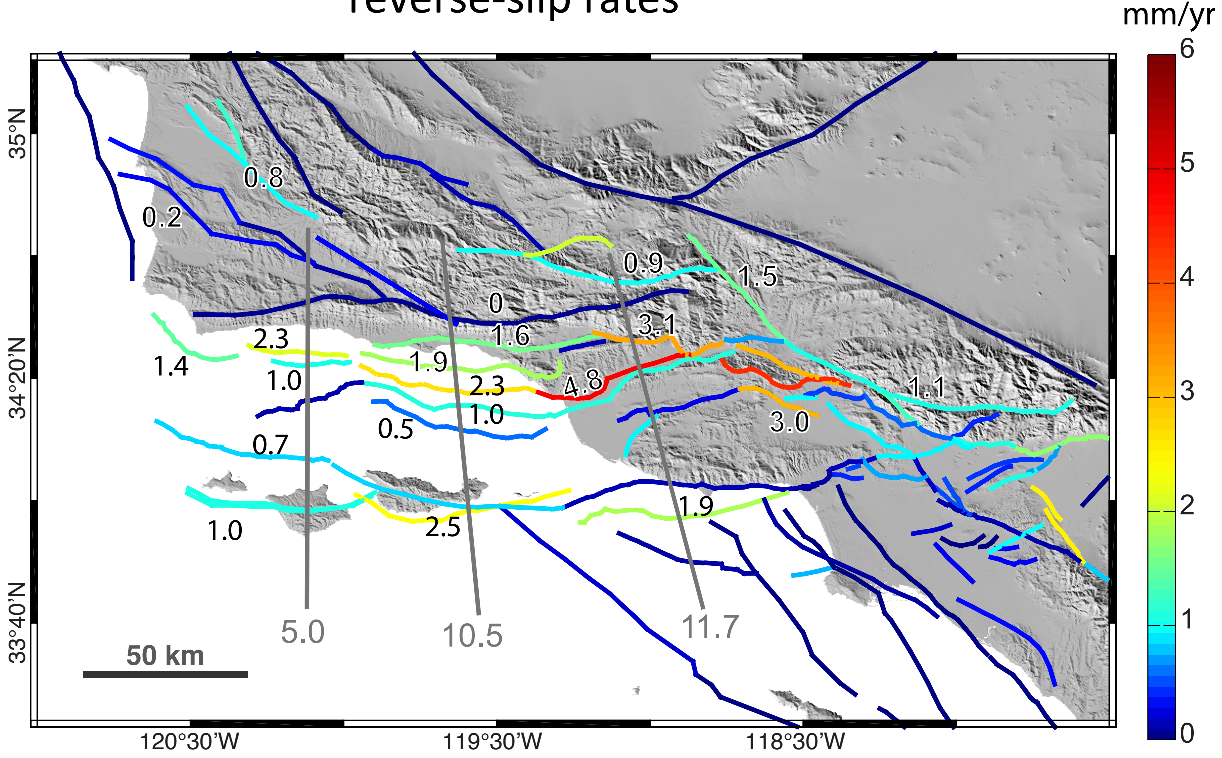


Slip Rate Estimates

strike-slip rates



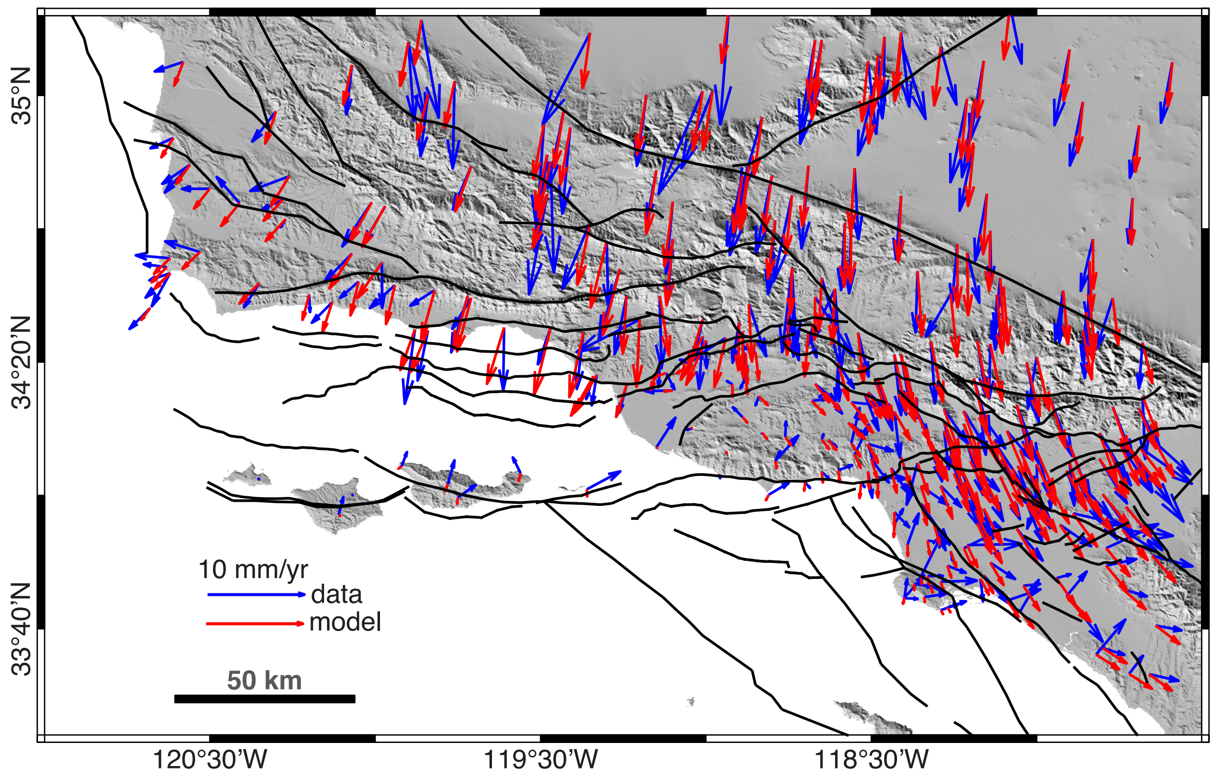
reverse-slip rates

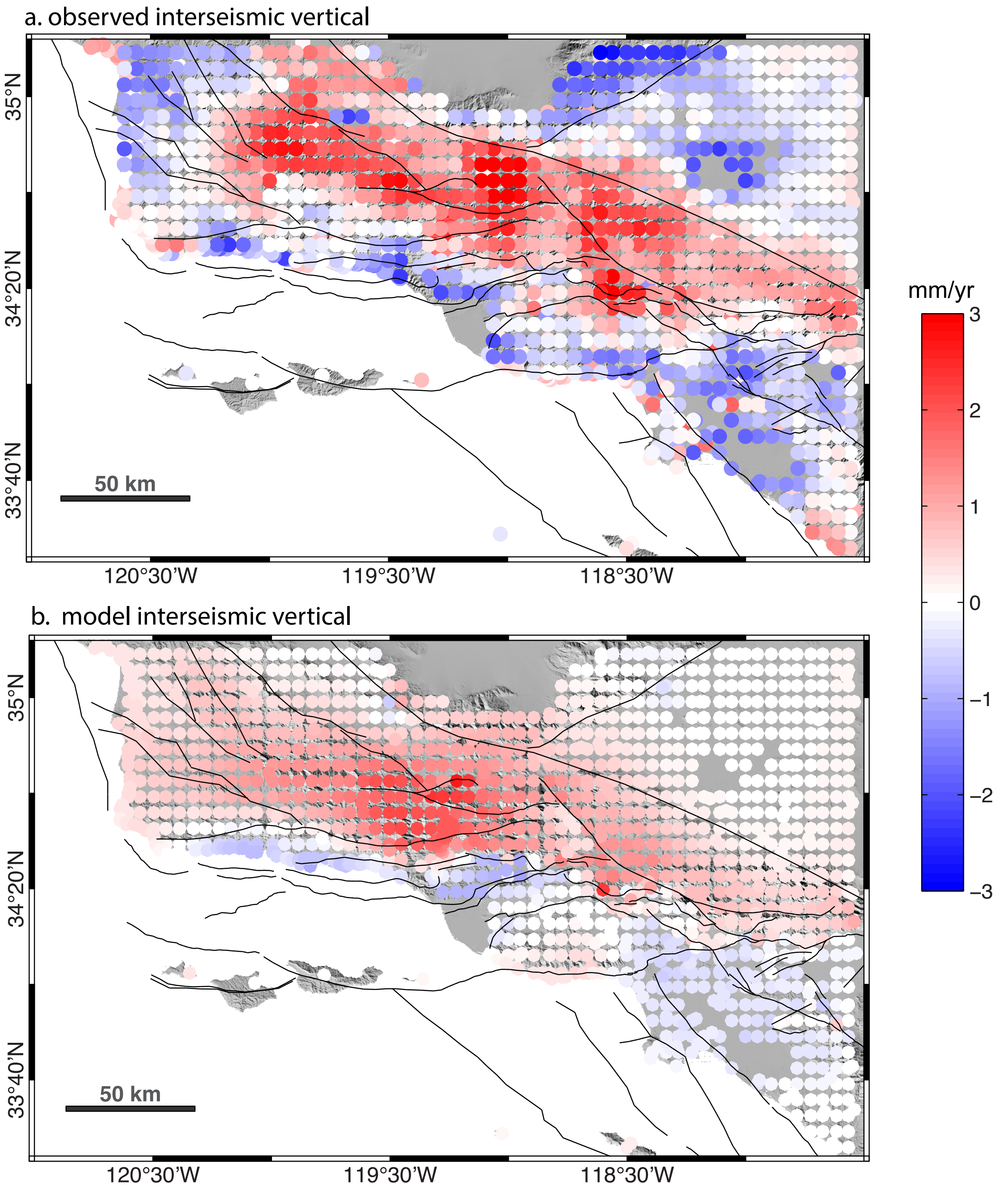


Predicted Deformation

horizontal motions
(contribution from major strike-slip faults removed)

B.

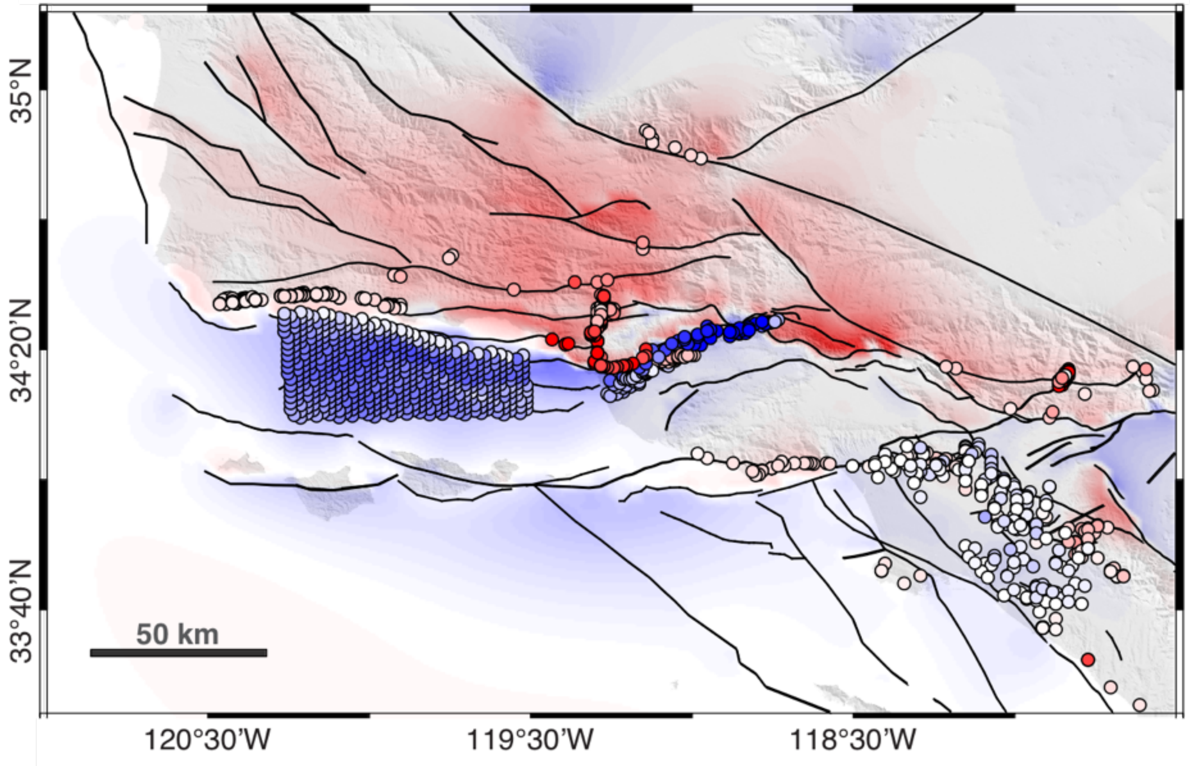




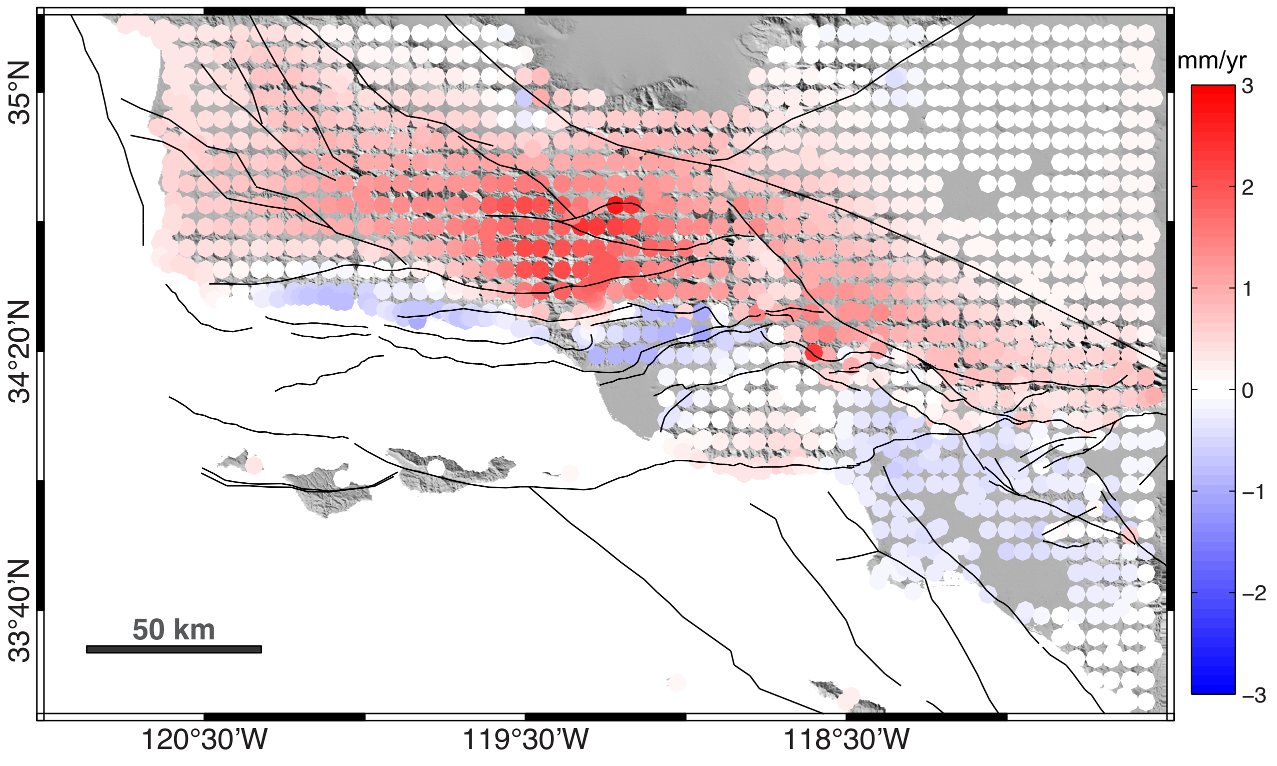
Predicted Deformation

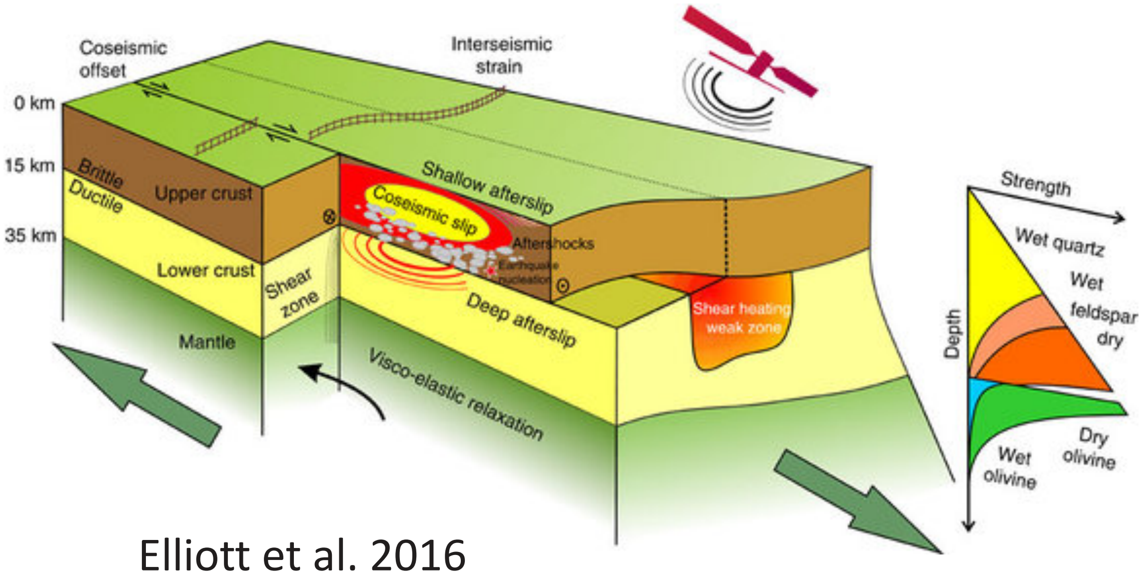
Conclusion: Geodetic indeed record elastic recoverable and long-term tectonic uplift in Western Transverse Ranges!

predicted and observed long-term vertical



predicted interseismic vertical





Elliott et al. 2016

Questions Regarding Vertical Motions:

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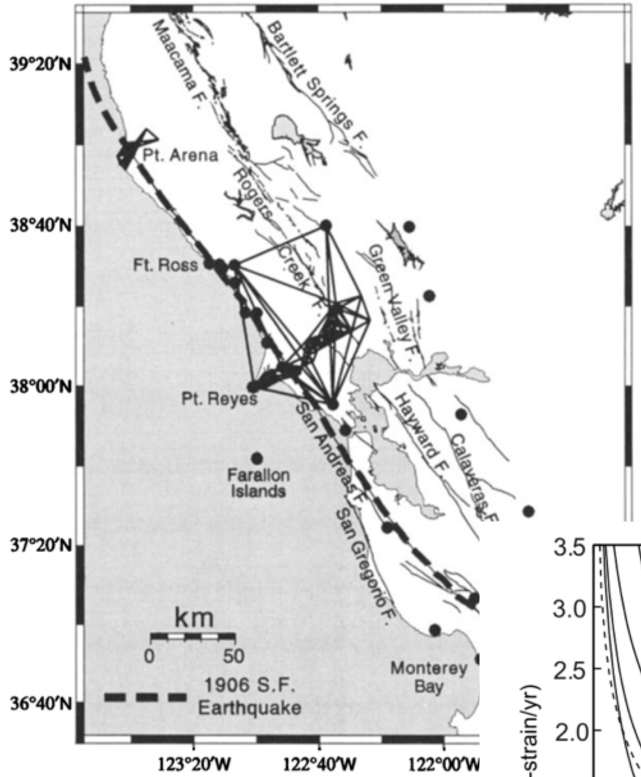
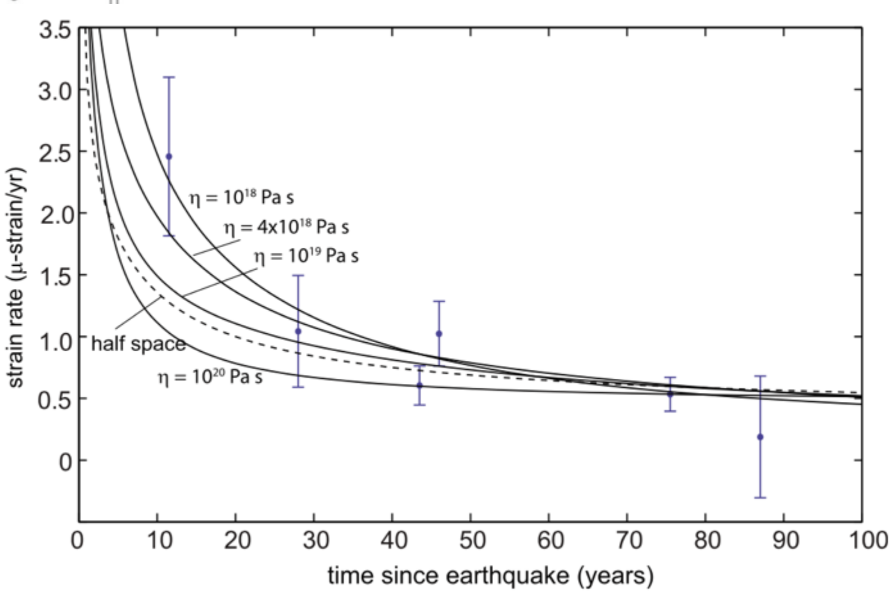
Long-lived Transients

1906 M7.8 San Francisco Earthquake

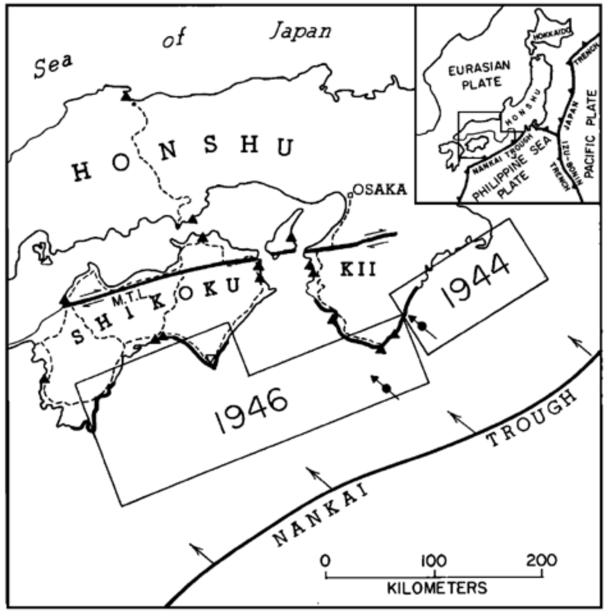


~90 years accelerated postseismic deformation



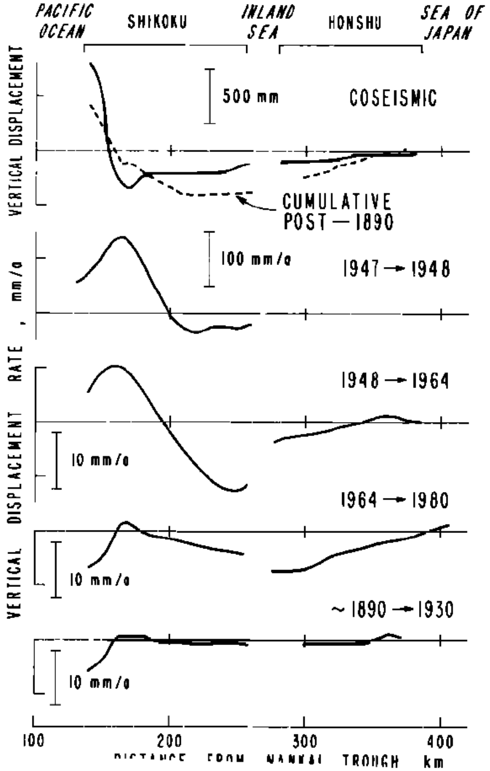
Kenner and Segall, 2000
Johnson and Segall, 2004
Johnson and Fukuda, 2010

Earthquake Cycle – SW Japan

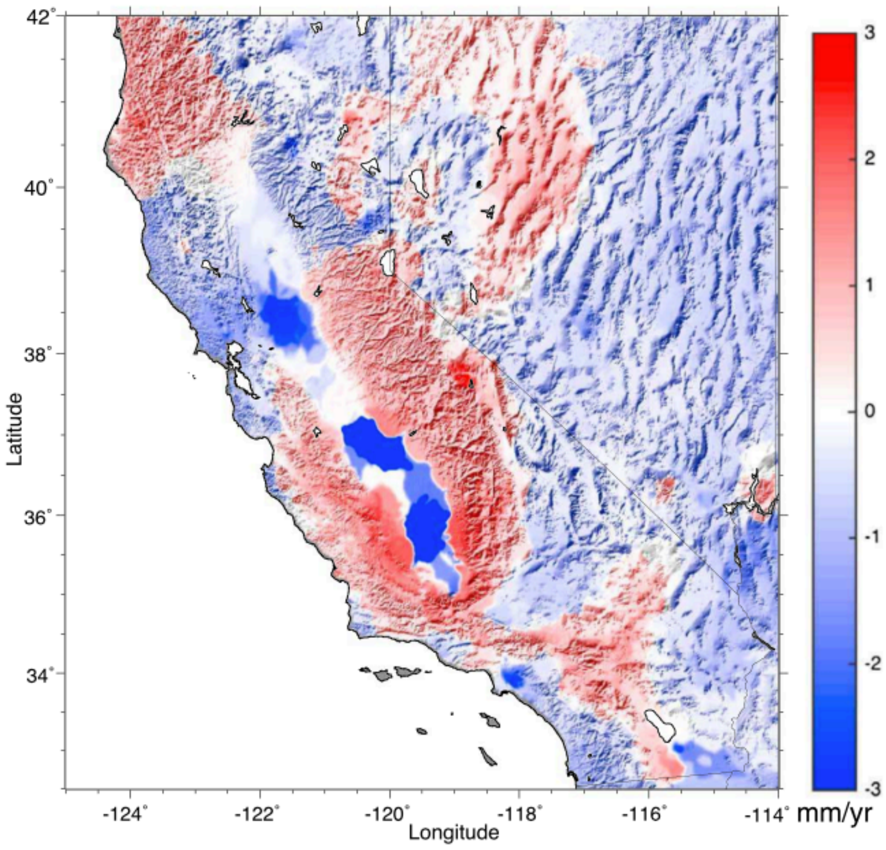


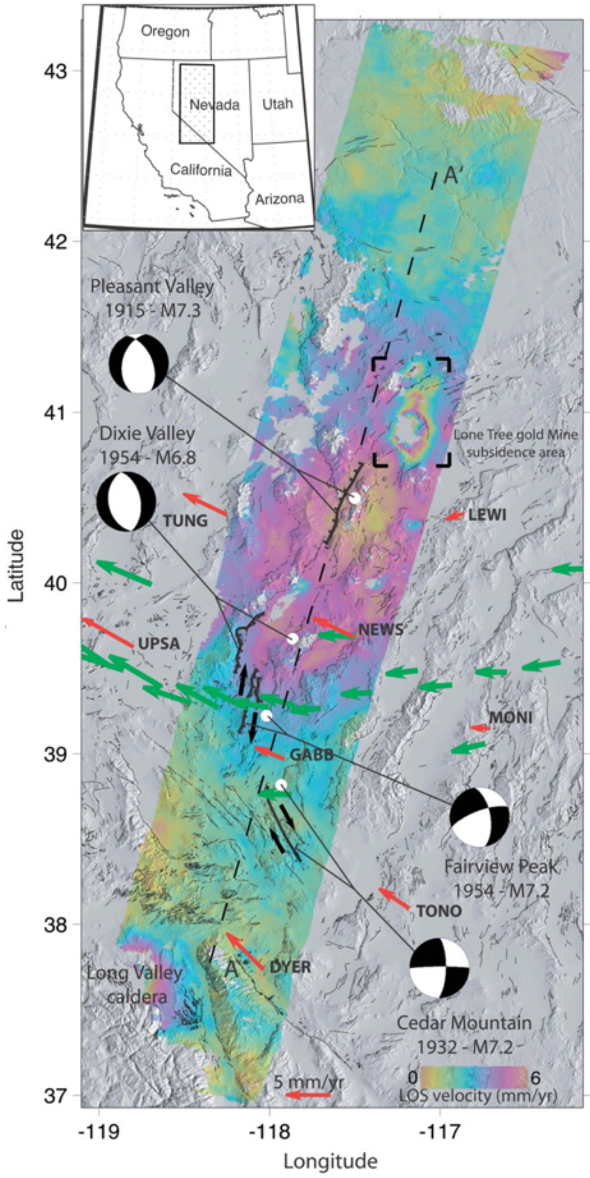
Thatcher, 1984

~90 years non-steady postseismic/interseismic deformation

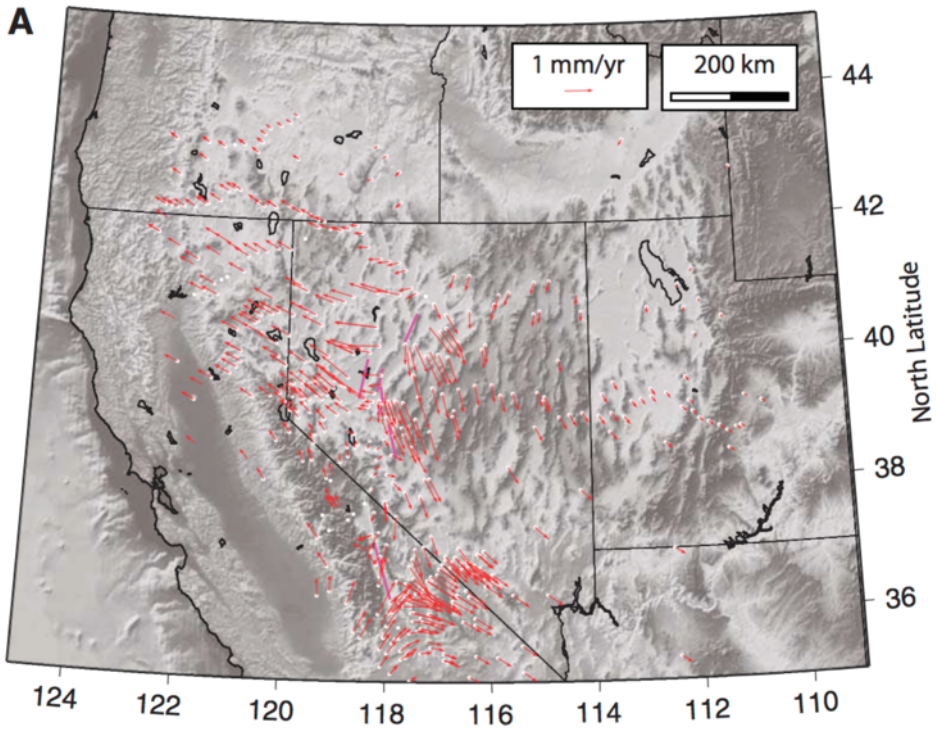


“Ghost Transients”





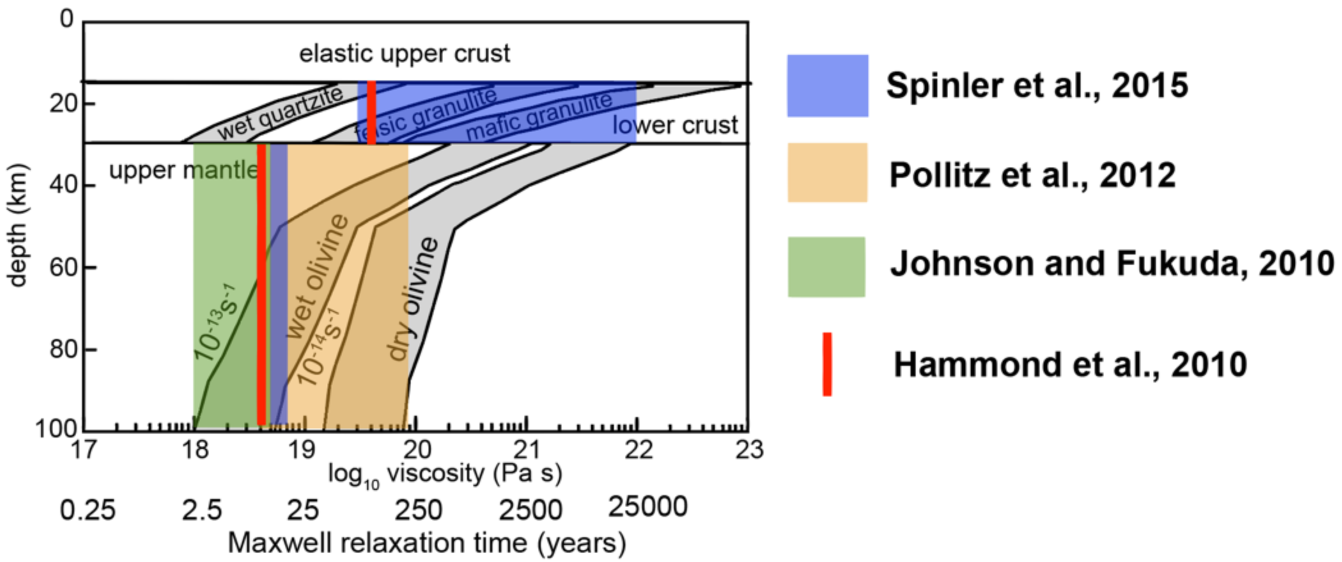
Gourmelen and Amelung, 2005



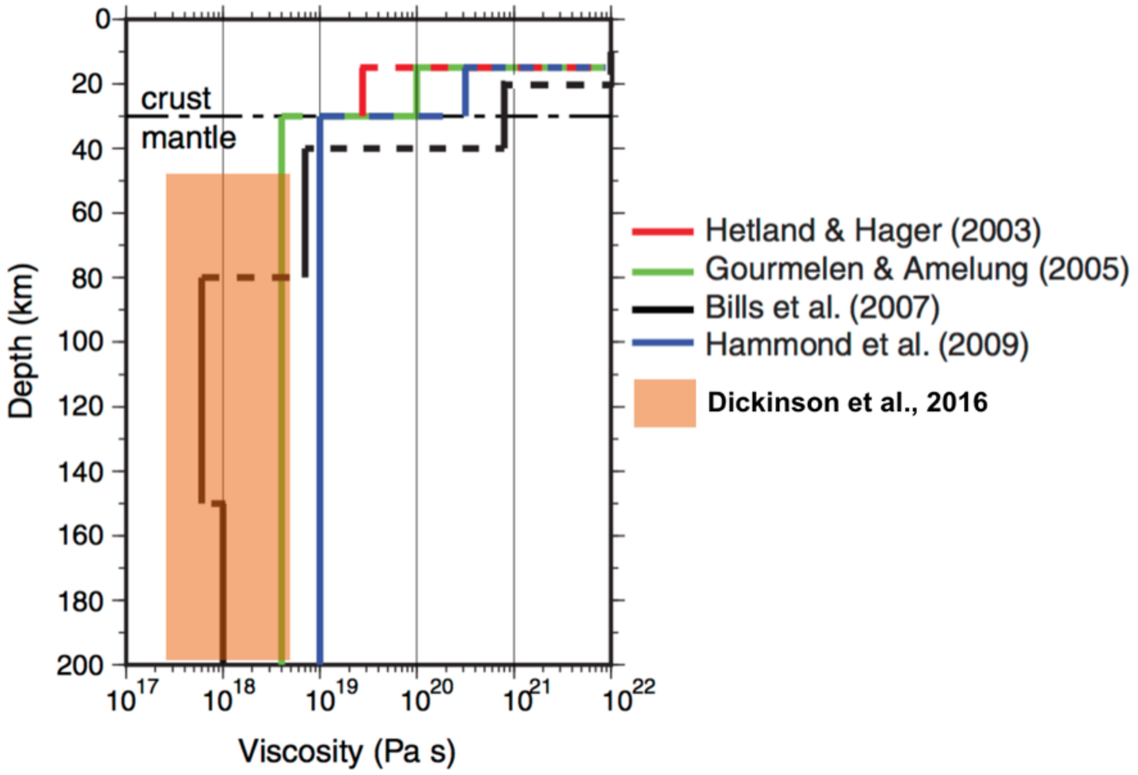
Hammond et al., 2009

Viscous Rheology of Lower Crust and Upper Mantle Western US

California



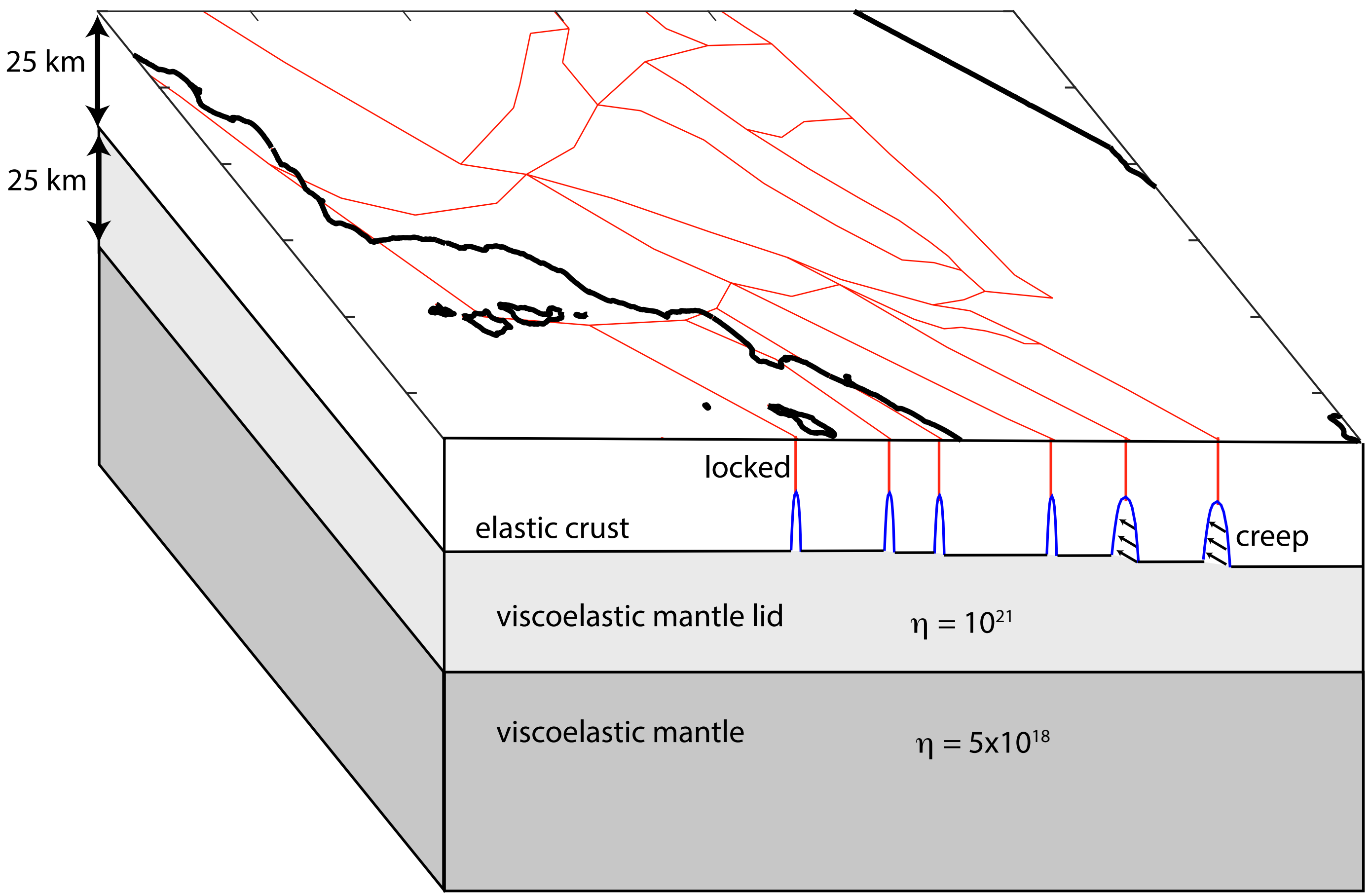
Central Nevada

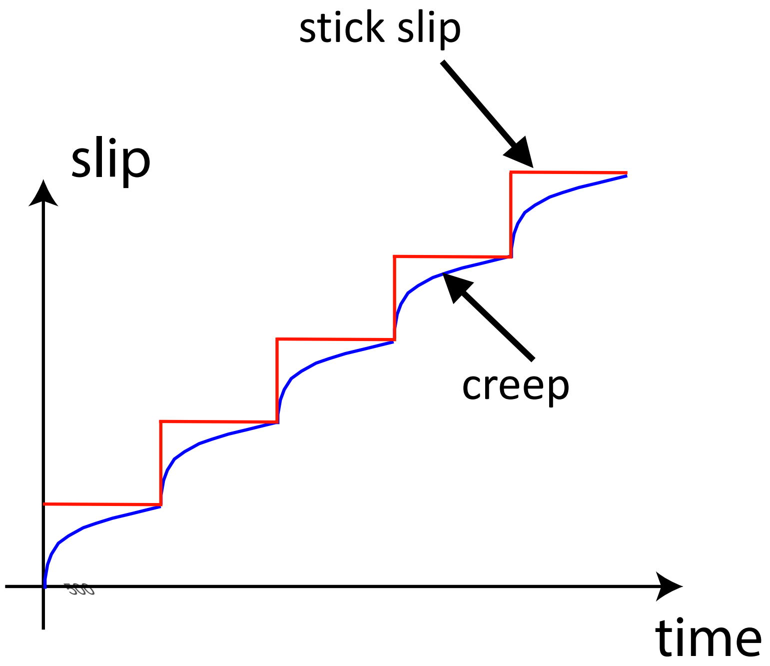


Mantle viscosities of order 10^{18} to 10^{19} Pa s
➔ Significant temporal varations in surface deformation at earthquake cycle time scales

Viscoelastic Earthquake Cycle Model

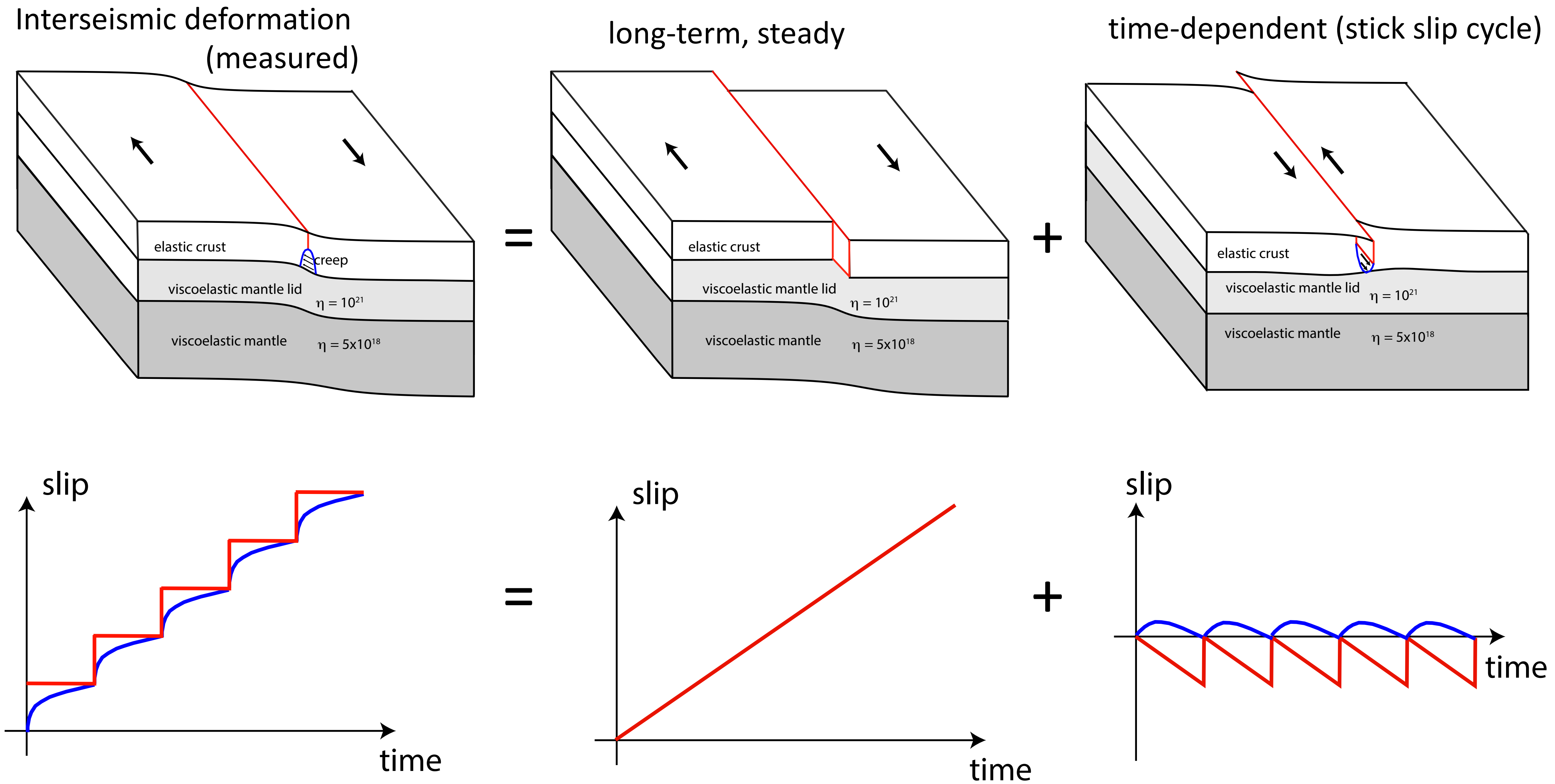
(semi-analytical models)

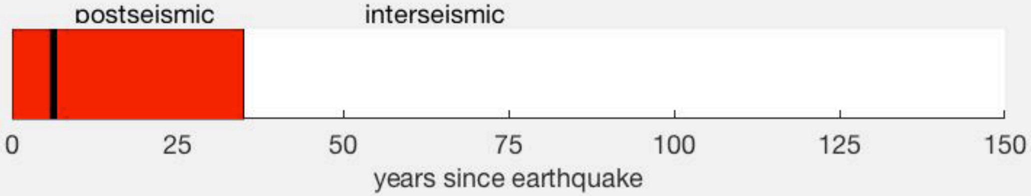




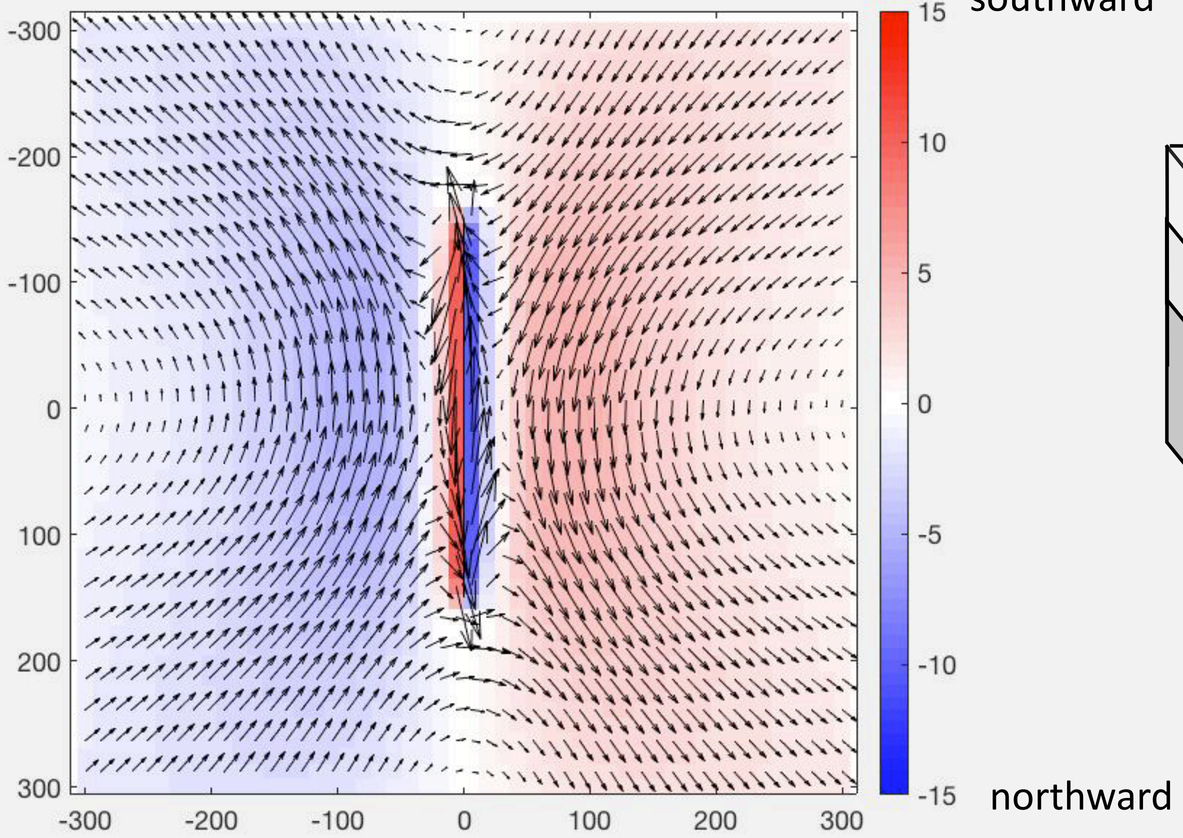
Johnson and Fukuda (2010), Johnson (2013)

Viscoelastic Earthquake Cycle Model

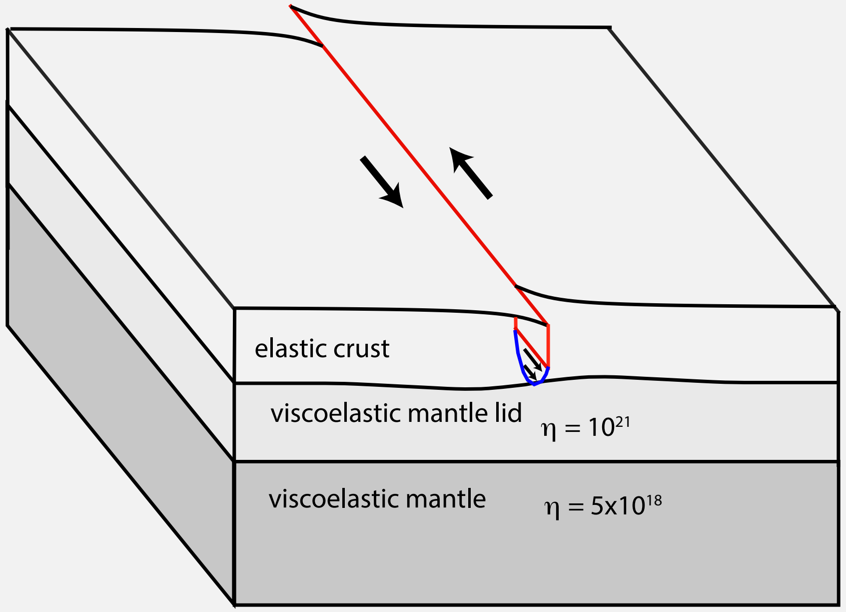




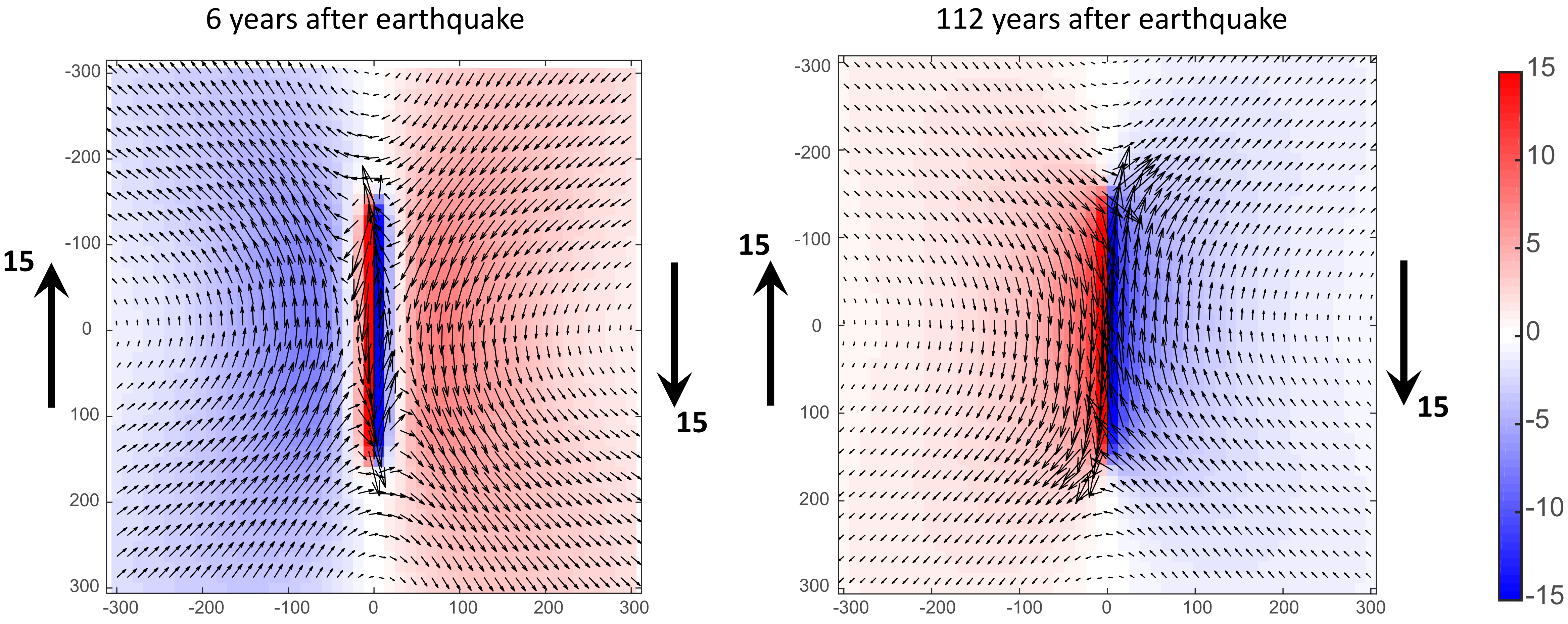
horizontal velocities



time-dependent (stick slip cycle)

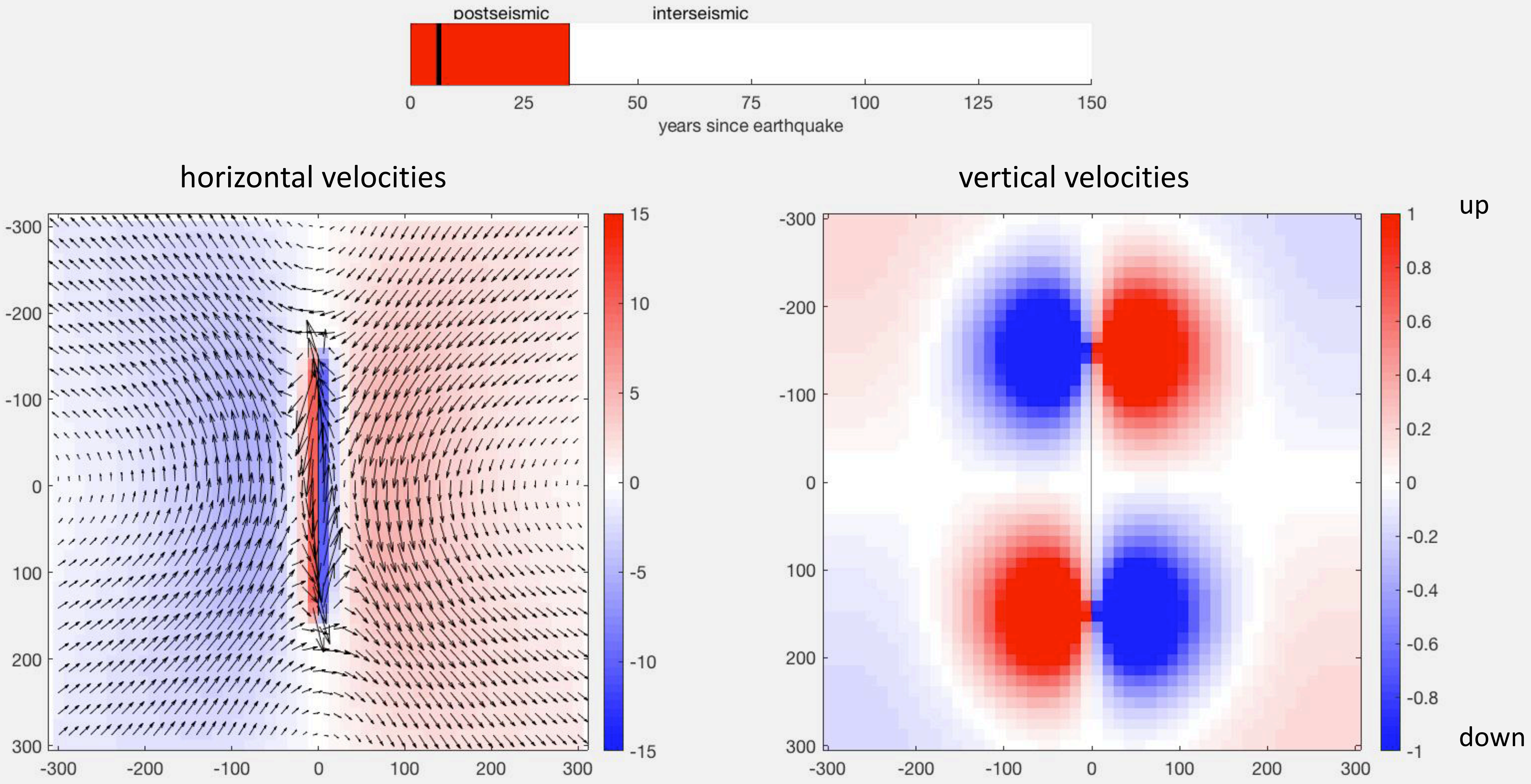


Viscoelastic Earthquake Cycle

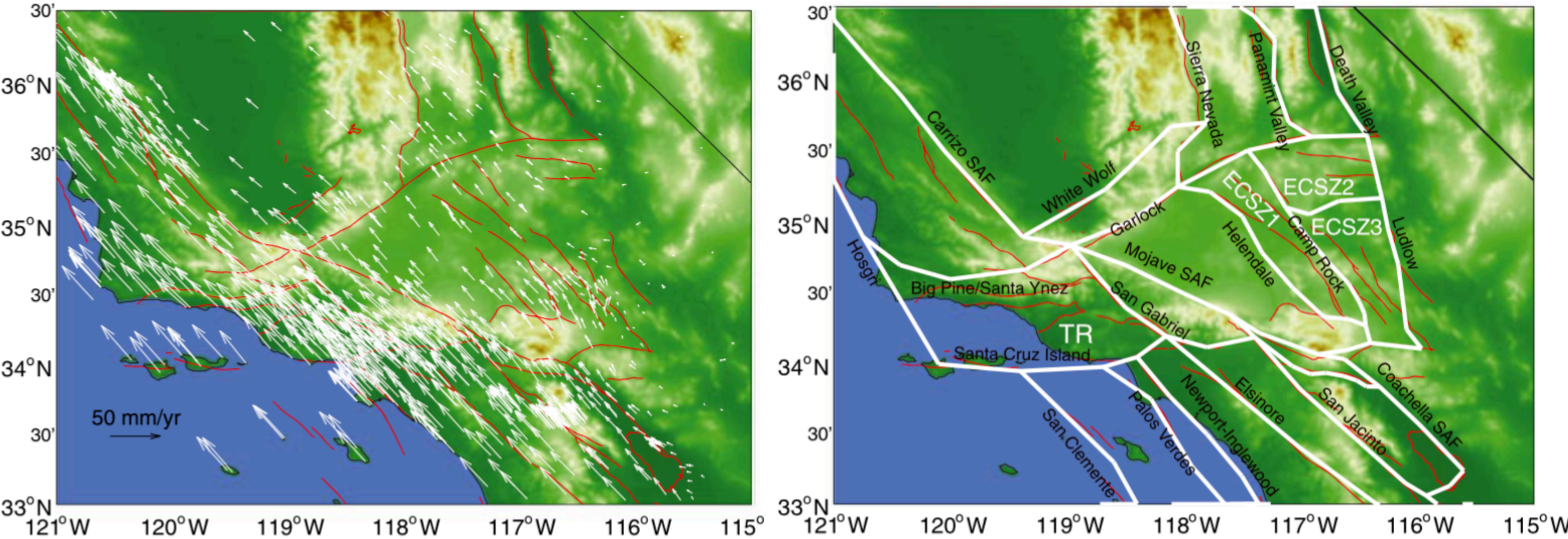


faster than long-term rate

slower than long-term rate

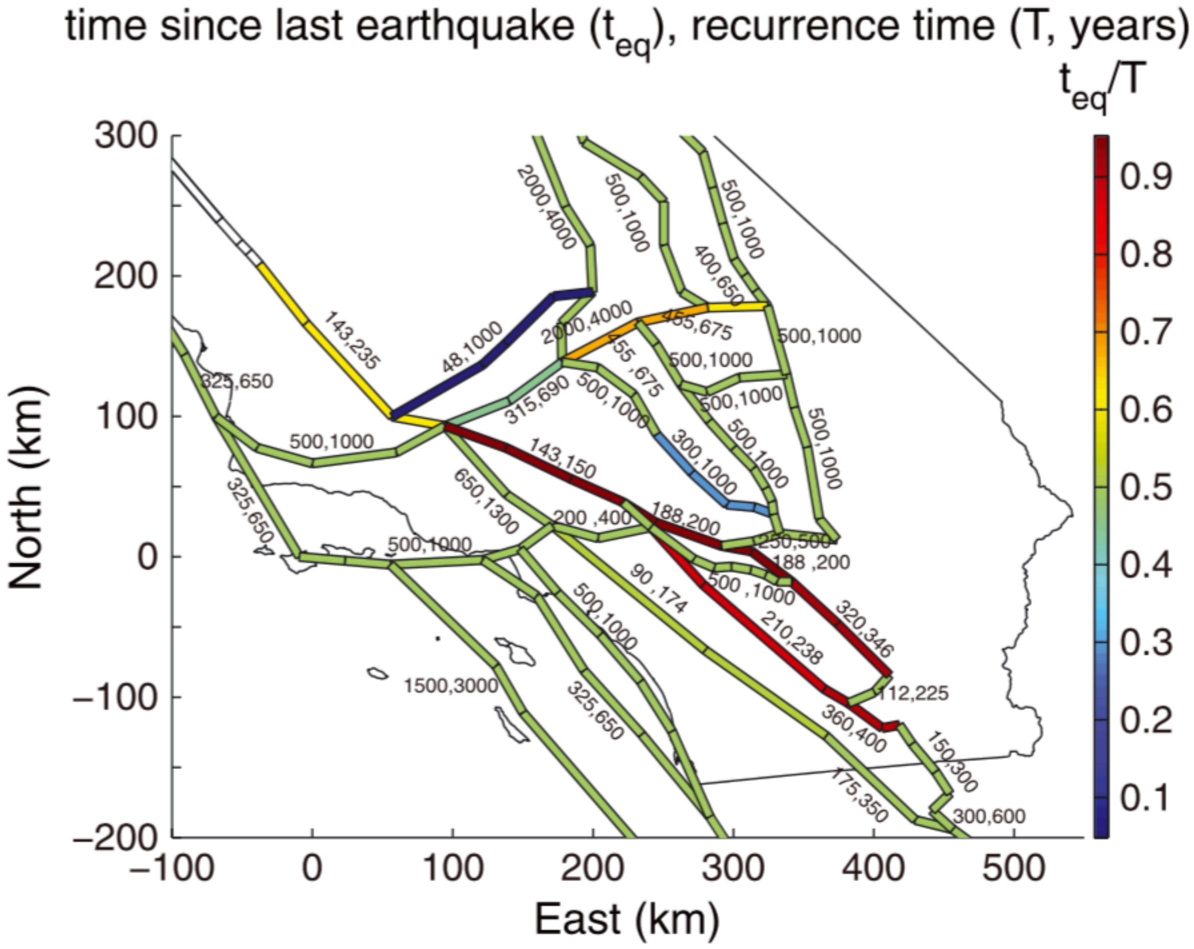

postseismic
interseismic
0
25
50
75
100
125
150
years since earthquake
horizontal velocities
vertical velocities
up
down

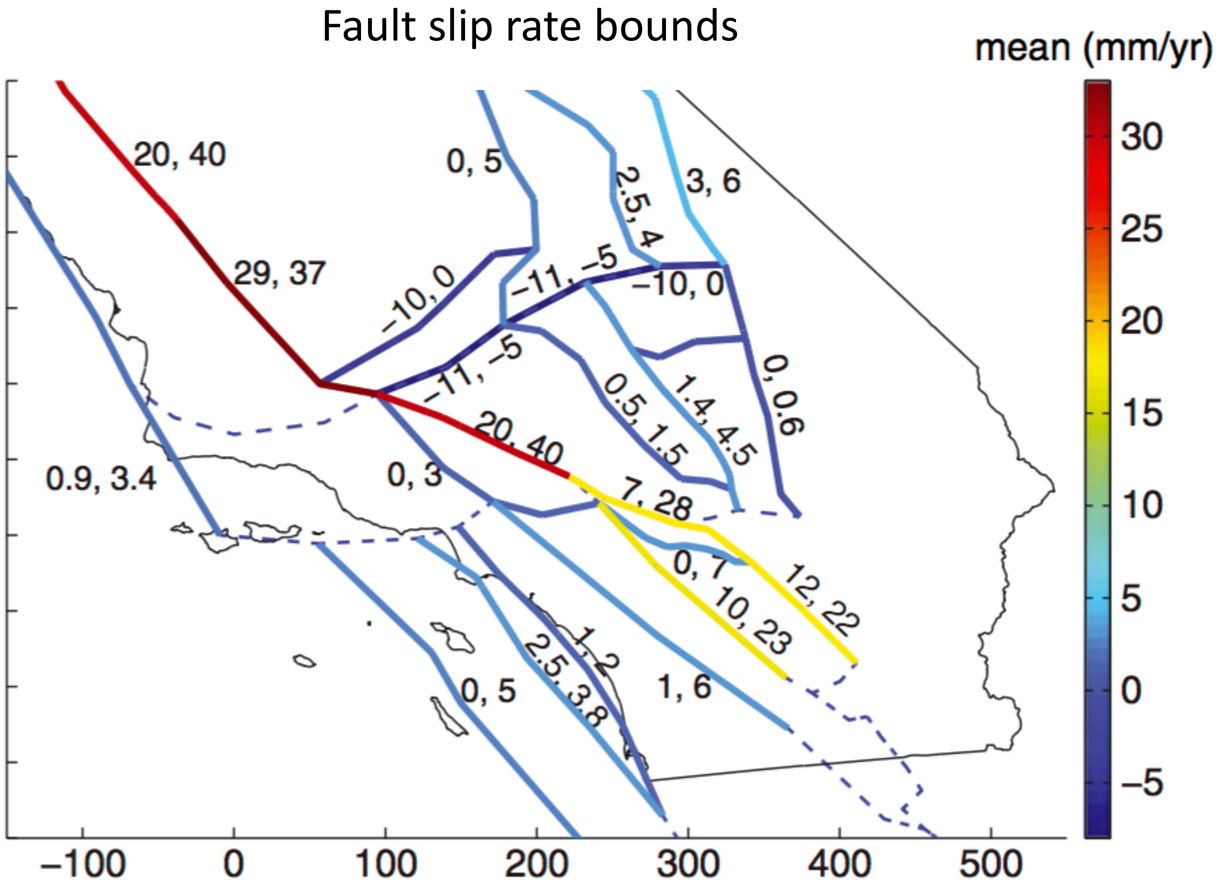
Viscoelastic Earthquake Cycle Model
Southern California



Johnson, 2013

Viscoelastic Earthquake Cycle Model
Southern California

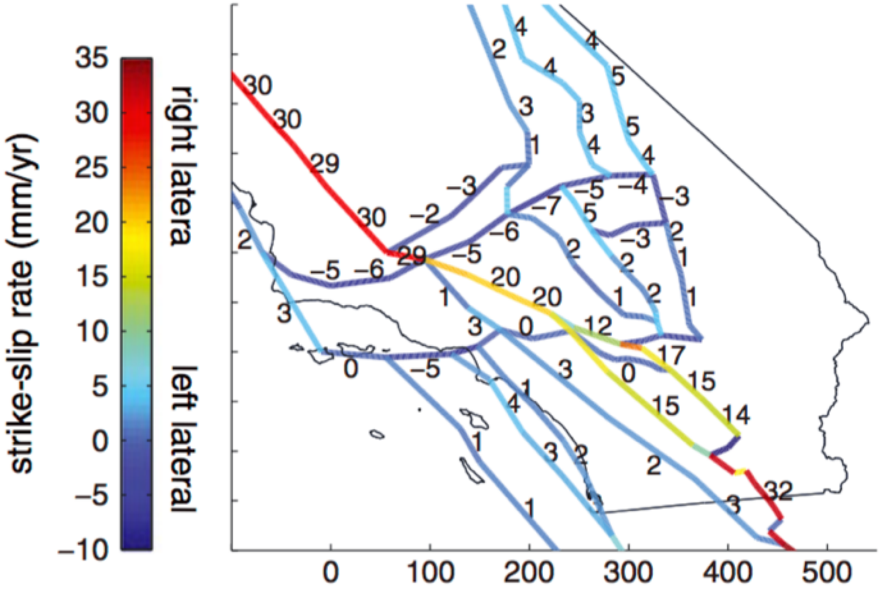


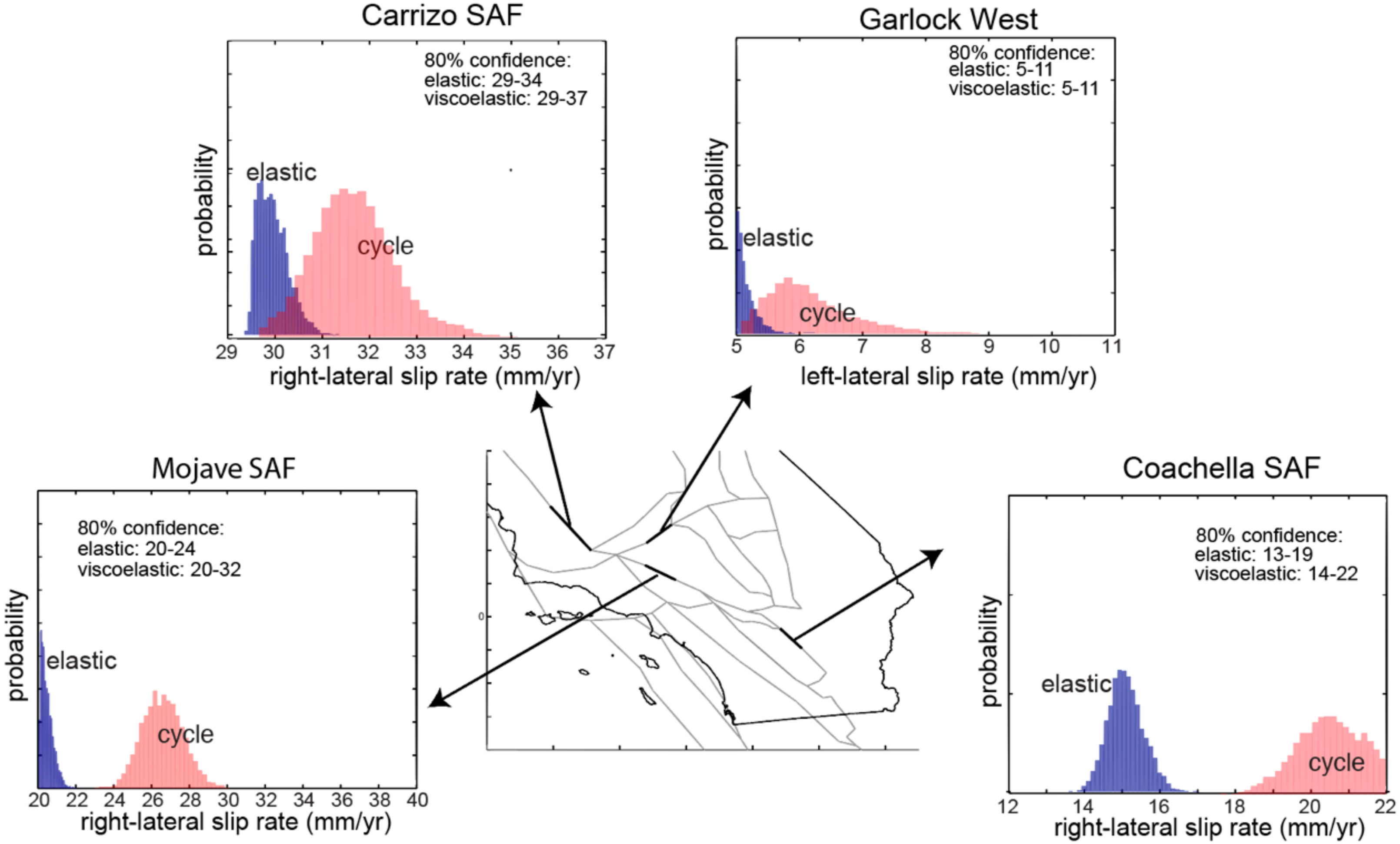


Johnson, 2013

Slip Rate Estimates

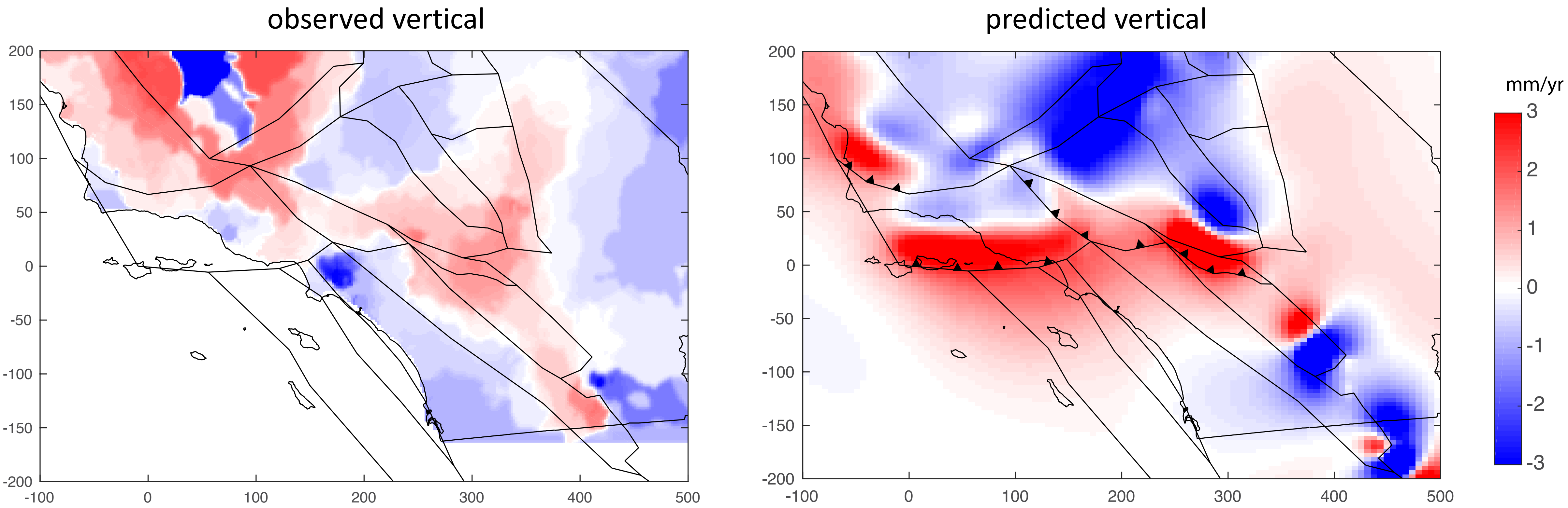
Elastic block model





viscoelastic cycle model → faster slip rates on several major strike-slip systems

What about the vertical rates?
(vertical data not used to constrain model)

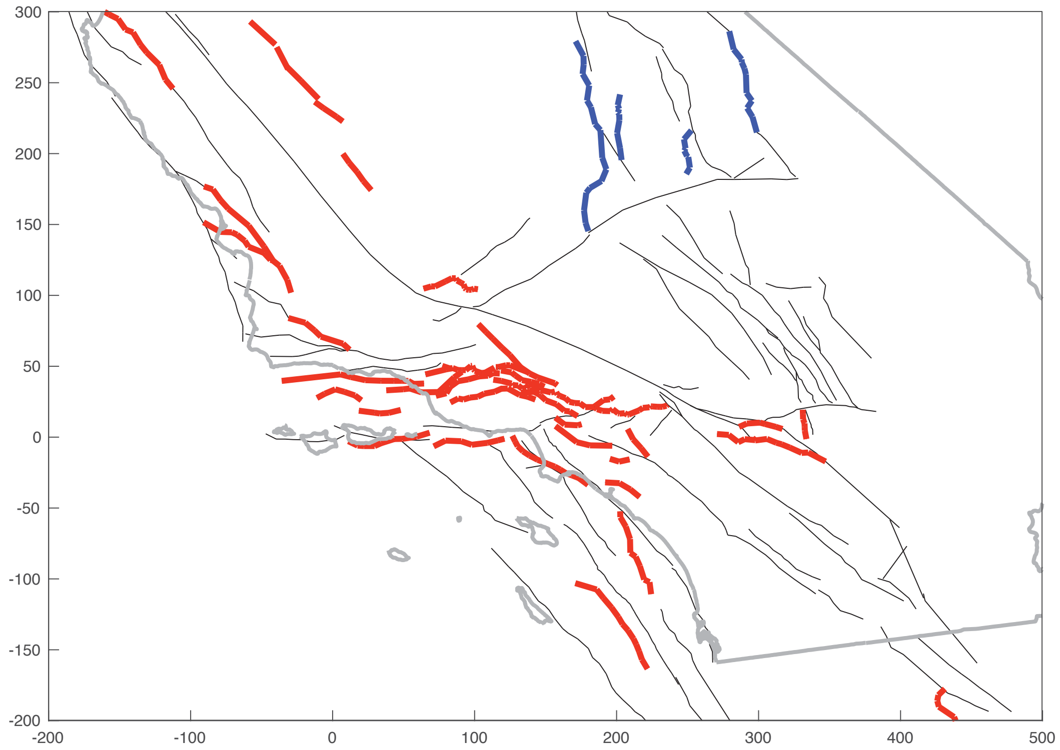


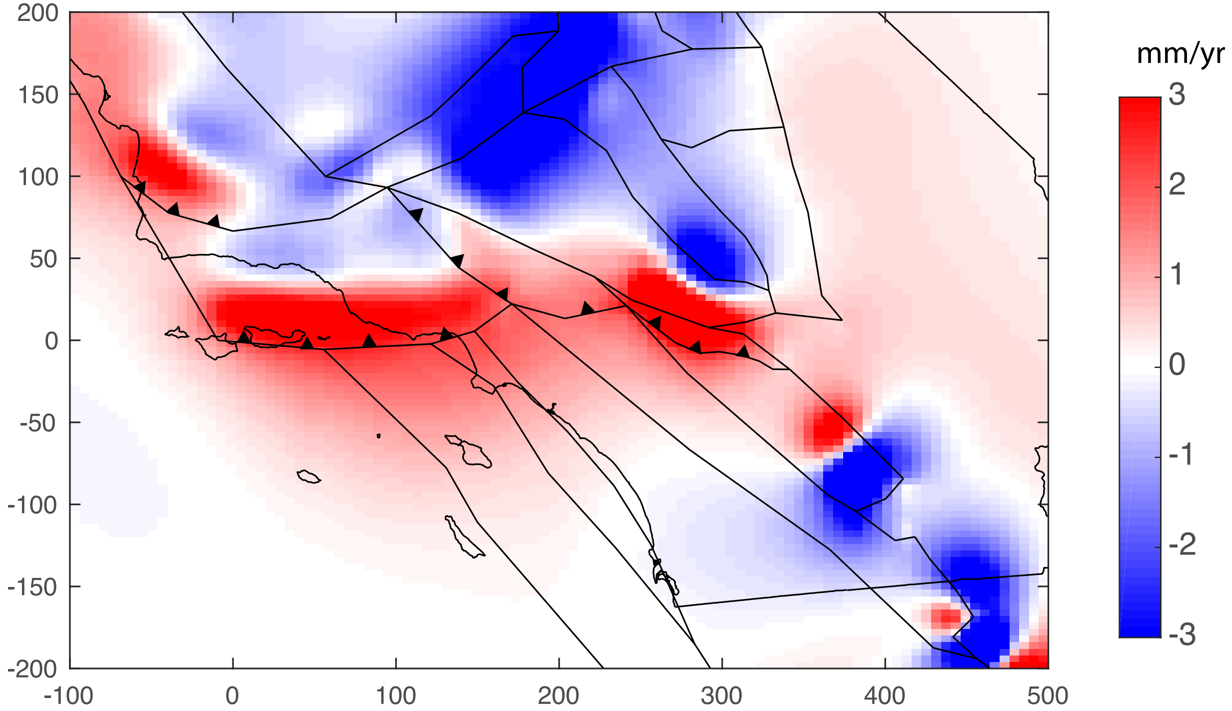
Predicted verticals are a total embarrassment! Block model is a poor representation of faults.

Modeling Vertical Deformation Field Requires A Better Fault Model

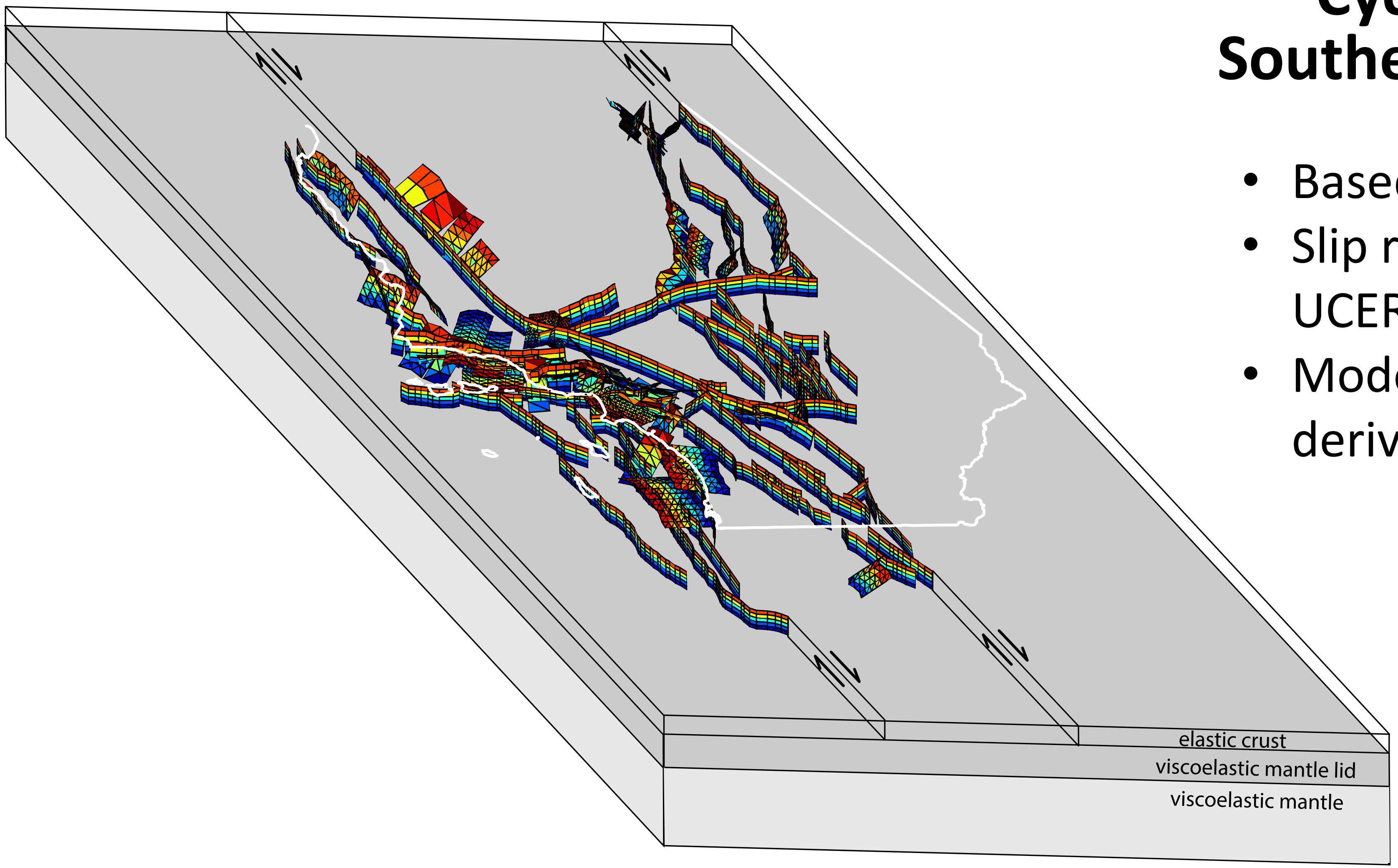
reverse

normal



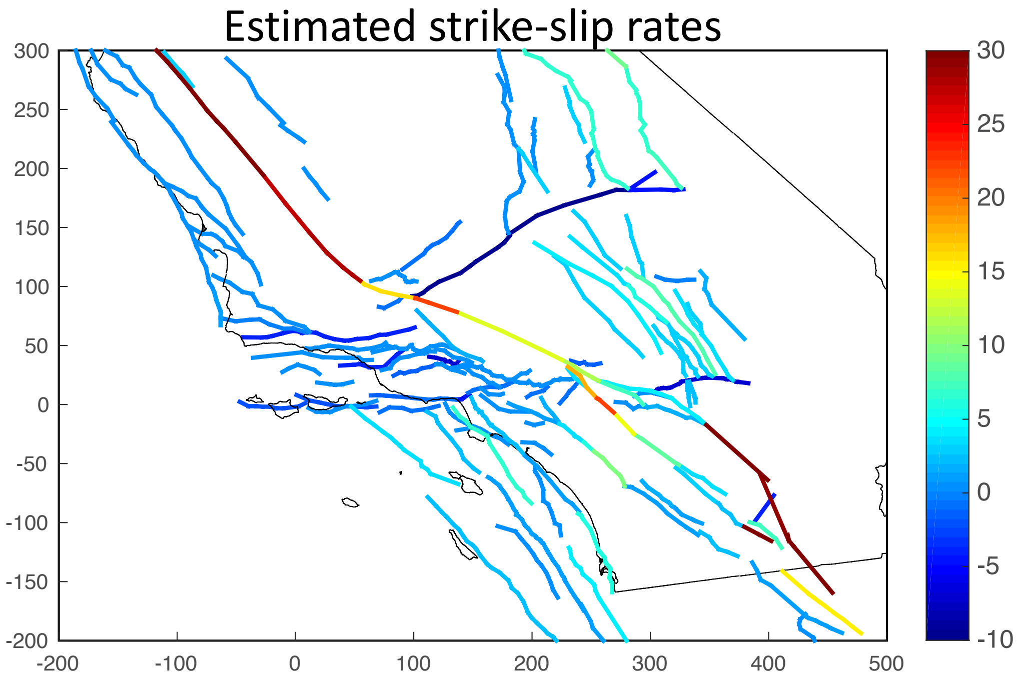


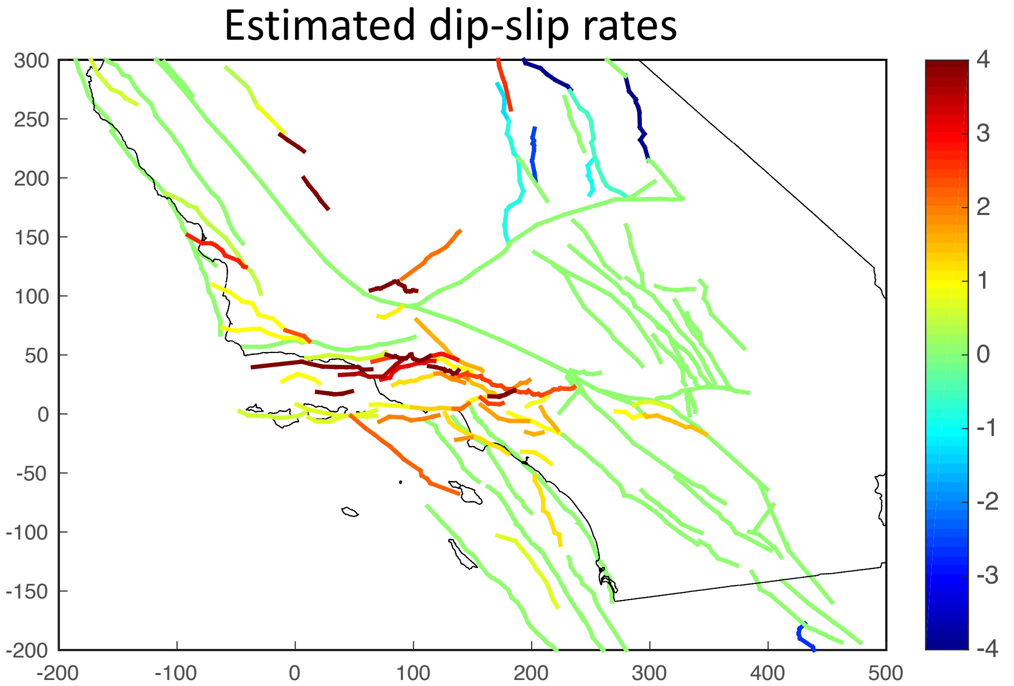
Fault-based Viscoelastic Earthquake Cycle Model
Southern California

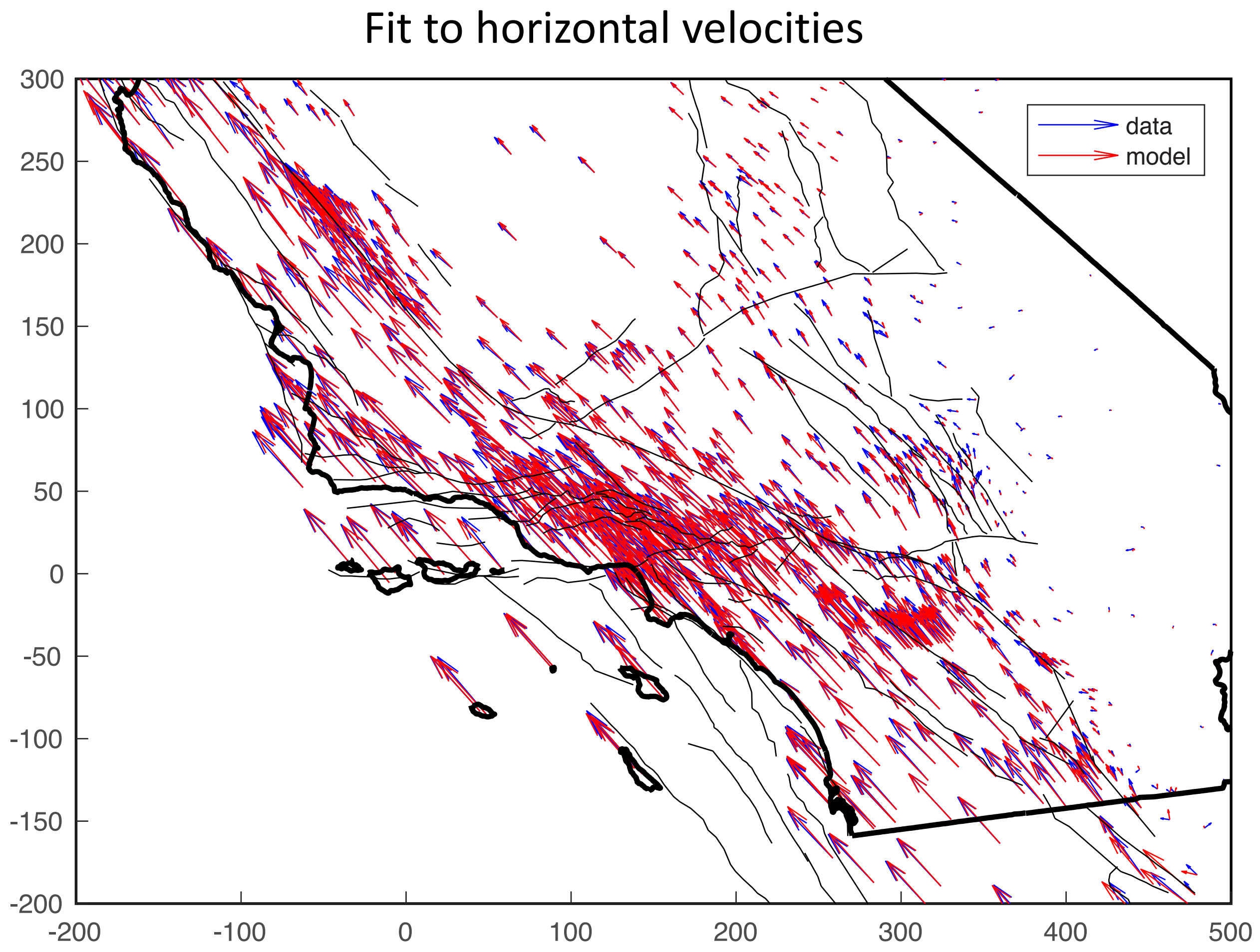


- Based on UCERF3 fault geometry
- Slip rate bounds and rake from UCERF3
- Model horizontal and vertical GPS-derived velocity fields

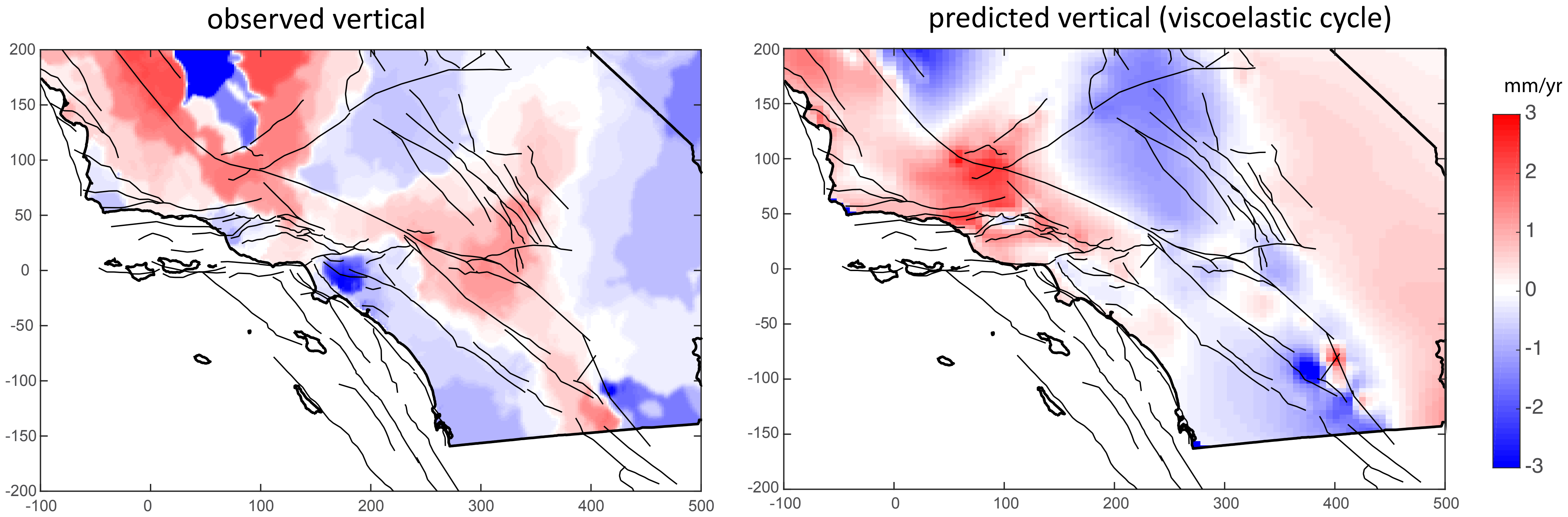
Viscoelastic Earthquake Cycle Model Southern California





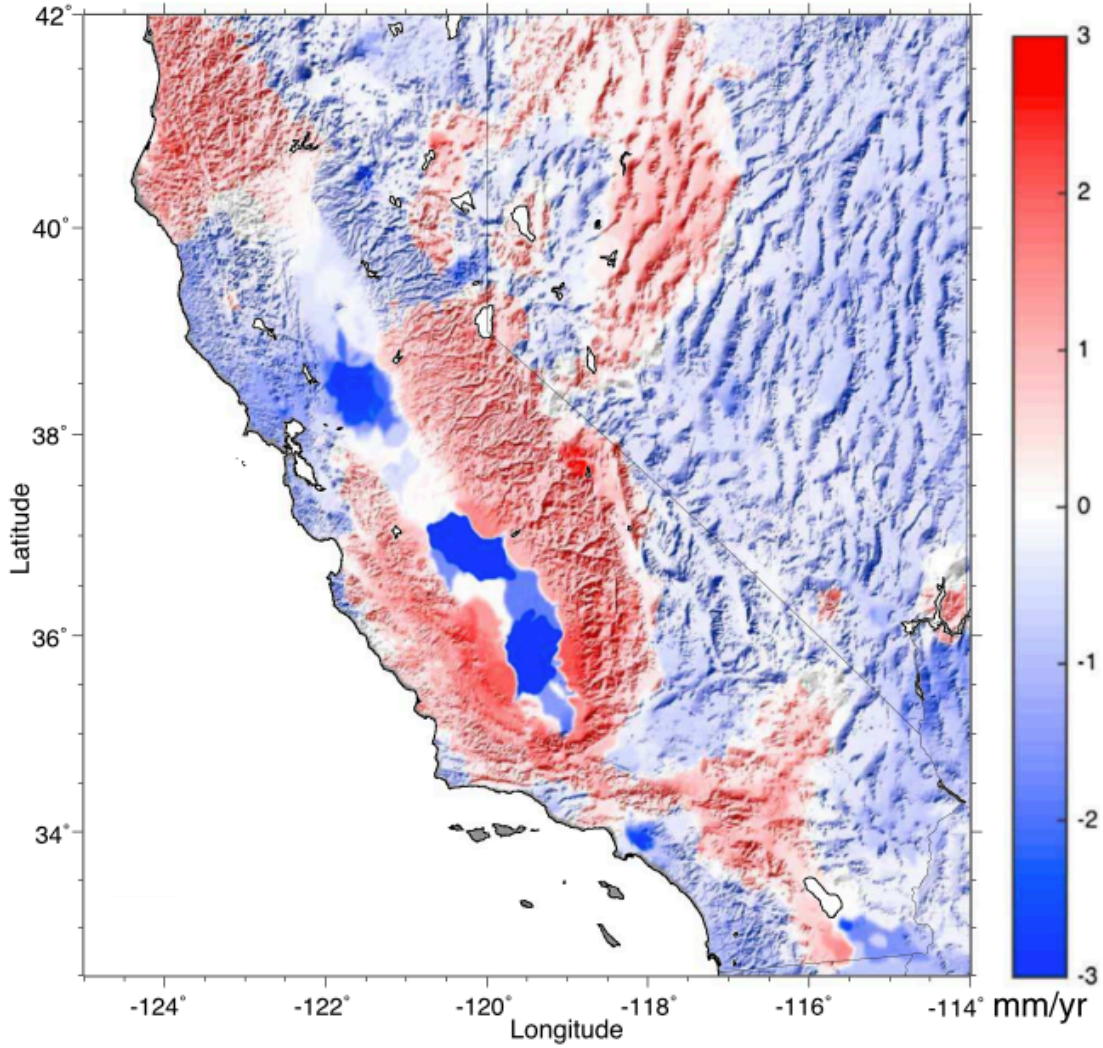


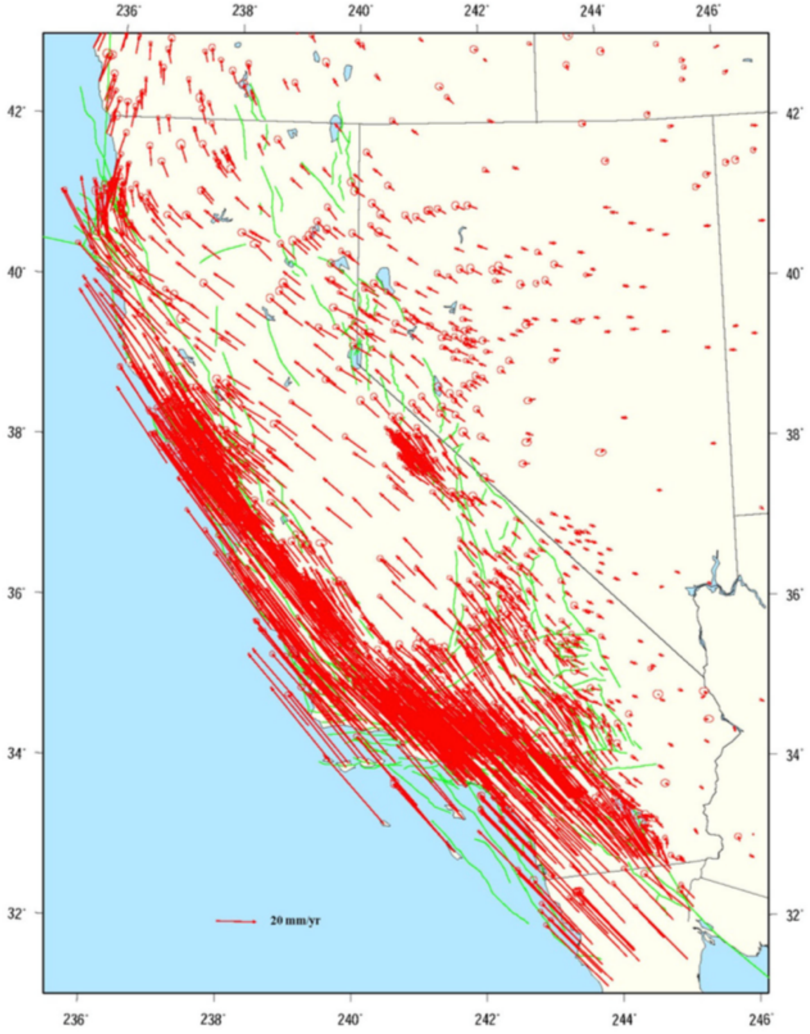
Viscoelastic Earthquake Cycle Model
Southern California

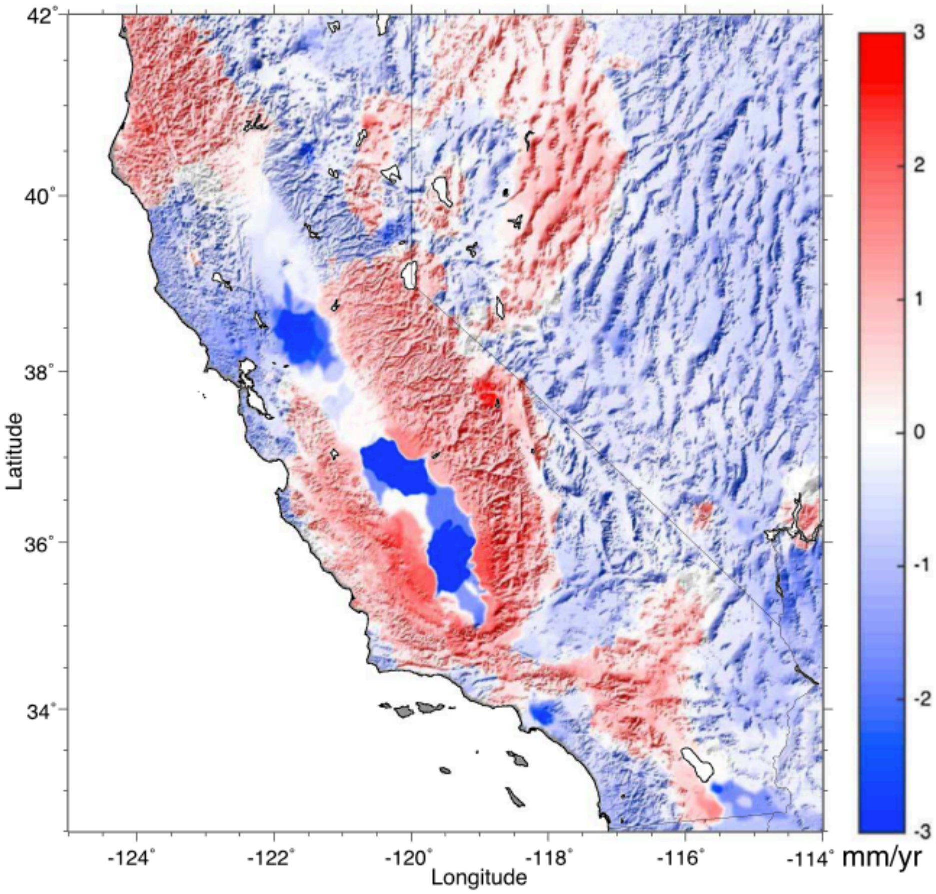


Next Step…

Viscoelastic cycle model for Western US







Summary

- Lingering “ghost transients” associated with mantle flow and past earthquakes are subtle in horizontal motions
- Fault slip rate estimates sensitive to assumed role of mantle flow on surface deformation
- Small, spatially-coherent vertical motions are now resolvable with GPS
- Predictable ~200 km-long wavelength vertical motions associated with mantle flow and viscoelastic earthquake cycle
- Vertical GPS velocity field can help us tease out transient deformation contribution to present-day velocity field