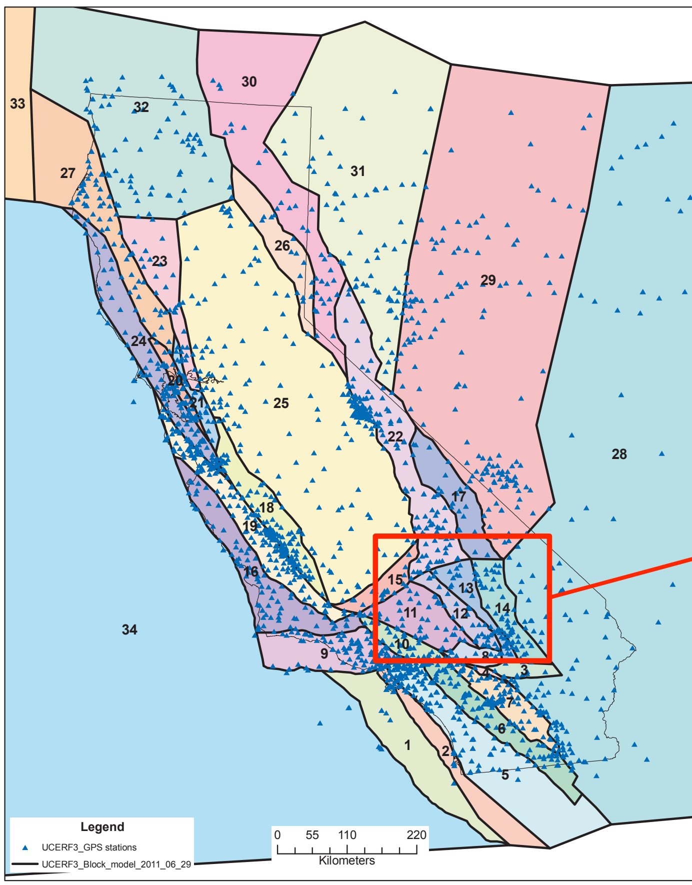
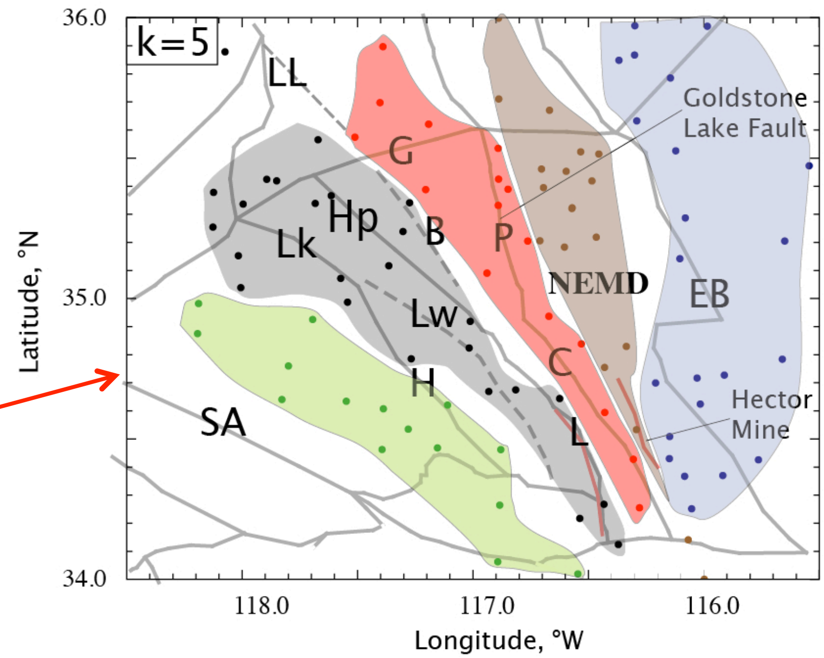
Scientific issues raised by using GPS data to estimate fault slip rates

Kaj Johnson & UCERF3/GPS Group, Bob Simpson, Jim Savage, and Wayne Thatcher

Assumed UCERF3 GPS Block Geometry
(Kaj Johnson et al, 2012)



Block Geometry Derived from Mojave GPS Cluster Analysis
(Savage & Simpson, 2012, in prep)



Major Issues in Modeling GPS Data to Understand Active Continental Tectonics & Estimate Fault Slip Rates

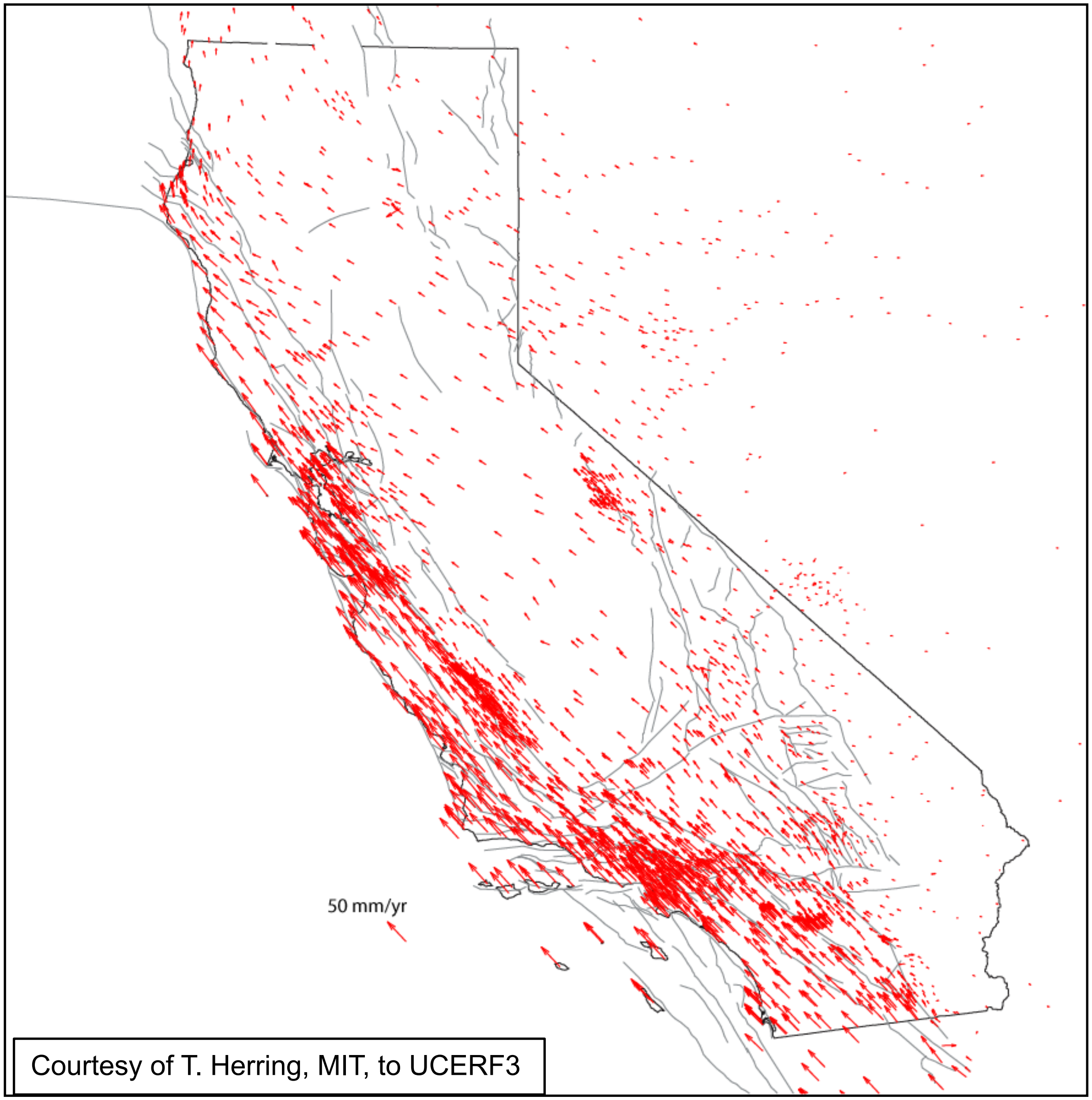
- Are block models the best way to analyze GPS data?
- If so, how many blocks are needed to summarize GPS Data?
- Early models used few blocks, current models have many
- Hard to fit current, more accurate data within uncertainties
- Choice of block geometry is subjective and affects results

New Application of Cluster Analysis May Help Remove Subjectivity
(Discussed Later in Presentation)

UNIFORM CALIFORNIA EARTHQUAKE RUPTURE FORCAST (Version 3)
UCERF3

APPLICATION OF GPS DATA to DEFORMATION MODELS

GPS Velocity Field Used in UCERF3



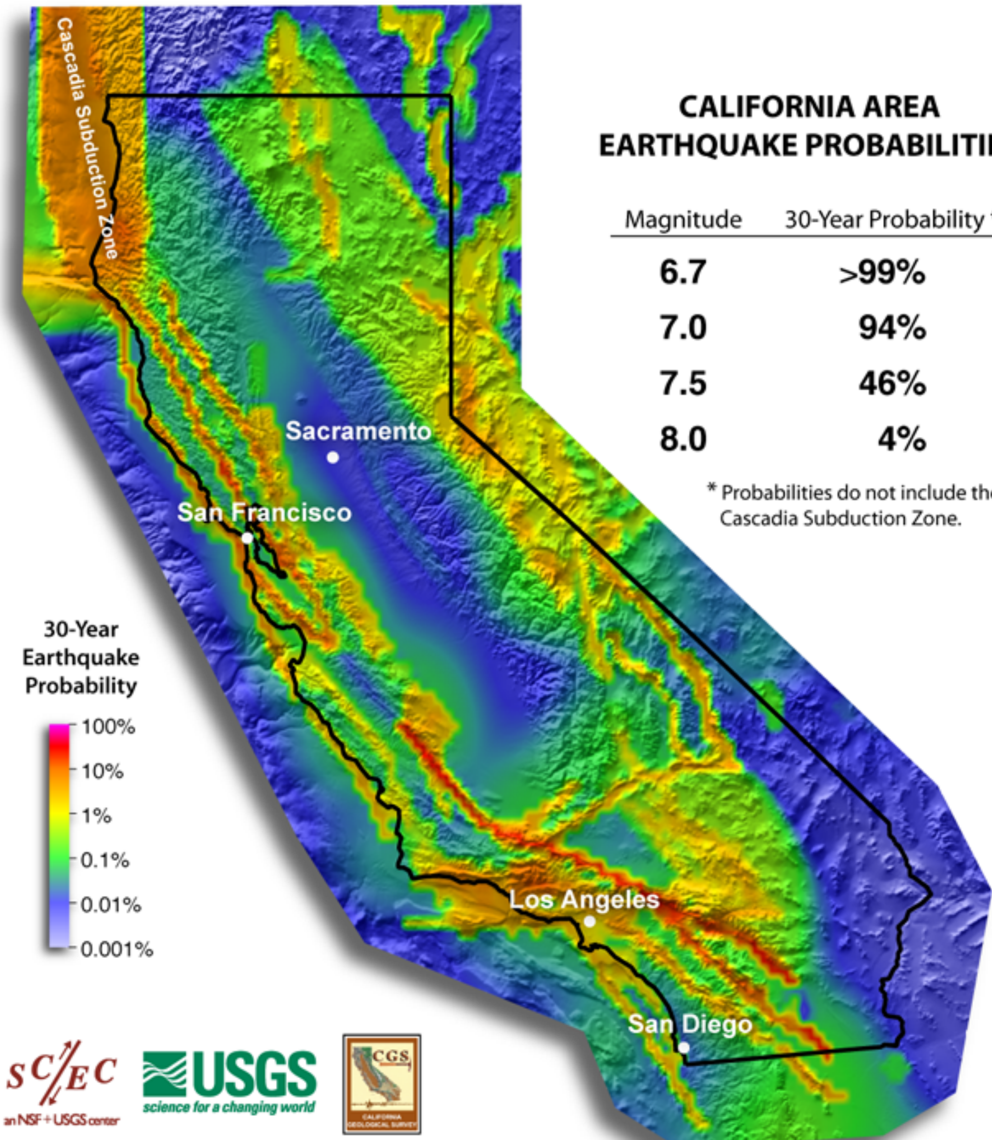
Courtesy of T. Herring, MIT, to UCERF3

Why Do We Want to Know Slip Rates?

Uniform California Earthquake Rupture Forecast, version 2 (UCERF2)

Working Group on California Earthquake Probabilities, 2009

UCERF3 due July 1, 2012



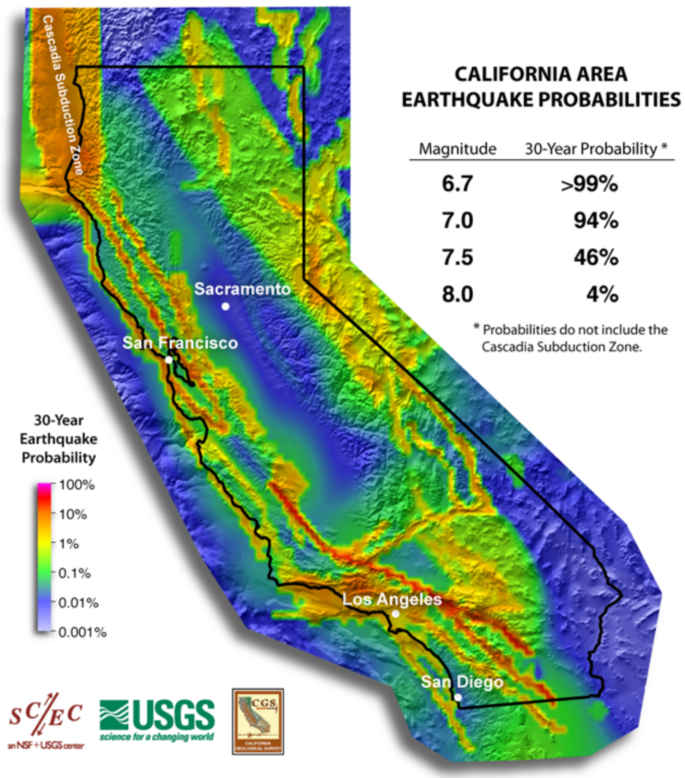
CALIFORNIA AREA EARTHQUAKE PROBABILITIES

Magnitude	30-Year Probability *
6.7	>99%
7.0	94%
7.5	46%
8.0	4%

* Probabilities do not include the Cascadia Subduction Zone.

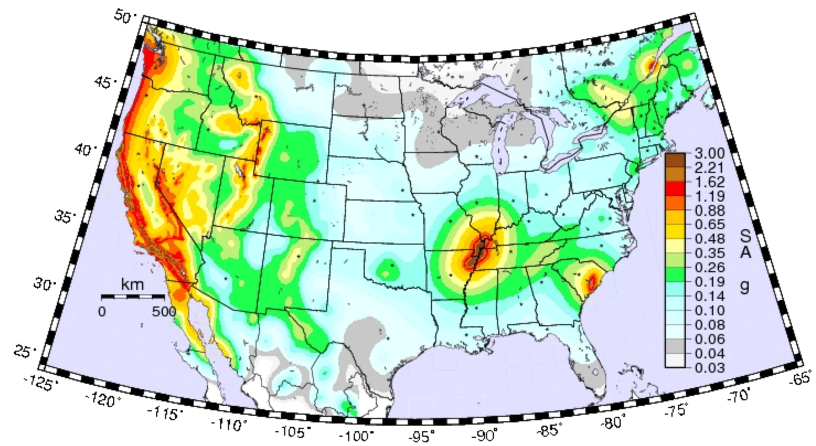
Why Do We Want to Know Slip Rates?

UCERF3 Report Due July 2012



USGS National Seismic Hazard Maps

New Version Due in 2014



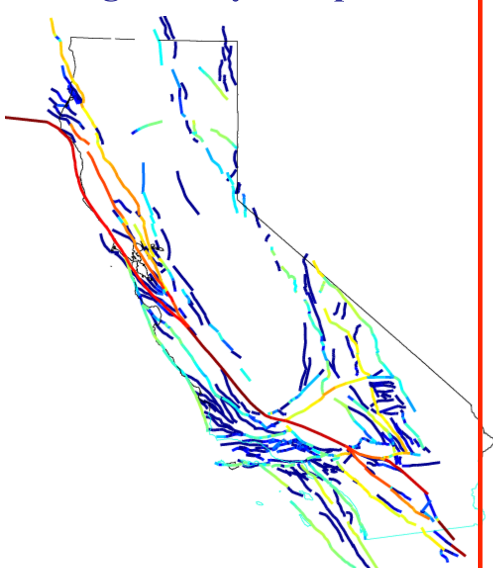
CEA CALIFORNIA EARTHQUAKE AUTHORITY

UCERF 3

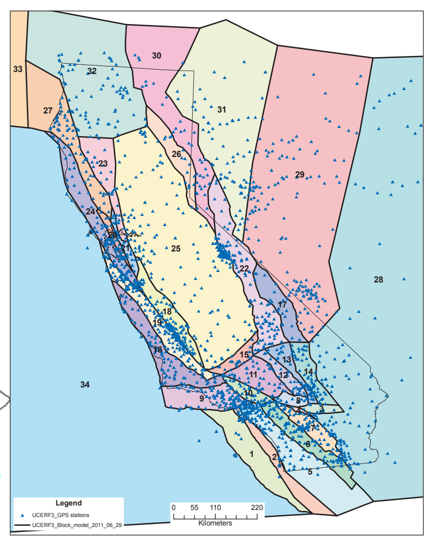
The Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3)

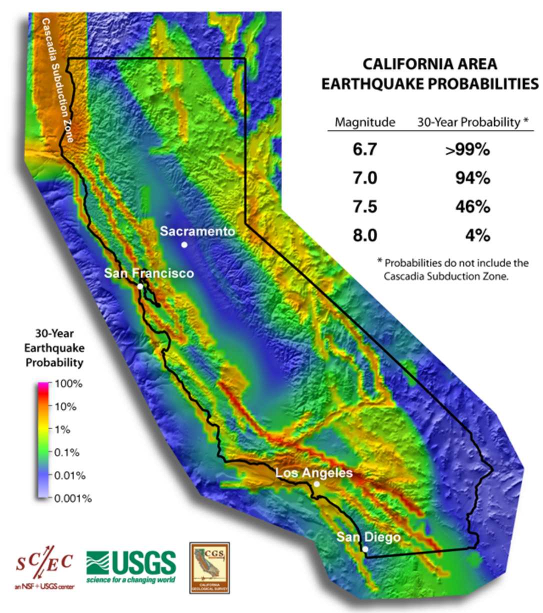
Fault Models	Deformation Models	Earthquake-Rate Models	Probability Models
Specifies the spatial geometry of larger, more active faults.	Provides fault slip rates used to calculate seismic moment release.	Gives the long-term rate of all possible damaging earthquakes throughout a region.	Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.
Active Fault Geology Data	Block Models Fit to GPS	(e.g. G-R, Characteristic Eq)	

Fault geometry & slip rates



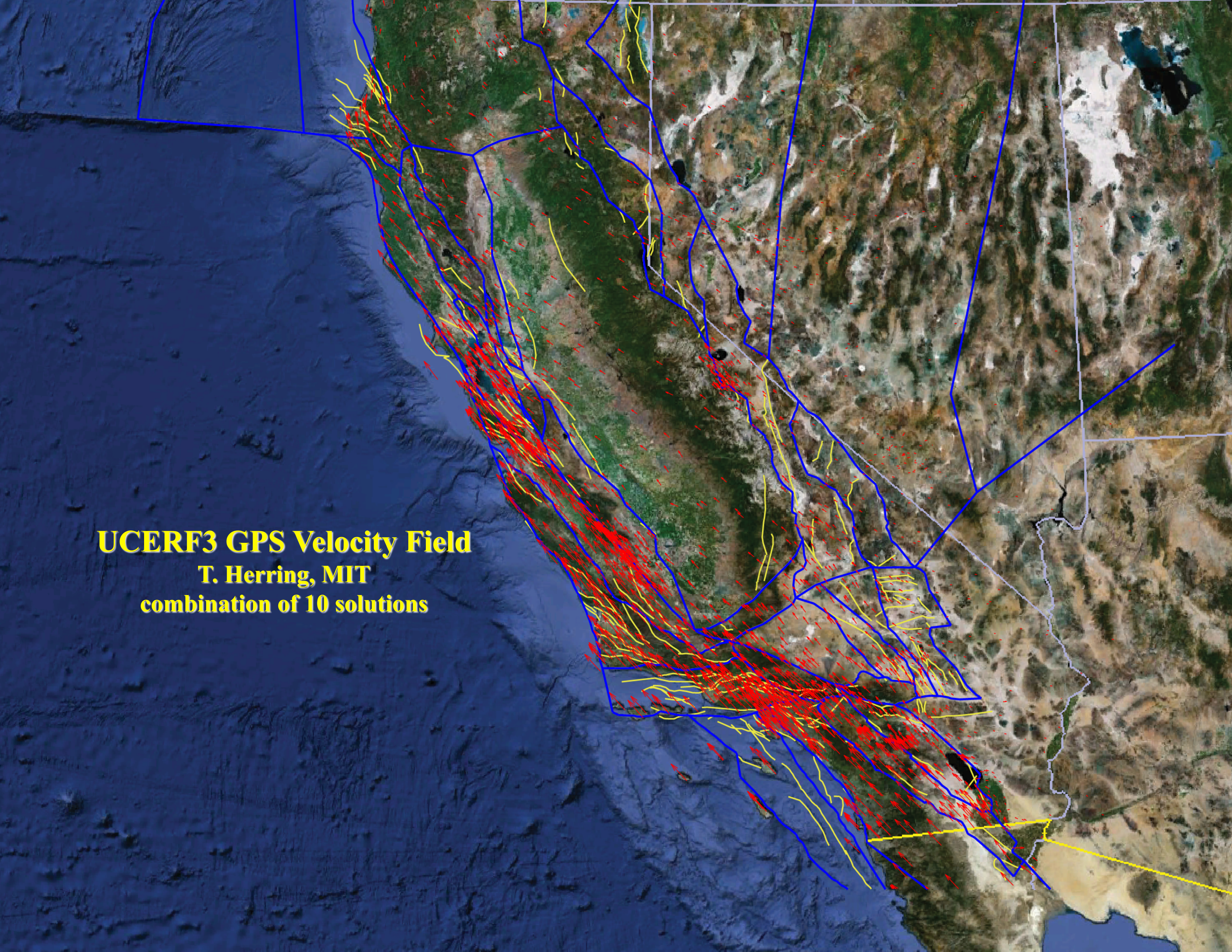
Geodetic fault slip rates
Estimated from block models

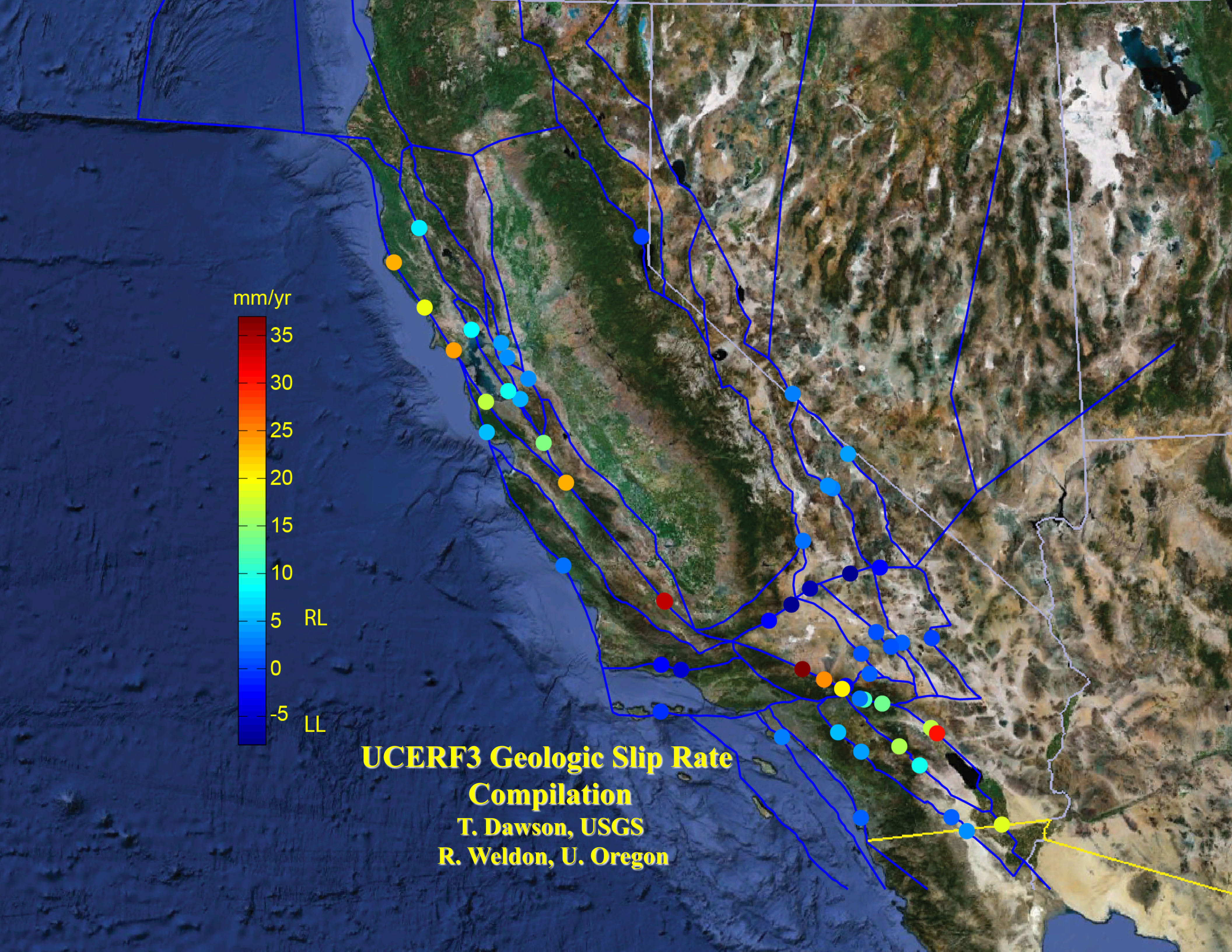





UCERF3 Faults

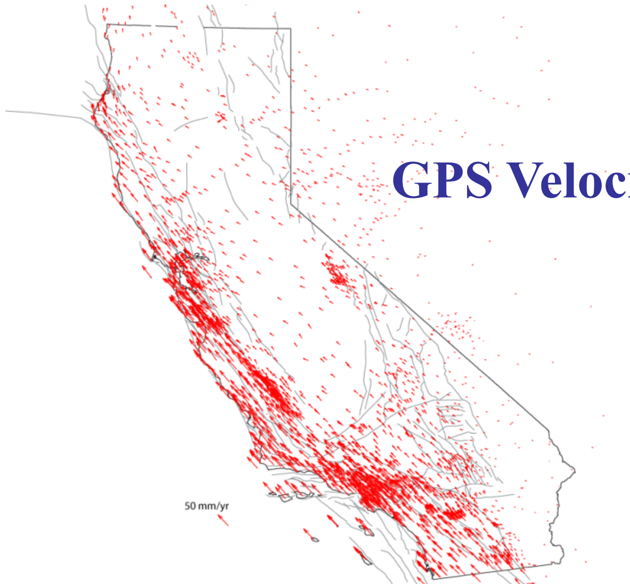

UCERF3 Block Geometry


UCERF3 GPS Velocity Field
T. Herring, MIT
combination of 10 solutions

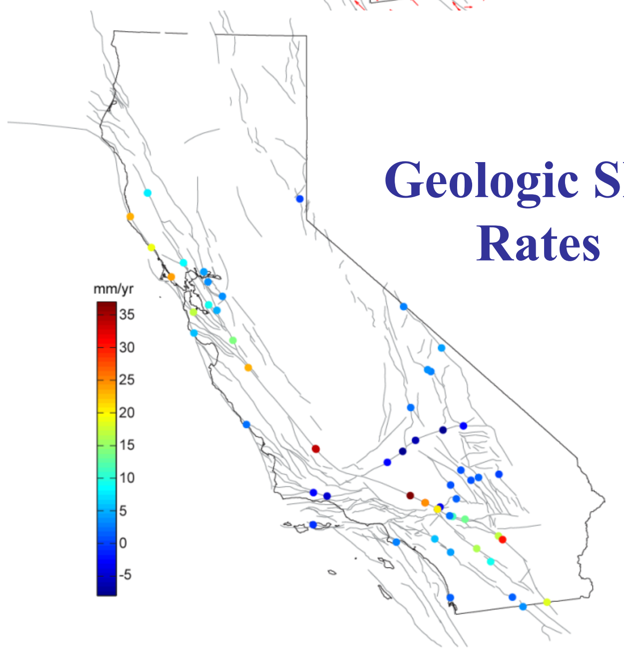

mm/yr
35
30
25
20
15
10
5
RL
0
-5
LL
UCERF3 Geologic Slip Rate
Compilation
T. Dawson, USGS
R. Weldon, U. Oregon

UCERF 3 Modeling Objectives

GPS Velocities

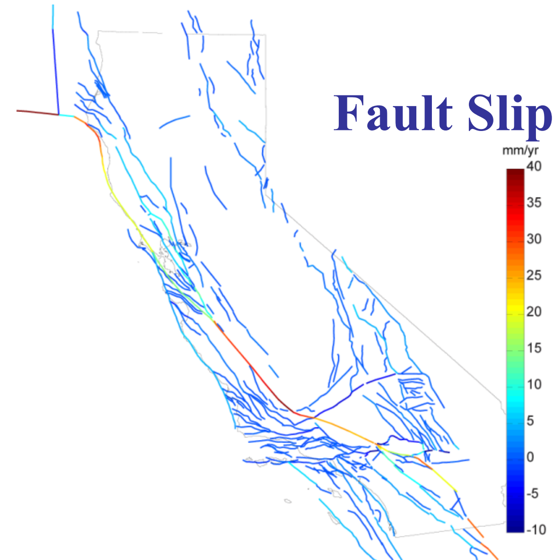


Geologic Slip Rates

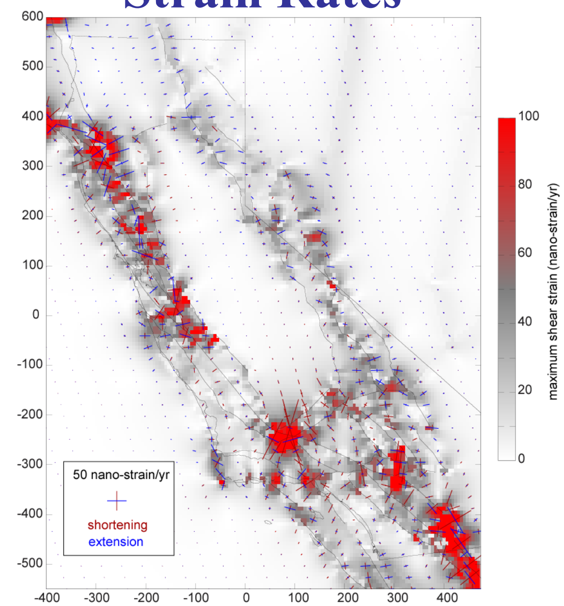


models

Fault Slip Rates



Strain Rates

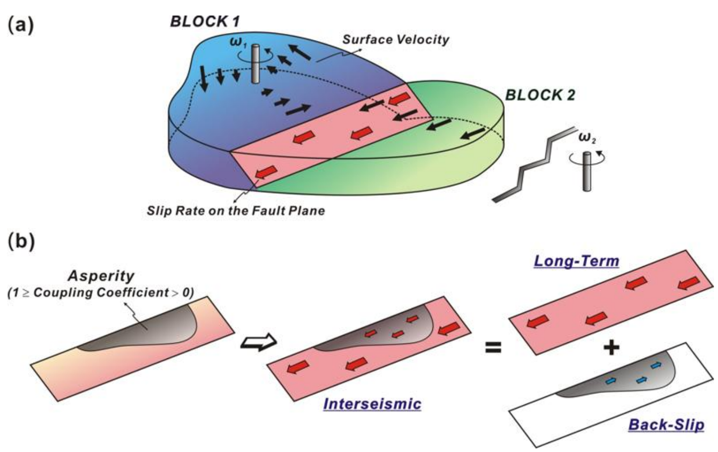


8 UCERF3 Kinematic Models

Block models

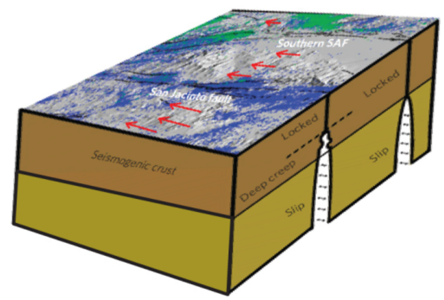
- Rob McCaffrey
- Bill Hammond
- Kaj Johnson

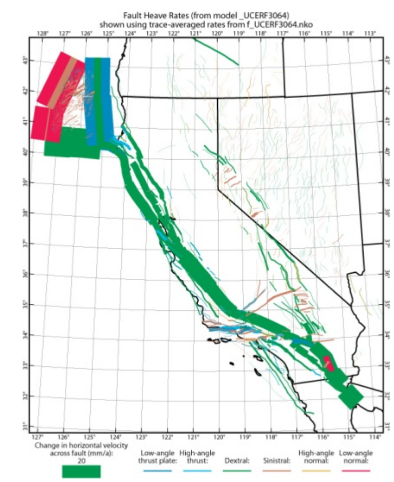
- Peter Bird
- Yuehua Zeng



Non-block models

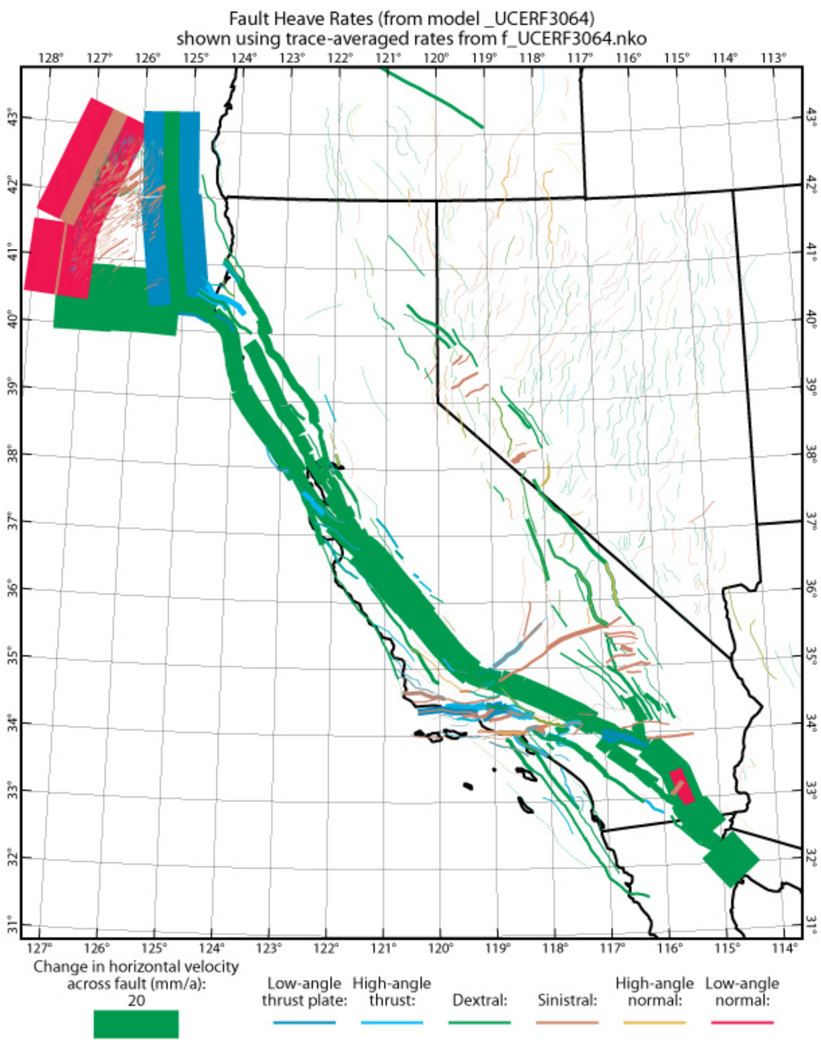
- Peter Bird
- Yuehua Zeng

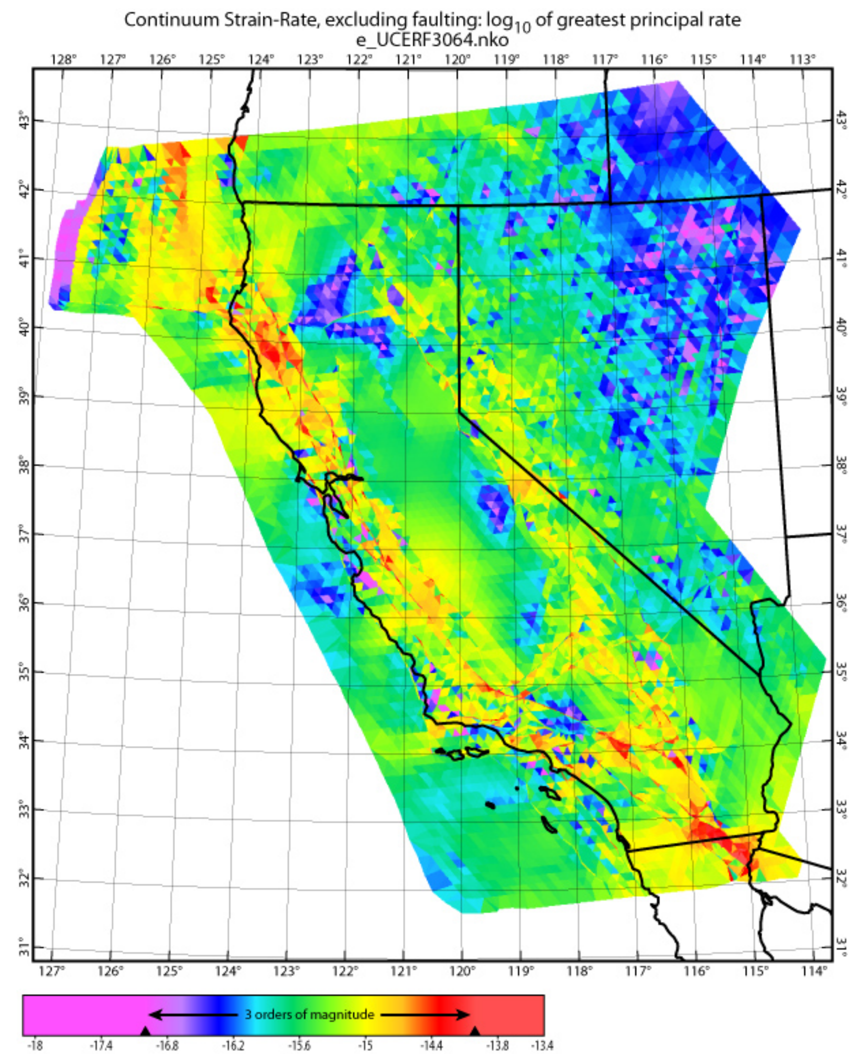




Non-Block (fault-based) Models

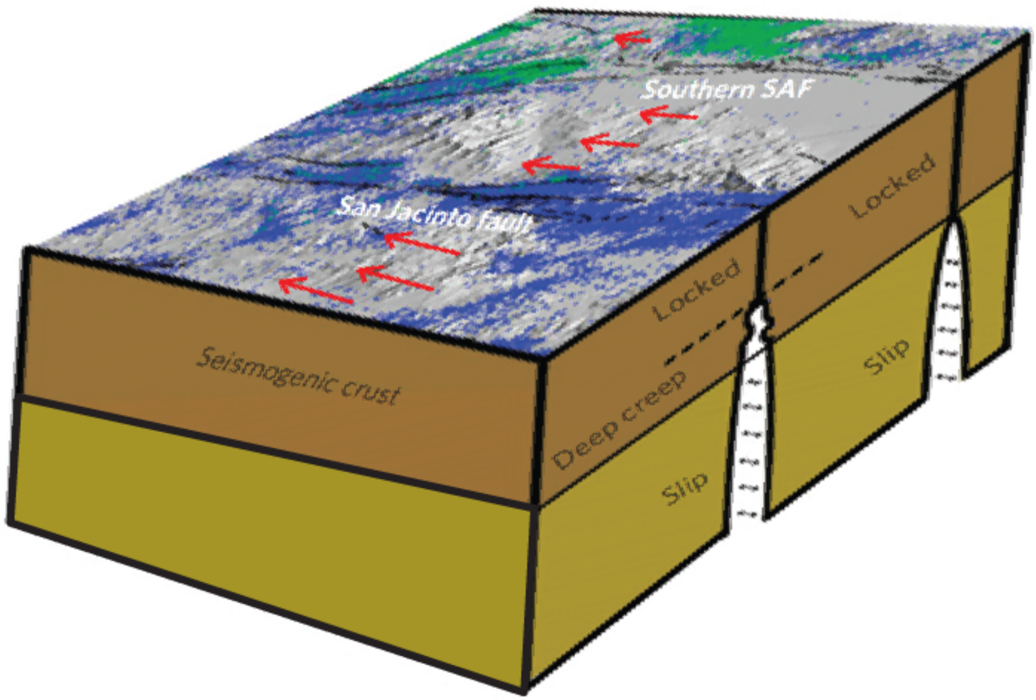
Neokinema (Peter Bird, UCLA)
FE mesh – fit smoothed velocity field



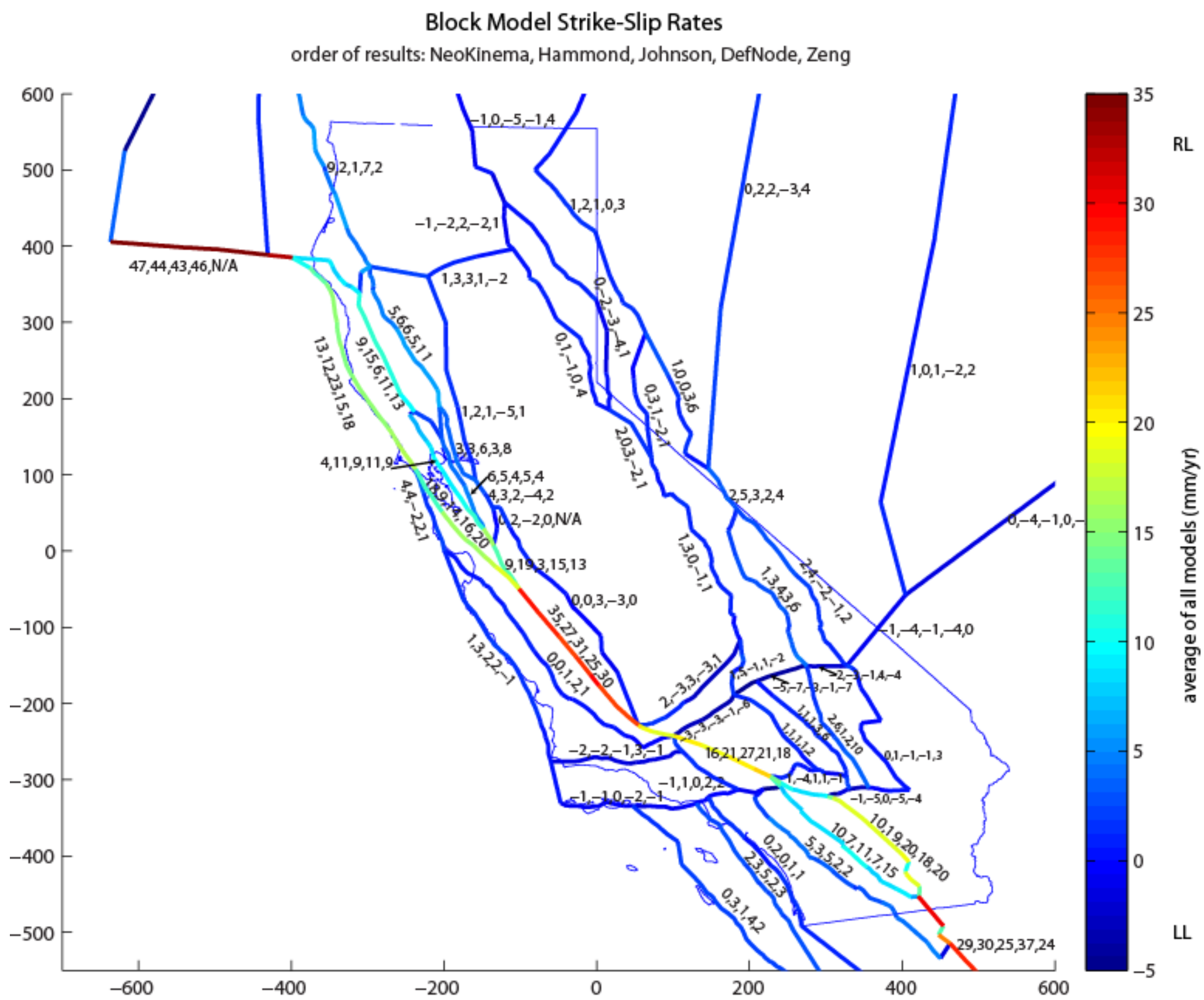


Non-Block (fault-based) Models

Yuehua Zeng, USGS
buried elastic dislocations

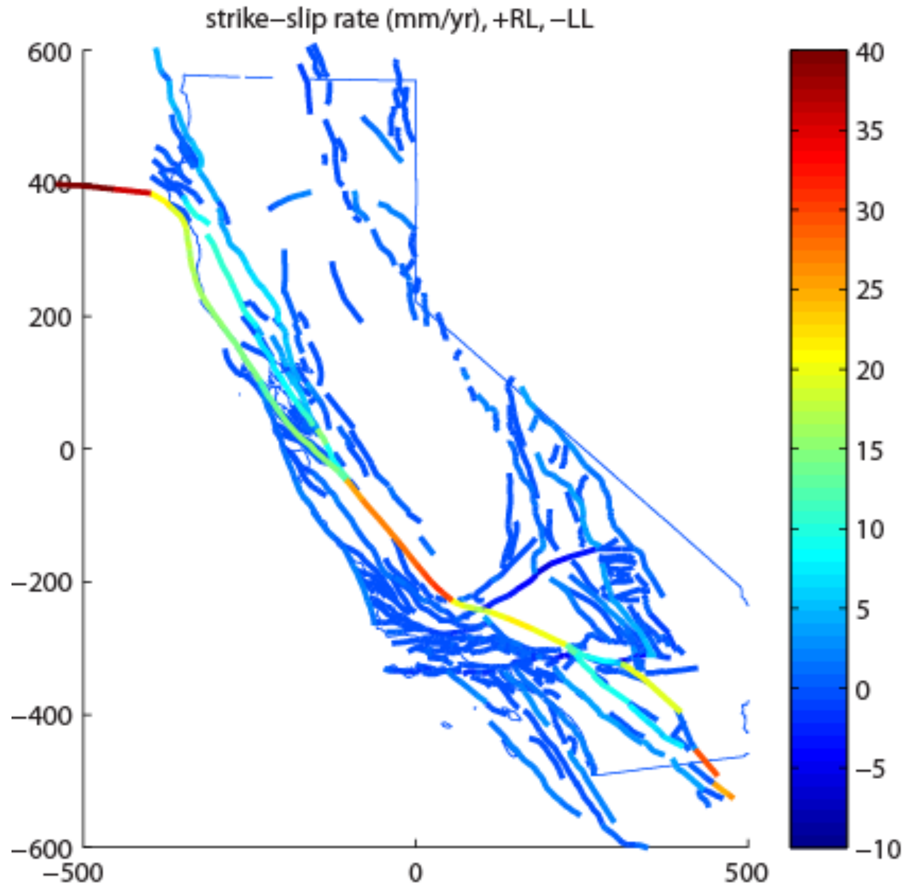


Strike-Slip Rates (in mm/yr) for All 5 Block Models

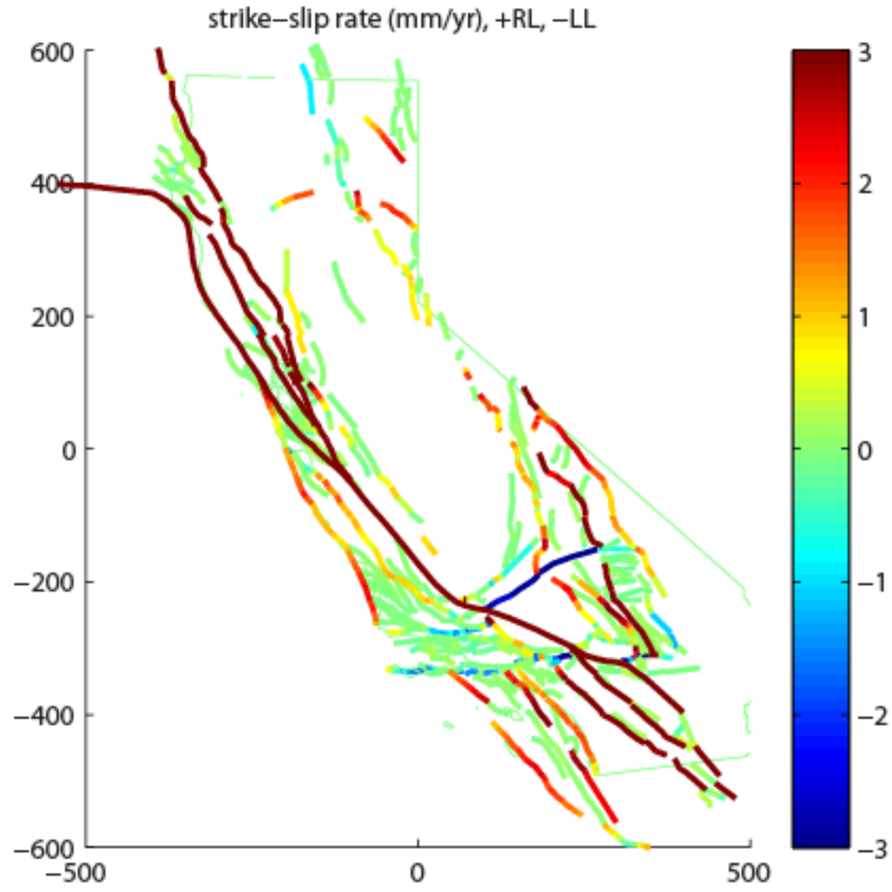


Average Block Model: Strike Slip Rates

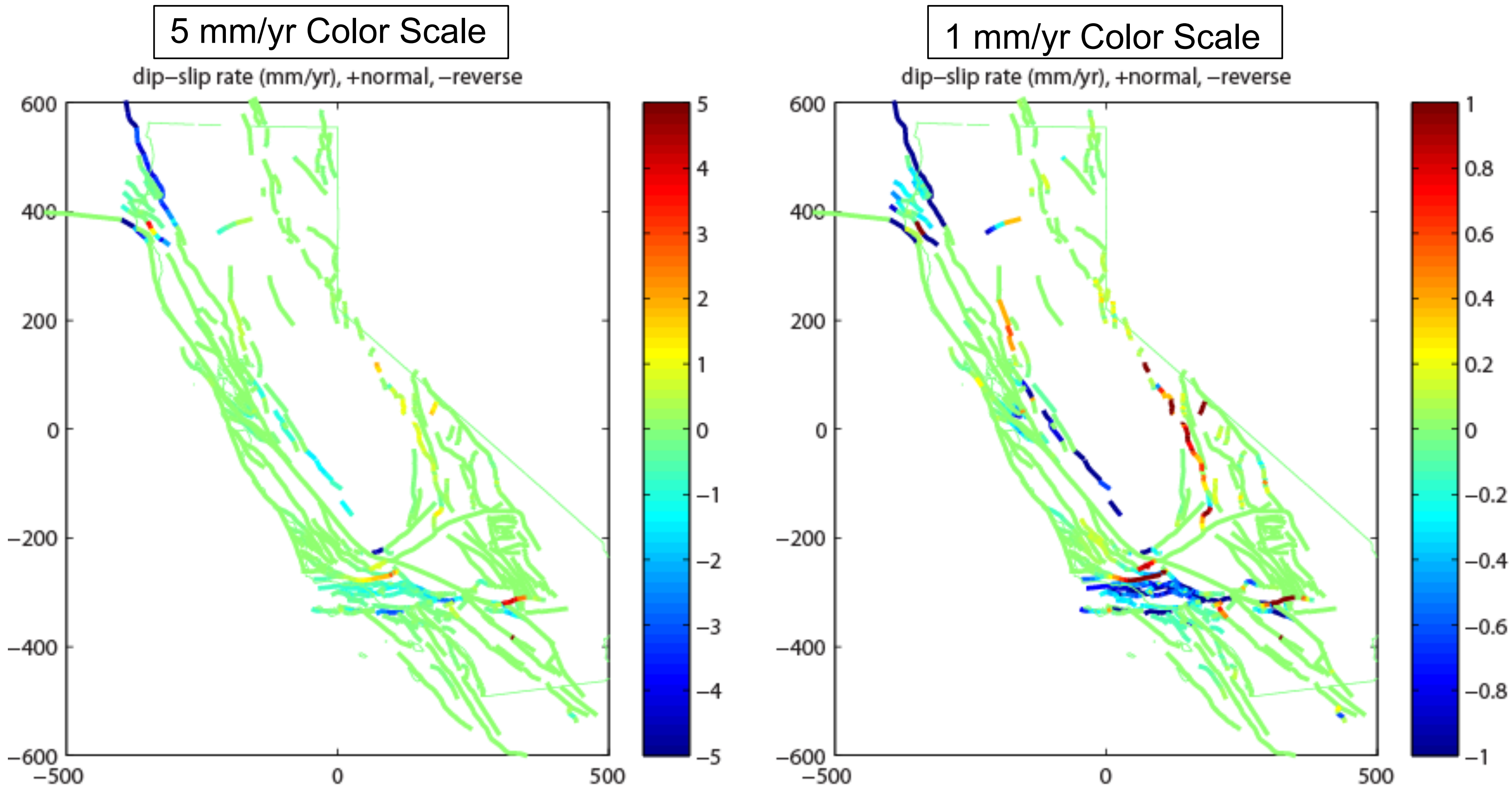
40 mm/yr Color Scale



3 mm/yr Color Scale

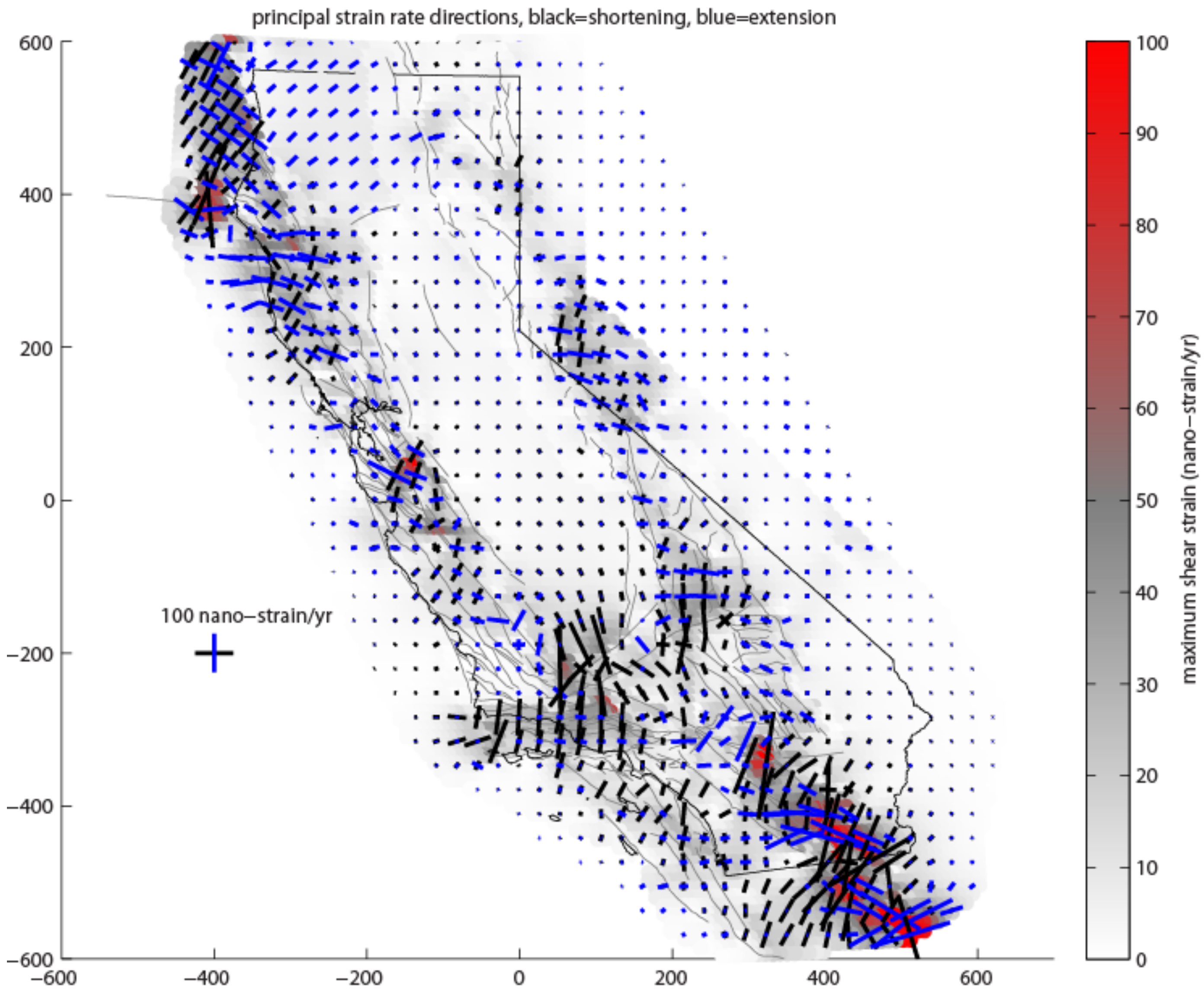


Average Block Model: Dip Slip Rates



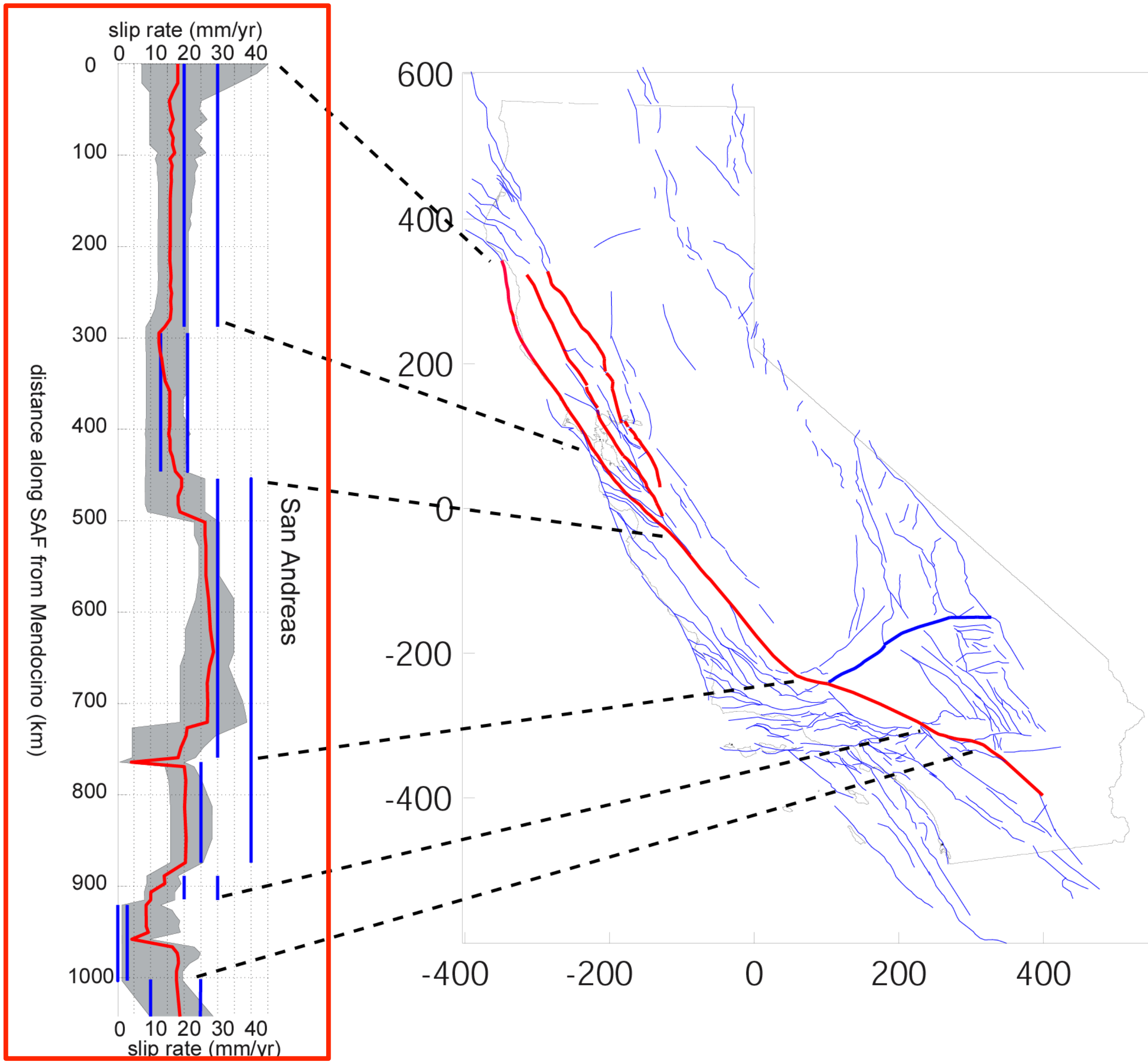
Average Block Model: Principal Strain Rates

GPS Model Strain Rates Within Blocks are Surprisingly High



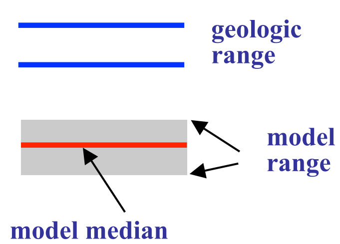
Average Model Slip Rates: San Andreas

GPS Model Slip Rates Tend to Underestimate SAF Geologic Slip Rates



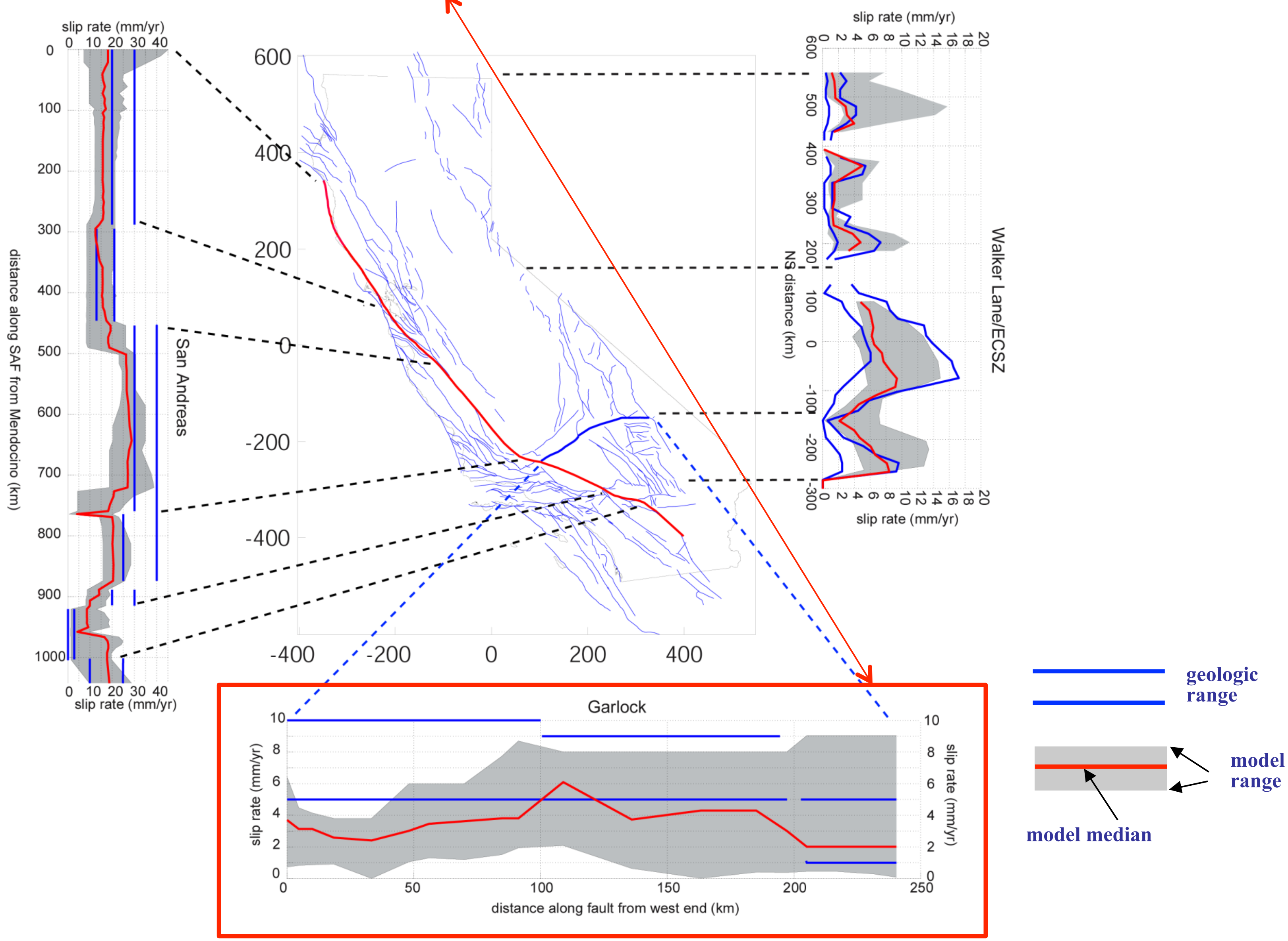
UCERF 3 compilation of 8 block models:

Kaj Johnson
Rob McCaffrey, RPI
Bill Hammond, U. Nevada
Peter Bird, UCLA
Yuehua Zeng, USGS



Average Model Slip Rates: San Andreas, Garlock, ECSZ

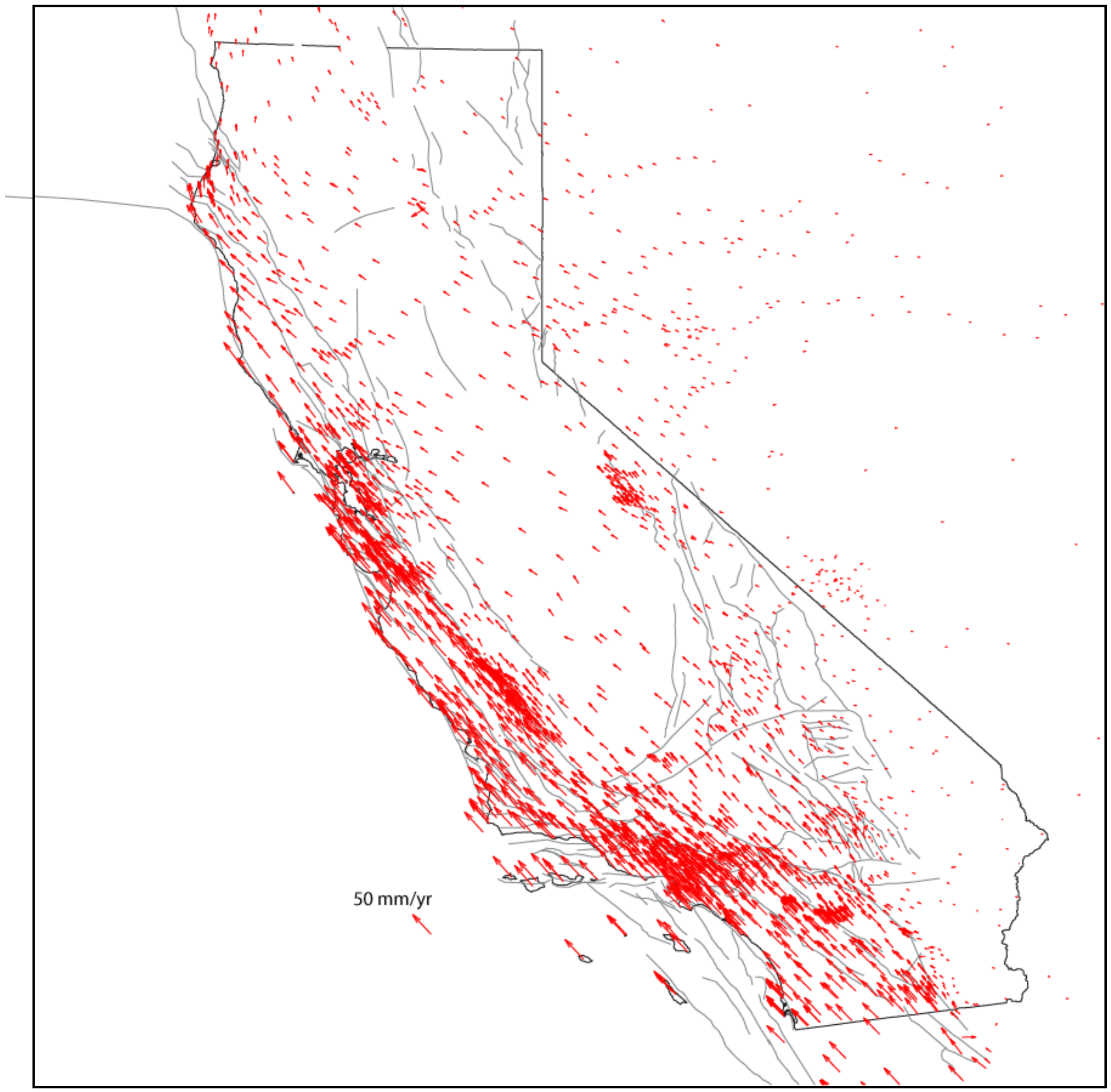
GPS Model Slip Rates for Garlock Underestimate Geologic Slip Rates



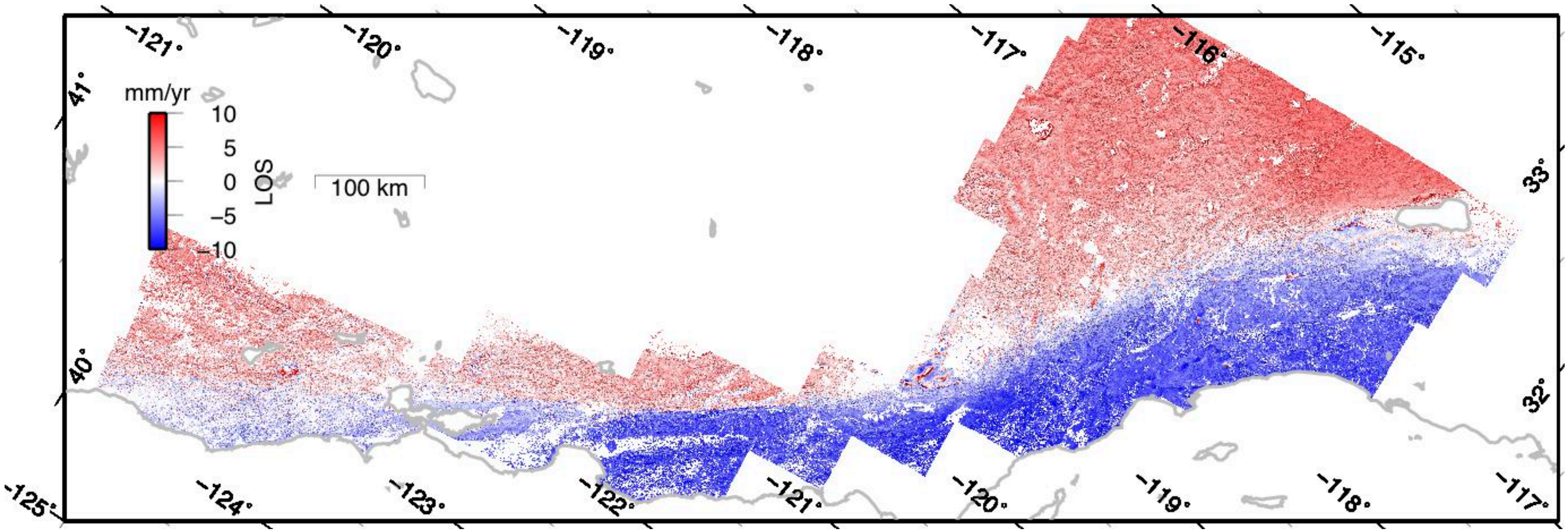
BETTER GPS & INSAR DATA NEEDED

GPS Velocity Field is Incomplete & Spatially Aliased

Strain Rates Derived from Current GPS Data are Very Non-Unique!



InSAR Offers Promise of Better Spatial Resolution (ALOS Image of Entire SAF)



Tong & Sandwell, submitted 2012

Future Research Directions/Issues Beyond UCERF3

- Why are SAF slip rates often systematically lower than the geologic rates?

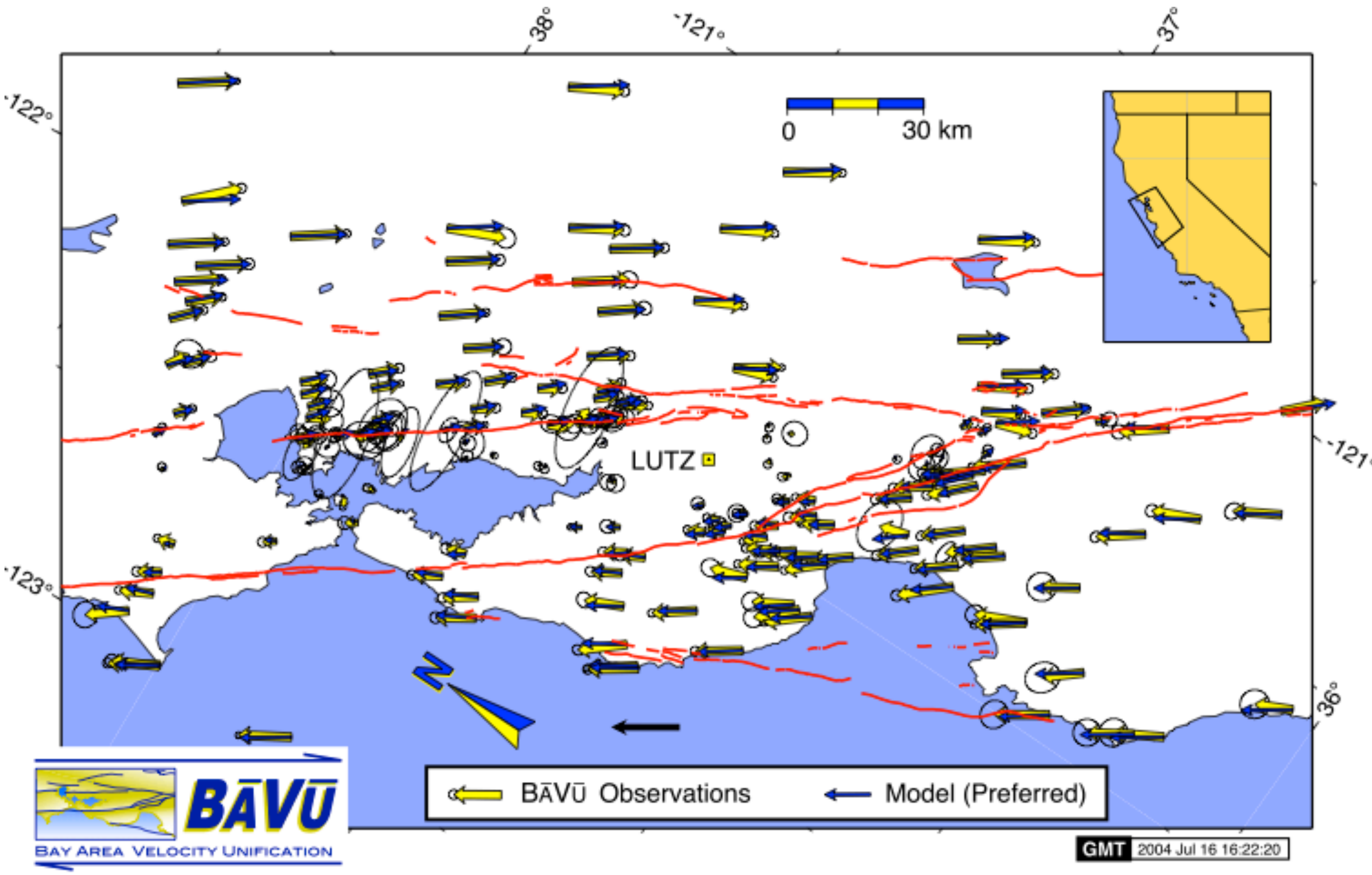
- Is the off-fault deformation inferred from kinematic models reasonable?
- Are the style and orientation of strain rates consistent with quaternary geology?
    - Are the rates of deformation consistent with geology?
    - Need better spatial coverage with GPS & InSAR to constrain

- Why do elastic block models produce systematic misfit to GPS data?
    - Are block models an insufficient description of deformation?
    - Are more blocks needed?
    - Consider simpler models with fewer blocks & accept misfits?

CLUSTER ANALYSIS OF GPS DATA

A New Method to Determine Block Geometry
& Estimate Geodetic Fault Slip Rates

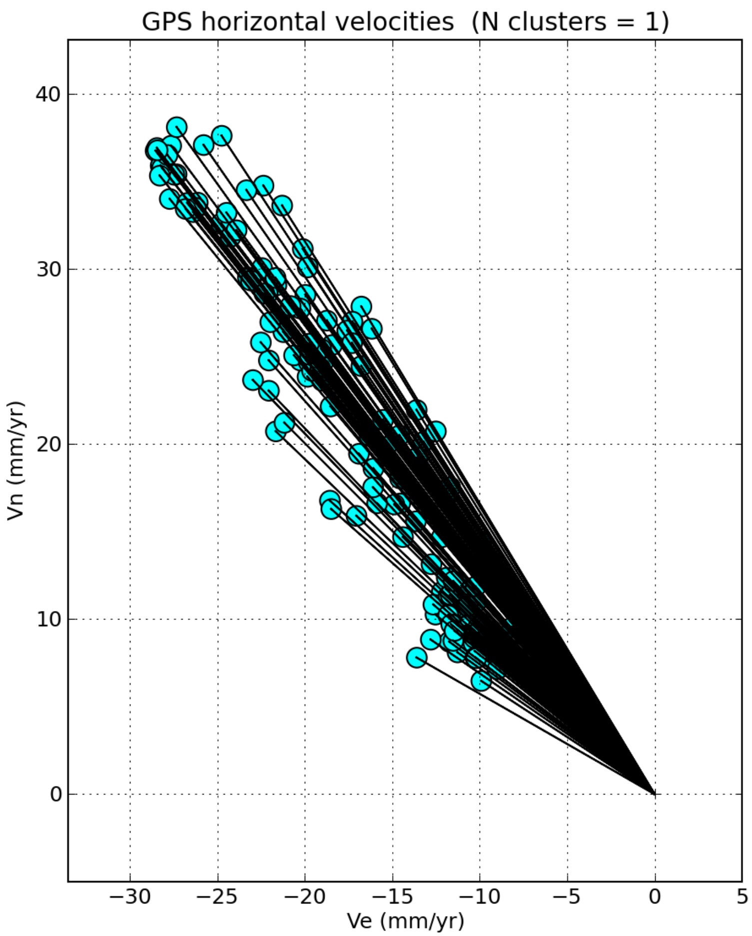
Application of Cluster Analysis to Well Studied Region: San Francisco Bay Area Velocity Field

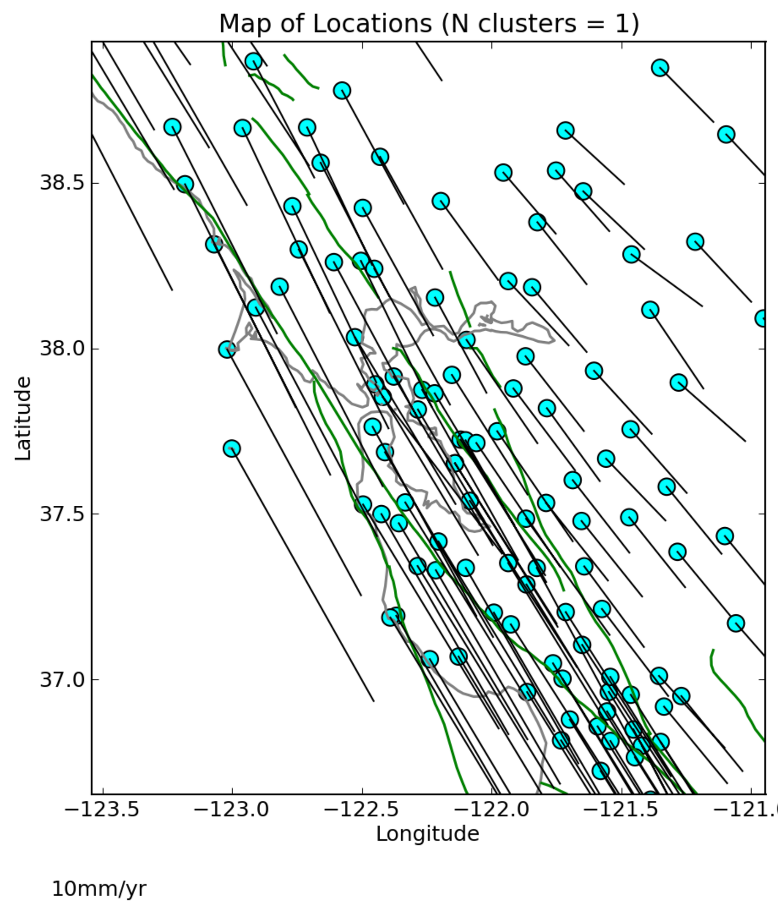


D'Alessio et al., 2005 JGR

d'Alessio et al. Figure 2
2004JB003496-p02_orig.eps

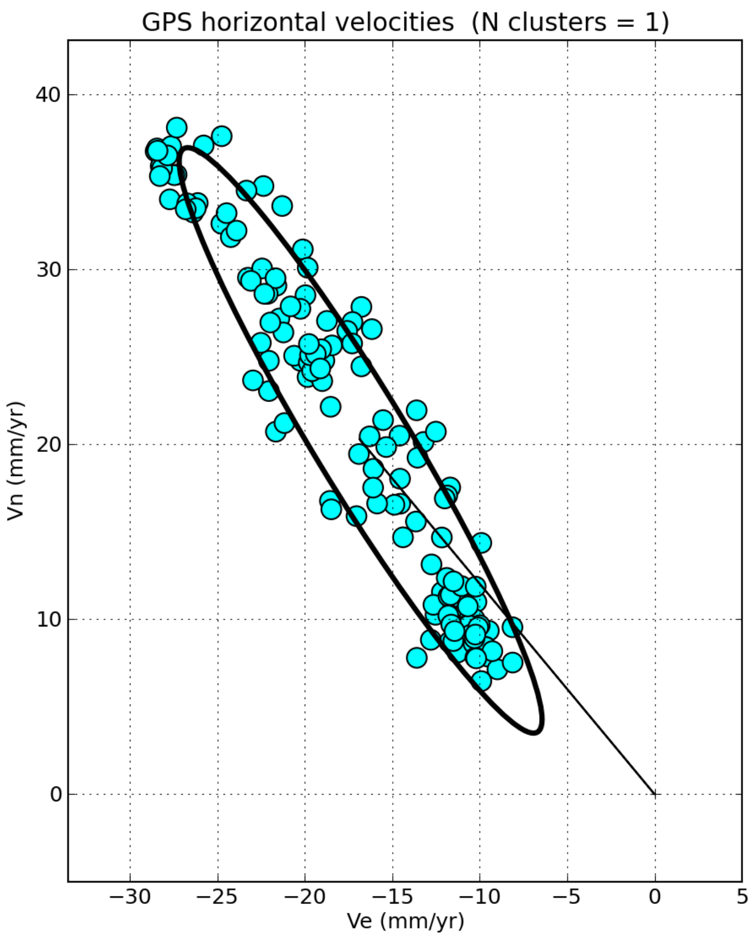
San Francisco Bay Area Velocity Field

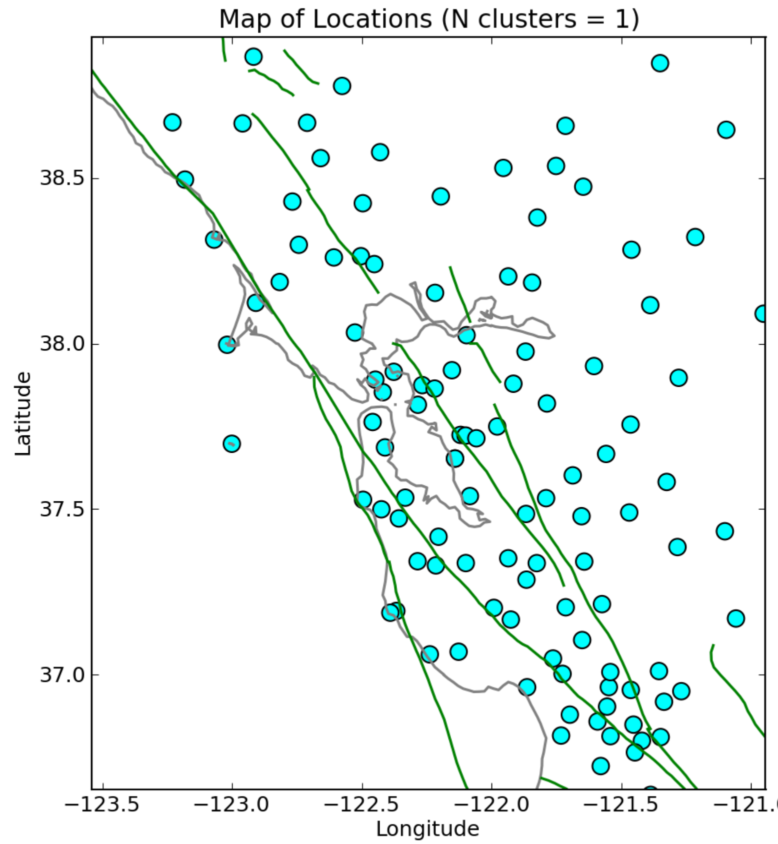




Simpson et al., GRL, 2012, in Review

San Francisco Bay Area Velocity Field

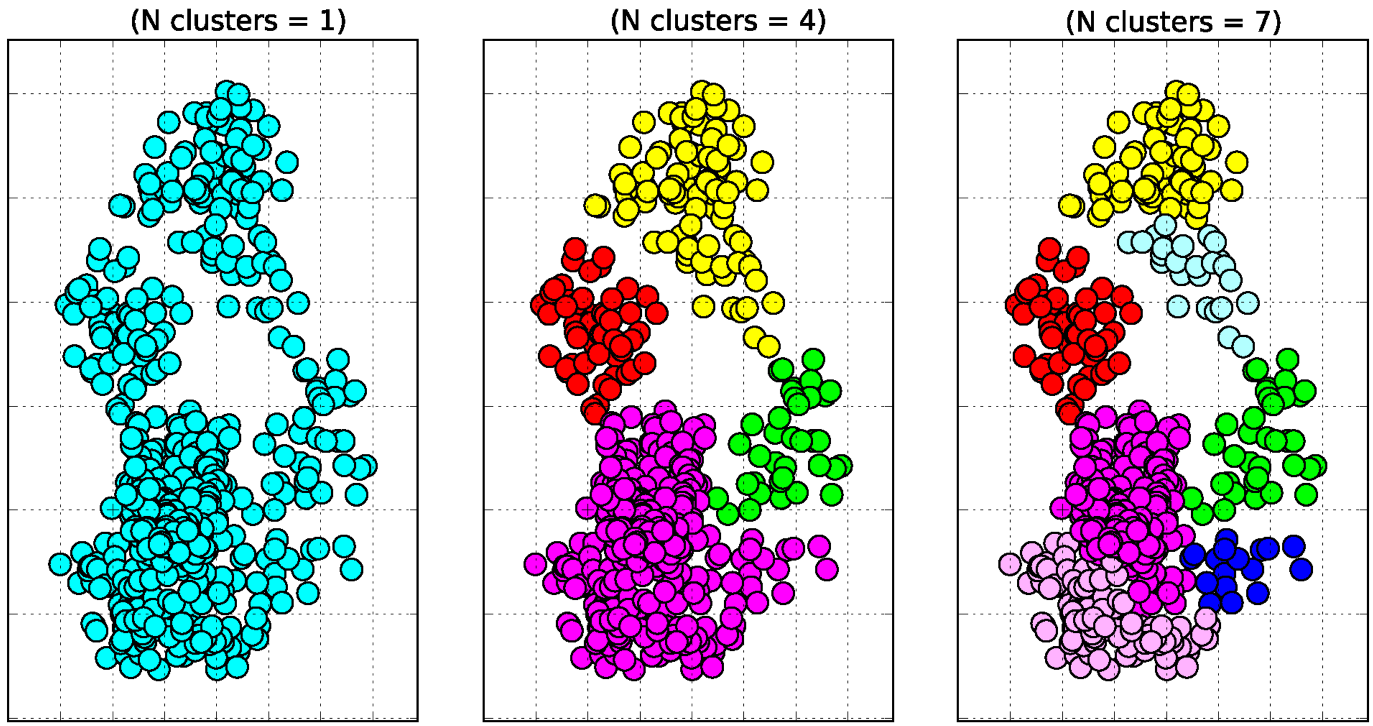




Simpson et al., GRL, 2012, in Review

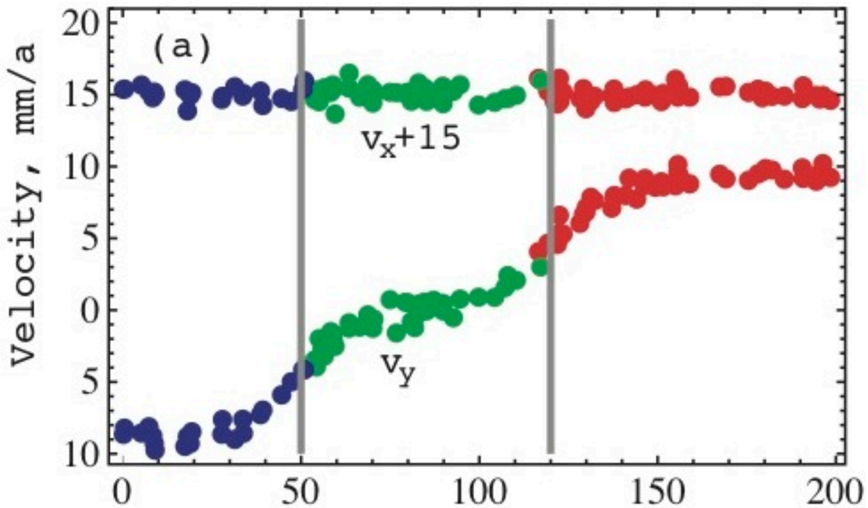
Schematic Illustration of Cluster Analysis Method

Example of Clustering
(Hierarchical Agglomerative Clustering)

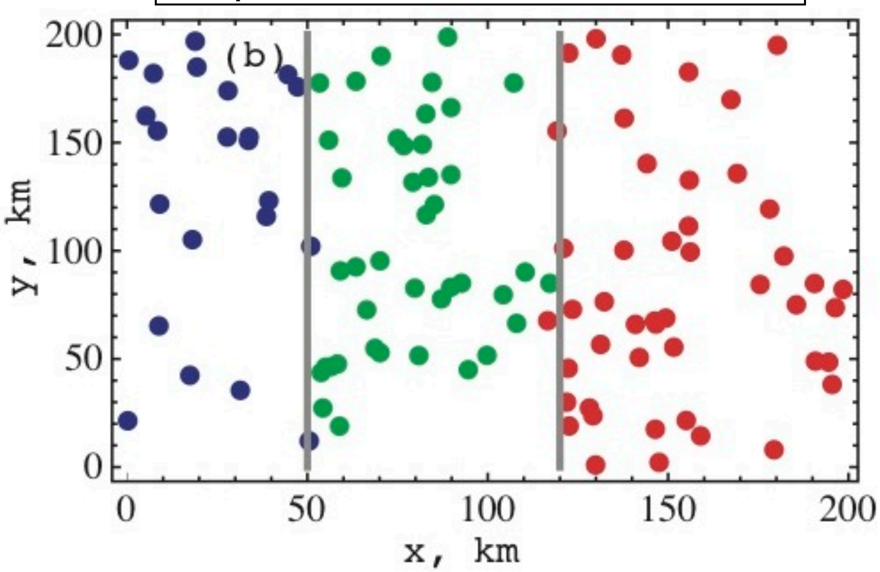


Synthetic Model Application of Cluster Analysis Method

Synthetic GPS Velocity Profiles



Map View of Clustered GPS Sites



MODEL

- 200 km by 200 km Elastic Half-Space
- 2 Parallel 2-D Vertical Strike Slip Faults
- Separated Horizontally by 70 km
- Each Locked to 10 km, slipping 10 mm/yr

SYNTHETIC DATA

- Calculated Model Velocities at 110 randomized locations
- Random Noise Error : 0.3 mm/yr

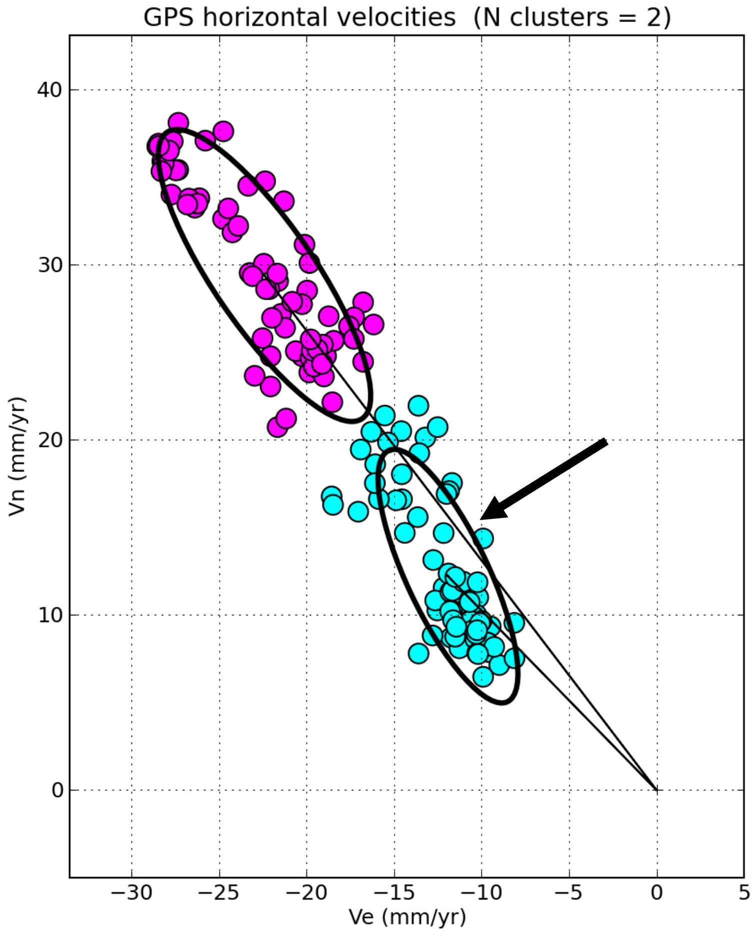
CLUSTER ANALYSIS RESULT

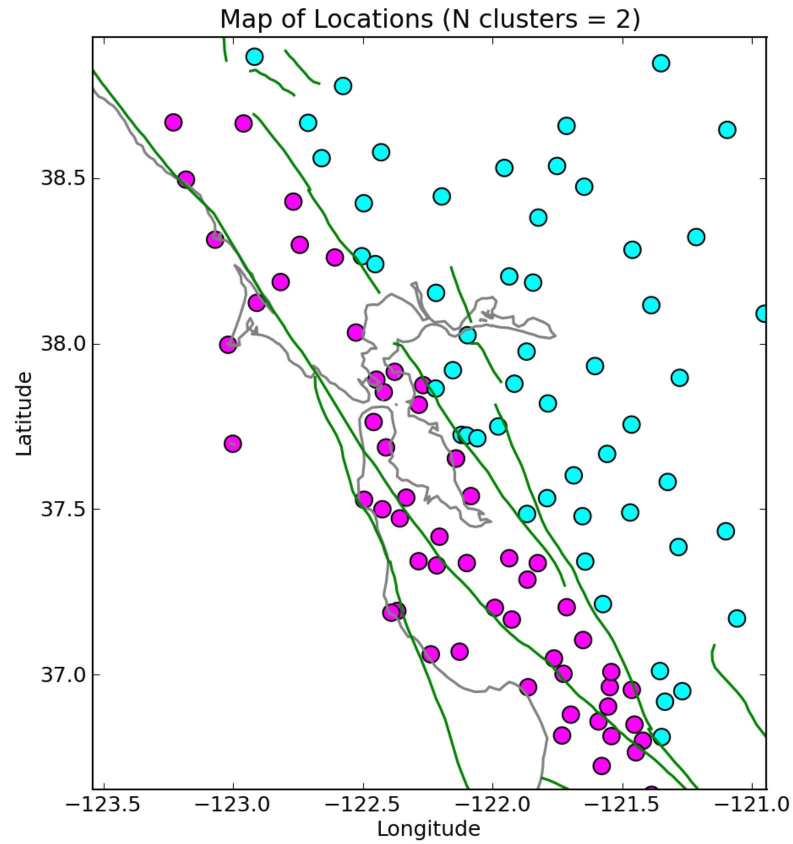
- 3 Statistically significant clusters found
- Correspond spatially with block boundaries

Savage & Simpson JGR, 2012, in prep.

Analysis with Two GPS Clusters Determined

Calaveras-Hayward-Rogers Creek Fault Boundary Identified

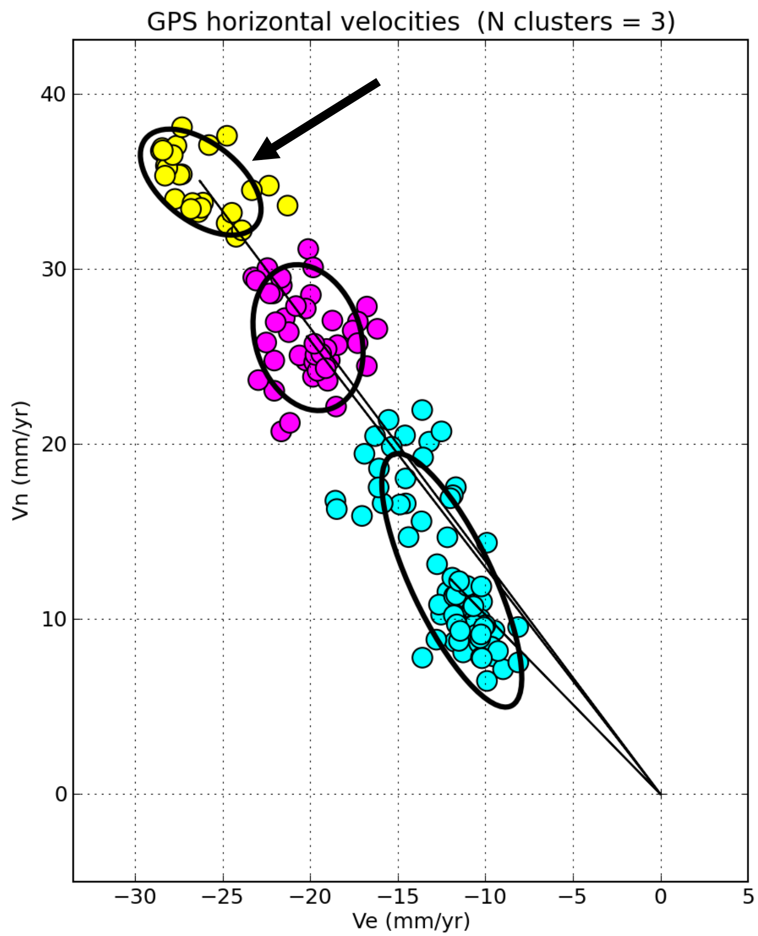


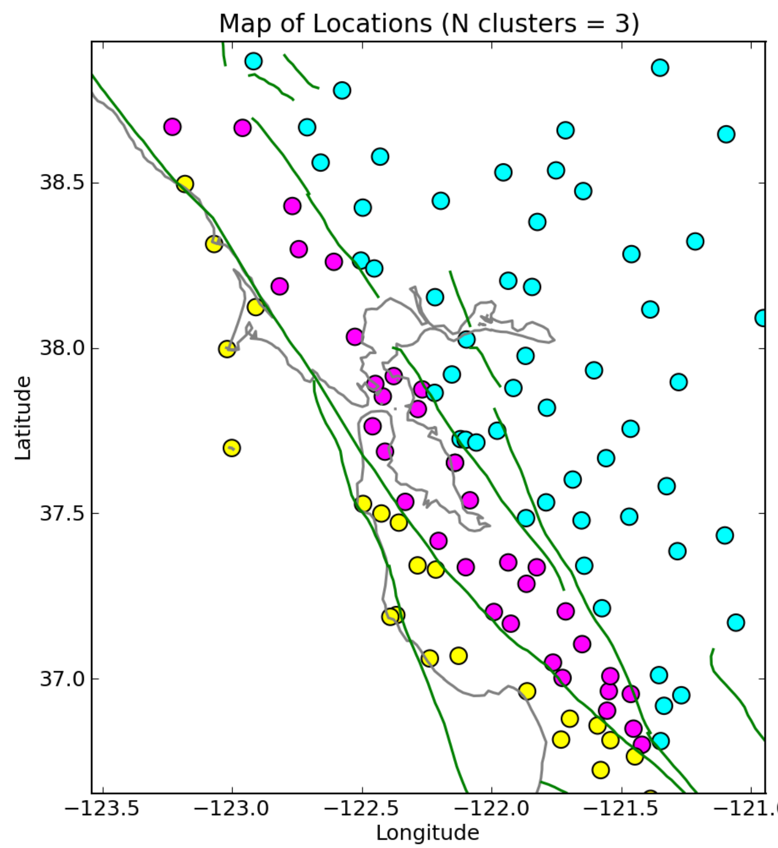


Simpson et al., GRL, 2012, in Review

Analysis with Three GPS Clusters Determined

San Andreas Fault Boundary Identified

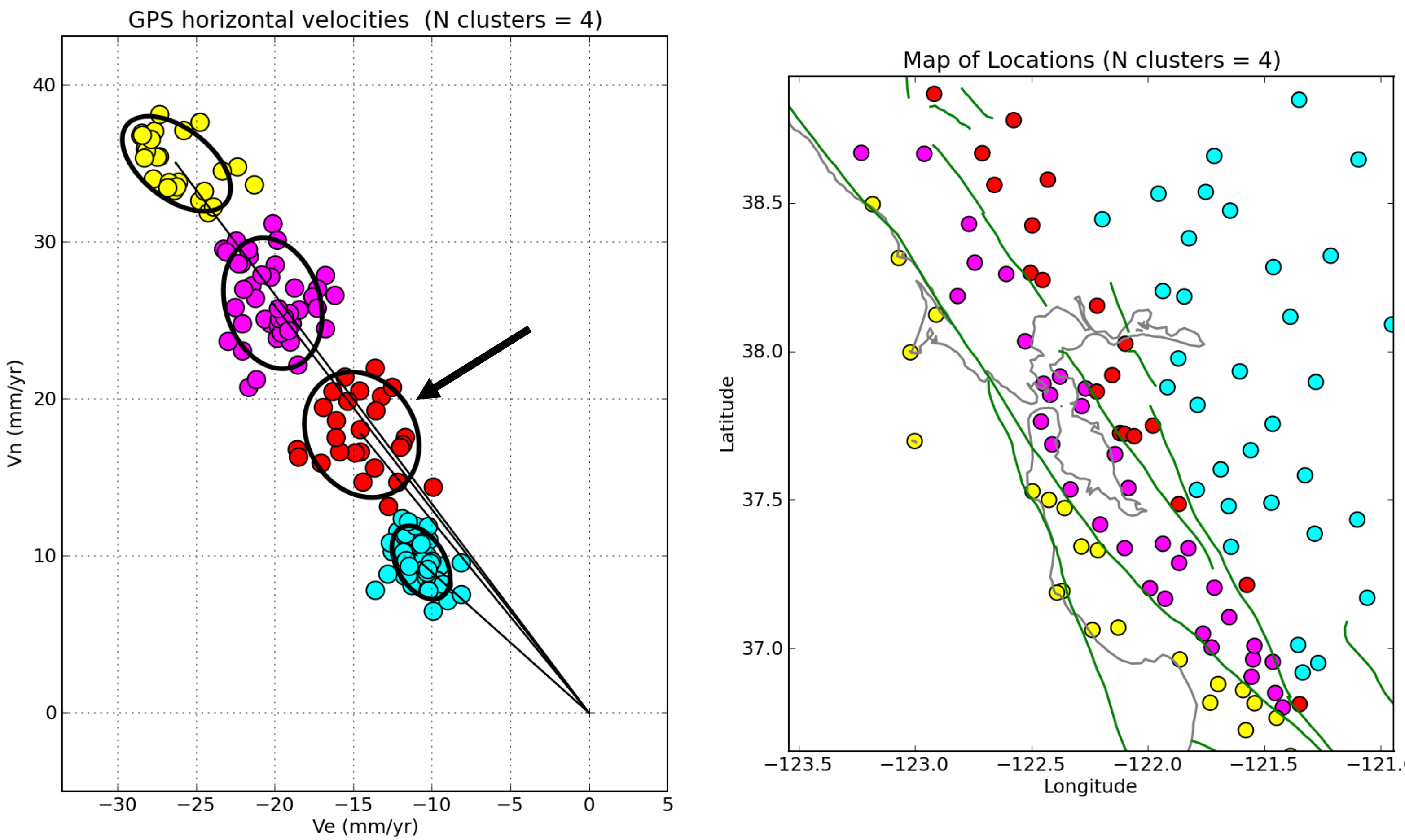




Simpson et al., GRL, 2012, in Review

Analysis with Four GPS Clusters Determined

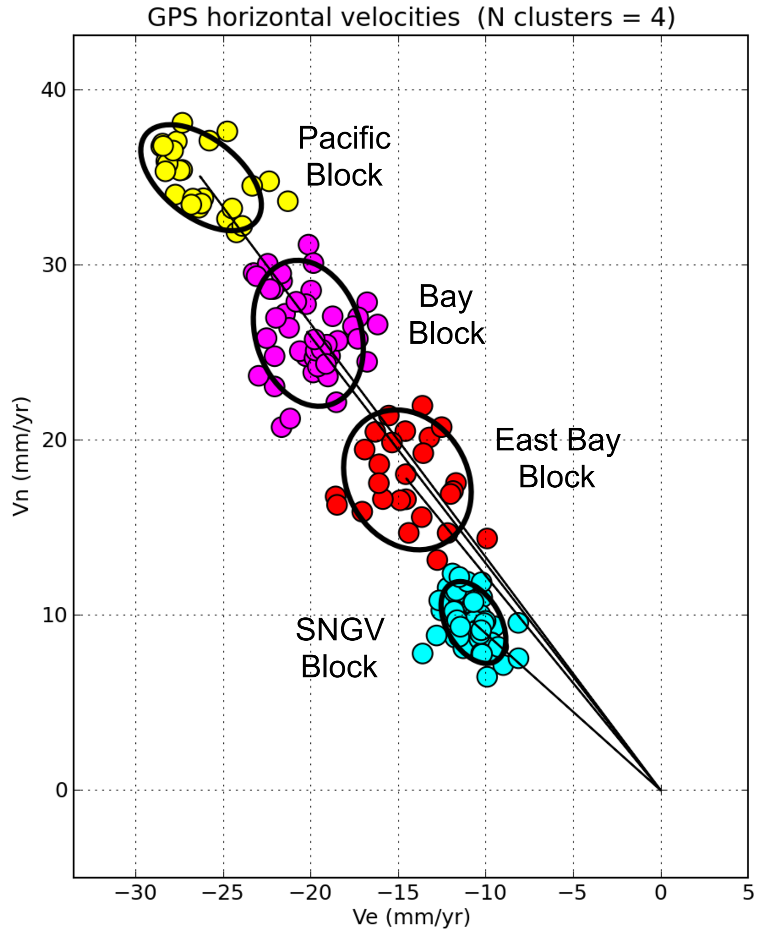
Calaveras-Concord-Green Valley Fault Boundary Identified

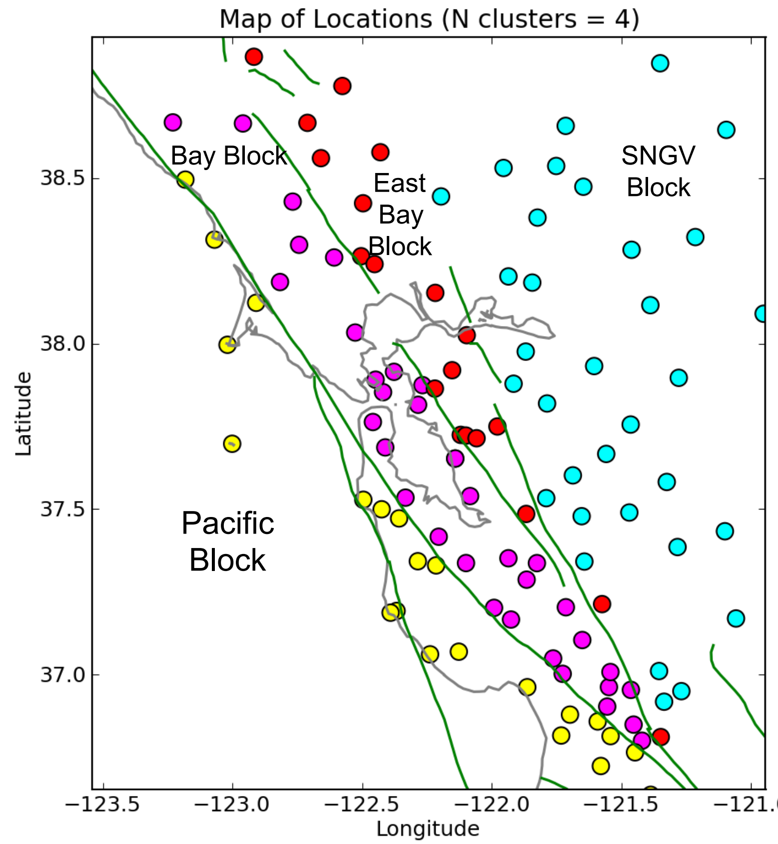


Simpson et al., GRL, 2012, in Review

Analysis with Four GPS Clusters Determined

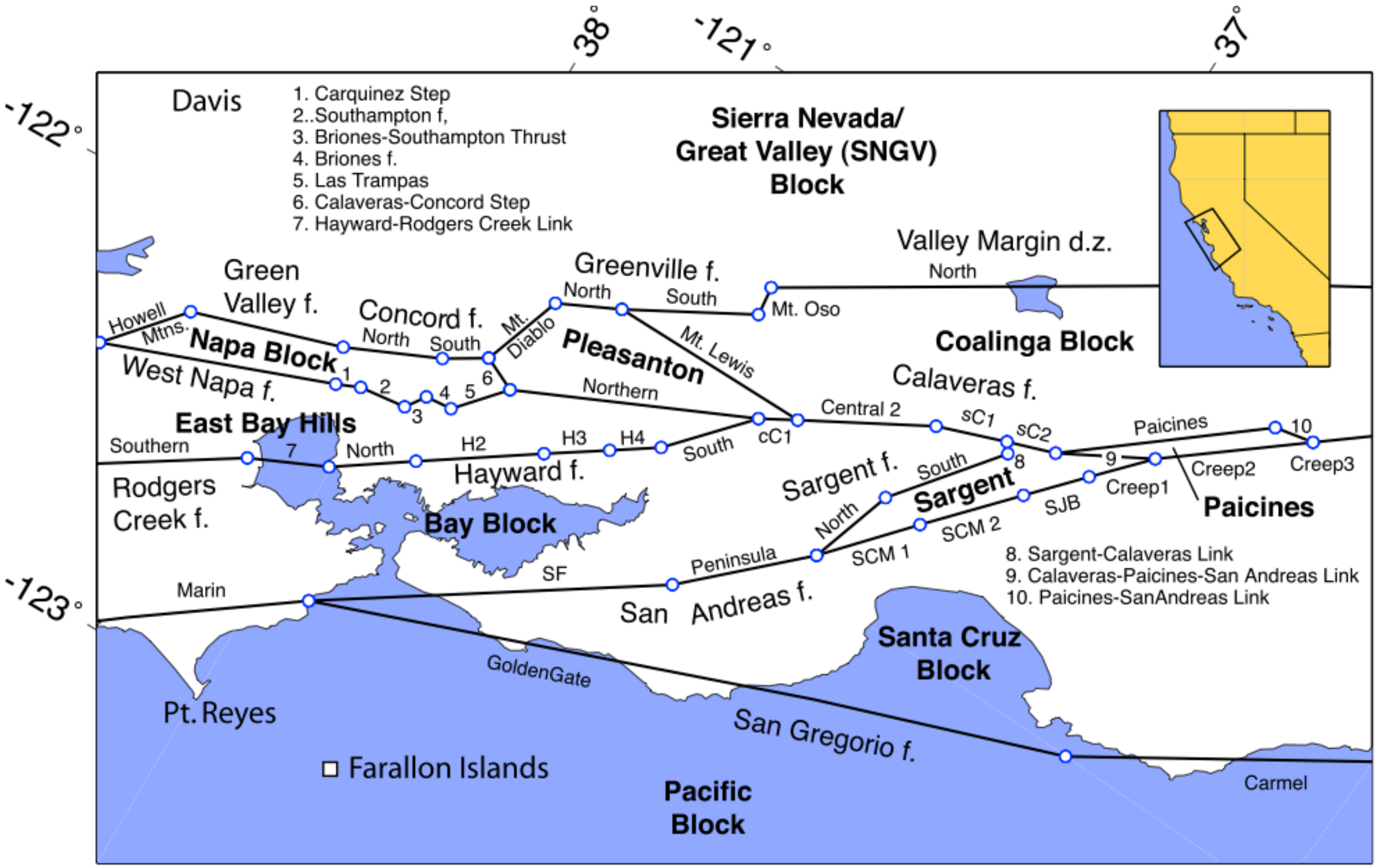
Four Blocks Clearly Identified Solely by Cluster Analysis





Simpson et al., GRL, 2012, in Review

Detailed 8 Block Model of d'Alessio

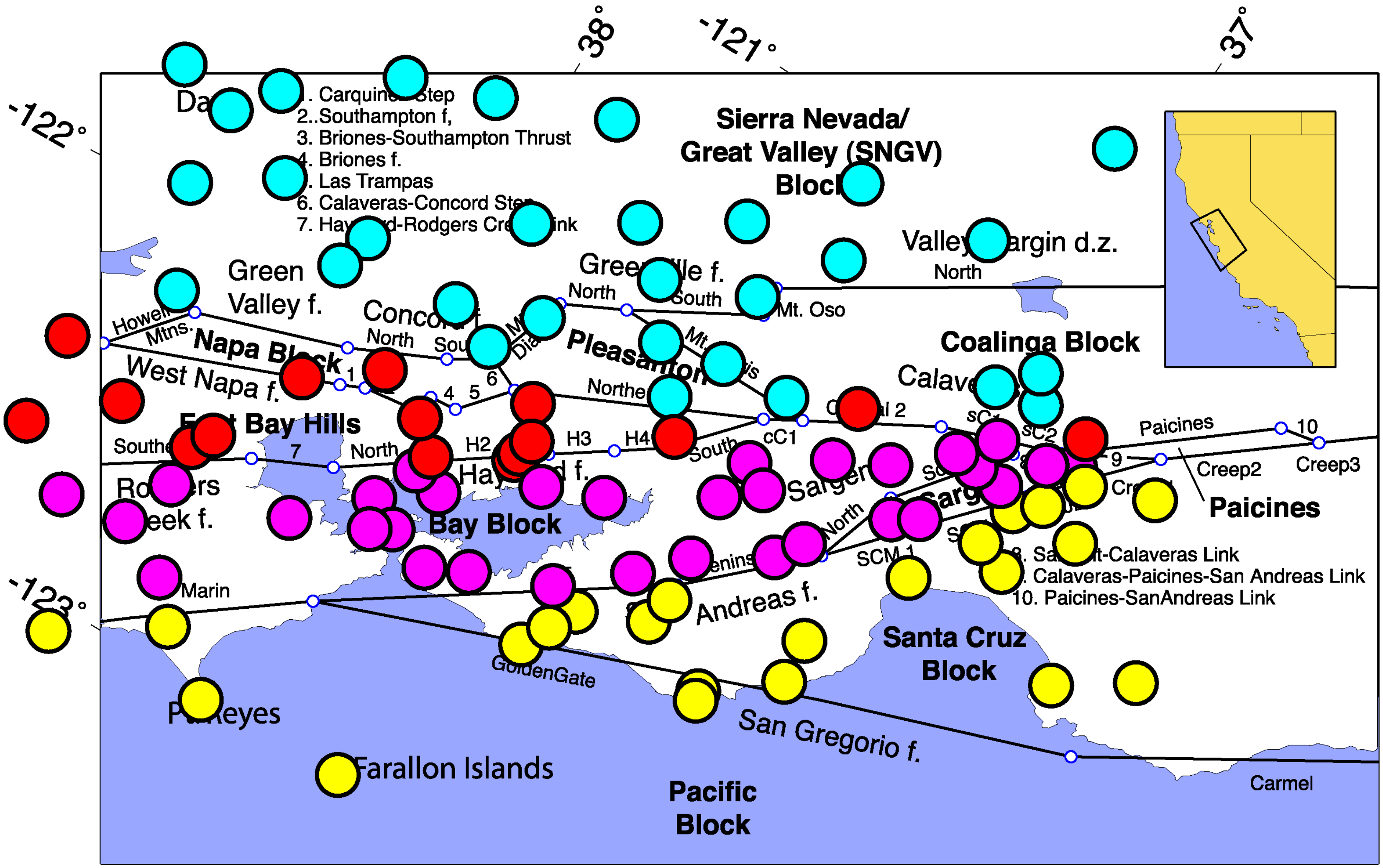


d'Alessio et al. Figure 4
2004JB003496-f04_orig.eps

D'Alessio et al., 2005 JGR

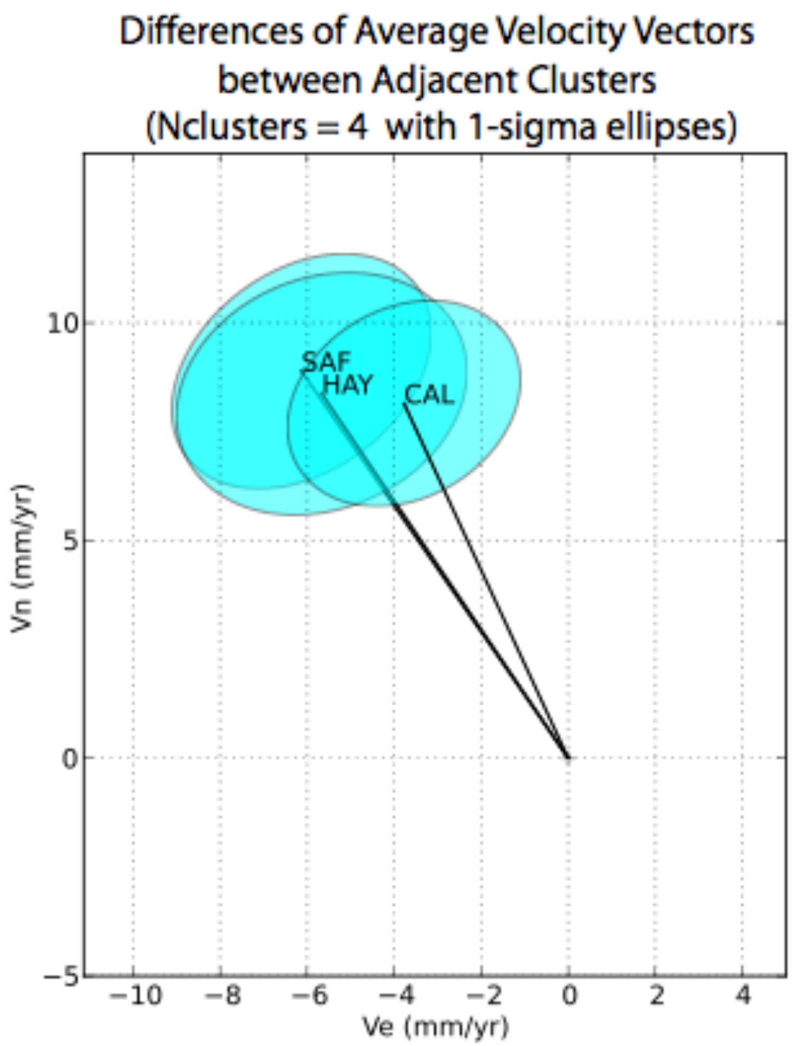
8 Block Model of d'Alessio Compared with Clusters for N=4

Good Correspondence Between d'Alessio & Cluster Analysis for 3 Blocks



d'Alessio et al. Figure 4
2004JB003496-f04_orig.eps

Cluster Analysis Provides Approximate Fault Slip Rates



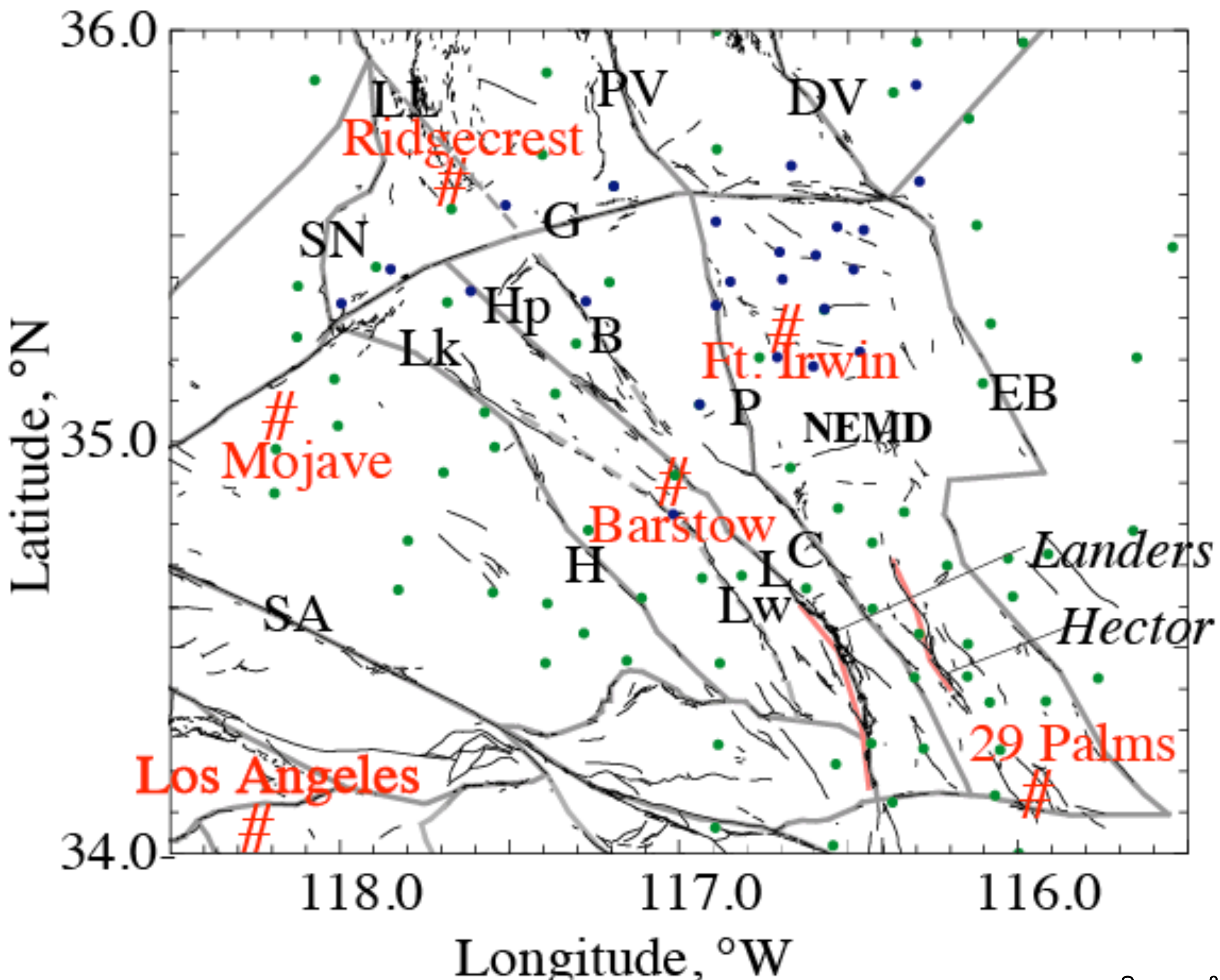
San Andreas ~ 11 ± 2 mm/yr
(N=7 suggests 15 ± 2 mm/yr)

Hayward-Calaveras ~ 10 ± 3 mm/yr

Northern Calaveras ~ 9 ± 2 mm/yr

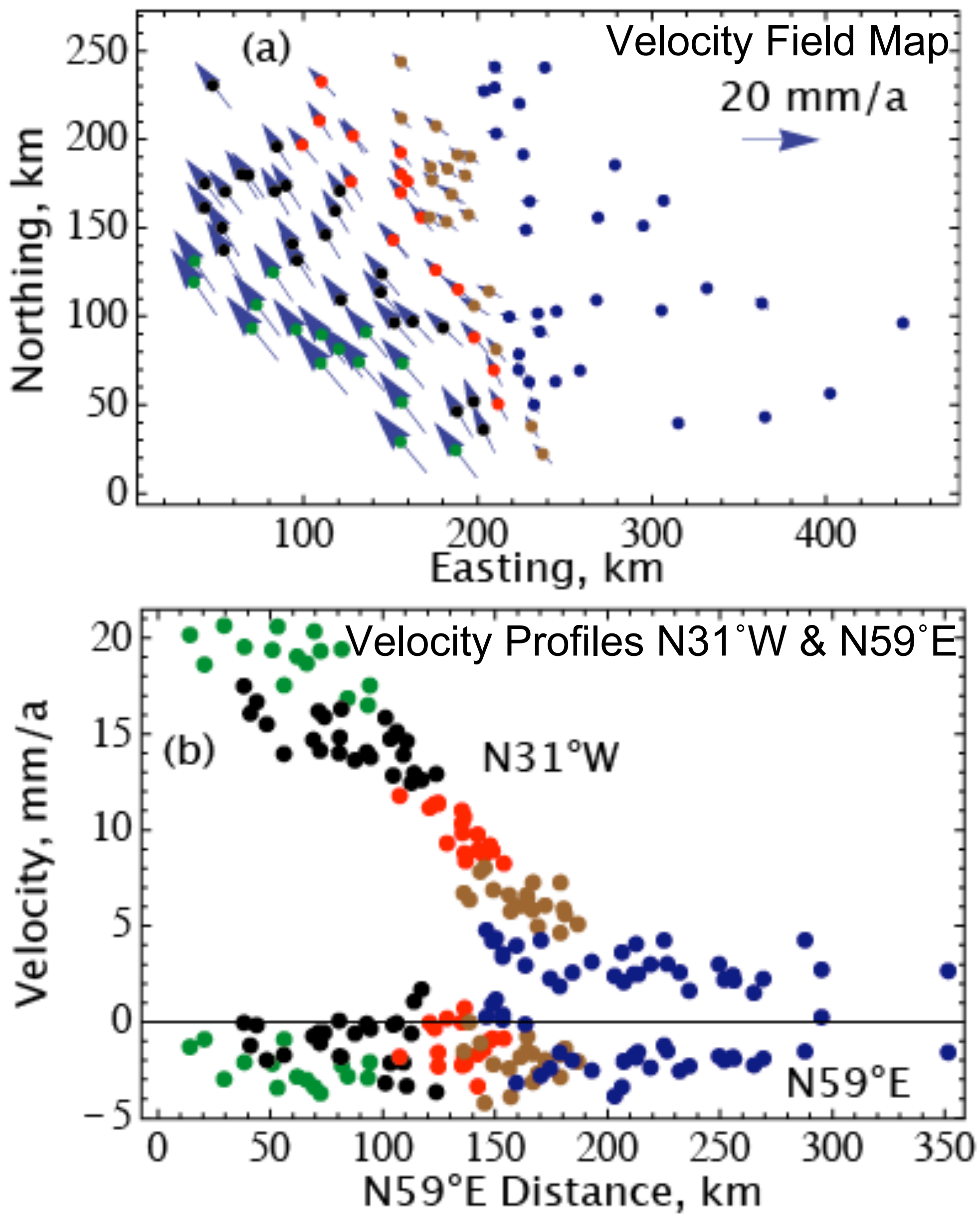
Simpson et al., GRL, 2012, in Review

Cluster Analysis Applied to Mojave Desert GPS with UCERF3 Block Boundaries (Grey Lines) & GPS Sites (Dots)



Savage & Simpson, 2012, in prep

Analysis with 5 Statistically Significant Clusters

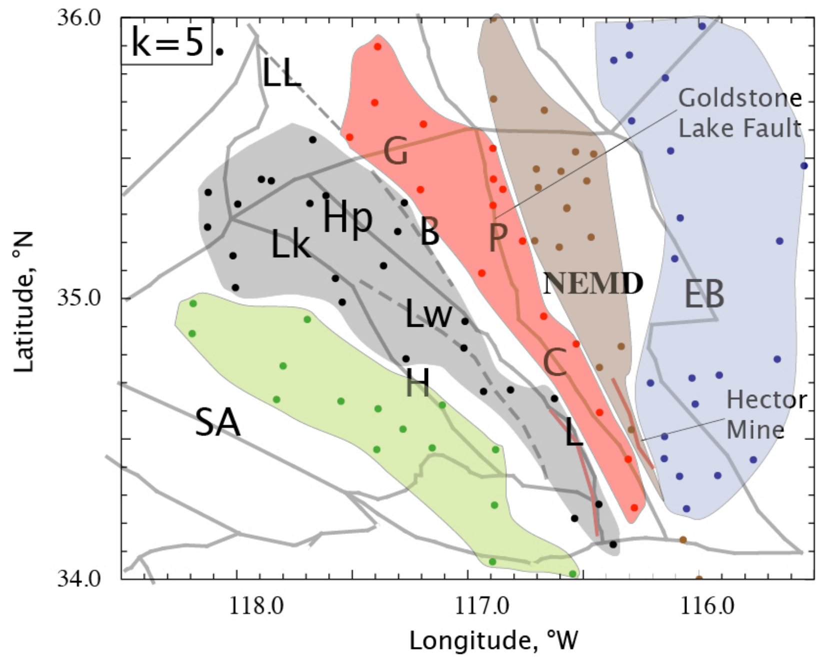


Savage & Simpson, 2012, in prep

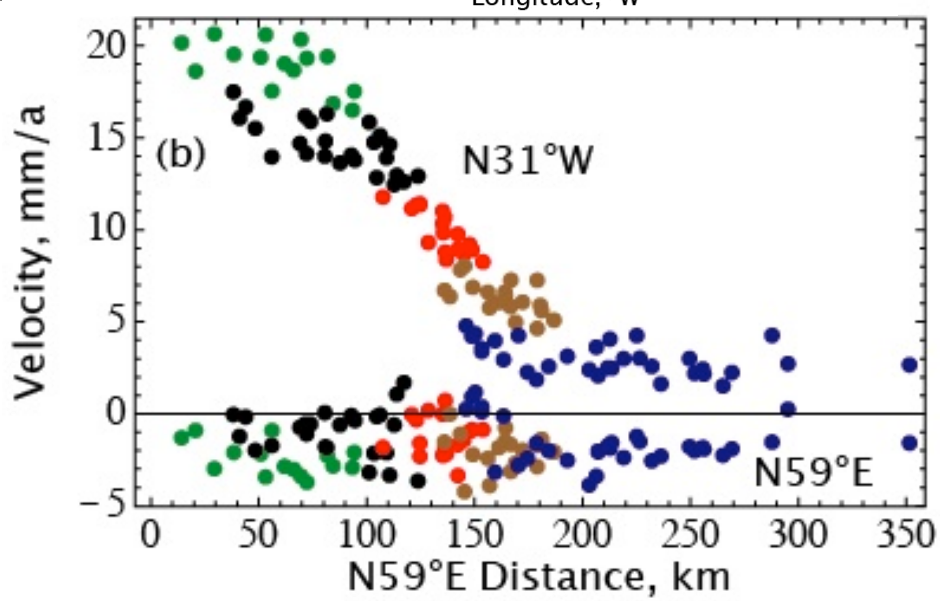
5 Statistically Significant Clusters are Spatially Coherent

Map of 5 Clusters

- Cluster Distribution Similar to UCERF3 Block Geometry
- However, Some Differences too
- Garlock Fault Not "Seen' by Cluster Analysis
- Existence of Smaller Blocks Not Precluded by Cluster Analysis



Velocity Profiles N31˚W & N59˚E



Savage & Simpson, 2012, in prep

Take Home Points from Cluster Analysis

- Offers visual, first-step reconnaissance to organize GPS velocities
- Provides an objective method for identifying major block boundaries
- Works best where Euler poles are distant and blocks ~translate
- Statistical tests of block-like behavior of clusters will help to refine analysis
- May be smaller blocks not identified as statistically significant in analysis
- Application to other regional GPS data sets & including block rotations now underway

CONCLUSIONS

1. Surface & upper crustal deformation economically & usefully described by relative motions among mosaics of elastic blocks in some but not all active regions (e.g. Ventura ‘Block’; LA Basin)

2. Cluster Analysis provides objective means of identifying larger blocks

3. Block models relate present-day tectonics to geologic measures of active deformation

4. GPS fault slip rates useful in tectonic studies (& earthquake hazard mapping) but must be critically assessed and reconciled with available geologic slip rates

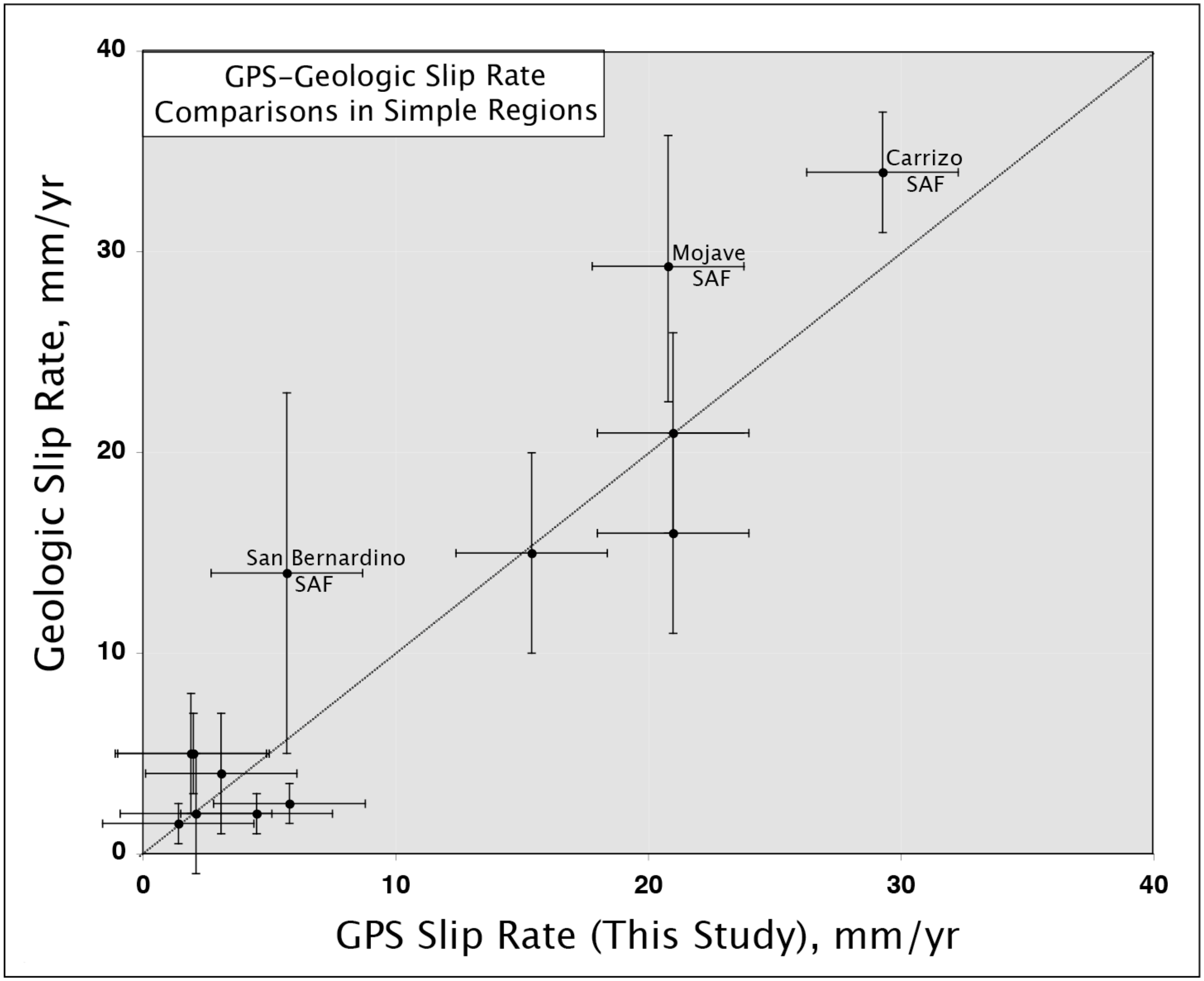
5. Better GPS & InSAR Data Needed in California (UCERF4!)

6. Innovative Models of Both Kinematics & Dynamics Needed (CIG!)

Comparison of GPS & Geologic Fault Slip Rates

Executive Summary: Mostly They Agree

GPS & Geological Slip Rate Estimates Generally Agree in “Simple Regions” of Southern California



Thatcher & Murray-Moraleda, 2009

TAKE HOME POINTS for Southern California

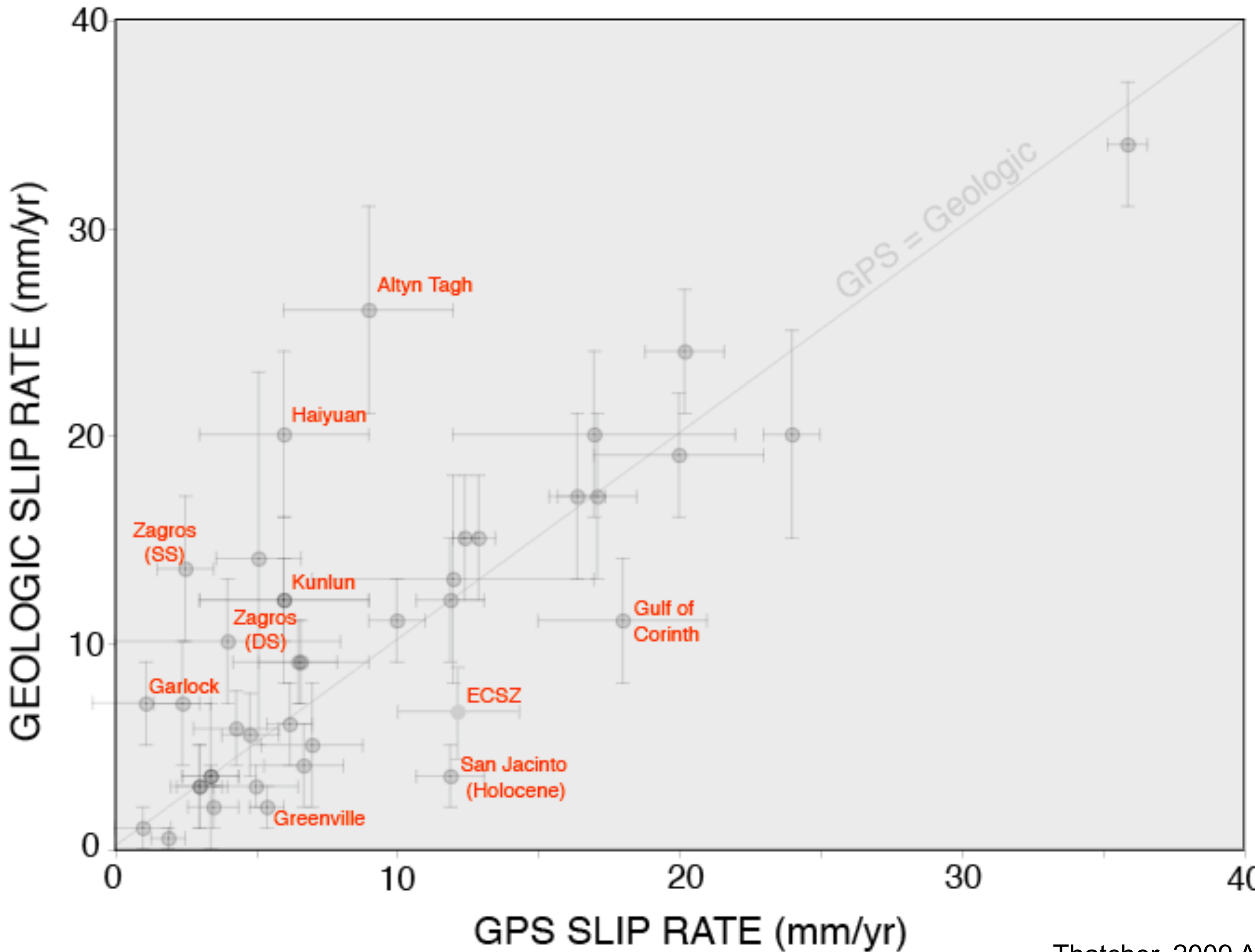
1. In most of southern California, block structure uncontroversial, GPS slip rates on individual faults generally agree from one study to another and are also consistent with geologic slip rate estimates

2. In these simple regions, slip rates may be used directly in hazard calculations once GPS rates are agreed to among geodesists and are judiciously incorporated with geological estimates to obtain consensus rates

3. In the Transverse Ranges, Los Angeles Basin and Central & Eastern Mojave Desert, faults are densely distributed, slip rates on several faults are comparable, and a simple block description is not be useful. Garlock Fault is also a problem!

Worldwide Comparison
of
GPS and Geologic Fault Slip Rates

General Agreement of Geologic & GPS Fault Slip Rates



Thatcher, 2009 AREPS

Four Ways to Evaluate Differences Between GPS and Geologic Slip Rates

1. Is there even-handed assessment of random & systematic errors?

2. Are rate estimates obtained by >1 geodetic (e.g. GPS, InSAR) or geologic (e.g. multiple dated offsets) method?

3. Is proposed rate change mechanism consistent with examples of changes in style and rate of deformation preserved in the geologic record (e.g SAF system evolution, normal-to-thrust inversion…)?

4. Is there a quantitative analysis of mechanism proposed to explain rate change?

Average Block Model Residuals