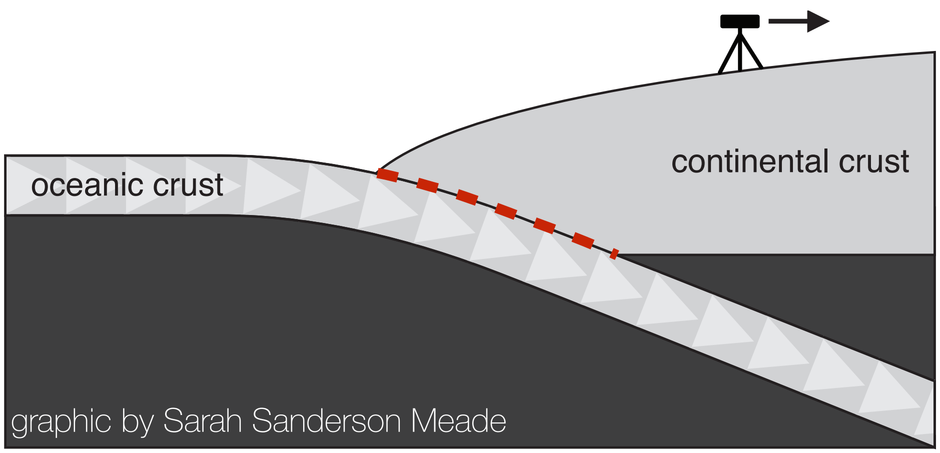
Geodesy for understanding seismic hazard

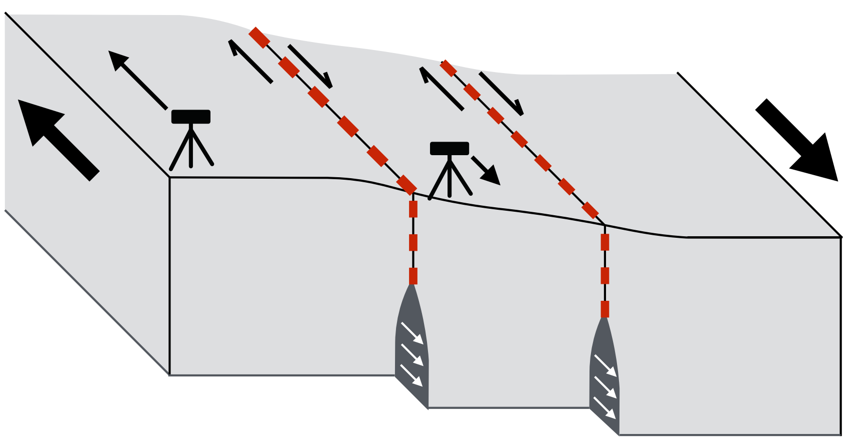
Eileen Evans
U.S. Geological Survey
CIG CDM Workshop
28. June, 2017

Imaging active deformation in the western United States

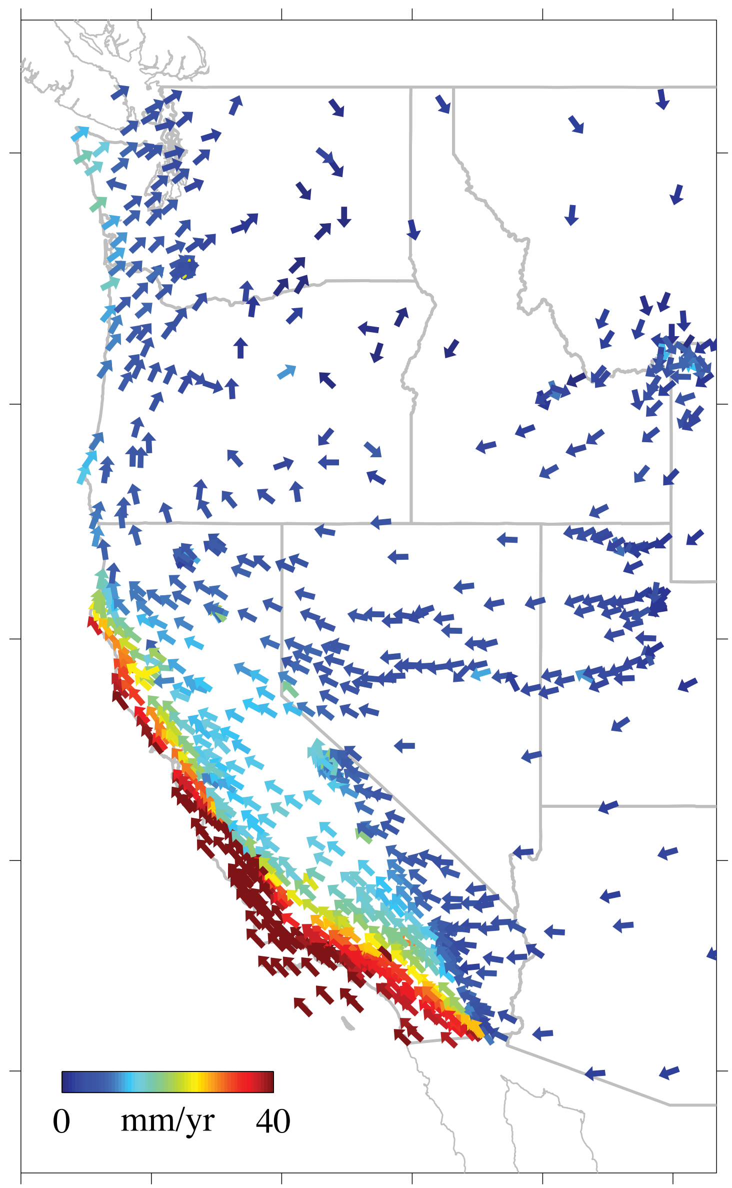
The earthquake cycle

Interseismic deformation





Interseismic velocities



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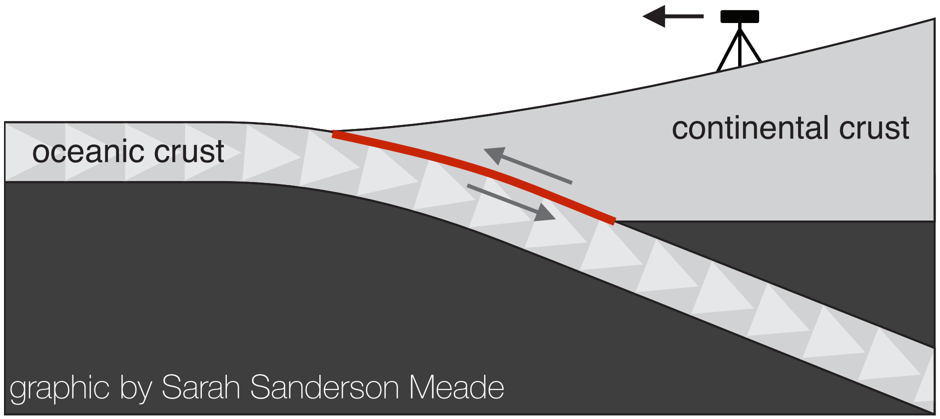
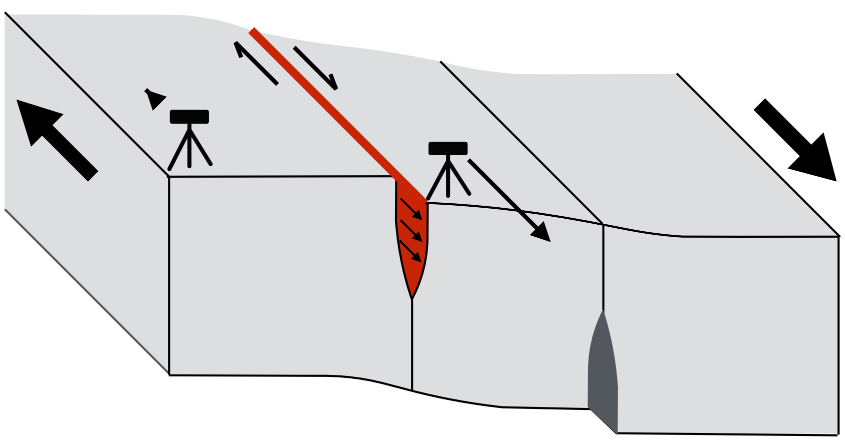
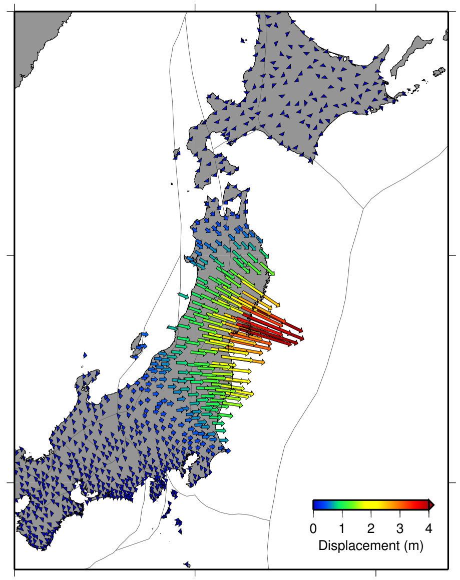


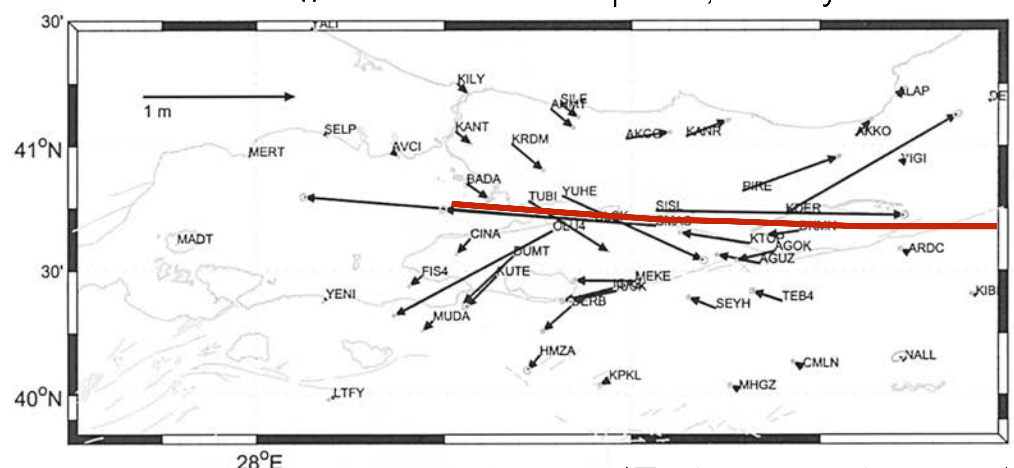


Coseismic displacements

2011 M_W=9.0 Tohoku earthquake, Japan



1999 M_W=7.4 Izmit earthquake, Turkey



(*Ergintav et al.*, 2002)

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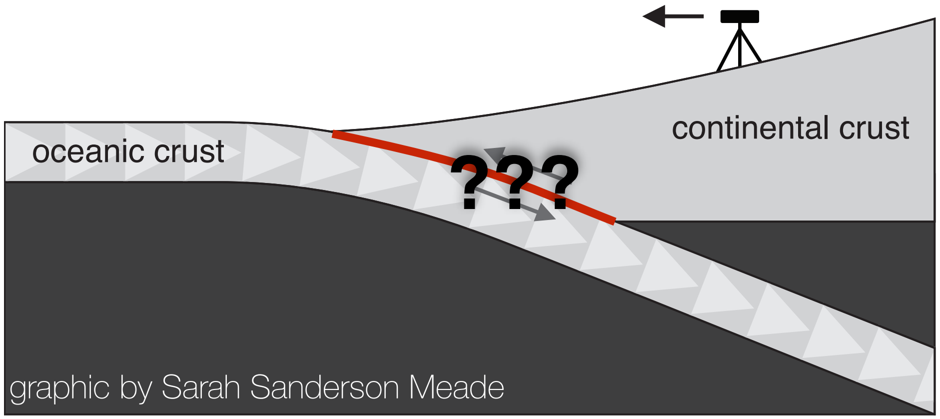
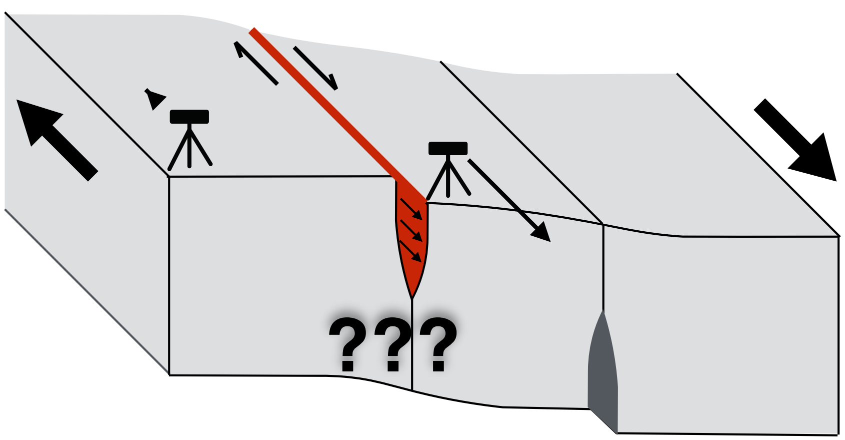
The earthquake cycle

Postseismic deformation





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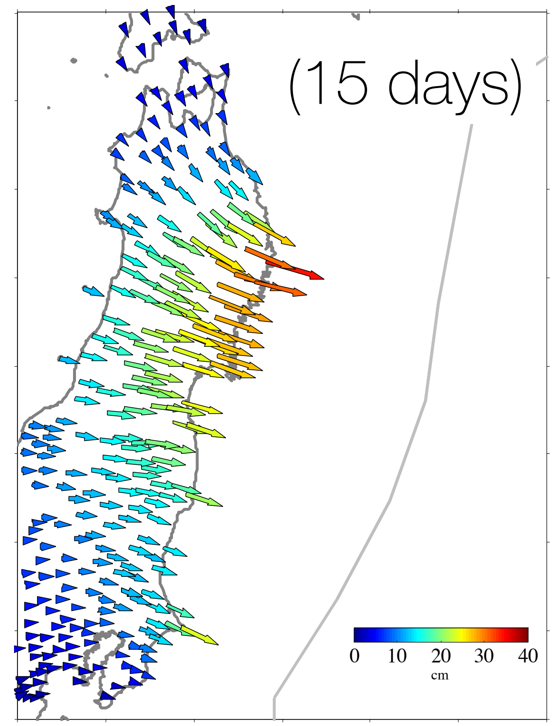
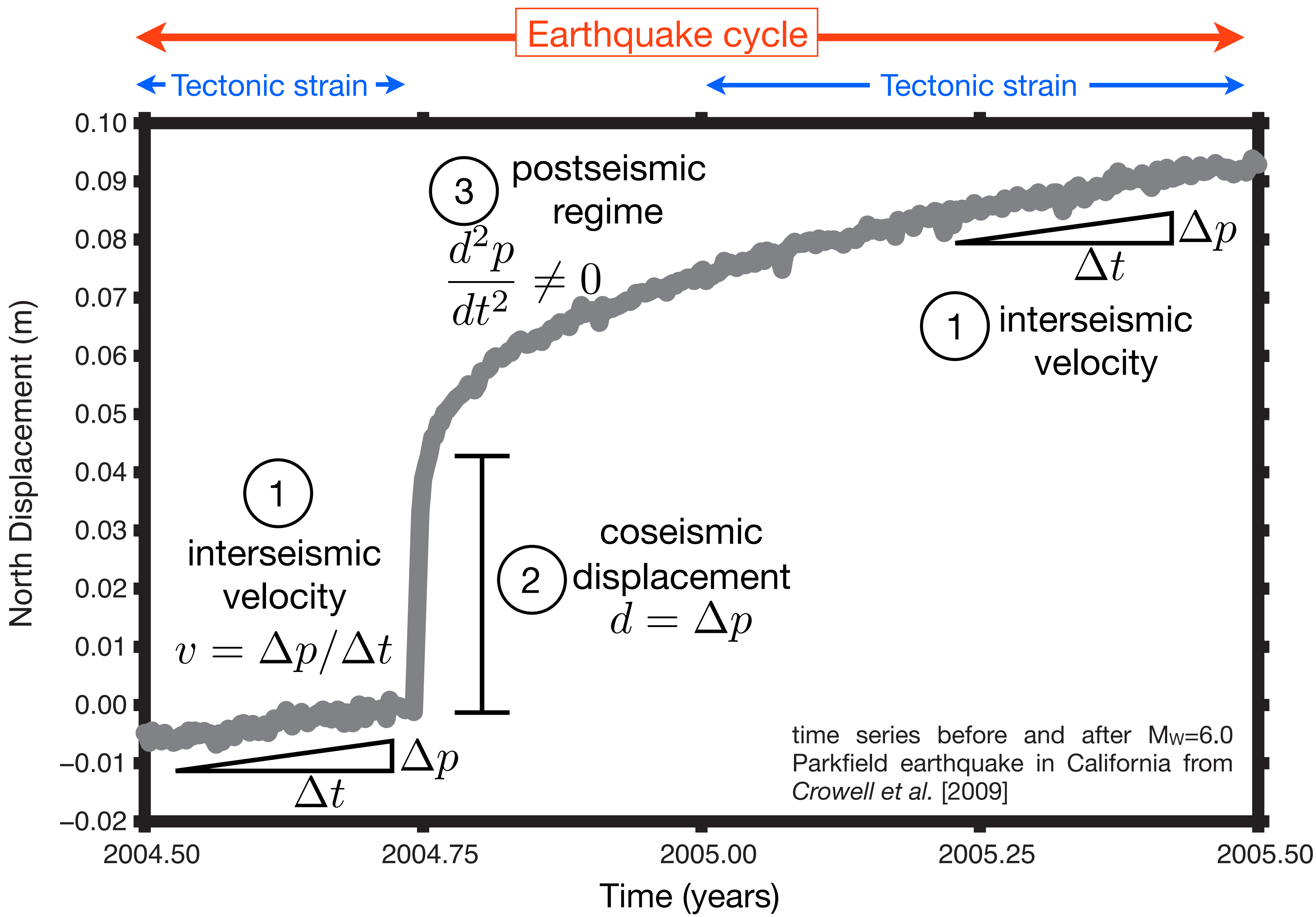
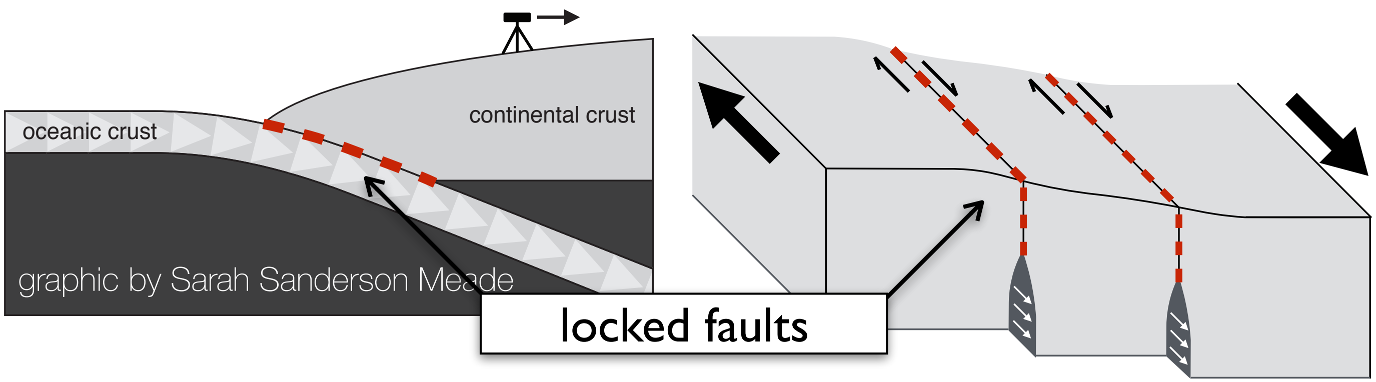


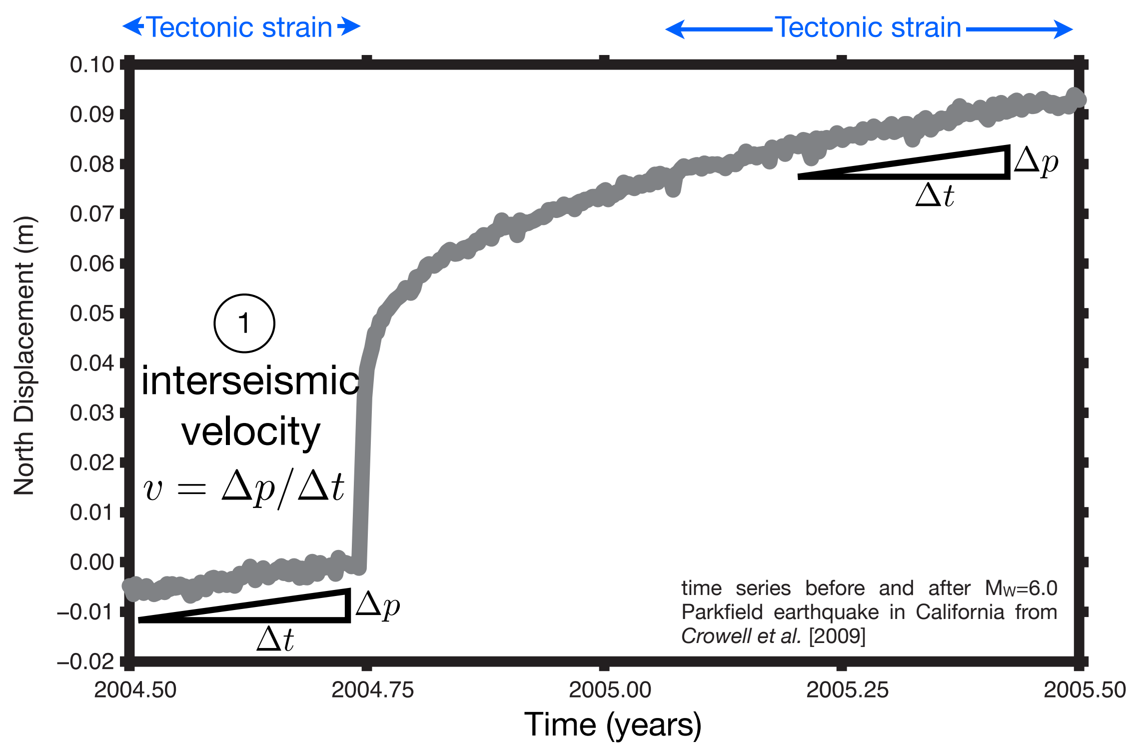
Imaging active deformation in the western United States

The earthquake cycle: a single station



Western U.S. deformation





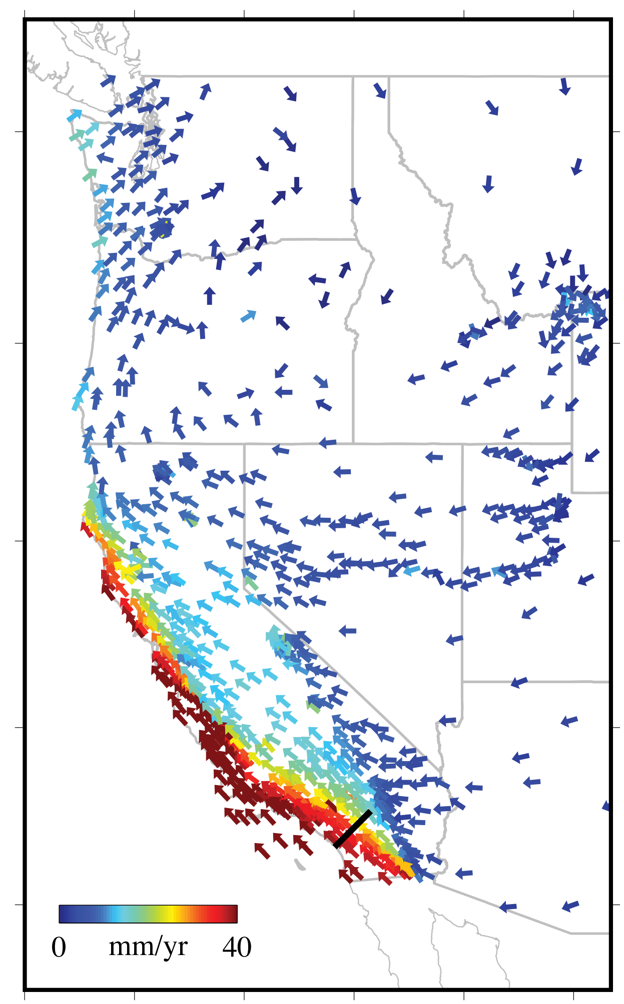
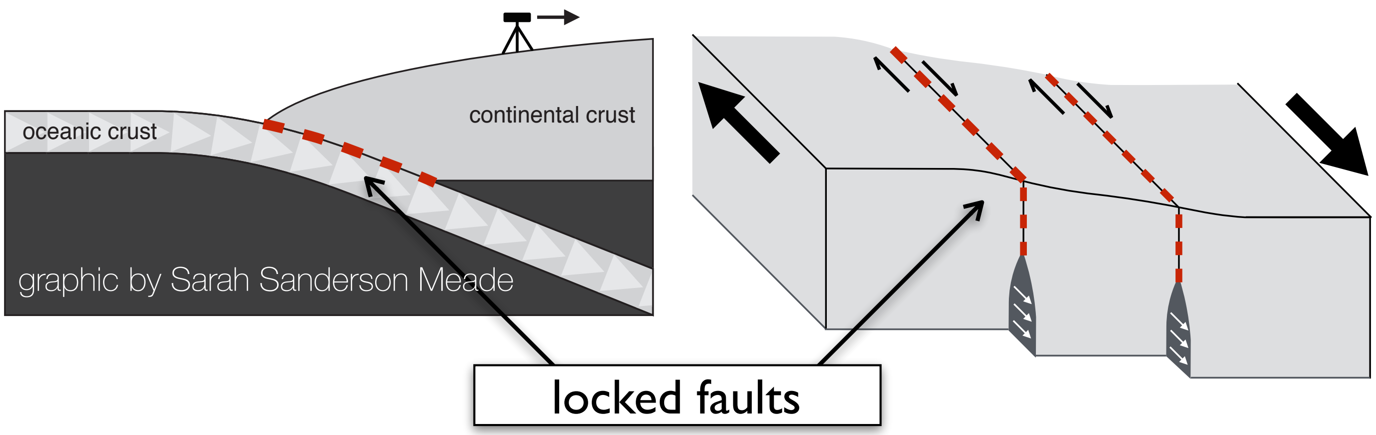
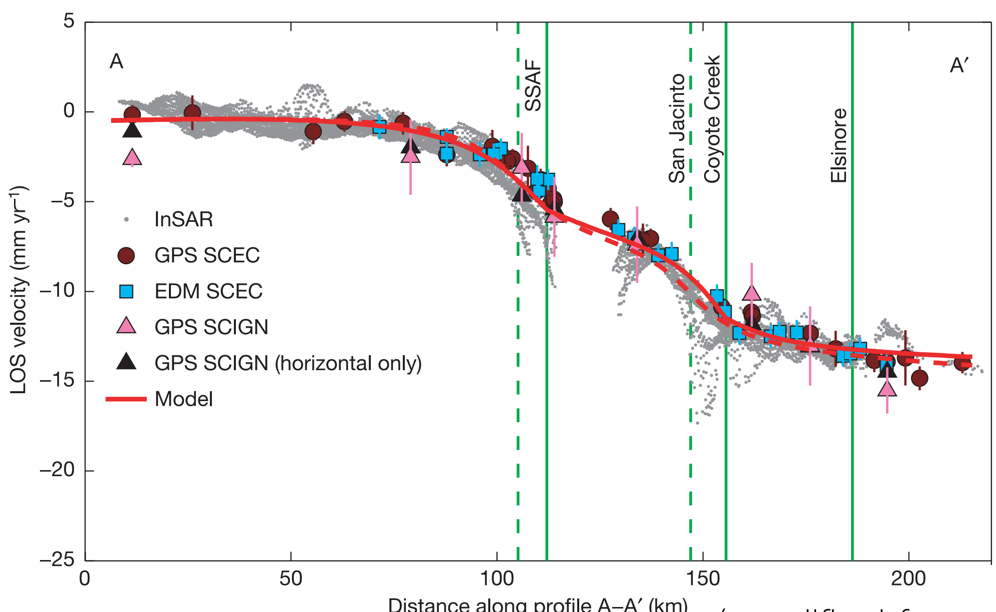


Plate Boundary Observatory
(http://pboweb.unavco.org/)

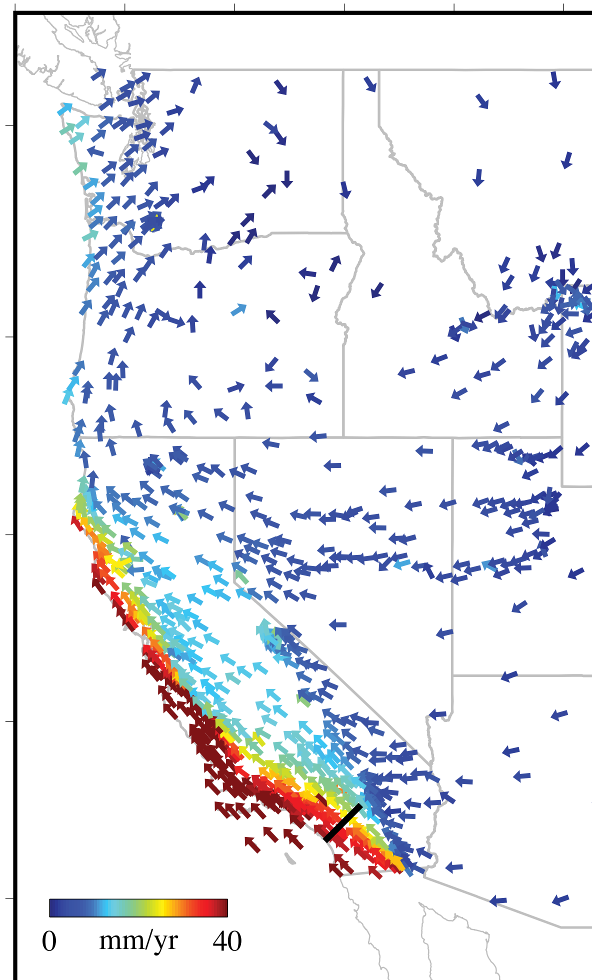
Interseismic deformation

Western U.S. deformation





(modified from *Fialko*, 2006)



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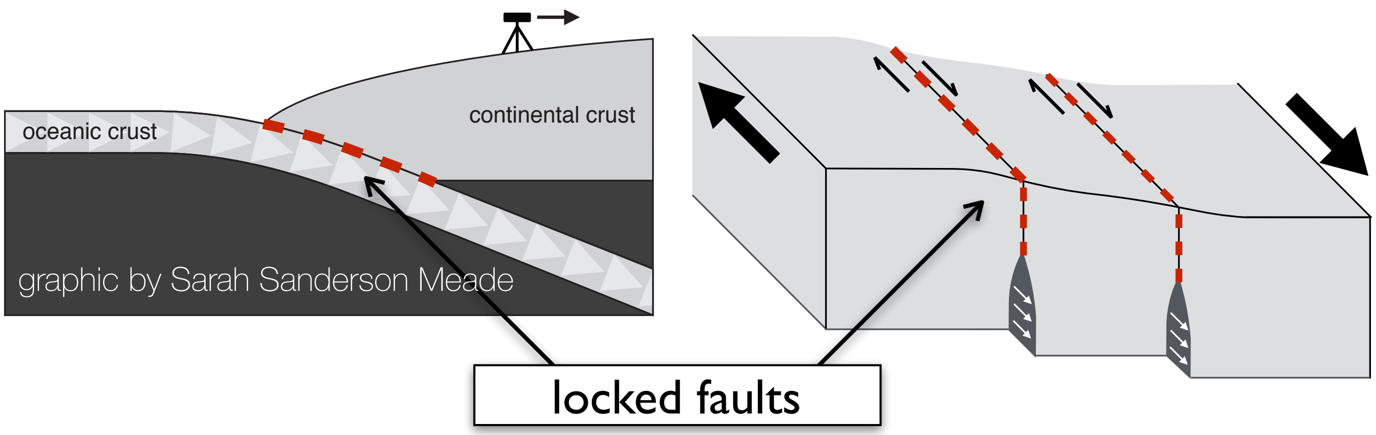

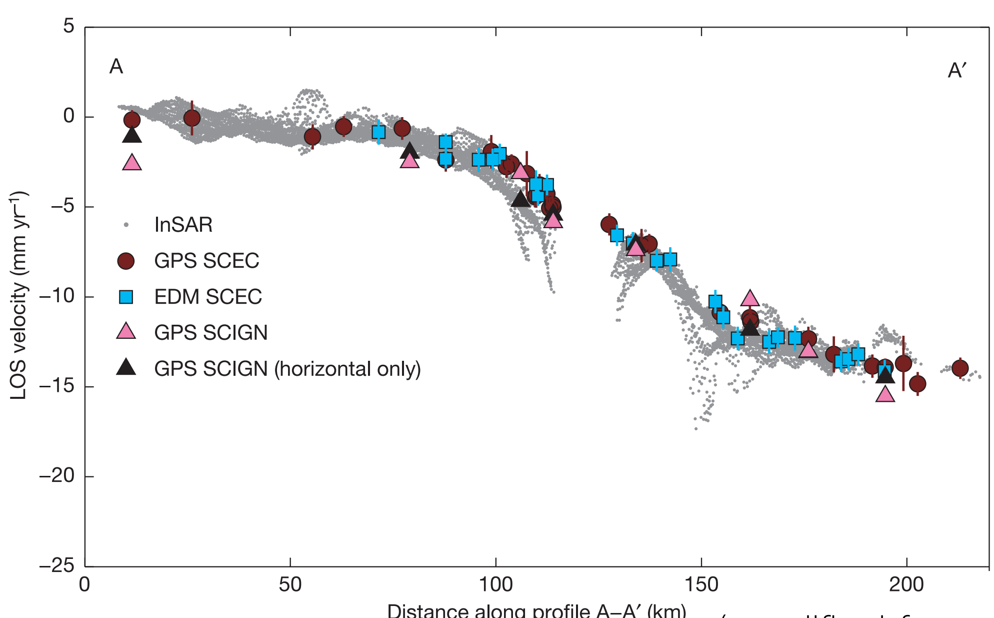

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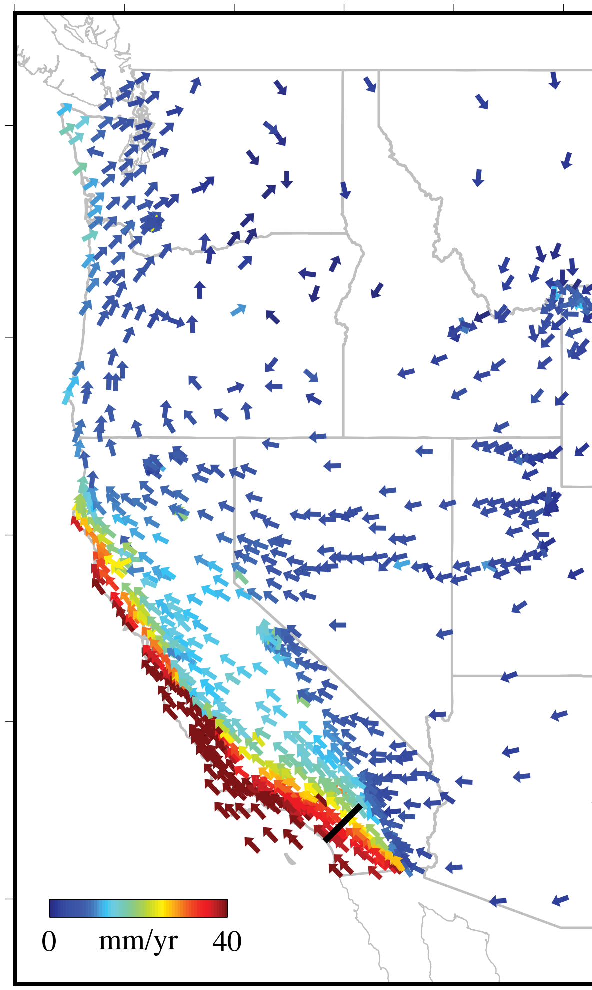

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Interseismic deformation

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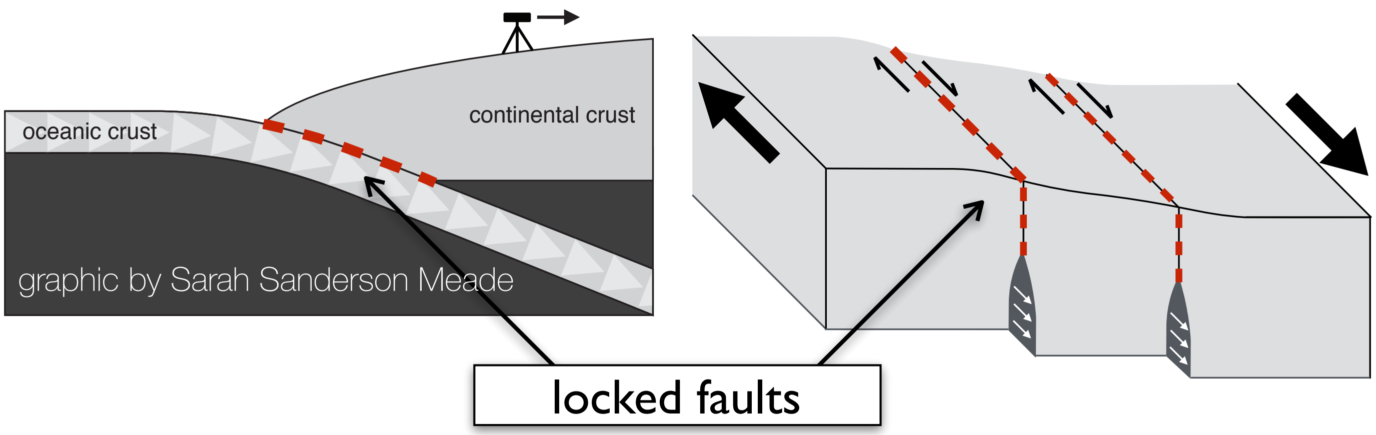

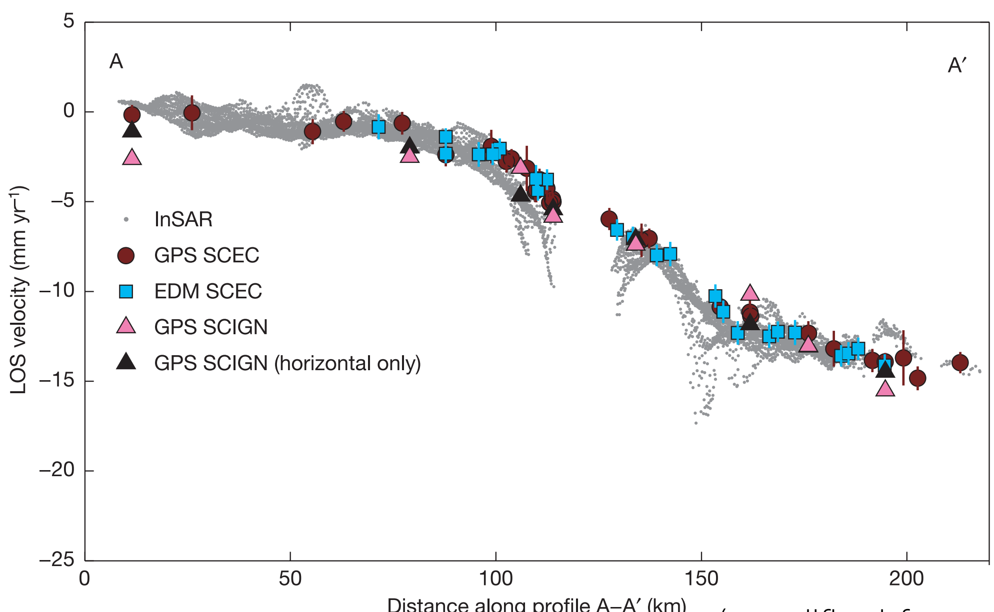

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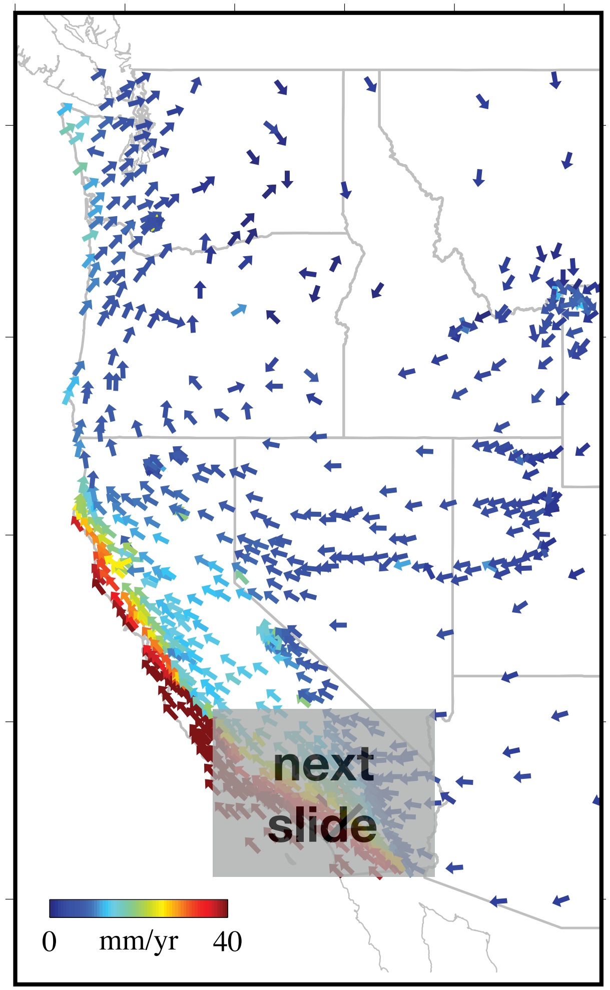

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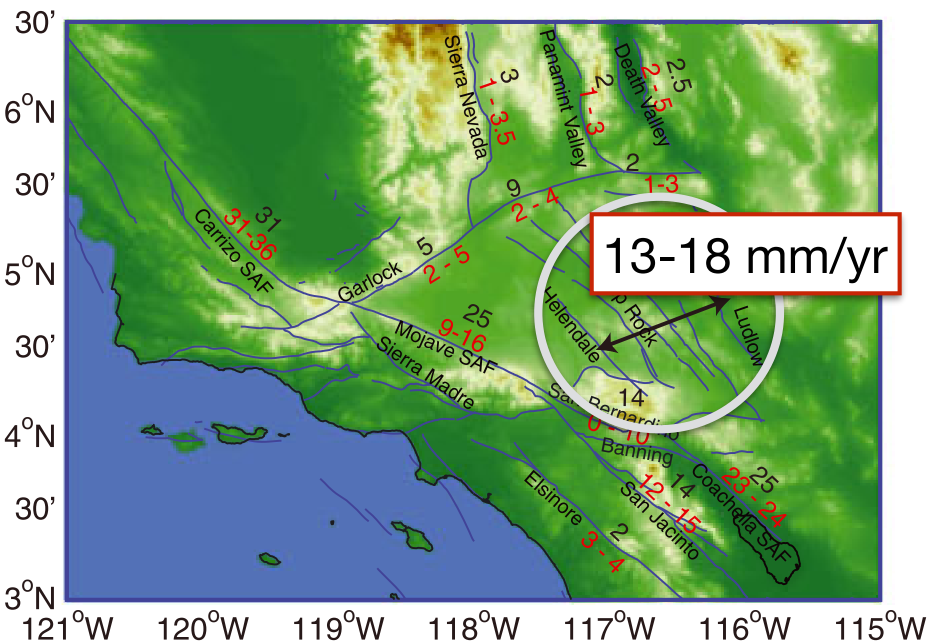
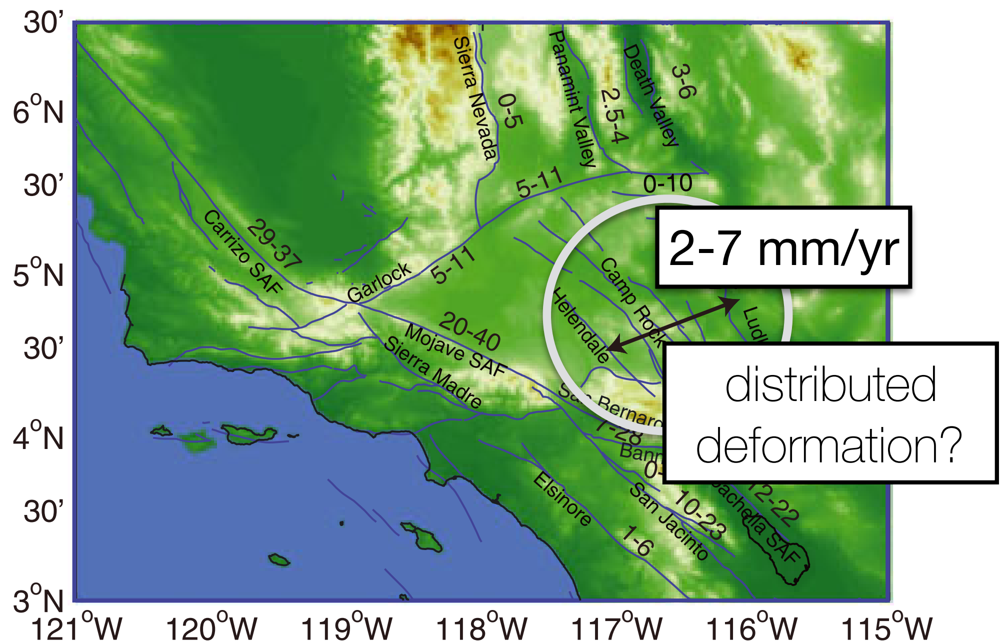
Interseismic deformation

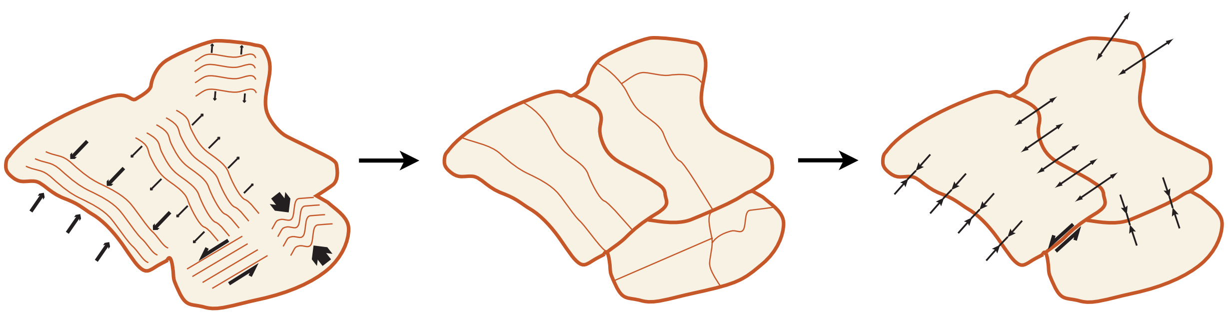
Eastern California shear zone

Geodetic rates ≠ geologic rates





(*Johnson*, 2013)

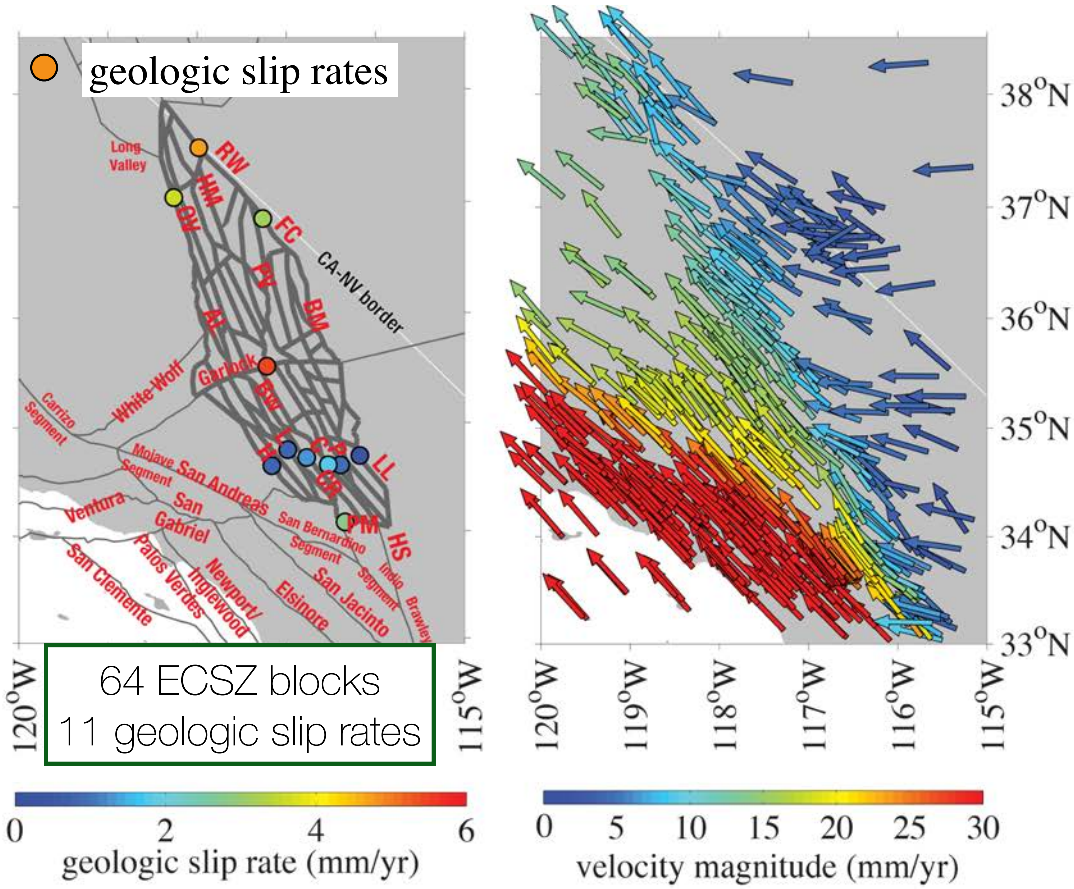


(*Thatcher*, 2009)

continuum model → block models → plate tectonics

Eastern California shear zone

Dense block model

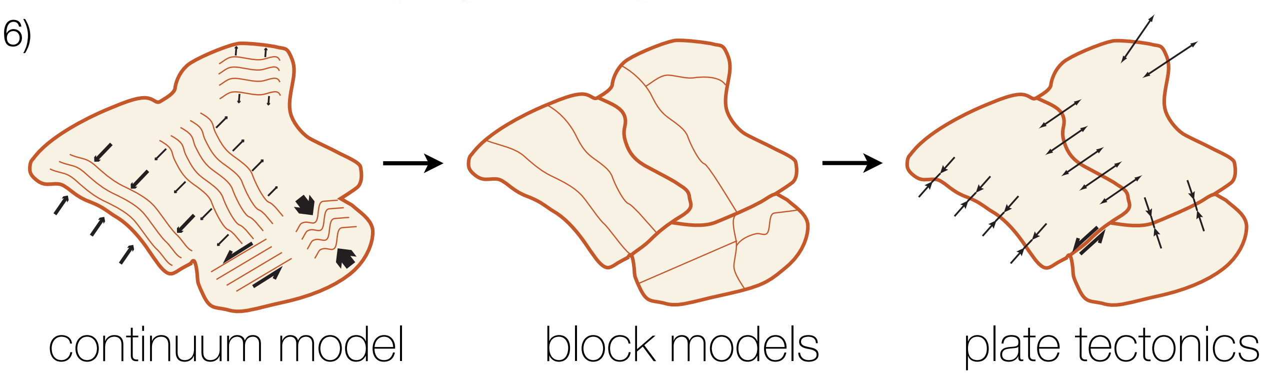


(*Evans et al.*, 2016)

Block model:

- divide the crust into microplates bounded by faults
- constrained by GPS
- deformation defined in terms of relative rotations of microplates and elastic signal due to locked faults

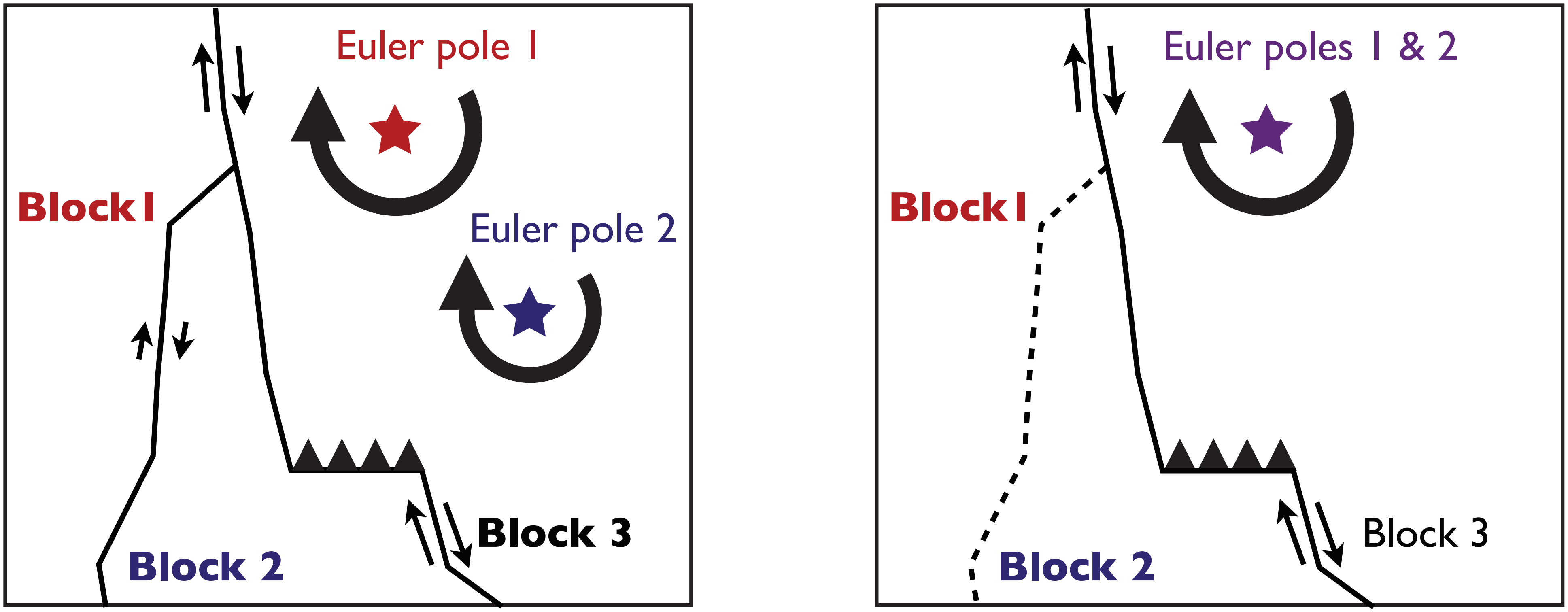
How many microplates are required to describe ECSZ deformation?



(*Thatcher*, 2009)

Eastern California shear zone

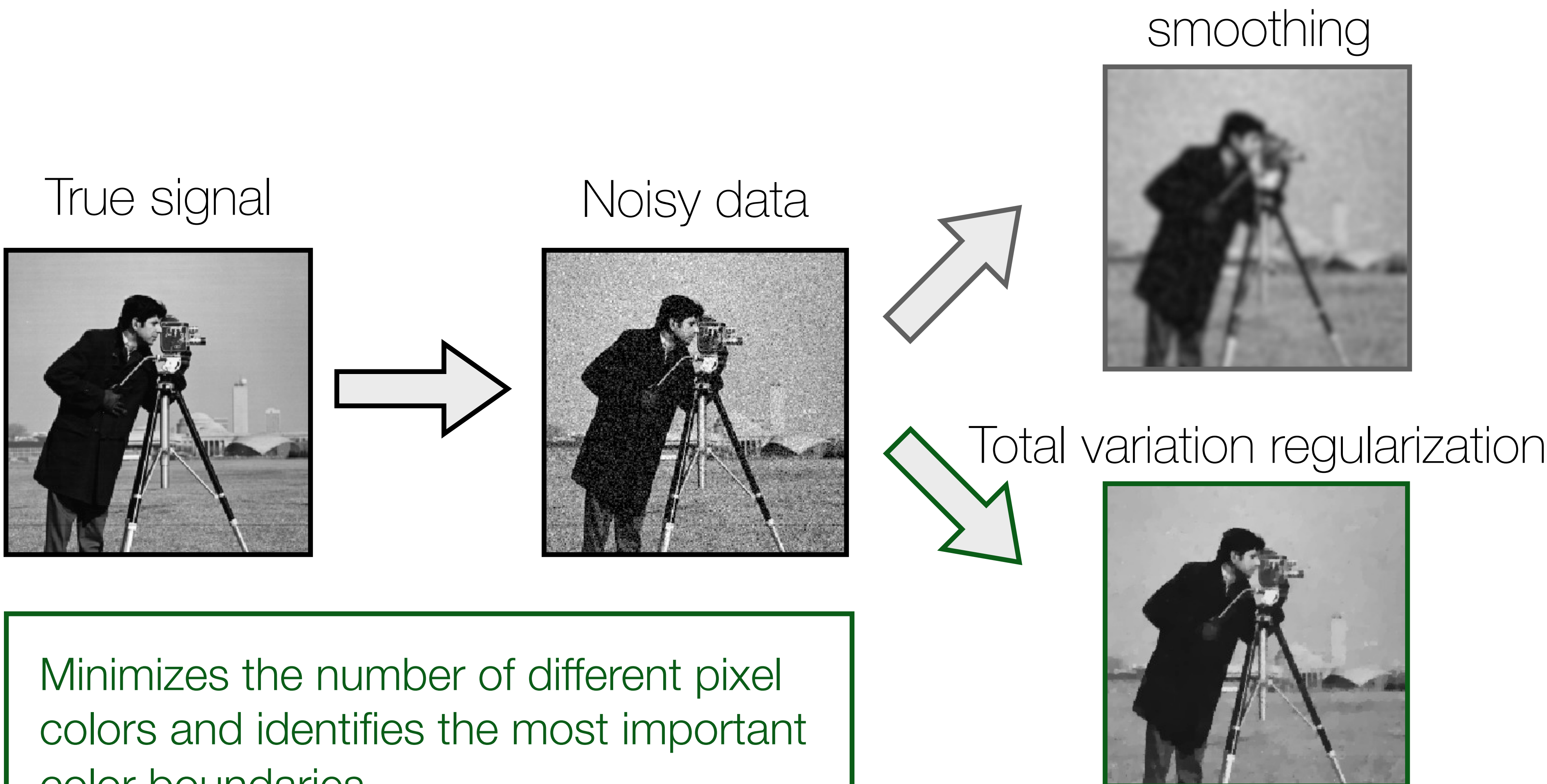
Blocks defined by Euler vectors



Want to find a solution in which many blocks have identical rotation vectors

(*Evans et al.*, 2015)

Total variation regularization



Minimizes the number of different pixel colors and identifies the most important color boundaries

Block model solution methods

Total variation regularization (TVR)

$$\min \|\underbrace{\boxed{\mathbf{G\Omega - d}}}_{\text{Fit to data}}\|_{\mathbf{2}} + \lambda \|\underbrace{\boxed{\mathbf{D\Omega}}}_{\text{rotation vector differences}}\|_{\mathbf{1}}$$

Uses L_2 norm: $\|\mathbf{v}\|_2 = \left(\sum_{i=1}^{N} |v_i|^2\right)^{\frac{1}{2}}$ **and L_1 norm:** $\|\mathbf{v}\|_1 = \sum_{i=1}^{N} |v_i|$

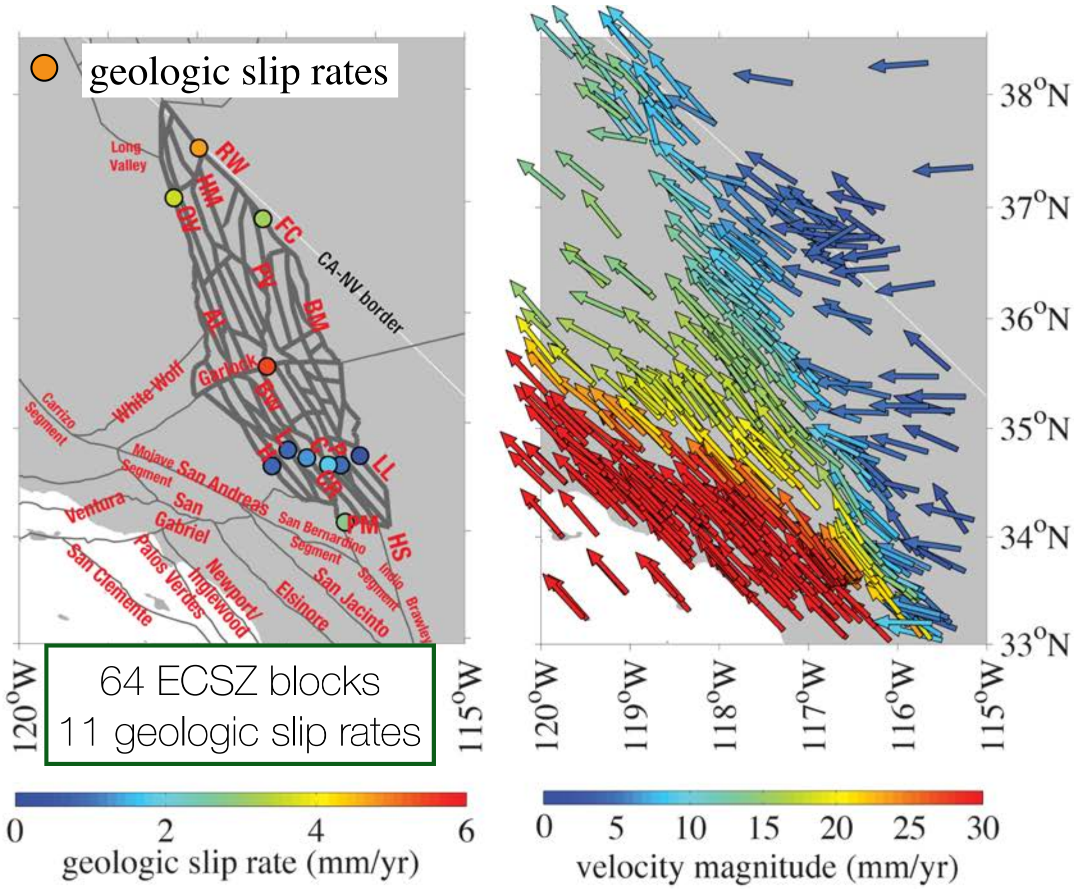
$\mathbf{D}$: linear differential operator

Solutions are grouped with many identical values

λ controls strength of grouping (high λ is very grouped)

Can be solved with convex optimization methods (*Jenson et al*., 2011; *Boyd and Vandenberghe*, 2004)

Back to the model



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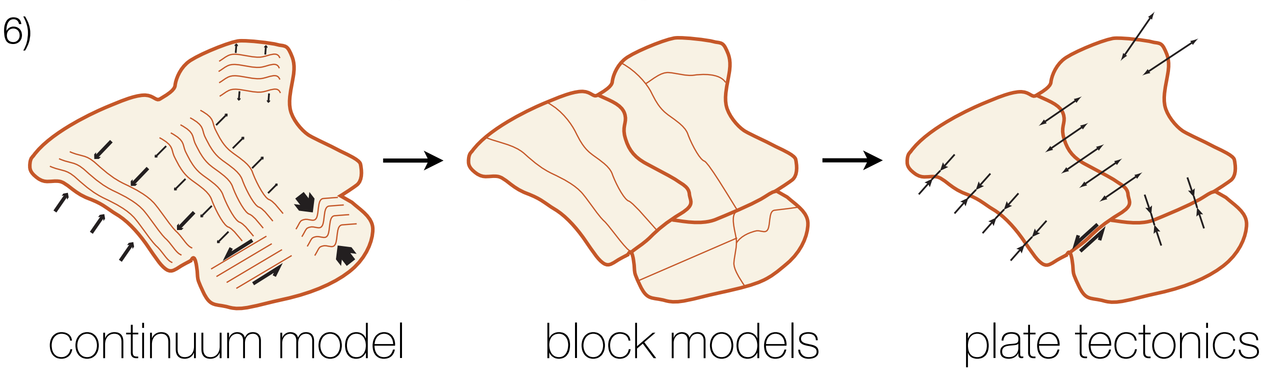


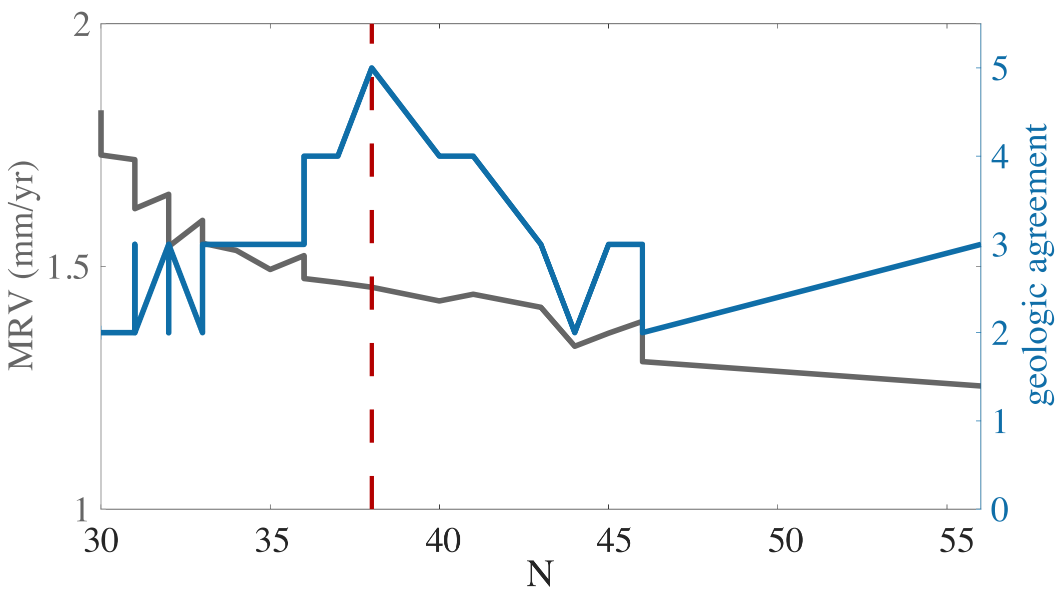
(*Thatcher*, 2009)

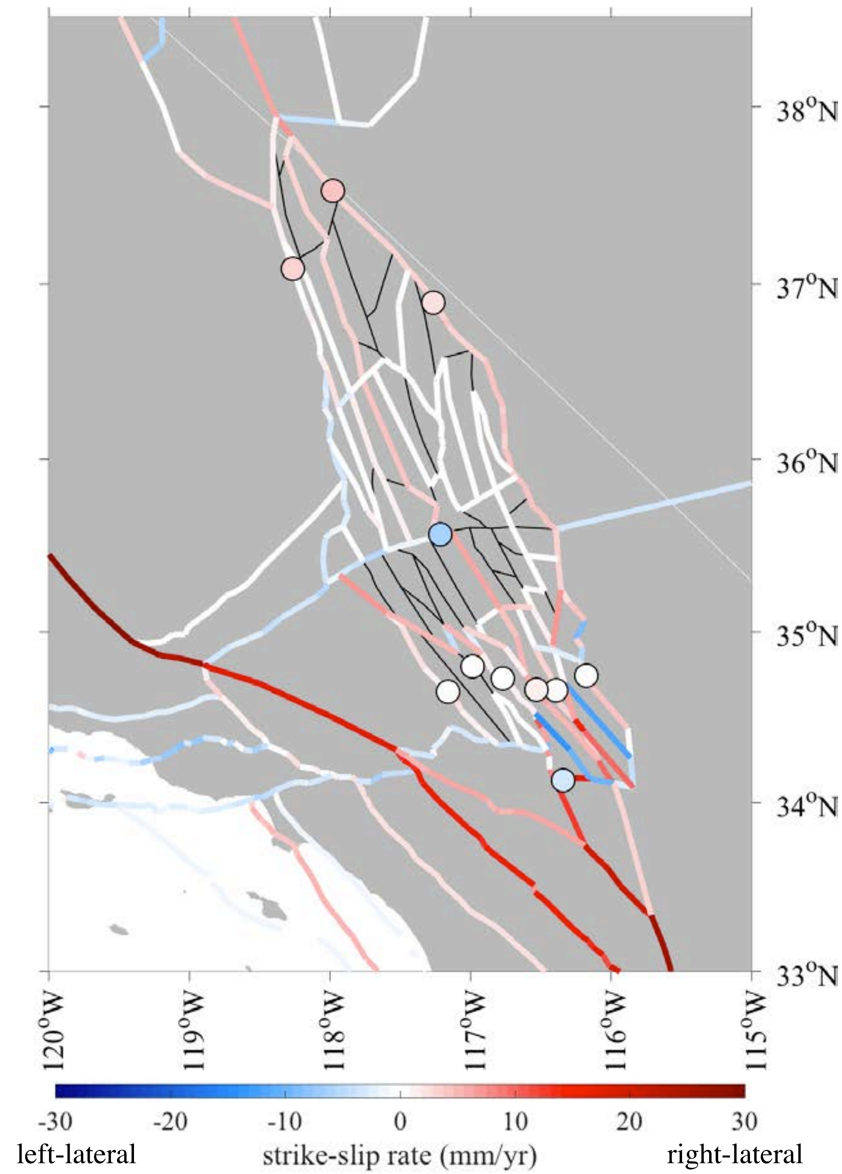
Eastern California shear zone

ECSZ fault slip rates

Which geodetic model is MOST consistent with the geologic slip rates?

Fault segment	Geologic rate (mm/yr)	Reference
Pinto Mountain	–2.8 ± 2.5	Anderson, 1979; Petersen and Wesnousky, 1994
Camp Rock	≤1.4 ± 1.4	Oskin et al., 2008
Death Valley–Furnace Creek	3.1 ± 0.4	Frankel et al., 2007b
Garlock	–5.3 +1/–2.3	Ganev et al., 2012
Helendale	0.8 ± 0.8	Oskin et al., 2008
Ludlow	≤0.4 ± 0.4	Oskin et al., 2008
Owens Valley	3.7 ± 1.8	Frankel et al., 2007b
Pisgah	1.0 ± 0.5	Oskin et al., 2008
Death Valley–Red Wall Canyon	4.5 +1.6/–1.4	Frankel et al., 2007a
Lenwood	≤0.8 ± 0.4	Oskin et al., 2008
Calico	1.8 ± 0.7	Oskin et al., 2007





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Eastern California shear zone

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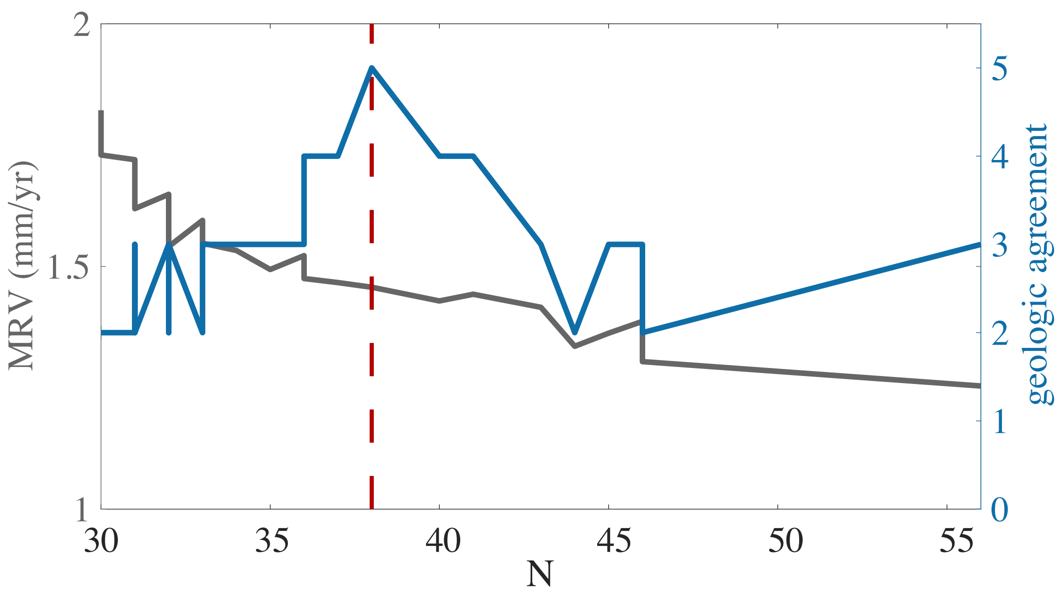
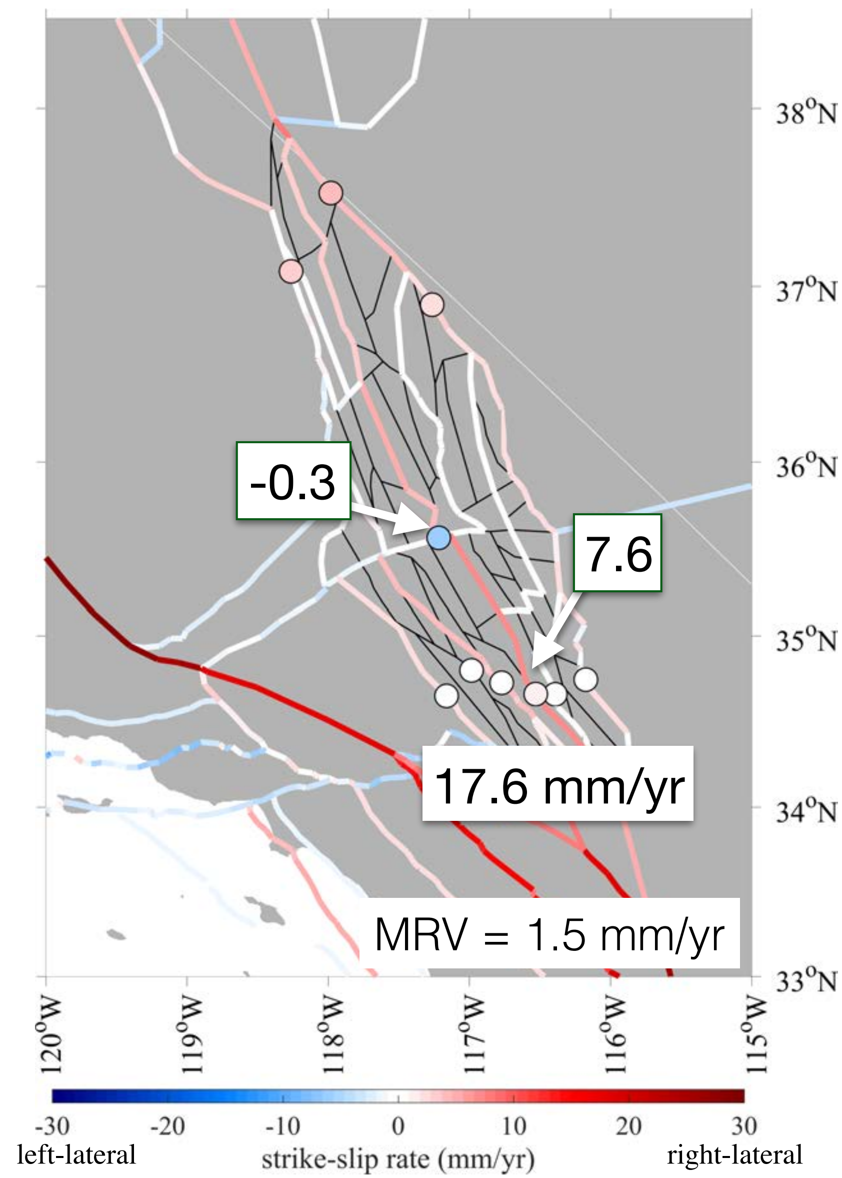
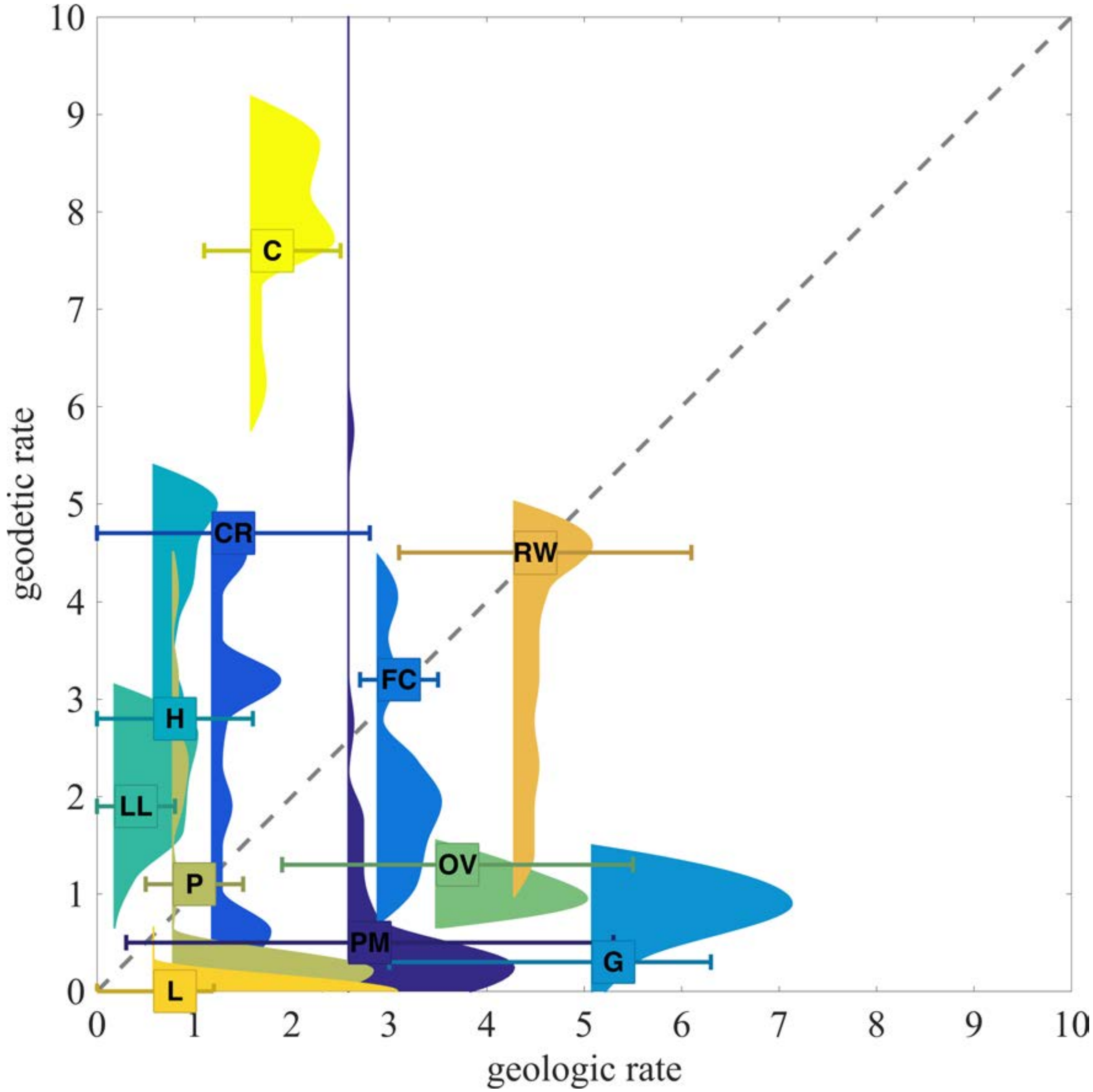


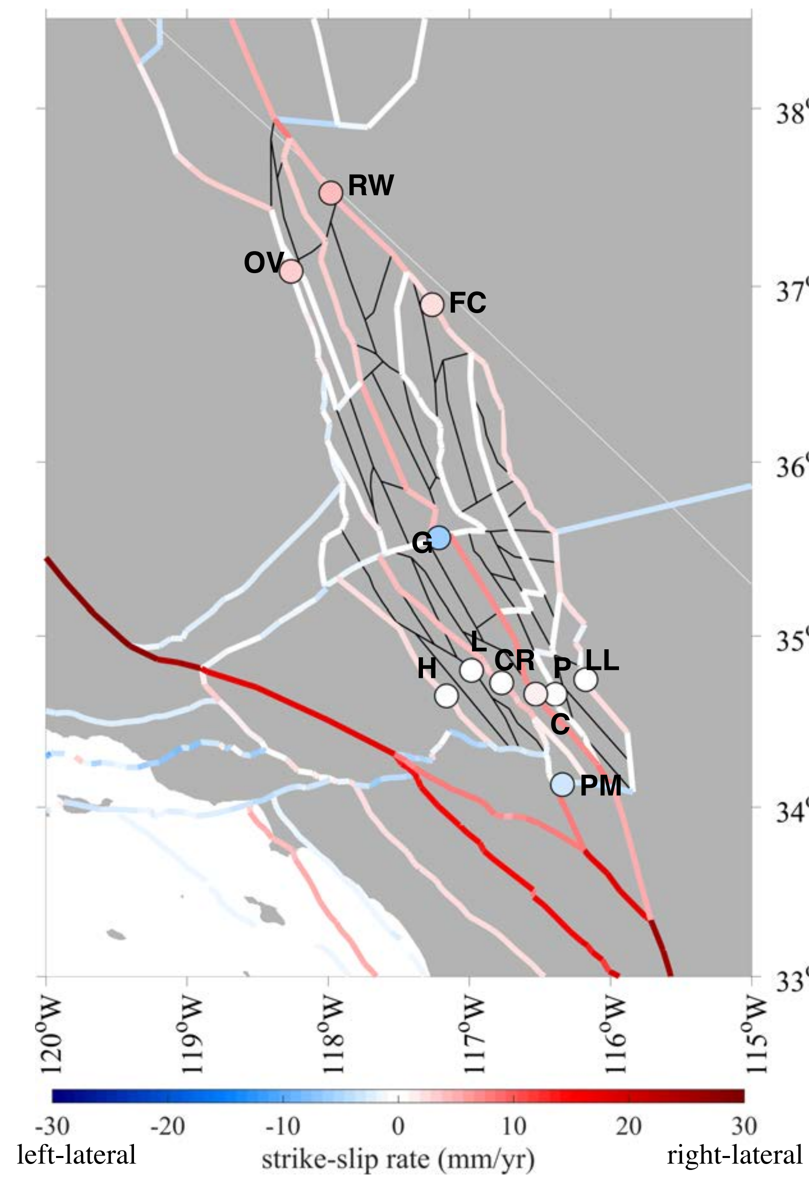


(*Evans et al.*, 2016)

Eastern California shear zone

Geologic comparison

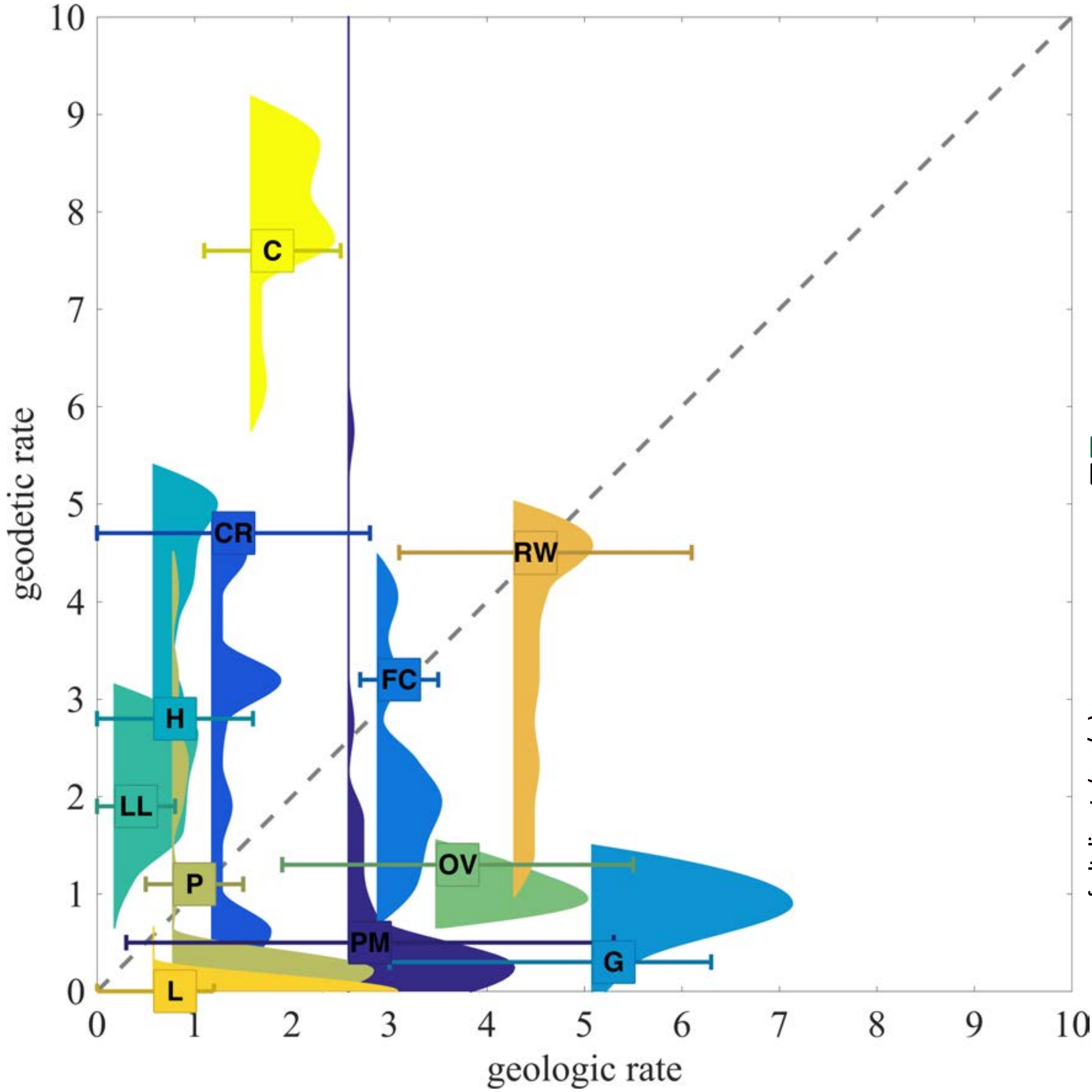


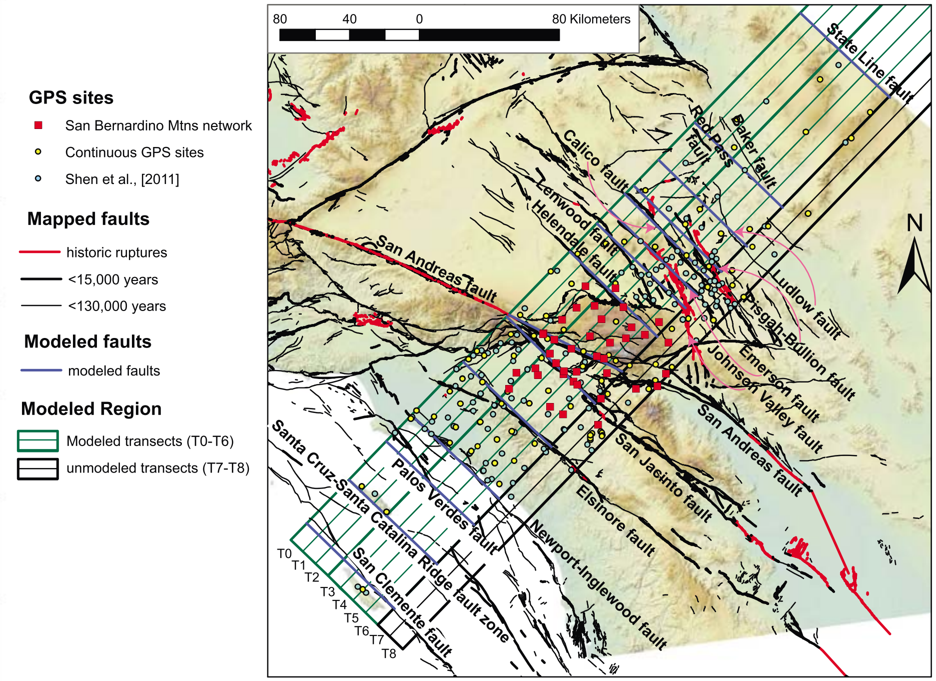


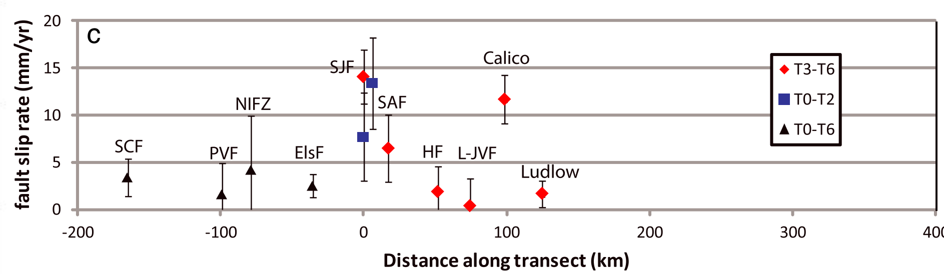
(*Evans et al.*, 2016)

Eastern California shear zone

Calico fault







(*Evans et al.*, 2016)

(*McGill et al.*, 2015)

Geodetic uncertainties

Variability indicates high model uncertainty

Fault Models

Specifies the spatial geometry of larger, more active faults.

Deformation Models

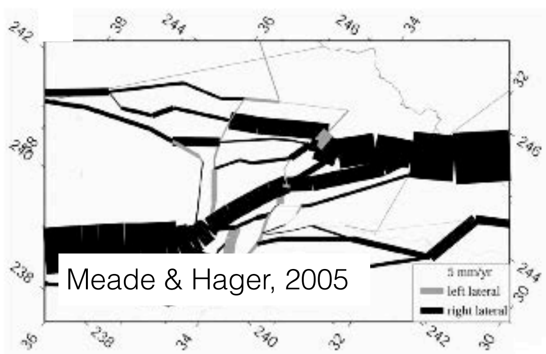
Provides fault slip rates used to calculate seismic moment release.

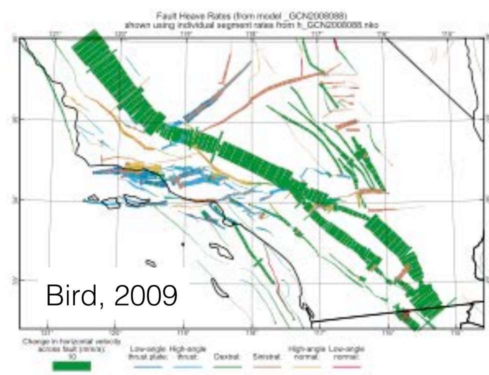
Earthquake-Rate Models

Gives the long-term rate of all possible damaging earthquakes throughout a region.

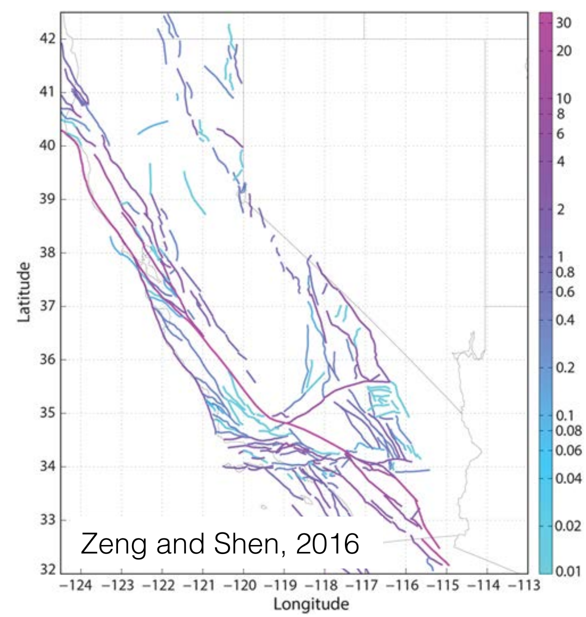
Probability Models

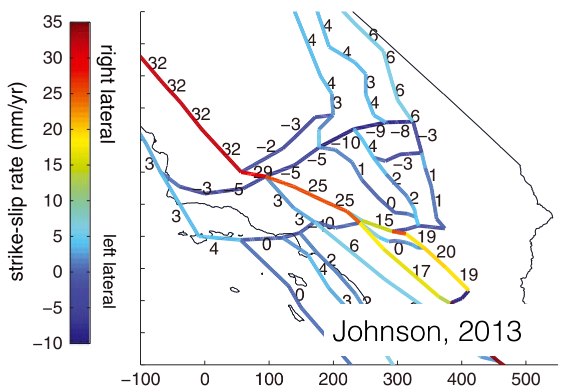
Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.

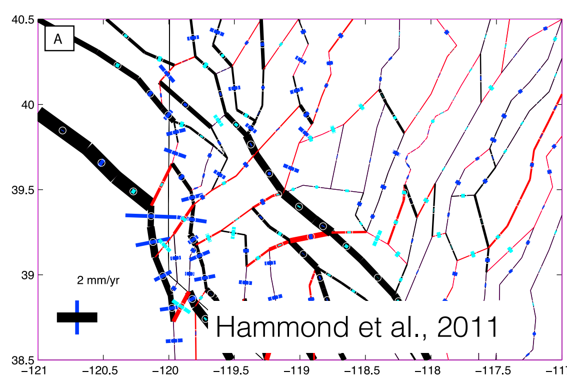




(from Uniform California Earthquake Rupture Forecast, UCERF3, *Field et al.*, 2013)

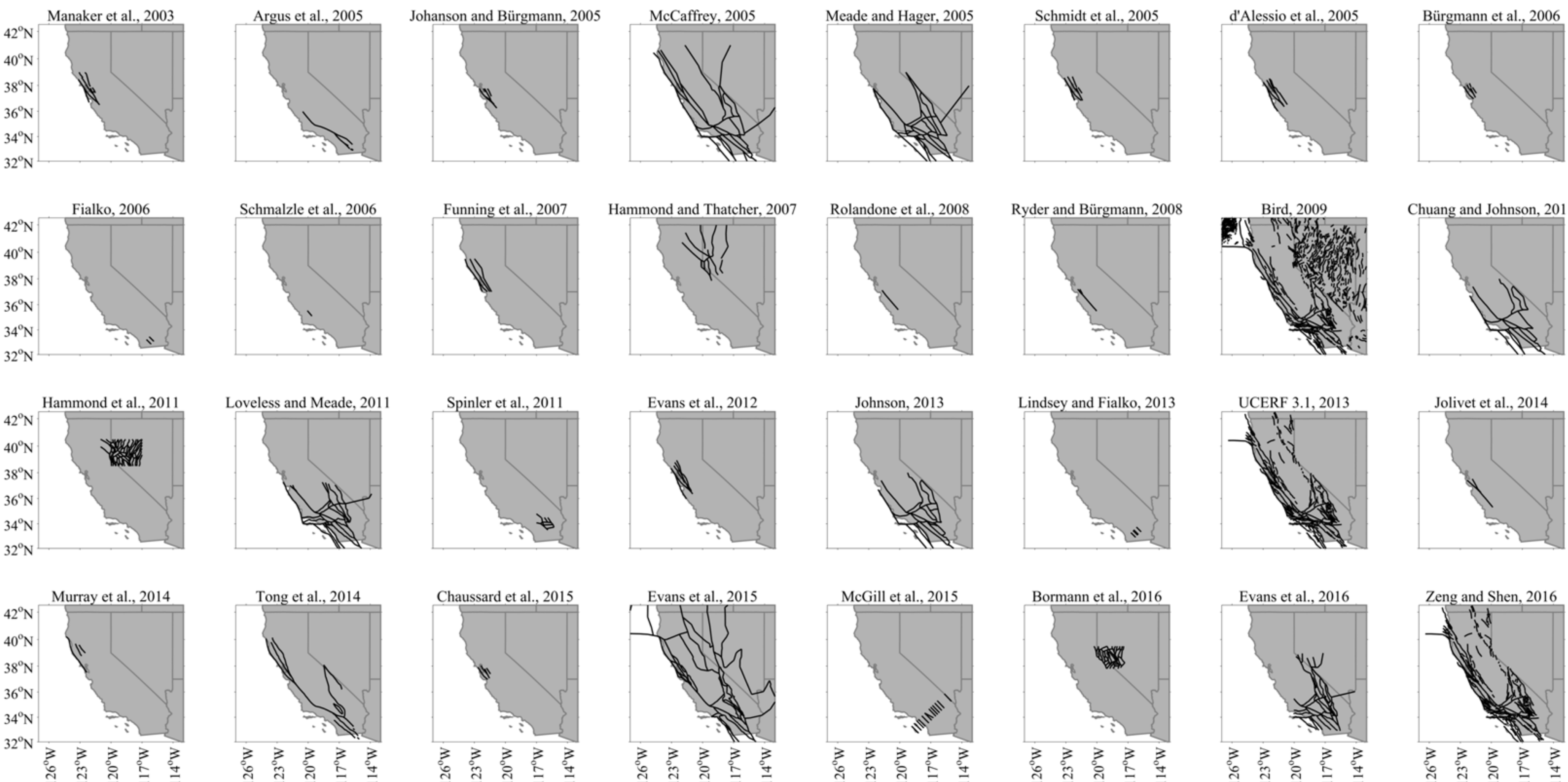






The fundamental challenge

33 slip rate models



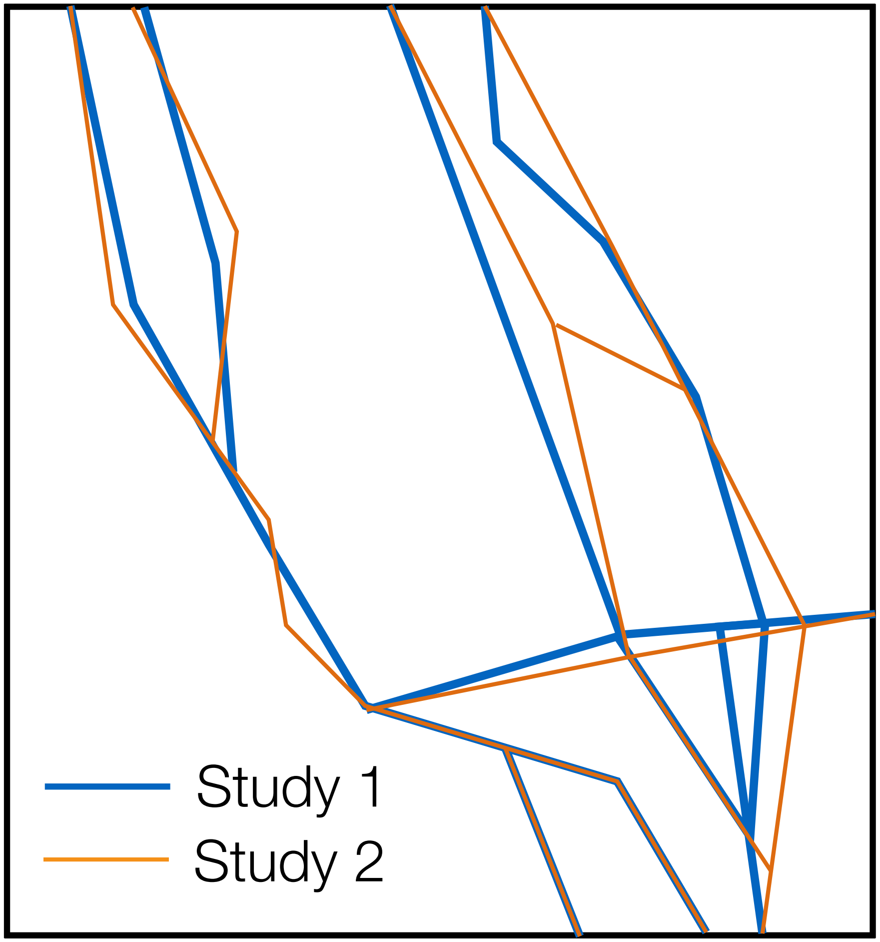
Compare models

How much do slip rates vary?

Two interpretations of the same fault system:

Compiling slip rates:

- Do these slip rates agree?
- How much do they disagree?
- Disagreement represents inherent uncertainty in the fault system geometry (and other modeling parameters)



Proposed solution: compare slip rates on a grid

Compare models

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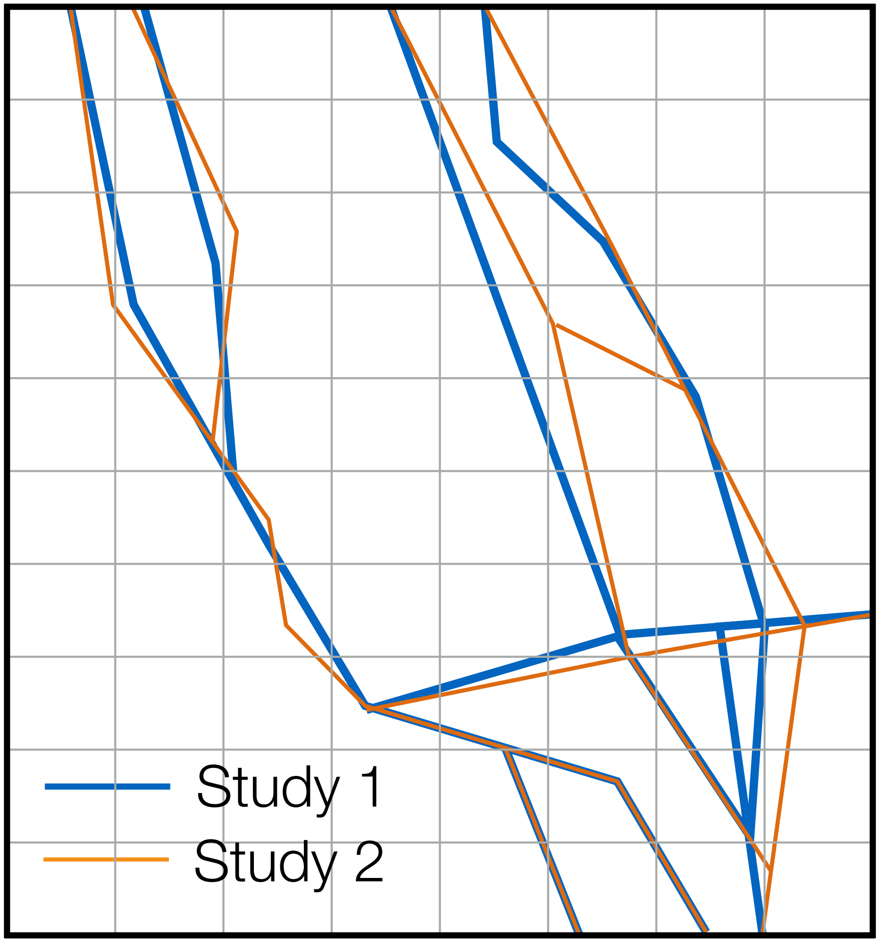

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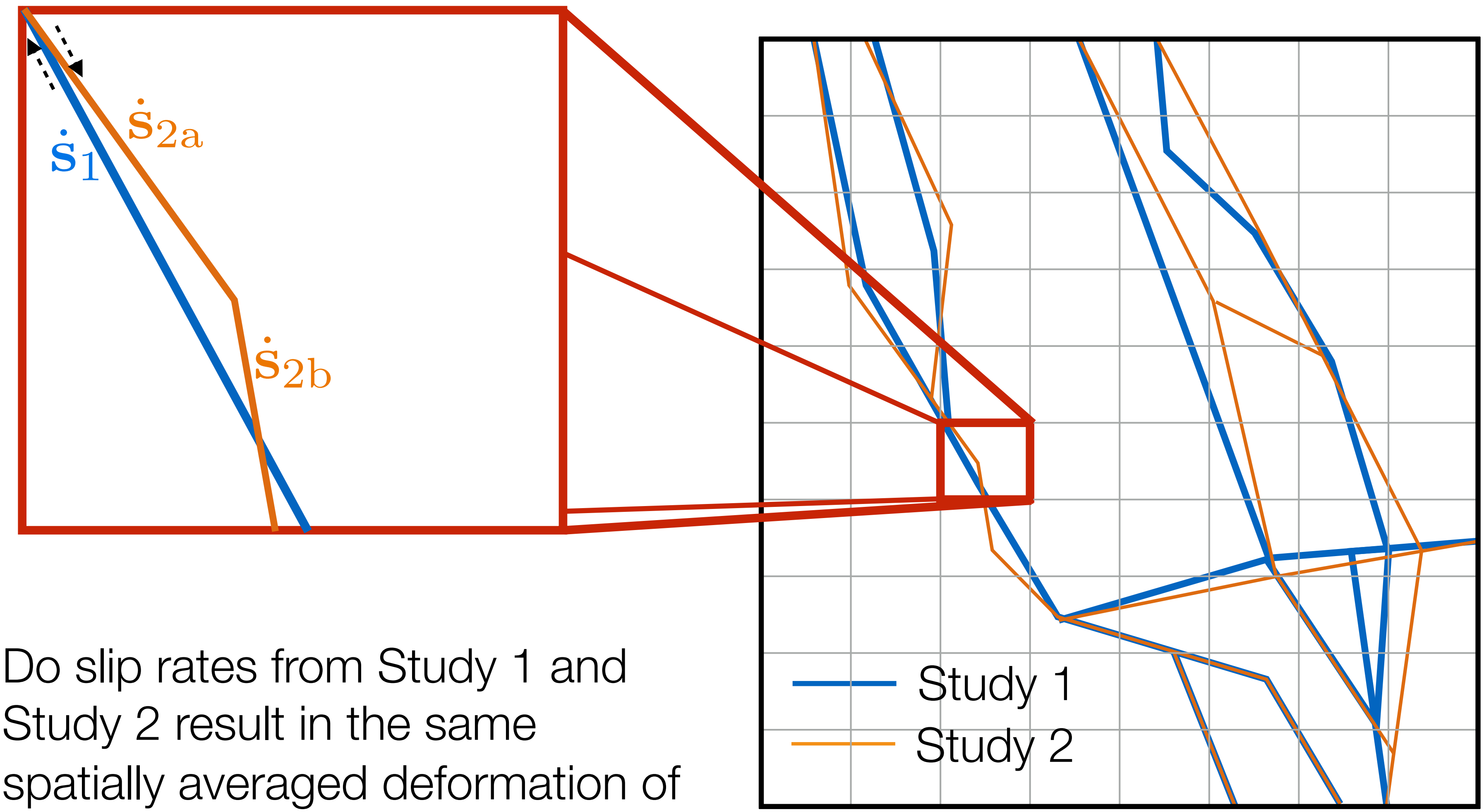
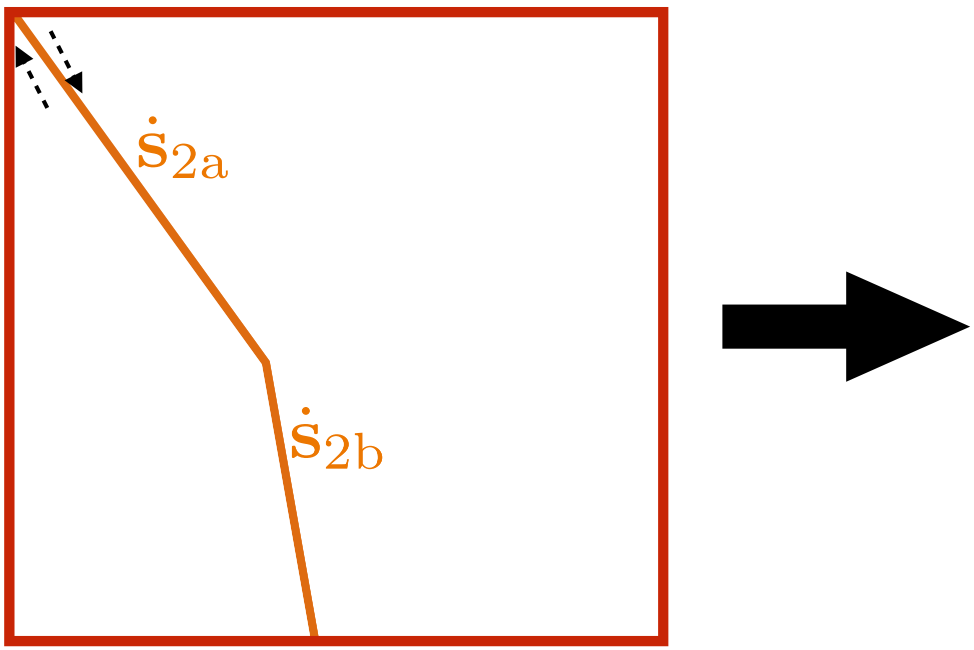
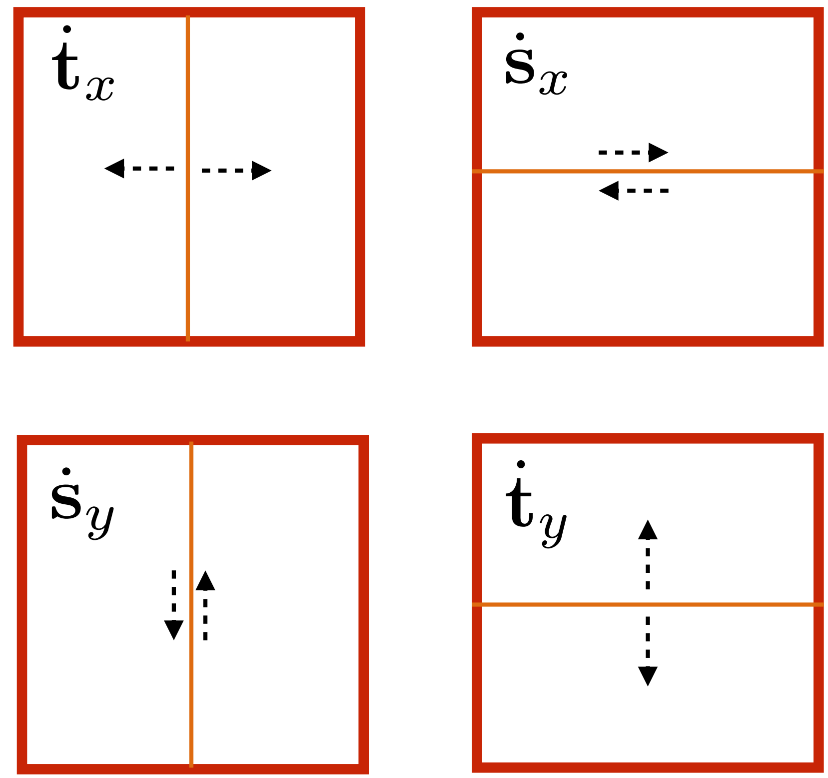


Do slip rates from Study 1 and Study 2 result in the same spatially averaged deformation of the cell?

Compare models

For every study, for every grid cell





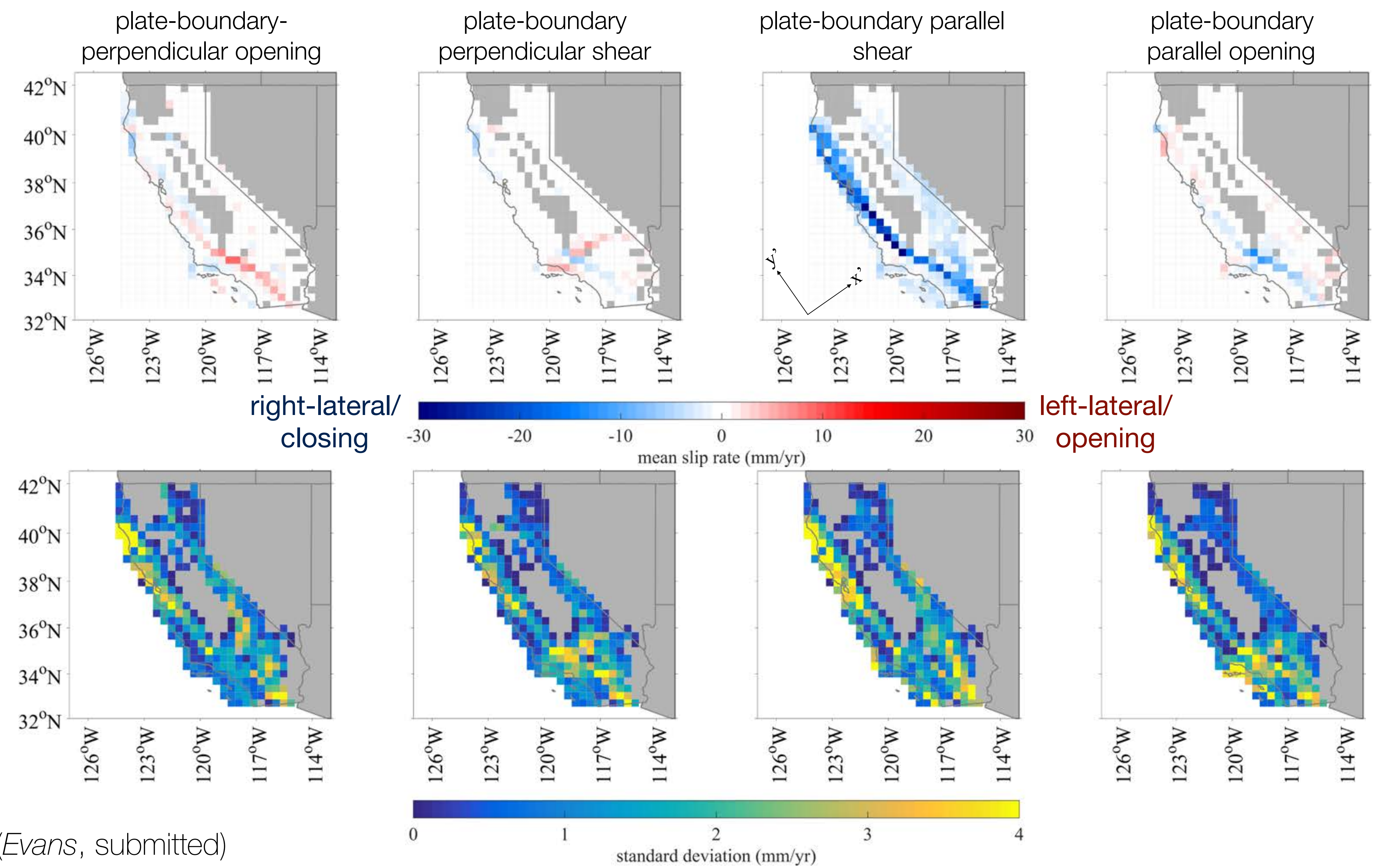
Do slip rates from Study 1 and Study 2 result in the same spatially averaged deformation of the cell?

Decompose every study into **spatially averaged** slip on 2 perpendicular structures in every grid cell:

4 components of slip for every study, in every cell

Compare models

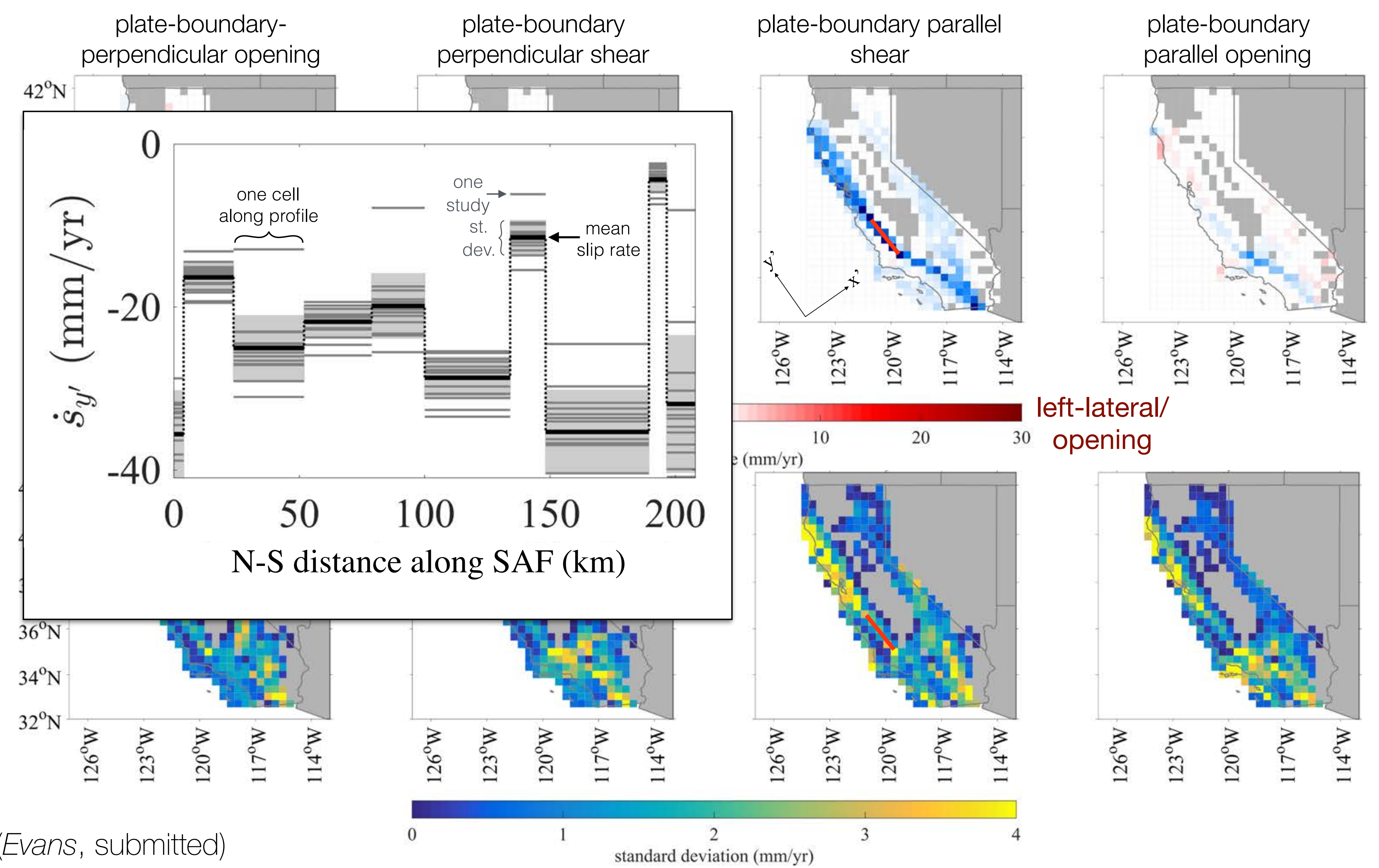
Mean and standard deviation of slip rate



(*Evans*, submitted)

Compare models

Mean and standard deviation of slip rate



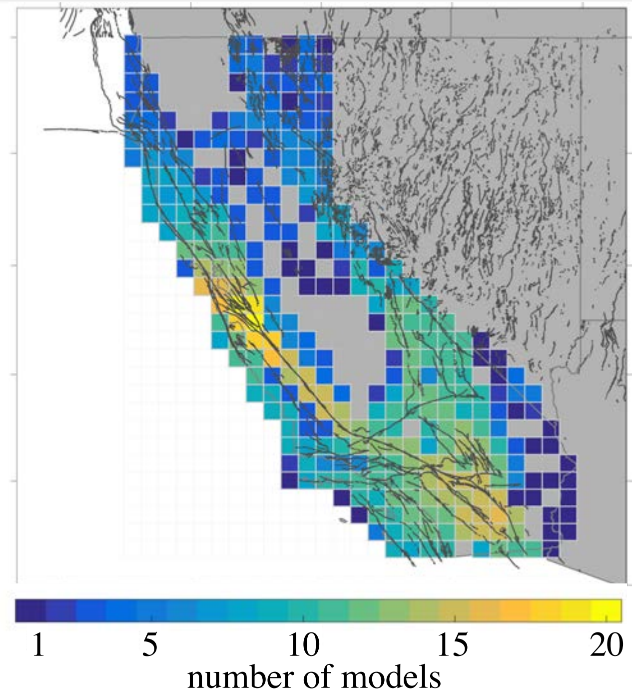
(*Evans*, submitted)

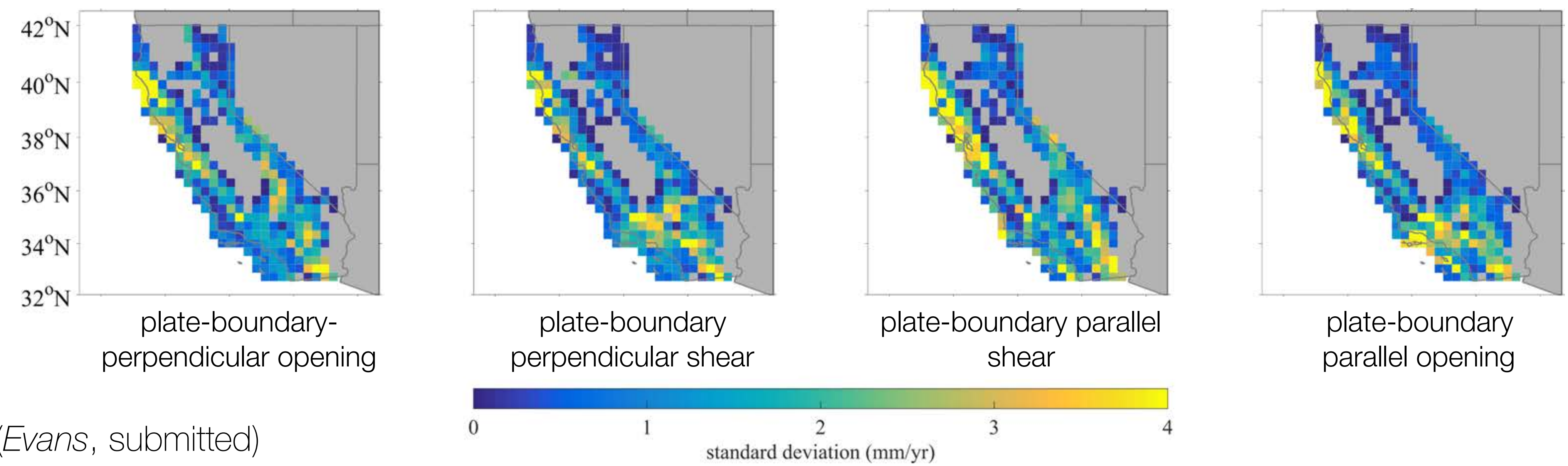
Compare models

Evaluate uncertainty

Standard deviation proxy for model uncertainty:

- Mean standard deviation **~1.5 mm/yr**
- Highest in complex fault systems with relatively few models (northern San Andreas, transverse ranges)
- Lowest where there are fewest models, and central San Andreas
- Target locations for future research

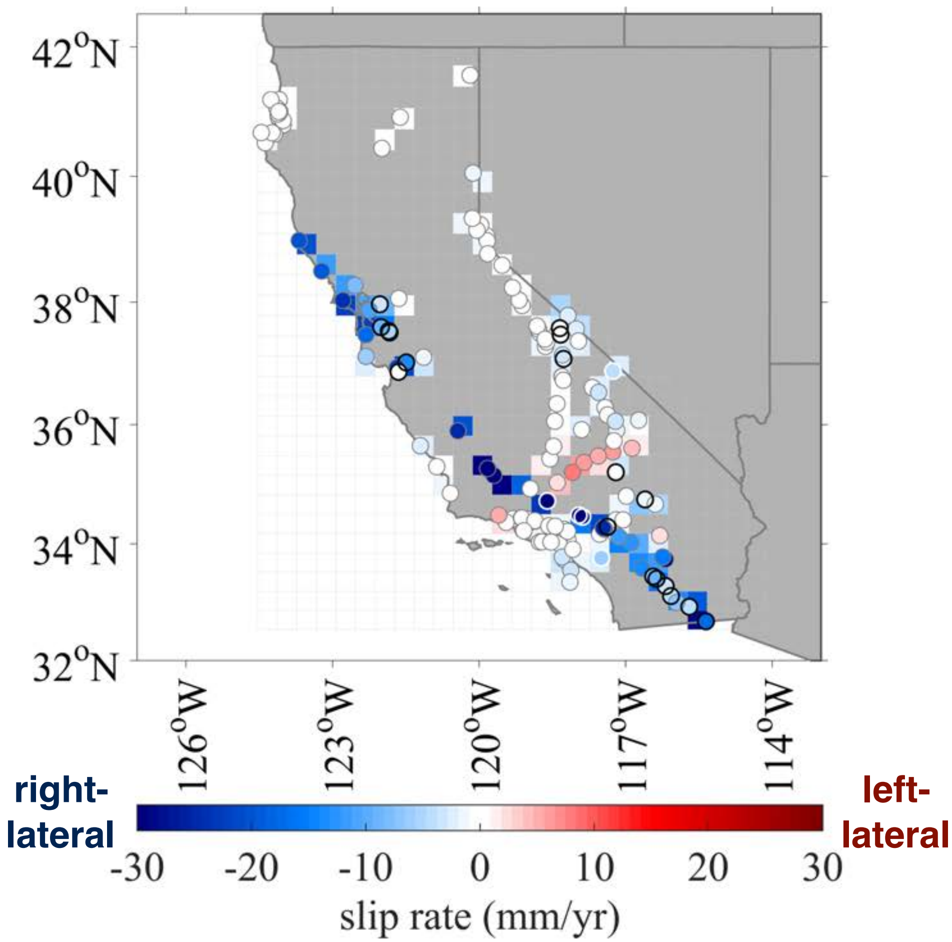


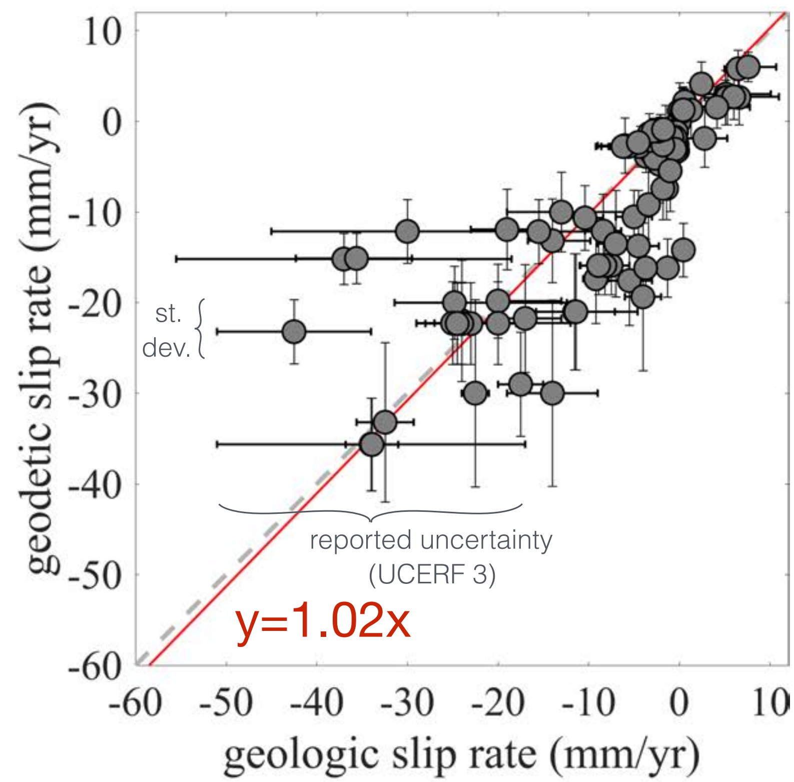


(*Evans*, submitted)

Compare models

Geologic vs. geodetic



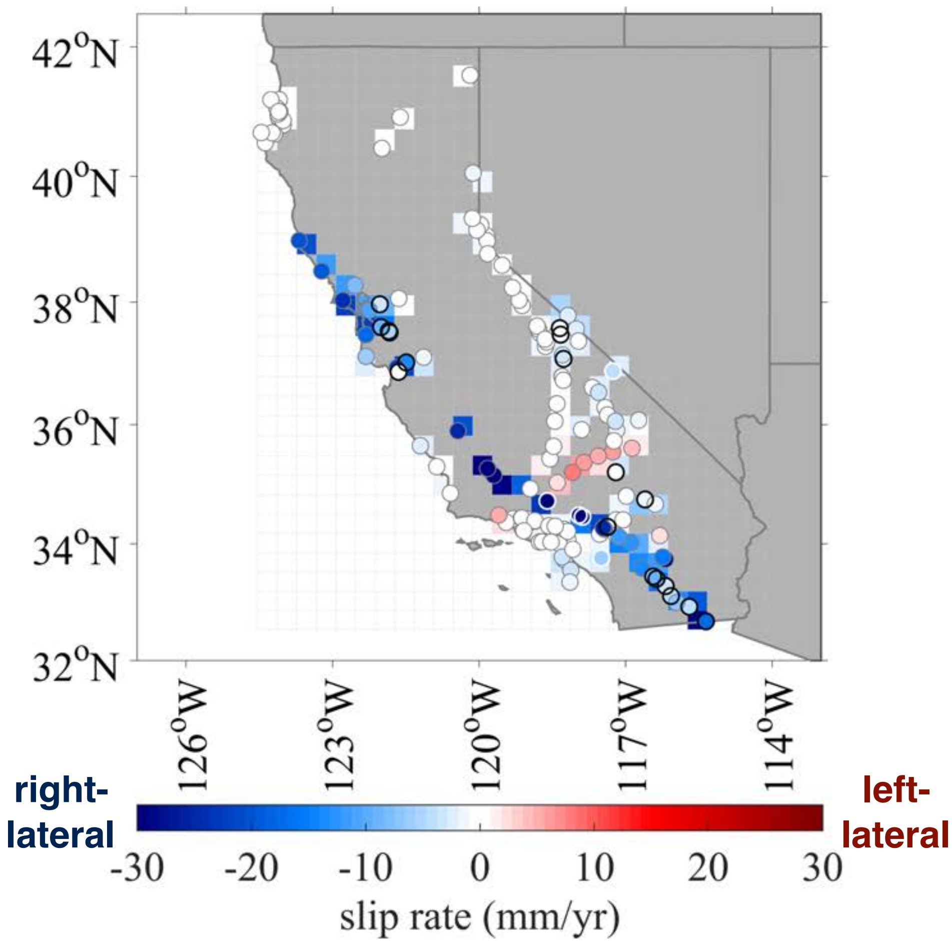


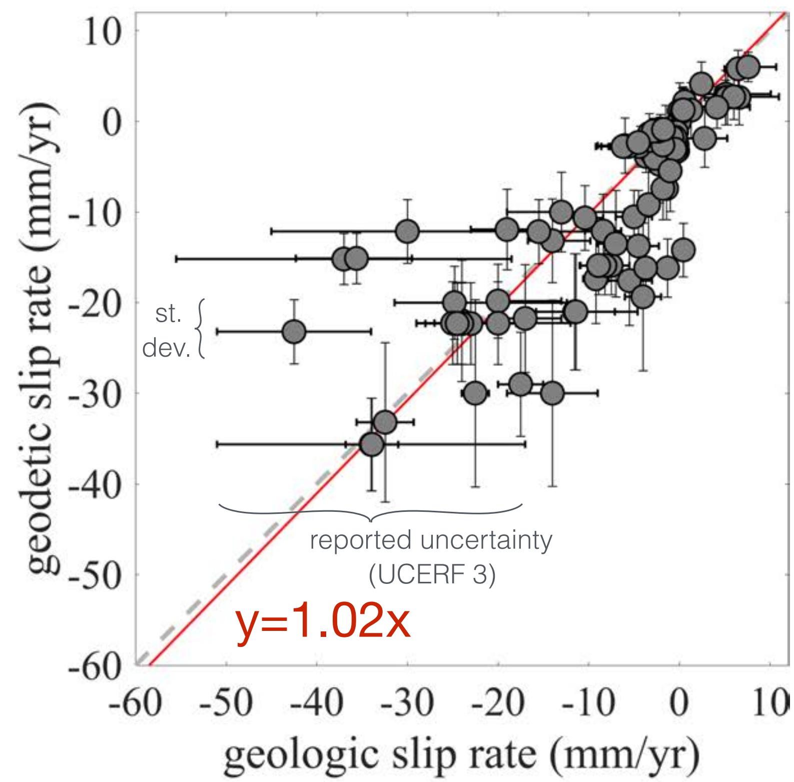
Geologic slip rates from UCERF 3 (Appendix B (*Dawson and Weldon*, 2013)

(*Evans*, submitted)

Compare models

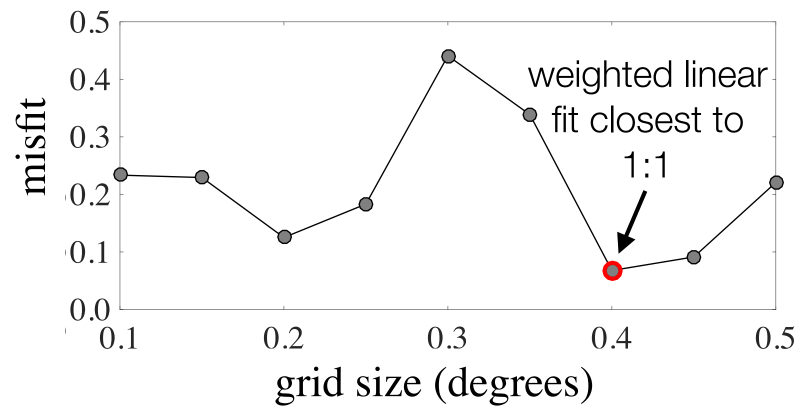
Geologic vs. geodetic





Geologic slip rates from UCERF 3 (Appendix B (*Dawson and Weldon*, 2013)

Grid size most consistent with geologic slip rates: ~35 km across



(*Evans*, submitted)

Compare models

Potency accumulation rate

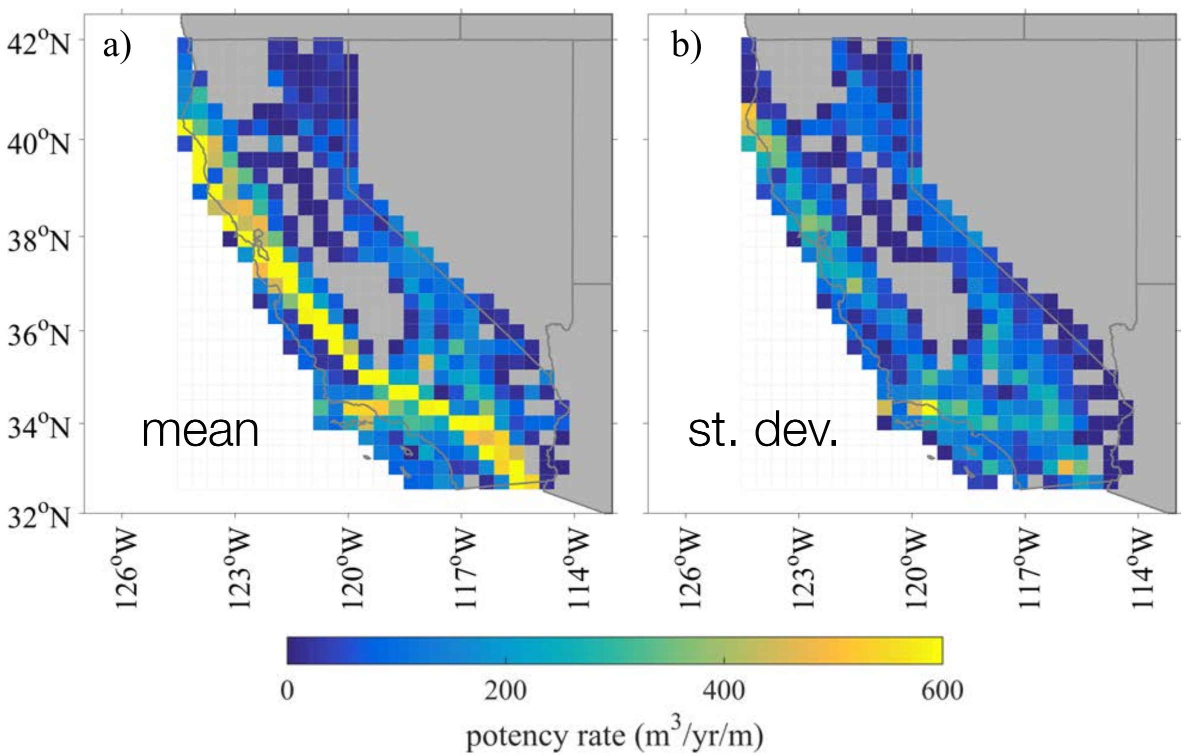
number of faults in this cell

slip rate magnitude on fault k

Potency rate per unit depth

$$\dot{\mathrm{P}}_0 = \sum_{k=1}^{N} \dot{\mathrm{s}}_k \mathrm{L}_k$$

length of fault k



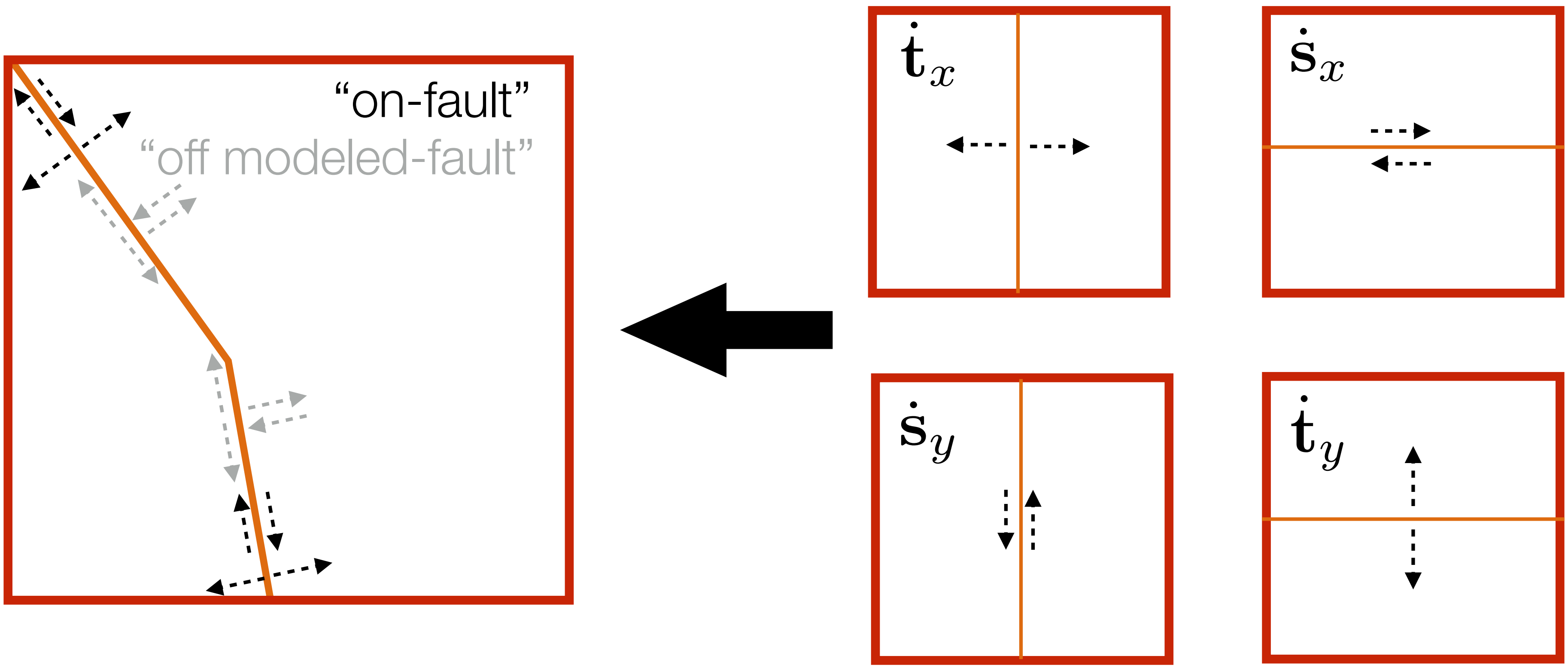
(*Evans*, submitted)

Total accumulation rate:

- **M** ≈ 8.1 earthquake every 100 years (10 km locking depth, 30 GPa shear modulus).
- **M** ≈ 8.0 released in the last 100 years (from ANSS catalog)
- 95% of potency accumulation rate occurs in 52% of the active area (most slip occurs on the fastest faults)

Summary model

Project onto UCERF faults



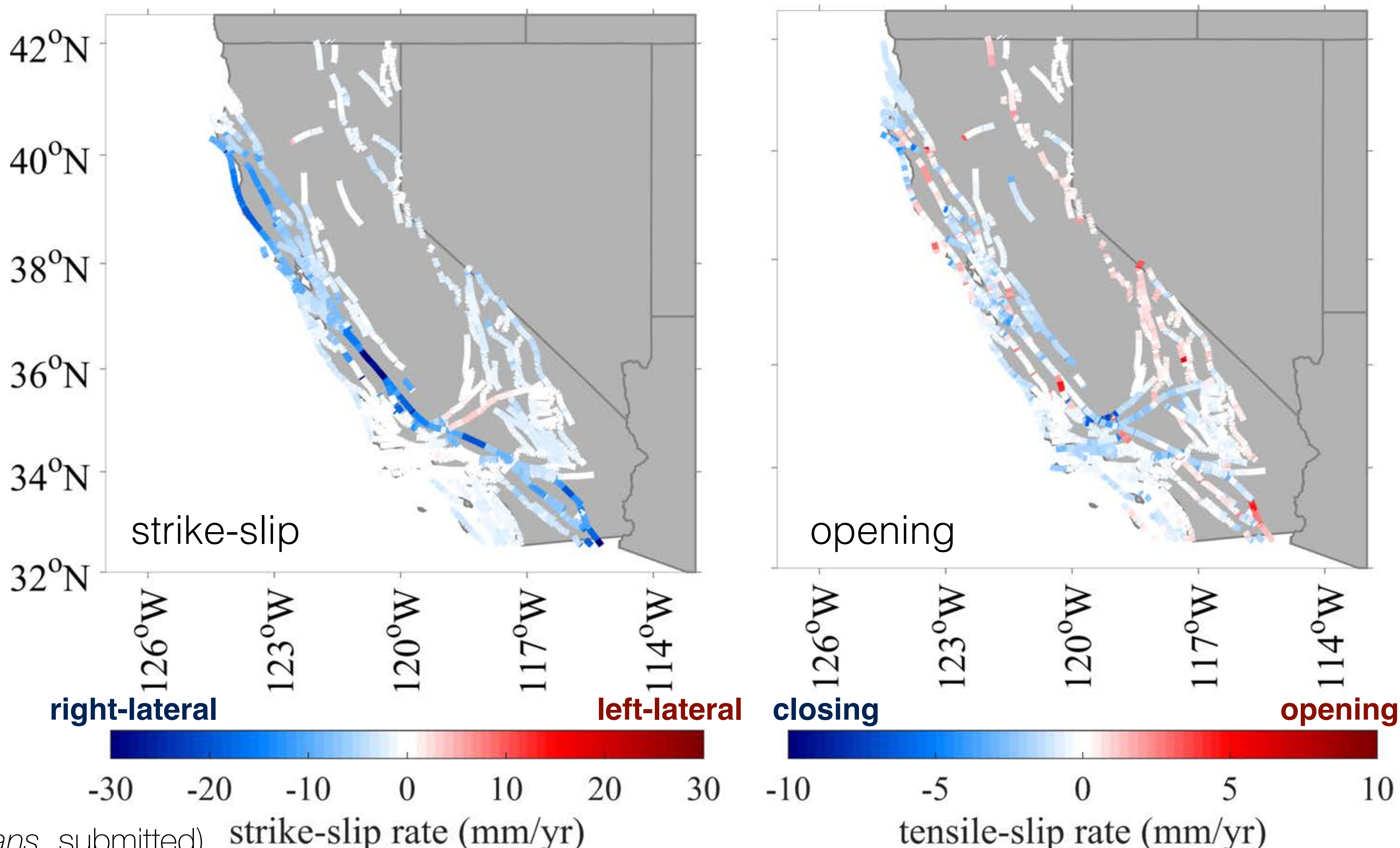
Project average slip rates back onto UCERF faults to produce a community average fault model, with model uncertainties

2 slip components produce an estimate of "off modeled-fault" deformation

Summary model

Project onto UCERF faults

Community average geodetic slip rates projected onto UCERF faults:

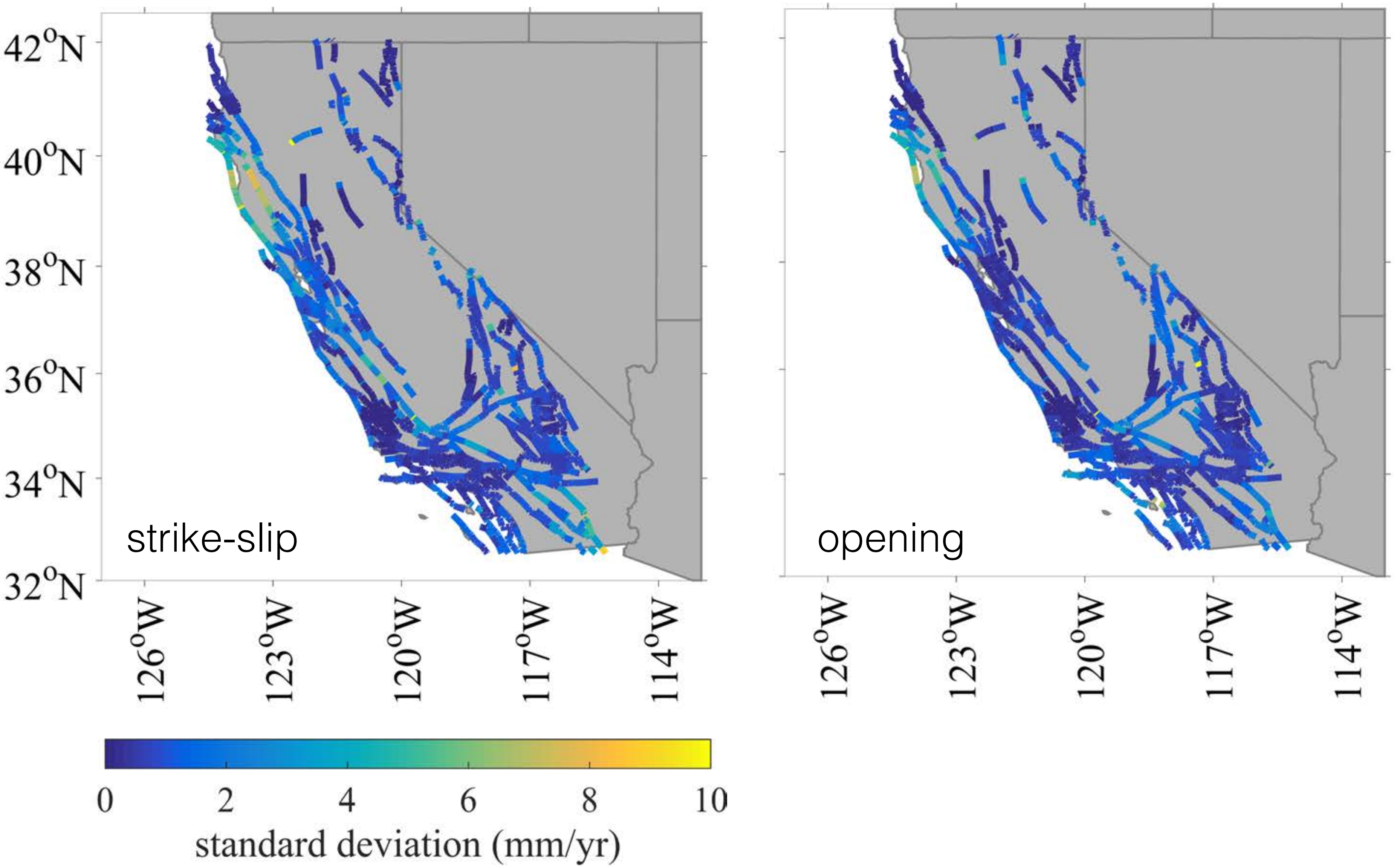


(*Evans*, submitted)

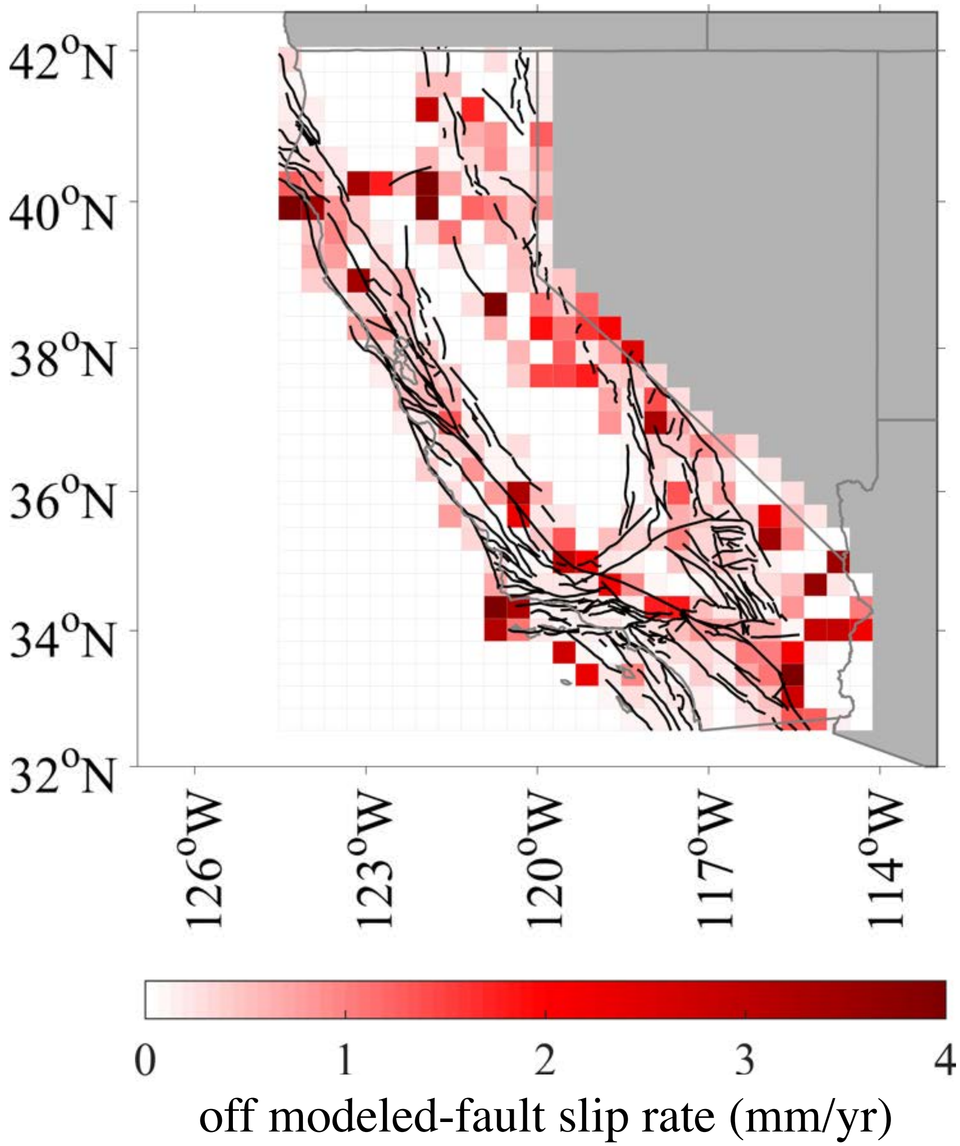
Summary model

Project onto UCERF faults

And model uncertainties:



Off modeled-fault deformation



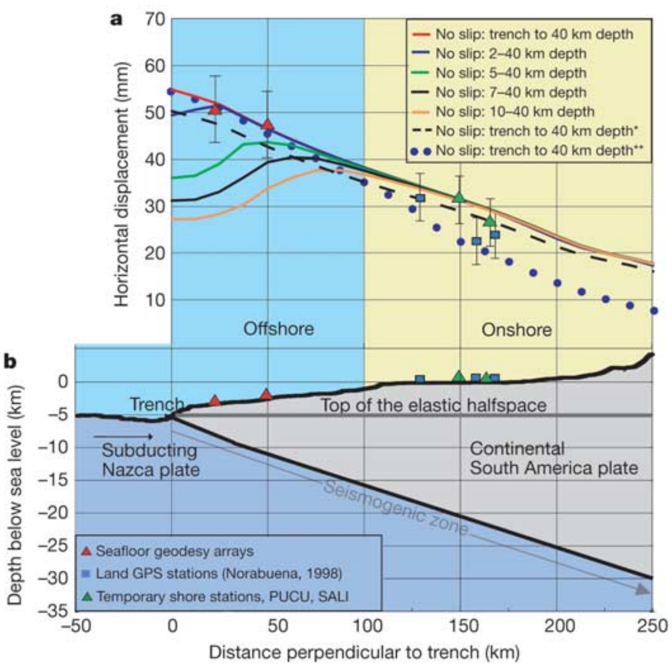
Off modeled-fault (OMF) deformation

- **28%** total summary deformation does not project onto UCERF faults
- **Most** (**75%**) OMF deformation occurs adjacent to major faults
- OMF deformation may often be a consequence of epistemic uncertainty in geodetic slip rate models

Seafloor geodesy

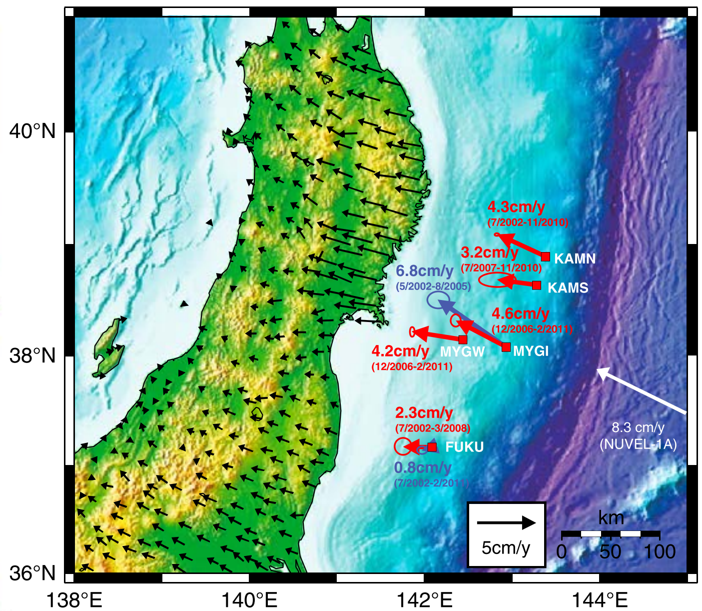
Is Cascadia locked at the trench?

Central Peru:
Yes, within ≤ 2 km



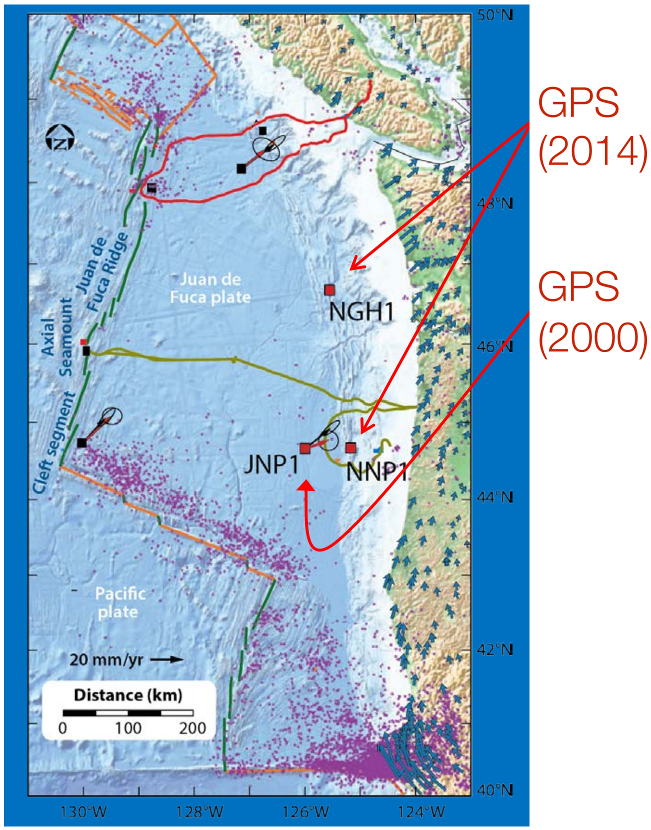
Gagnon et al., 2005

Northern Honshu:
temporally variable



Sato et al., 2013

Cascadia:
???



Dave Chadwell (chadwell@ucsd.edu)

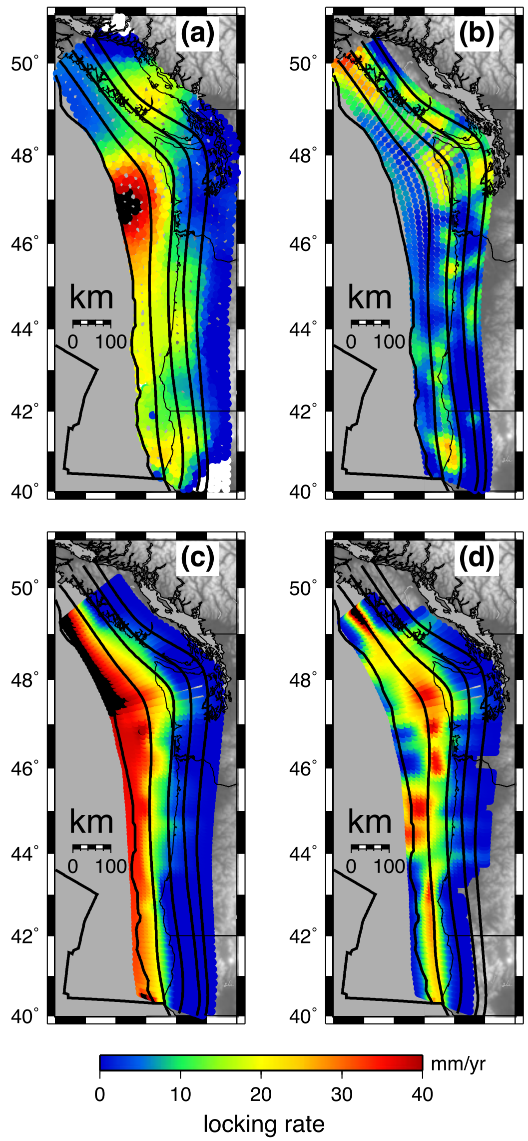
Seafloor geodesy

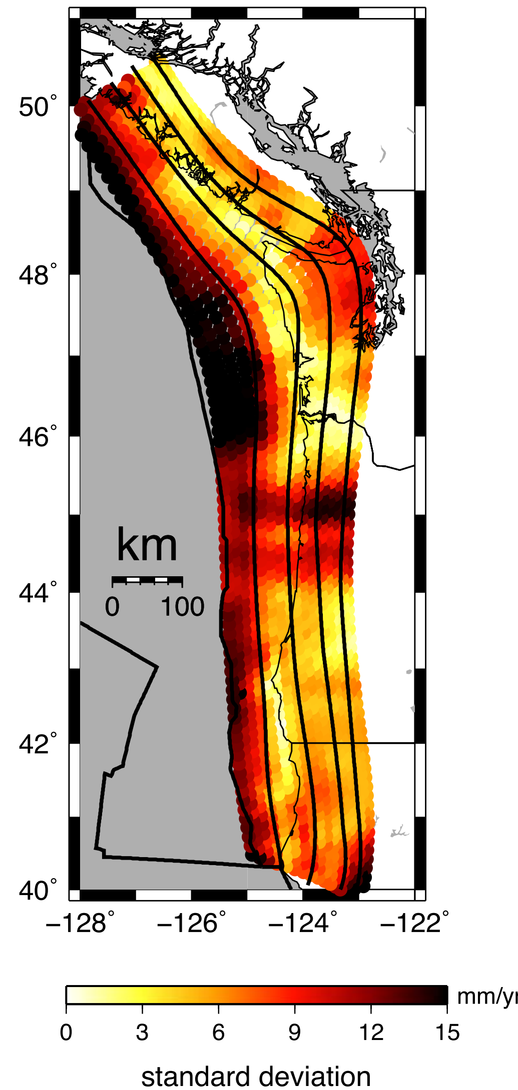
Is Cascadia locked at the trench?

$$\dot{s}_{\text{locked}} = \dot{s}_{\text{tectonic}} - \dot{s}_{\text{slow/creep}}$$

Locking rates from *Pollitz and Evans, 2017*

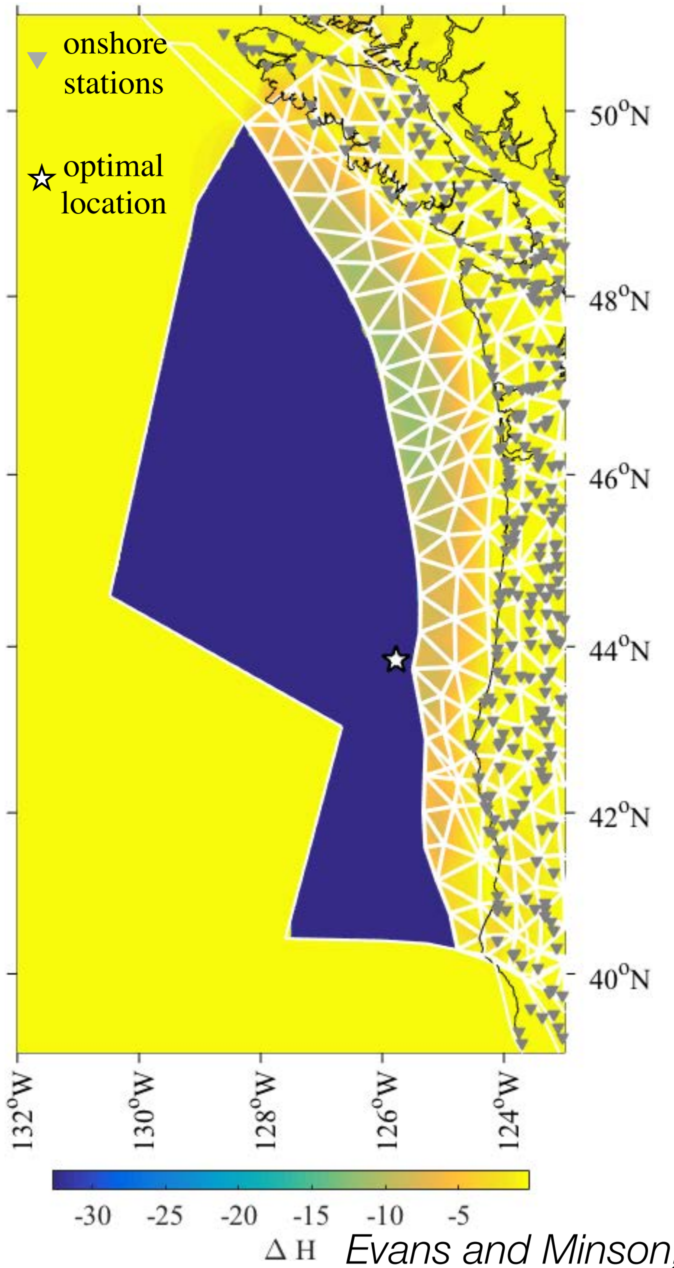
Locking rates from *McCaffrey et al., 2013*





Seafloor geodesy

Preliminary offshore analysis

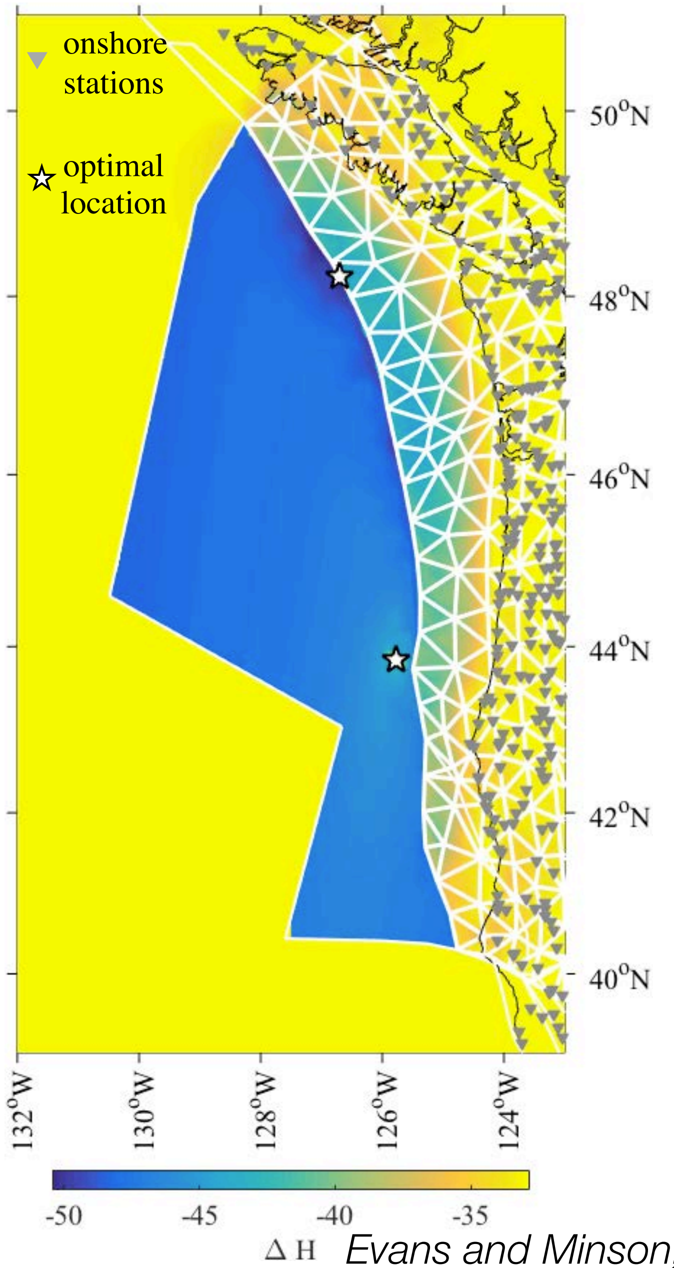


Evans and Minson, in prep

- To resolve locking: consider block model with embedded Cascadia subduction zone
- H is information entropy (*Shannon*, 1948), a measure of unpredictability, or average information content
- $\Delta\mathrm{H} = \mathrm{H}_{\mathrm{onshore}} - \mathrm{H}_{\mathrm{new\ station}}$
- First minimum $\Delta\mathrm{H}$ (most new information) on Juan de Fuca plate
- Subsequent stations along trench
- First onshore location after 23 offshore

Seafloor geodesy

Preliminary offshore analysis



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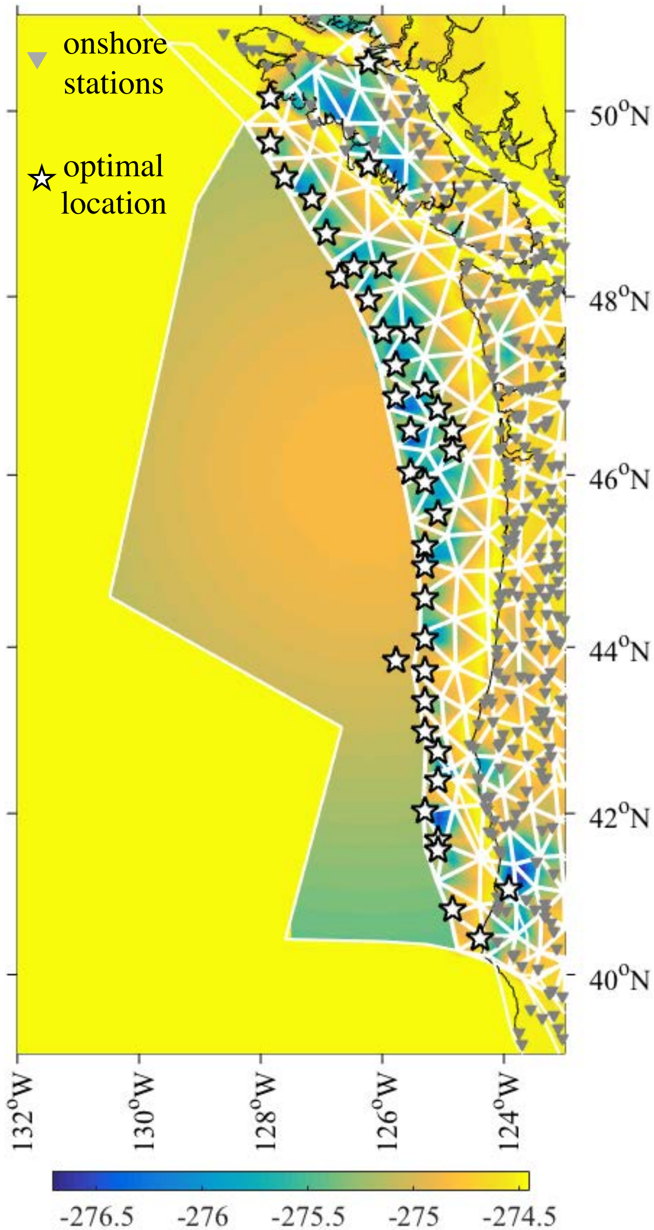
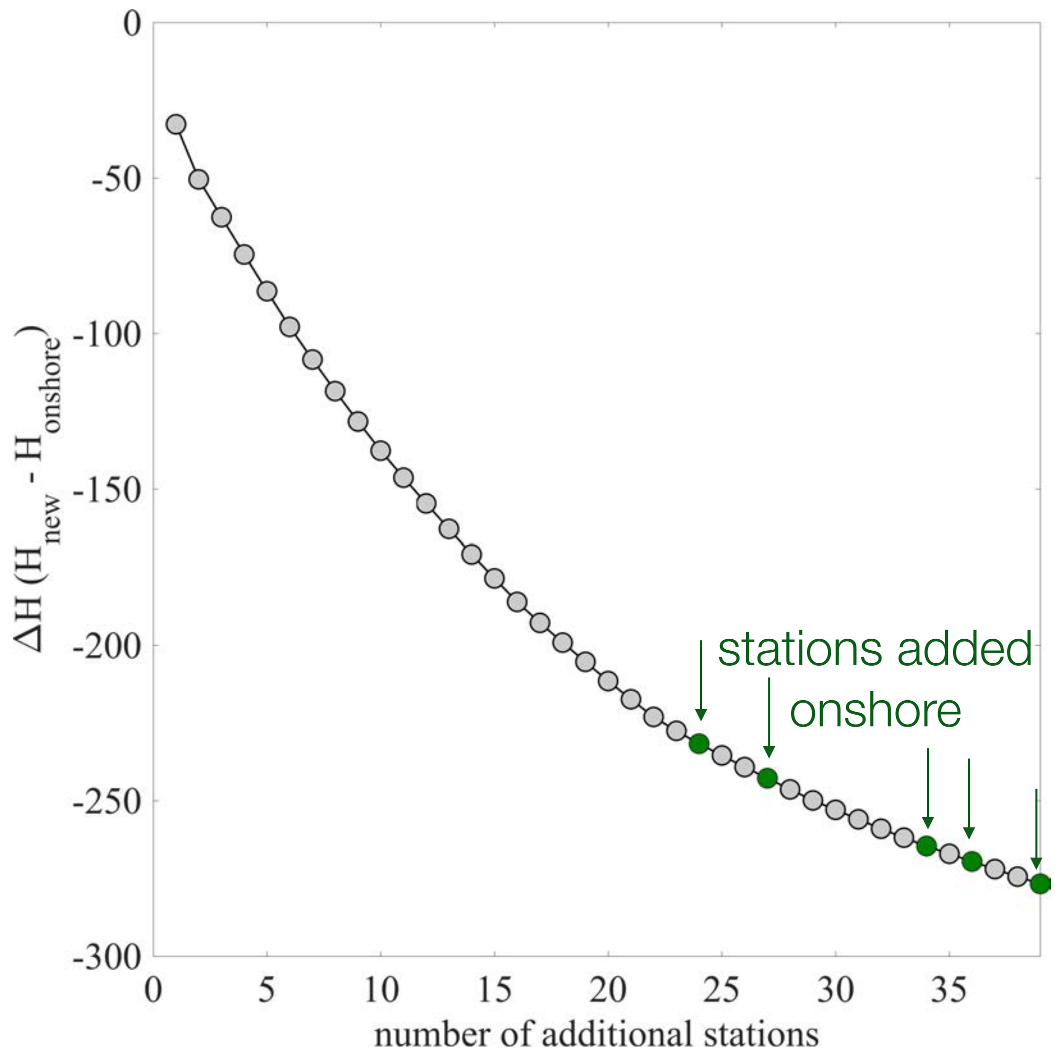
Seafloor geodesy

Preliminary offshore analysis

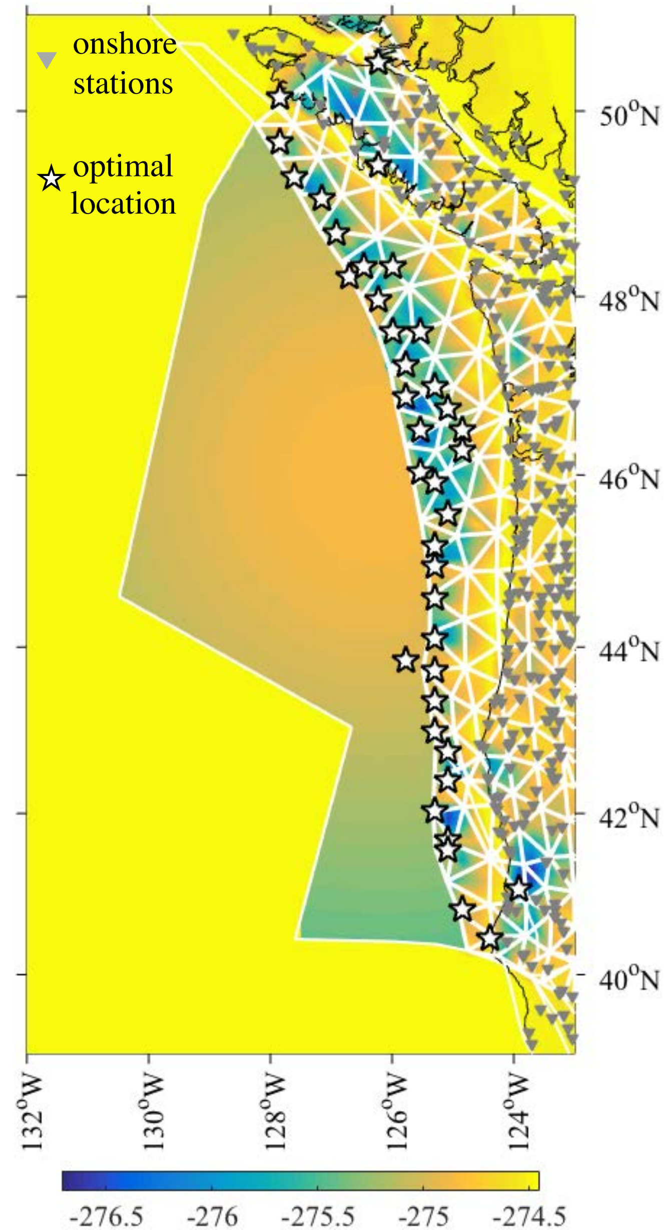


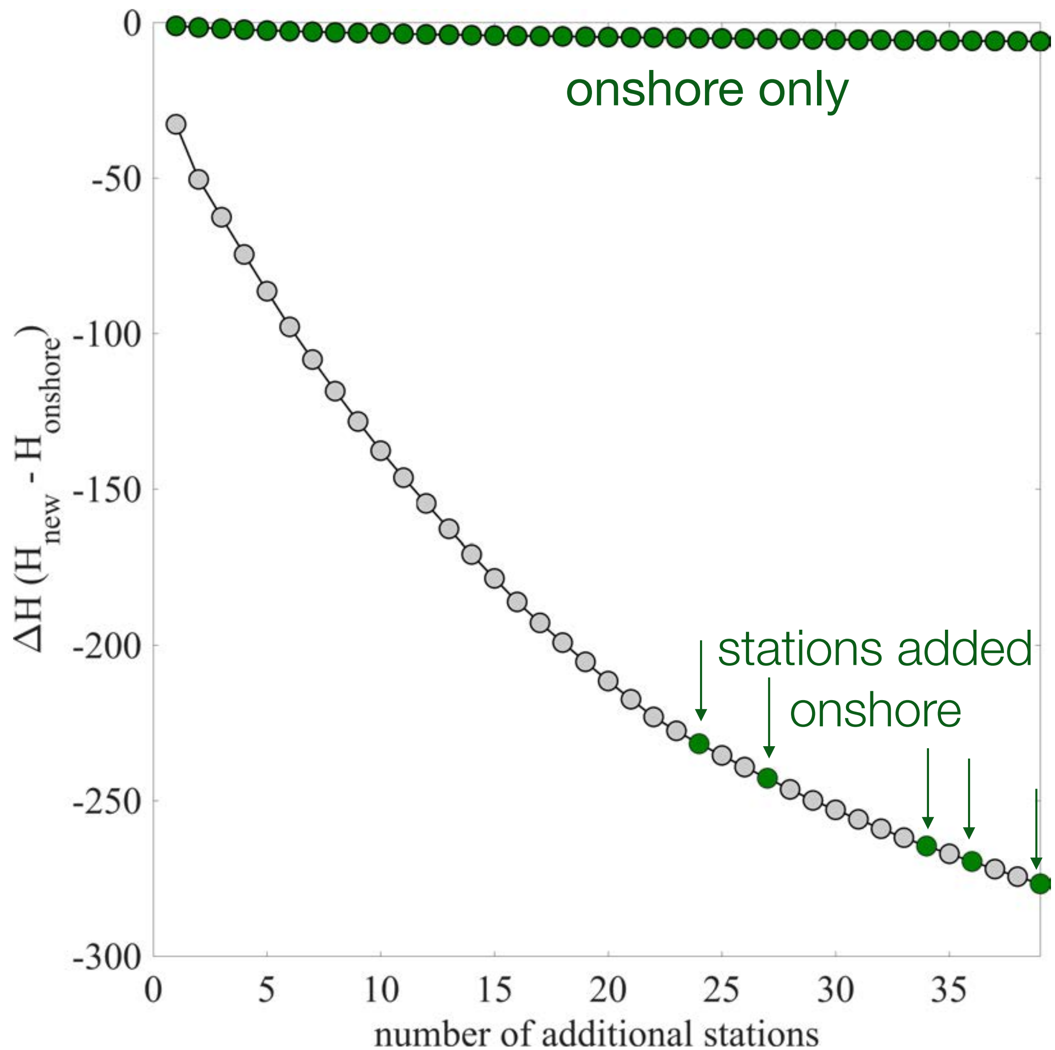


Evans and Minson, in prep

Seafloor geodesy

Preliminary offshore analysis





Evans and Minson, in prep

Conclusions

- Geodesy uniquely capable of observing strain accumulation rates and anticipating earthquake hazards
- Eastern California shear zone
  - Block model containing **7 ECSZ blocks** fits GPS velocities with MRV = 1.5 mm/yr, and is most consistent with geologic slip rates
  - Persistent slip rate discrepancies remain on the **Calico** and **Garlock** faults
- California slip rate summary
  - Leverage existing research for seismic hazard models
  - Generate a summary model of geodetic slip rates: ~**1.5 mm/yr** model uncertainty
  - **"off-fault" deformation may often be a product of epistemic uncertainty**
- Seafloor geodesy
  - No quantity of onshore observations can provide the information gain of a single offshore observation