Comparison of 17 Strain-Rate Models from GPS Geodesy

- overview of 17 strain rate models
- fits to dense GPS and – 12 models too smooth
- cross correlation among models and seismicity rate
- strain-rate tensor maps
- why GPS alone cannot uniquely map strain rate
- strain-rate from new InSAR satellites

Comparison of Strain-Rate Maps of Western North America

Thorsten Becker, University of Southern California
Peter Bird, University of California at Los Angeles
Jayne Bormann and Bill Hammond, UNR
Andrew Freed, Purdue University
Matthias Hackl, LMU, Munich, Germany
Brendan Meade and Jack Loveless, Harvard
William Holt, State University of New York, Stony Brook
Ben Hooks, University of Texas at El Paso
Sharon Kedar, Sean Baxter, JPL
Corne Kreemer, University of Nevada
Rob McCaffrey, Rensselaer Polytechnic Institute
Tom Parsons, USGS
Fred Pollitz, USGS Menlo Park
Zeng-Kang Shen, UCLA
Bridget Smith-Konter, University of Texas at El Paso
Carl Tape, Harvard
Yuehua Zeng, USGS

Velocity to Strain Rate

$v_i\left(x_j^k\right) \pm \sigma_i^k$ - vector velocity at point *k*

$i = 1, 2, 3 \quad j = 1, 2 \quad k = 1 - N$

⇓ 2-D interpolation and/or dislocation model

$v_i\left(x_j\right)$ - surface vector velocity (0.01˚)

⇓ differentiation (GMT grdgradient)

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$$

- 2D strain rate

principal strain rate

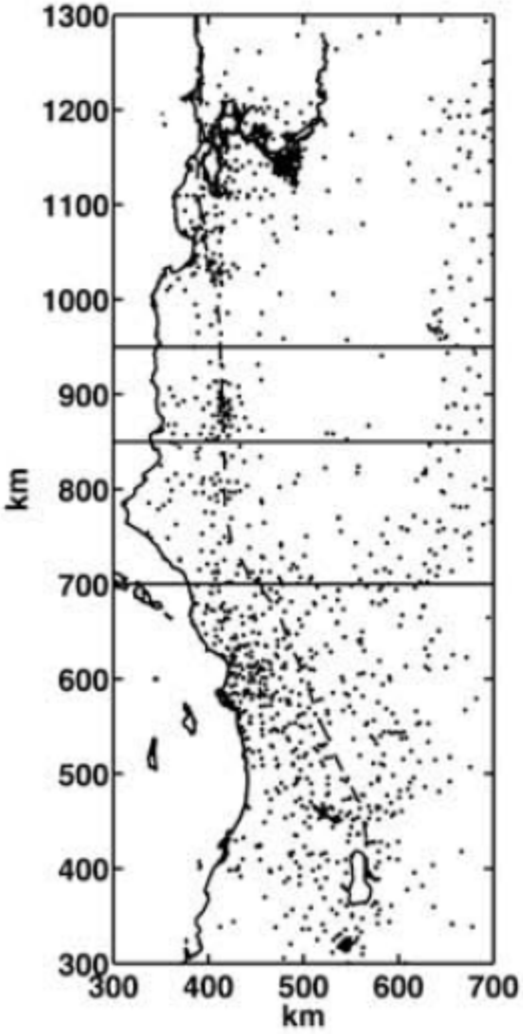
$$\dot{\varepsilon}_{1,2} = \frac{\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy}}{2} \pm \frac{1}{2}\left\{\left(\dot{\varepsilon}_{xx} - \dot{\varepsilon}_{yy}\right)^2 + 4\dot{\varepsilon}_{xy}^2\right\}^{1/2}$$

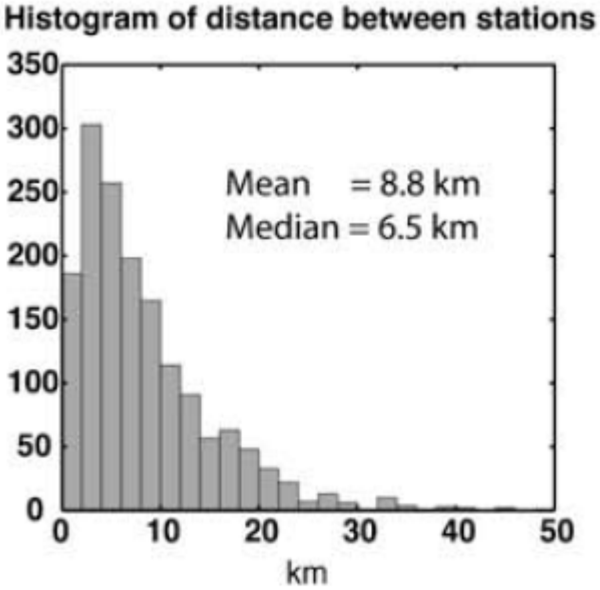
dilatation rate + maximum shear rate

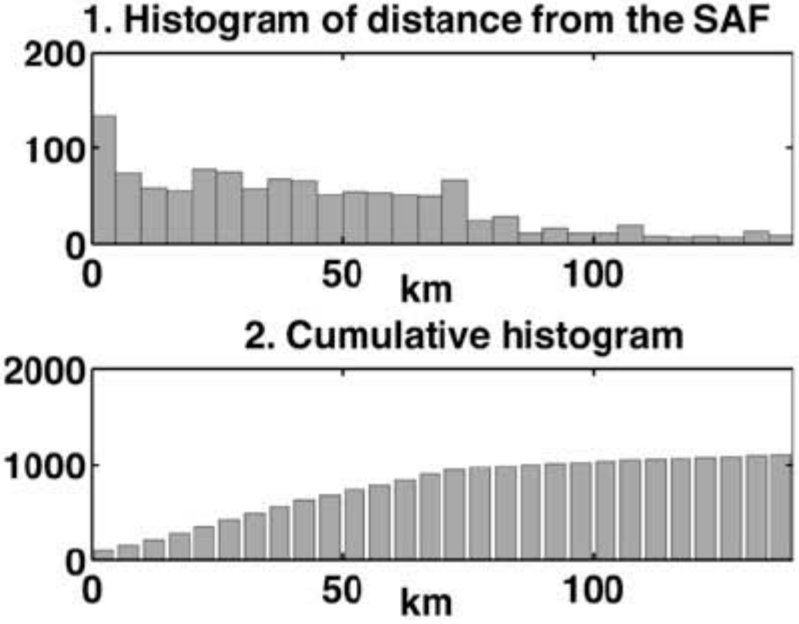
second invariant

$$\dot{\varepsilon}_{II} = \left(\dot{\varepsilon}_{xx}^2 + \dot{\varepsilon}_{yy}^2 + 2\dot{\varepsilon}_{xy}^2\right)^{1/2}$$

Median Spacing of GPS Stations







[Wei et al. 2010]

Different Methods and Assumptions to Overcome Incomplete Spatial Sampling

Four approaches are used:

1) isotropic interpolation;

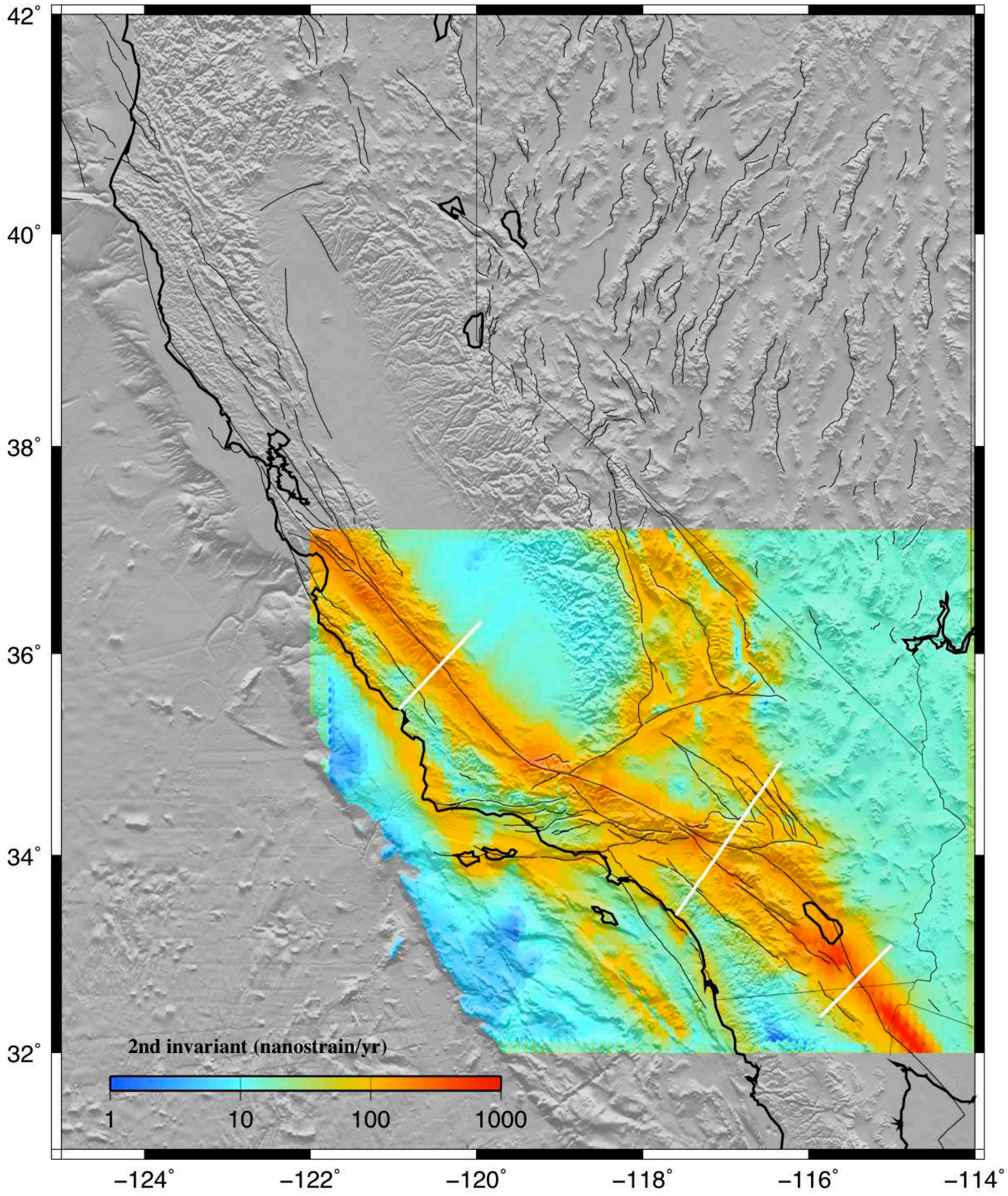
2) interpolation guided by known faults;

3) interpolation of a rheologically-layered lithosphere, and

4) model fitting using deep dislocations in an elastic layer or half space.

bormann_hammond **091 ηs**

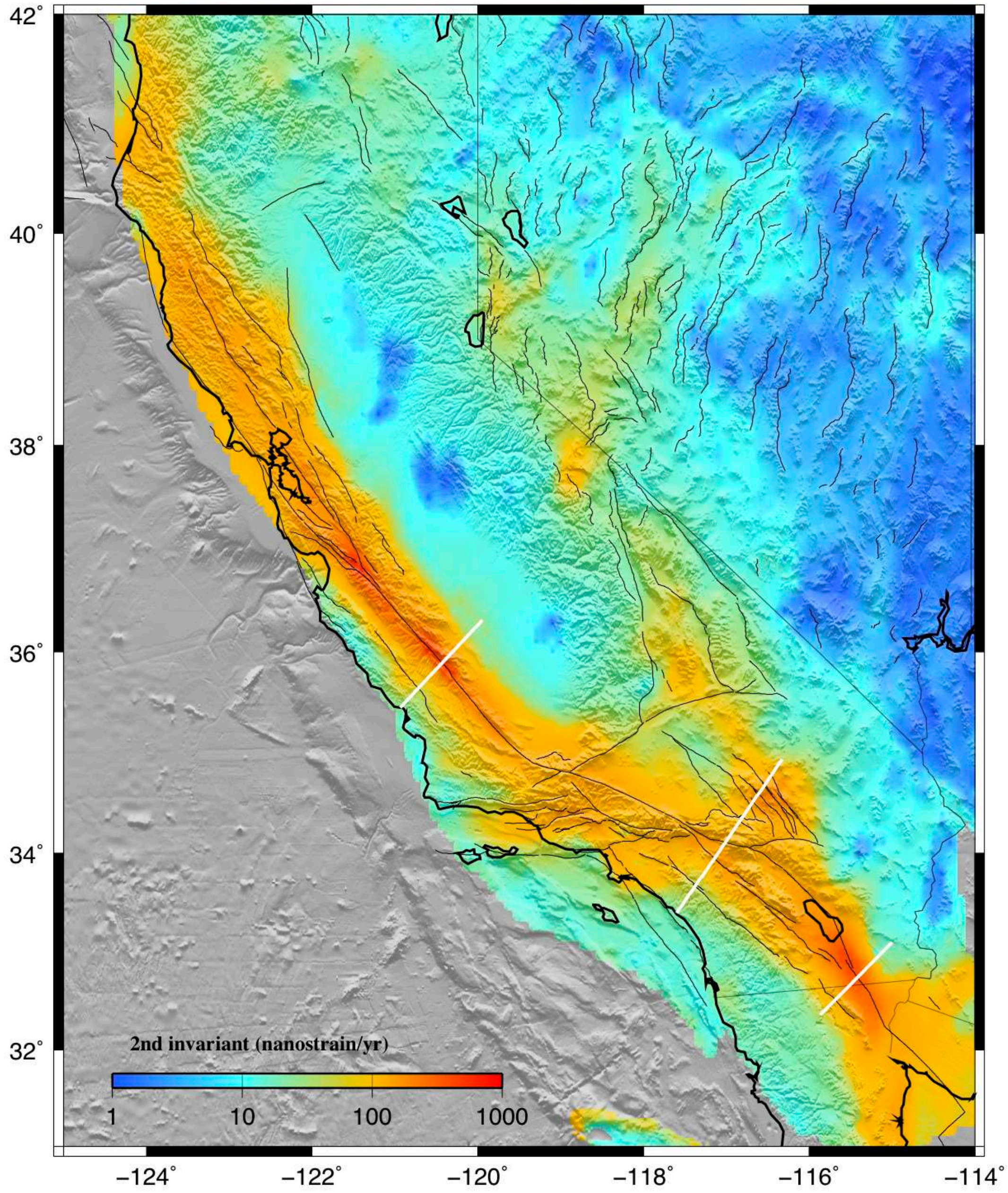
Jayne Bormann and Bill Hammond sent two velocity fields on a uniform grid constructed from their test exercise using CMM4. Hammond’s code was used. Surface creep was not included and a uniform locking depth of 15 km was used.



zeng

095 ηs

The GPS data for the western US are obtained from PBO velocity at UNAVCO site, Southern California Earthquake Center California Crustal Motion Map 1.0, McCaffrey et al. (2007) for Pacific Northwest, the GPS velocity field of Nevada and its surrounding area from the Nevada Geodetic Lab at the University of Nevada at Reno, and the GPS velocity field of the Wasatch-Front and the Yellowstone-Snake-River-River-Plain network from Bob Smith of University of Utah. These separate velocity fields are combined by adjusting their reference frames to make velocities match at collocated stations. I determined the Voronoi cells for this combined GPS stations and used their areas to weight the corresponding stations for inversion. I then interpolated those GPS observation into uniform grid point for the western US using the method of Wald (1998) and calculated the final strain rate map.

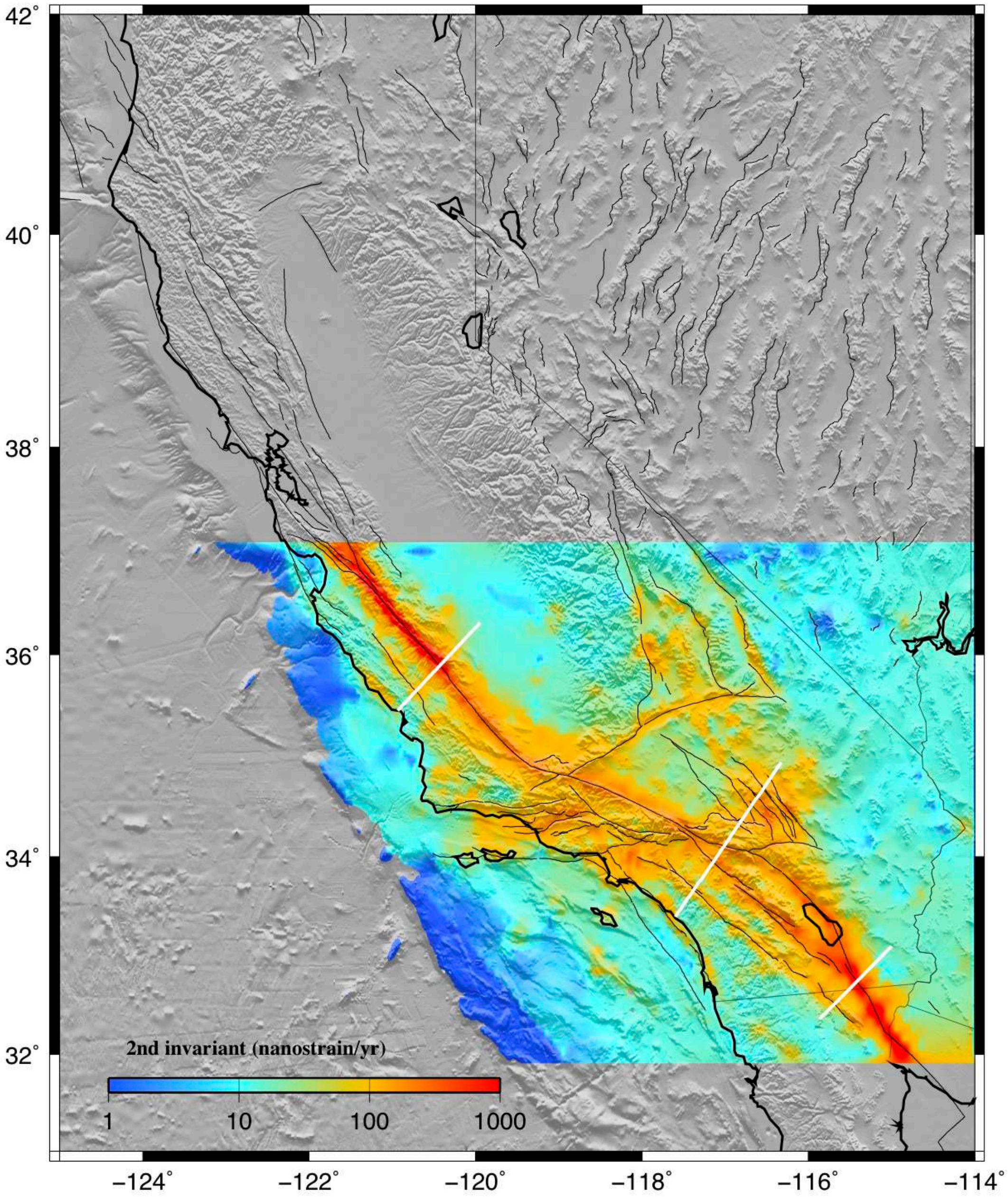


holt

111 ηs

What I do is use an anisotropic variance-covariance matrix for the strain rates. I do not build in fault slip rates, but I use the variance-covariance matrix to place a priori constraints on expected shear directions as well as some constraints on expected shear magntitudes. However, in the end the GPS velocities dictate the actual strain rates and styles of strain rate (where they are high, low, etc.). I am also limited by the finite-element grid, which is .1x.1 degree grid area spacing. It might be worthwhile to compare the solution I sent you with one obtained using fully isotropic uniform variances for all areas. That is, with an a priori expected strain rate distribution that is everywhere uniform. I can look into the reduced chi-squared misfit for both of

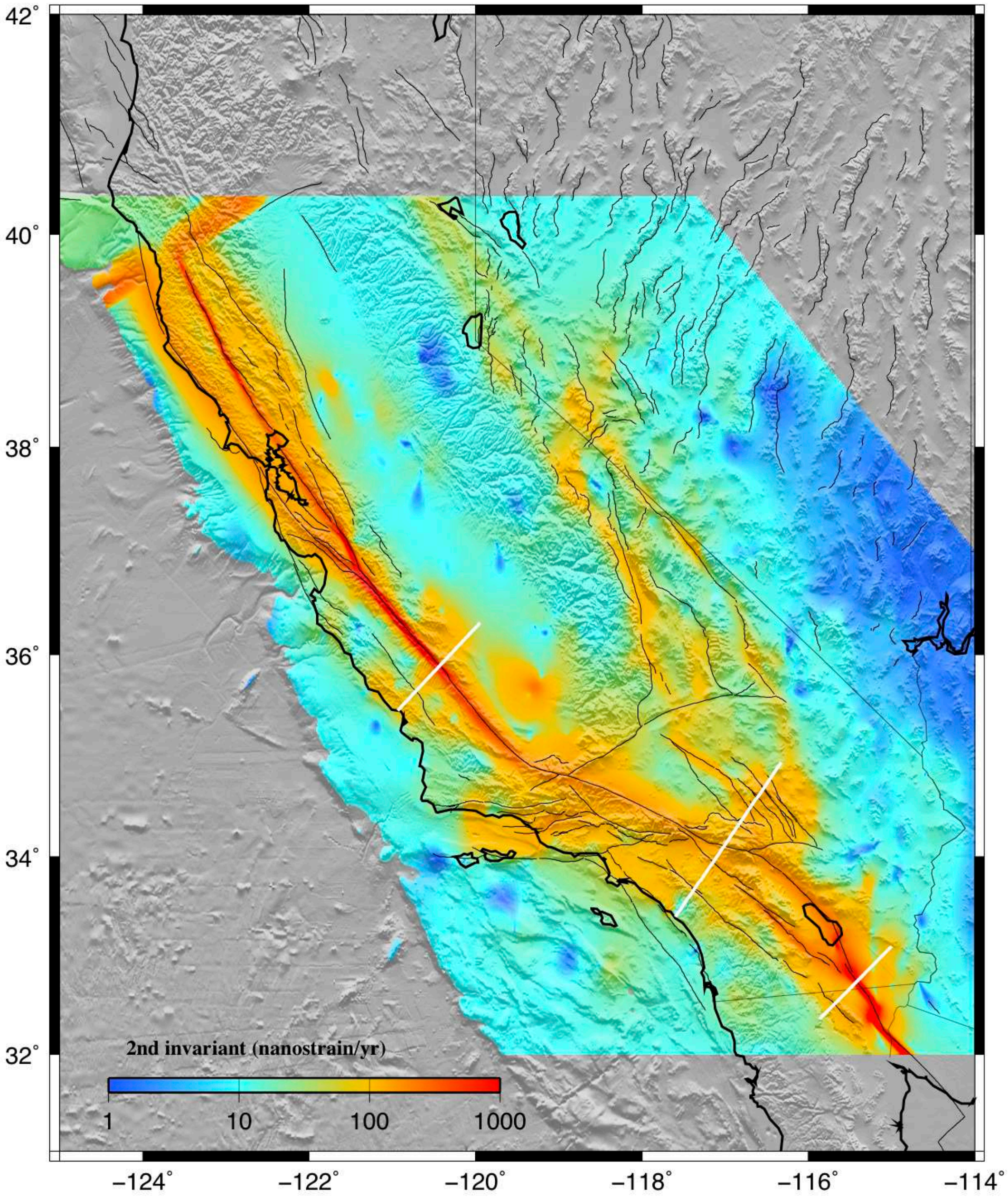
these cases.



smith_konter

123 ηs

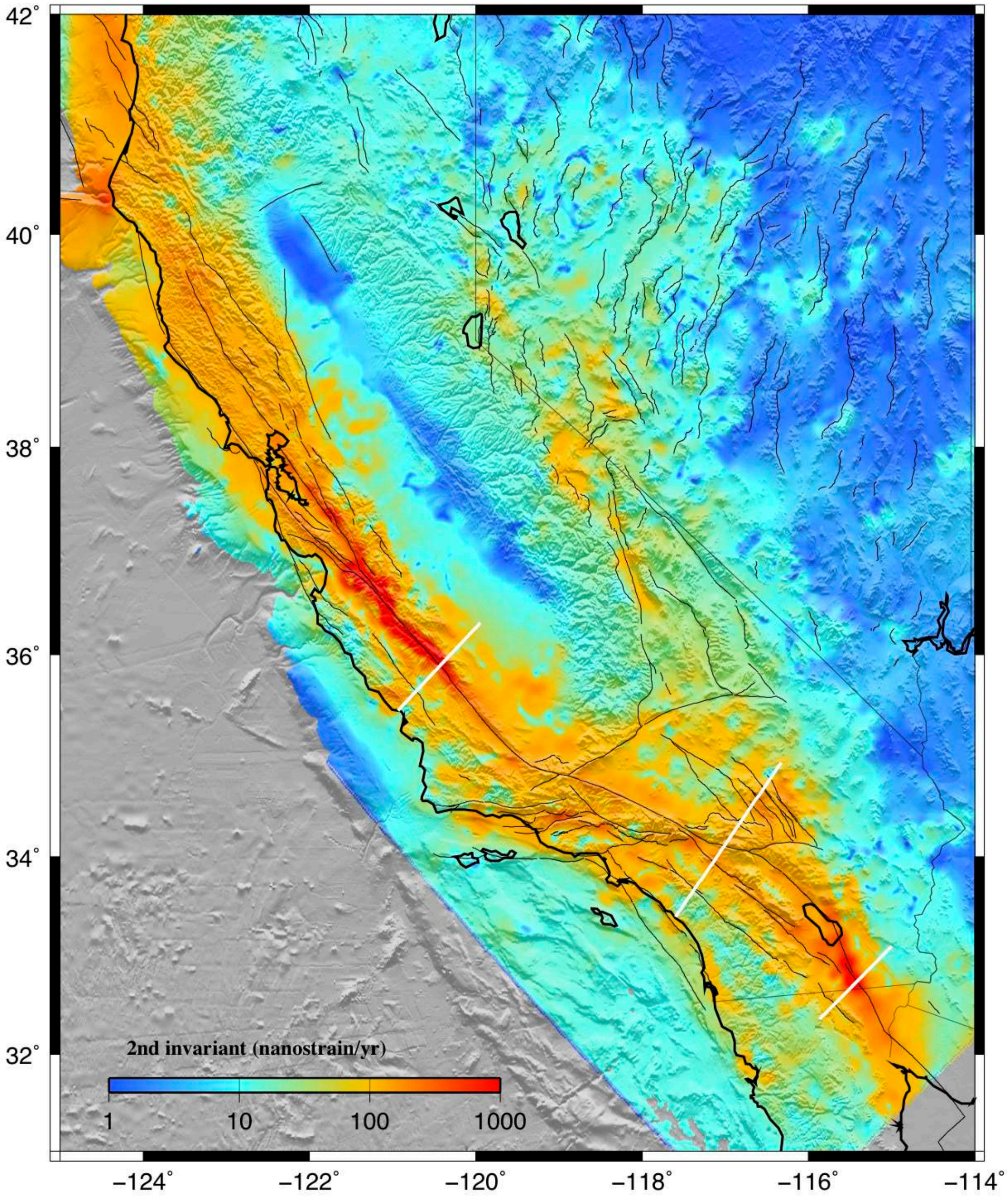
Strain rate derived from a dislocation model of the San Andreas Fault system [Smith-Konter and Sandwell, GRL, 2009]. 610 GPS velocity vectors were used to develop the model. The model consists of an elastic plate over a visco-elastic half space at 1 km horizontal resolution. Deep slip occurs on 41 major fault segments where rate is largely derived from geological studies. The locking depth is varied along each fault segment to provide a best fit to the GPS data. The model is fully 3-D and the vertical component of the GPS vectors is also used in the adjustment. An additional velocity model was developed by gridding the residuals to the GPS data using the GMT surface program with a tension of 0.35. This was added to the dislocation model.



kreemer

114 ηs

Strain rate tensor model derived from fitting a continuous horizontal velocity field through GPS velocities [Kreemer et al, 2009]. 2053 GPS velocities were used, of which 854 from our own analysis of (semi-)continuous sites and 1199 from published campaign measurements (all transformed into the same reference frame). The model assumes that the deformation is accommodated continuously, and lateral variation in damping is applied to ensure that the reduced chi^2 fit between observed and modeled velocities is ~1.0 for subregions.



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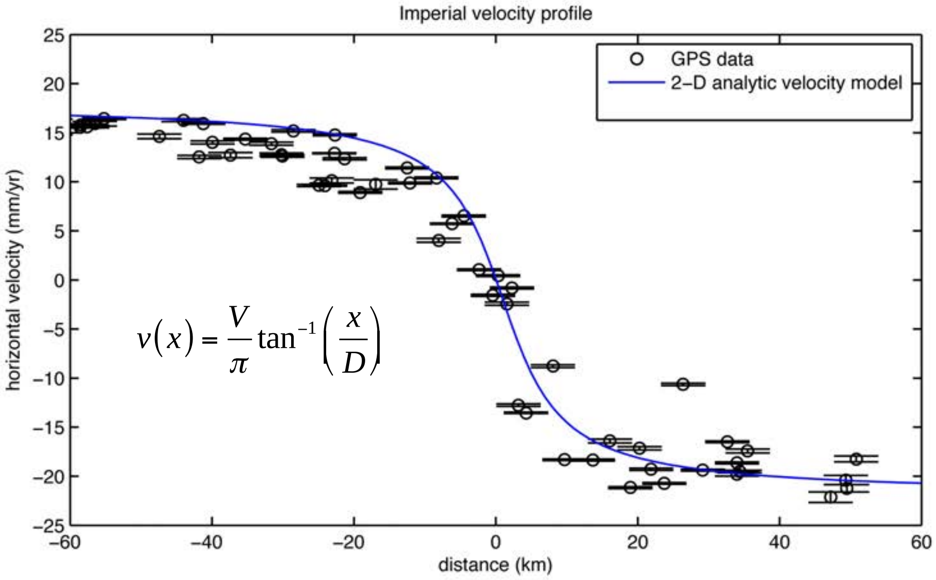
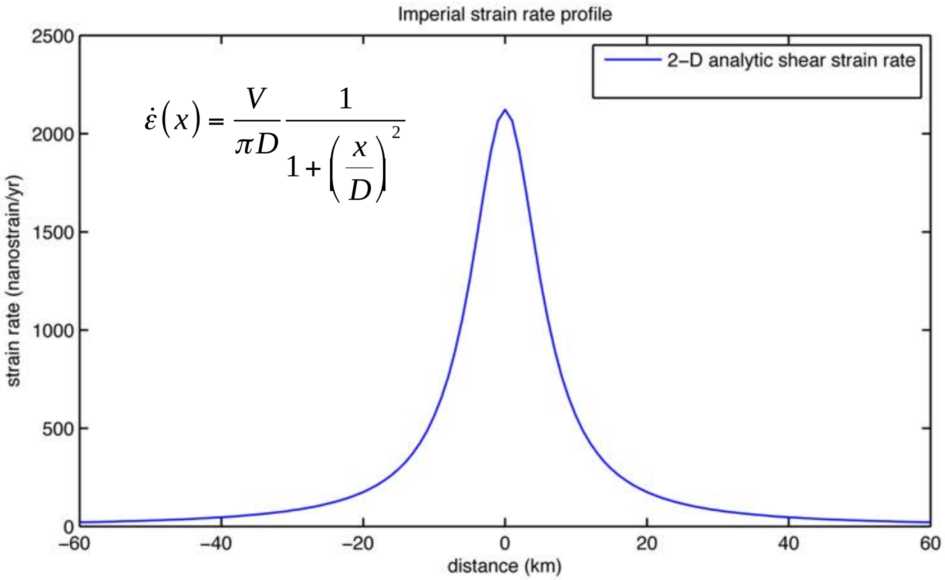
Imperial array

High density campaign GPS measurements across the Imperial fault provide the data needed to estimate the strain rate [Lyons et al., 2002]. The best-fit 2-D dislocation model has a velocity V_o of 40 mm/yr and a locking depth *D* of 6 km (upper plot). The derivative of this velocity profile provides the shear strain rate (lower plot). The peak strain rate is given by

$$\dot{\varepsilon} = \frac{V}{\pi D}$$

which in this case has a value of 2120 nanostrain/yr.





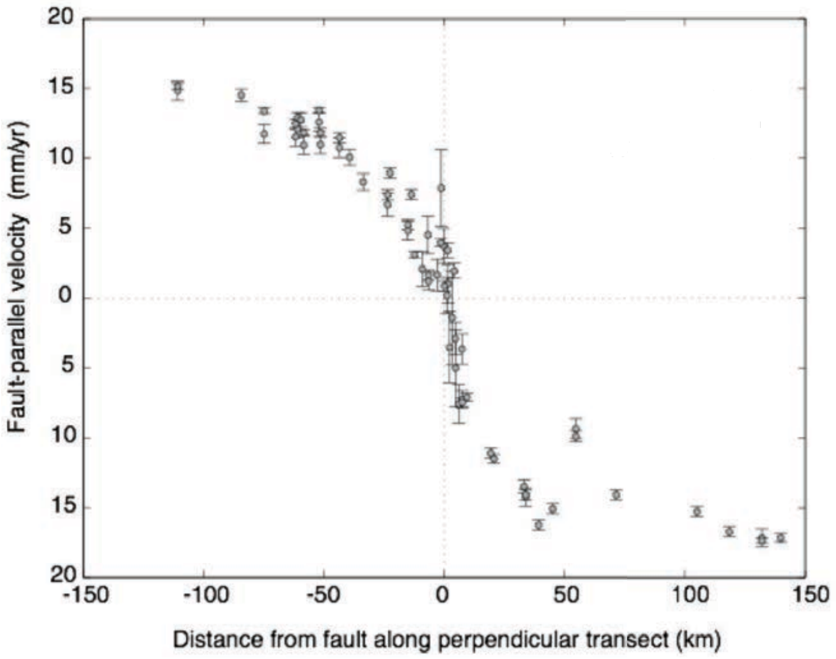
Carrizo GPS data

Earthquake Cycle Exercise, April, 2010.

“Participants were given a GPS velocity profile, that is, the fault-parallel velocity, one-sigma error, and distance to the fault for 64 GPS sites (Figure 10). The data were from the San Andreas Fault at the Carrizo Plain, though this was not mentioned in the exercise. Participants were asked to devise models that could explain the velocity profile.

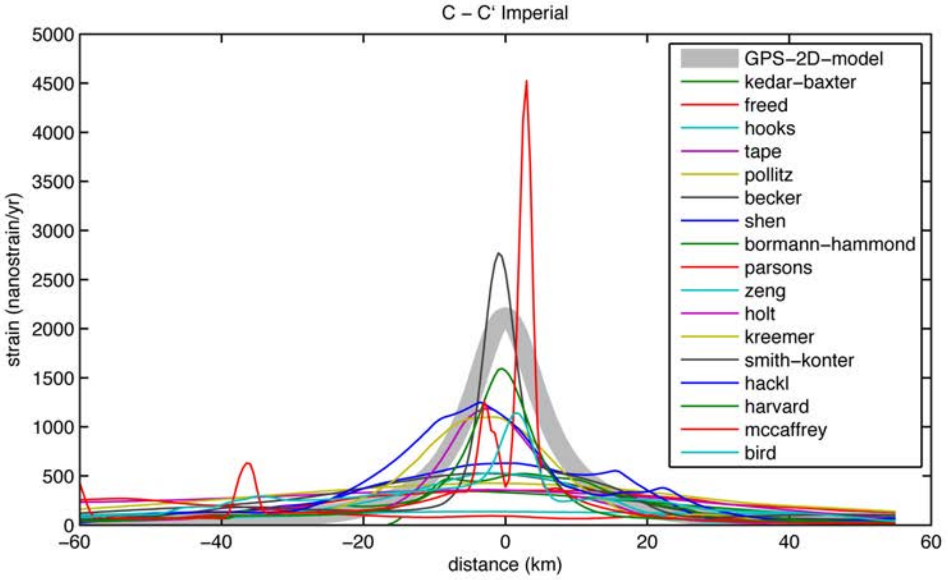
Elastic dislocation models, including those with a dipping fault and elastic heterogeneities, gave a slip rate of 33 to 35 mm/yr and a locking depth of 17 to 19 km.”

Using V=35 and D=17 and the peak strain rate is 790 nanostrain/yr.



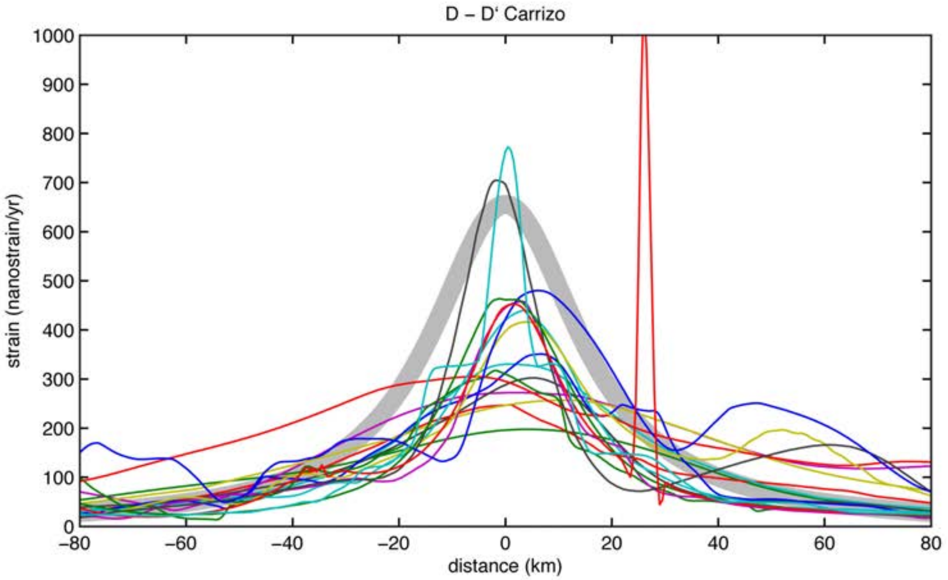
	elastic	**viscoelastic**	**“believable” viscoelastic**	**viscoelastic with fault creep**	**“believable”viscoelastic with fault creep**
Vo (mm/yr)	33.5 - 37	30-60	33-35 (36-40)	35-45	33-35 (35-40)
Zl (km)	16 - 19	6 to 25	16-18 (20-25)	5 -19	10 -15(10)
stress rate (kPa/yr)	25	18-30	25-26	23-25	20-25

Strain rate profiles from all 17 models.



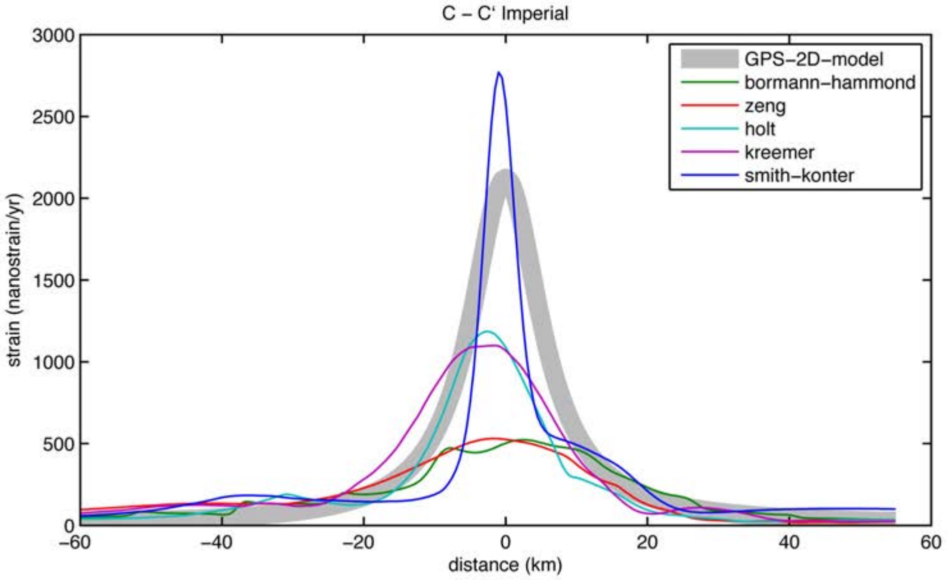
Comapred with best-fit 2-D Savage model

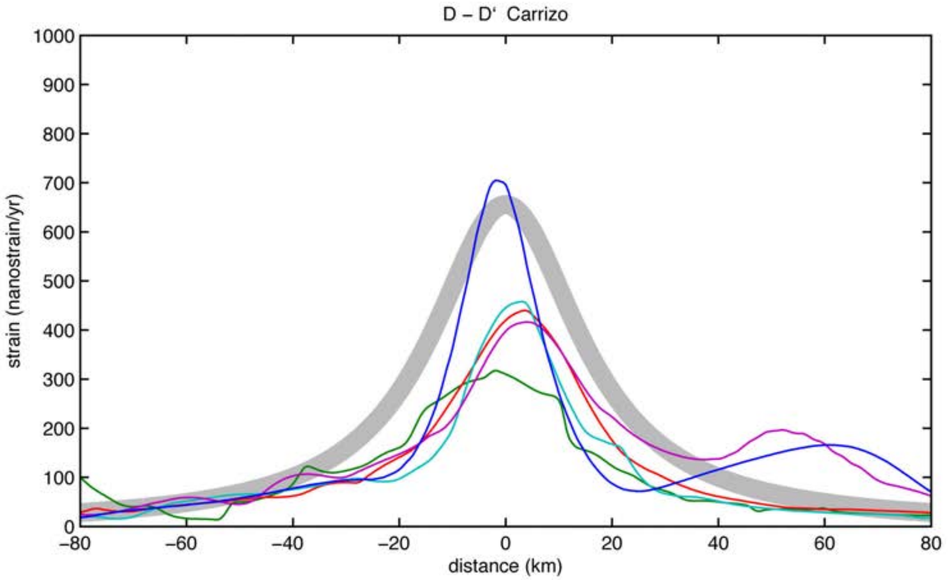
12 of the 17 models have unrealistic low strain rate above the fault which results in **unrealistic high strain rate away from faults**.



Strain rate profiles from 5 best models.

Comapred with best-fit 2-D Savage model





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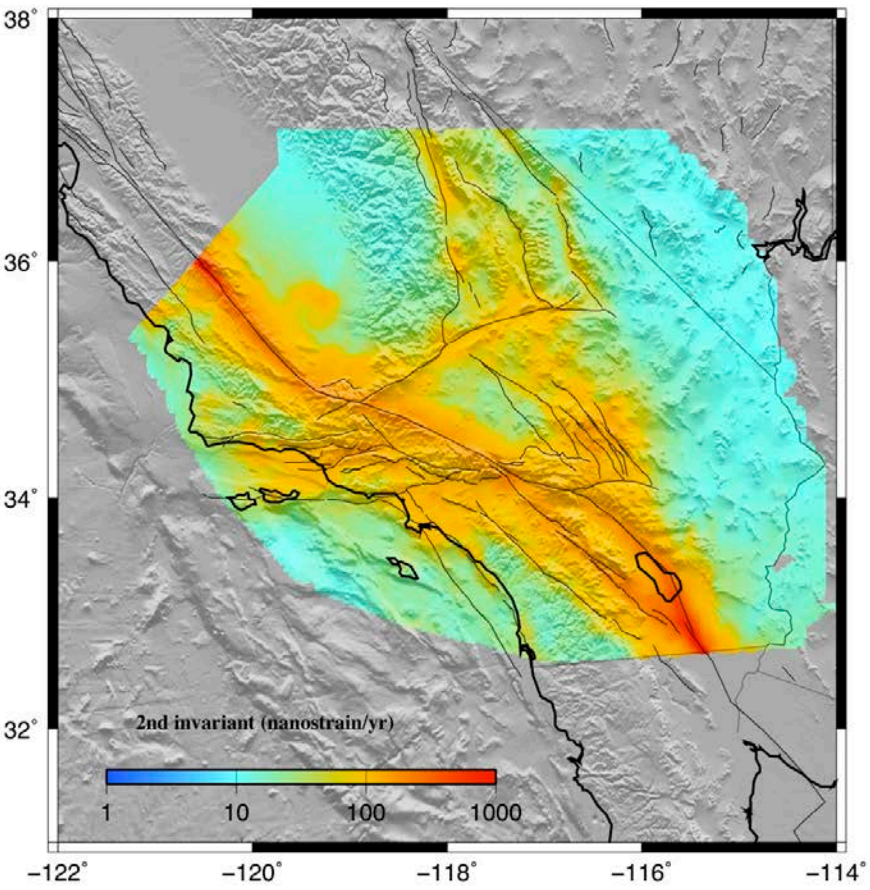
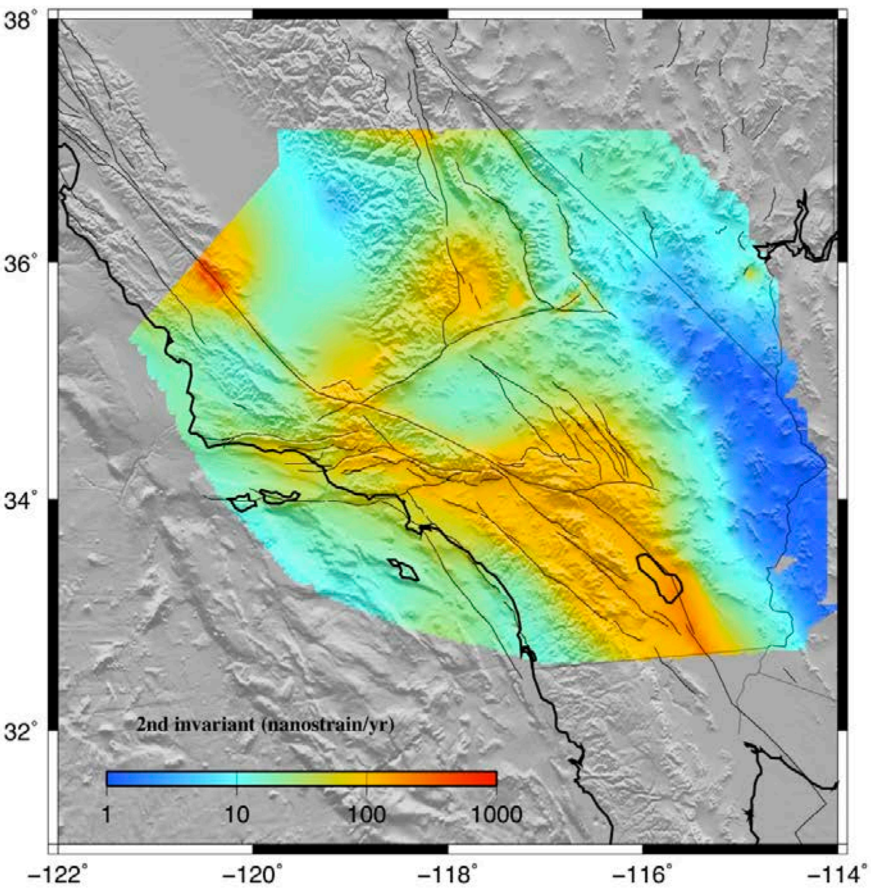
average of 5 “best” models

mean



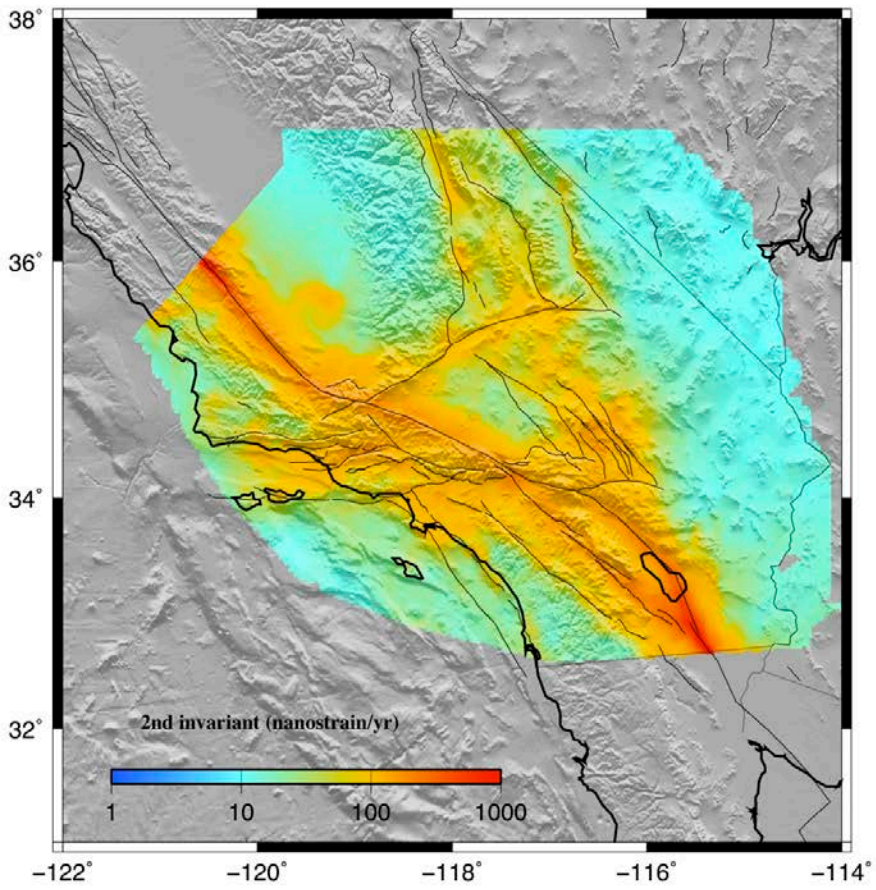
SEISM_strain = $10^{rate+5.3}$

SEISM



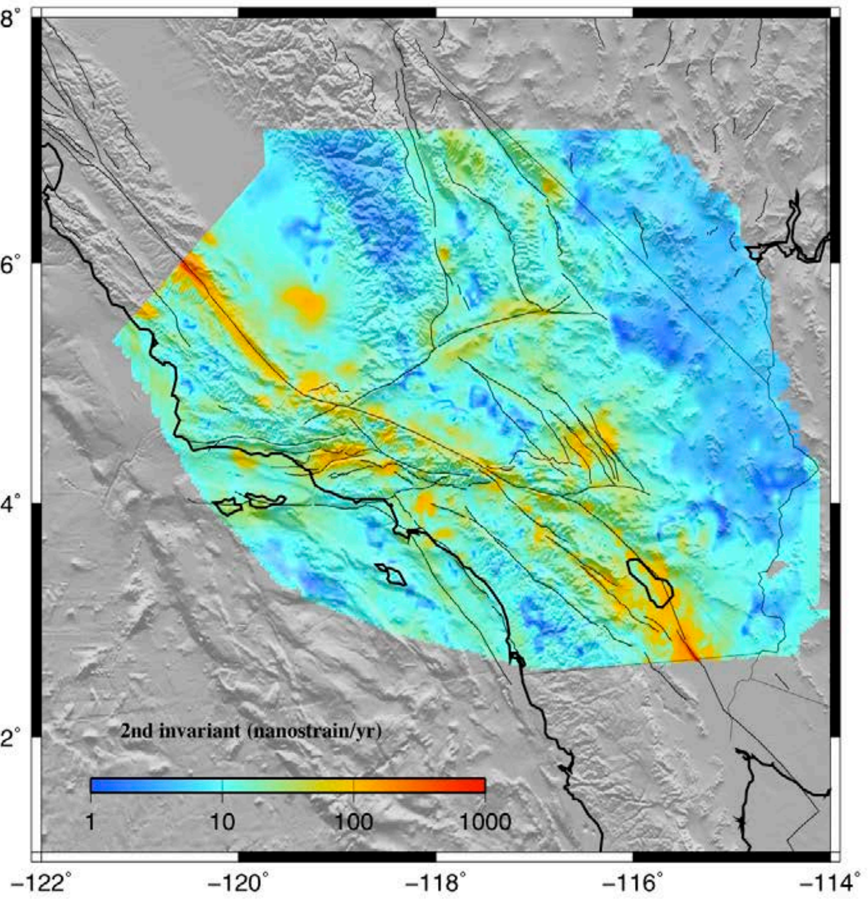
average of 5 “best” models

mean



std of 5 “best” models

std



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Overall Results

	UCERF2	SEISM	SHmax (rms ˚)	Rank
borman	.65	.71	20.1	5
holt	.76	.80	15.8	1
kreemer	.66	.79	18.1	4
smith_konter	.71	.75	14.0	2
zeng	.76	.75	17.2	3

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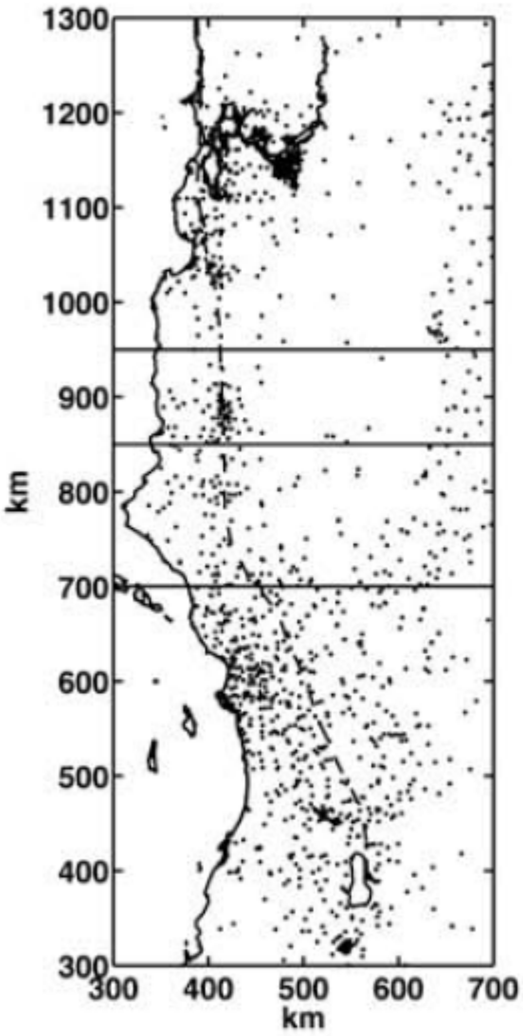
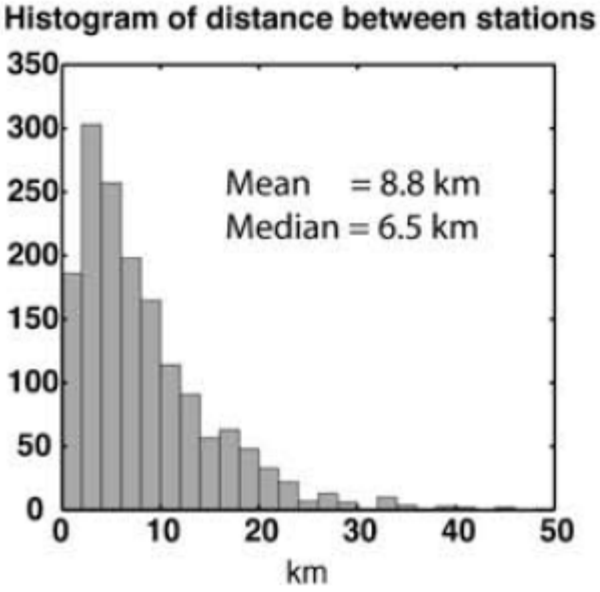
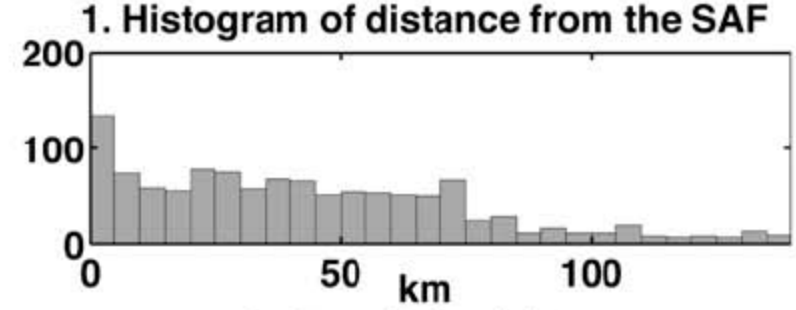
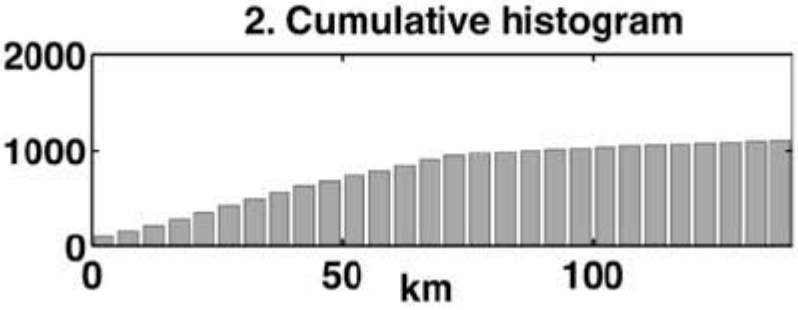
Median Spacing of GPS Stations



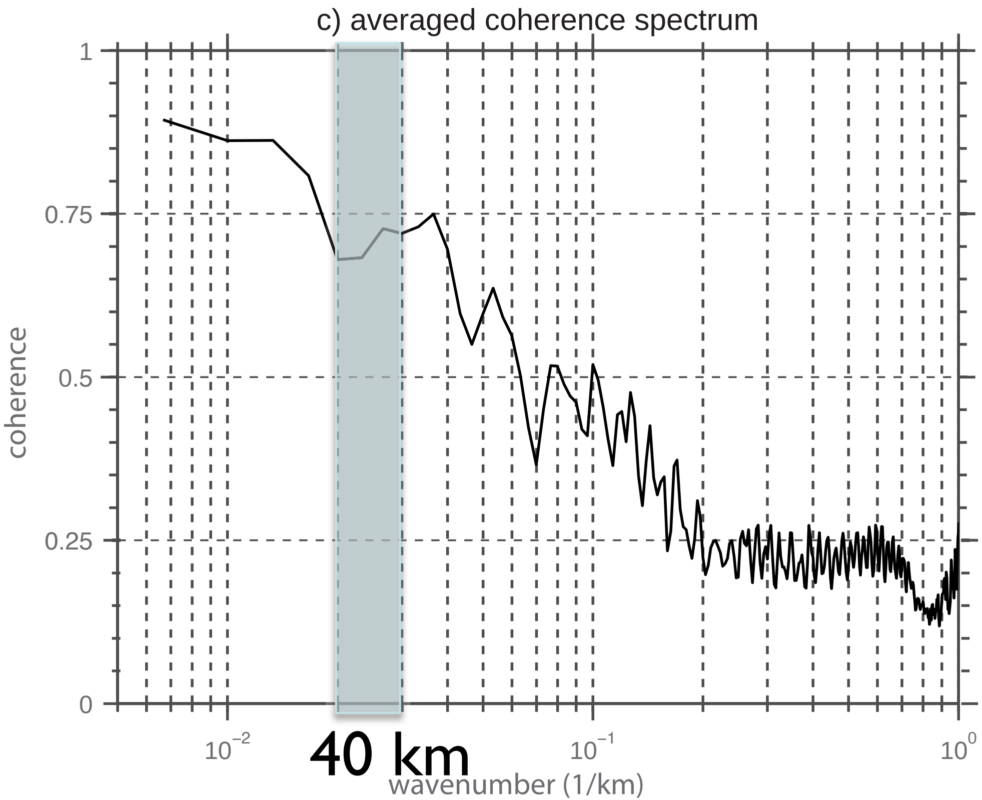




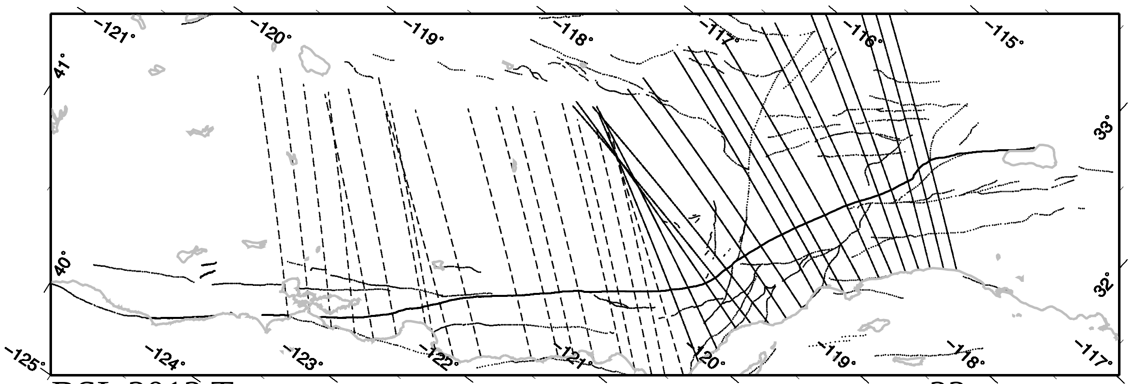


[Wei et al. 2010]

Coherence Spectrum of the 4 Block Models



- GPS model are coherent at wavelength > 40 km
- Due to the spacing of the GPS sites



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New Missions

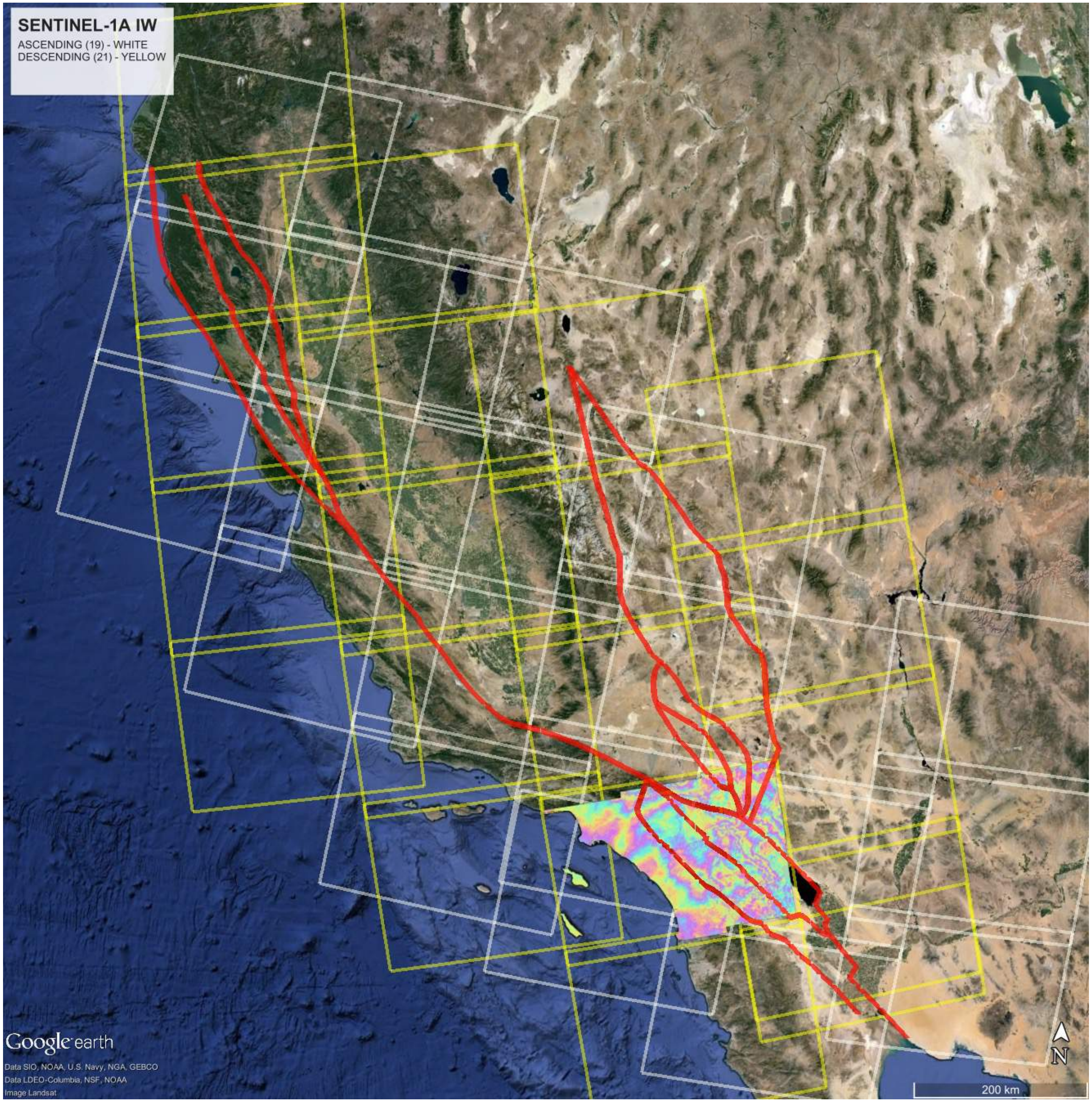
- Sentinel-1A (ESA) was successfully April 3, 2014, SAR collecting data!
  - C-band , 12-day repeat
  - Mostly ScanSAR coverage of the SAF, ascending and descending
  - completely open data access – finally!!
  - Sentinel-1B to be launched 2016 and will provide 6-day repeat interval

- ALOS-2 (JAXA) was successfully launched May 24, 2014, SAR collecting data!
  - L-band, 14-day repeat
  - Mostly ScanSAR coverage of the SAF on descending and swath-mode on ascending
  - PI proposal needed for data access
  - limited quantities per PI

Coverage of the San Andreas Fault System from Sentinel-1

Today each frame has 15 repeats on a 24-day cadence.

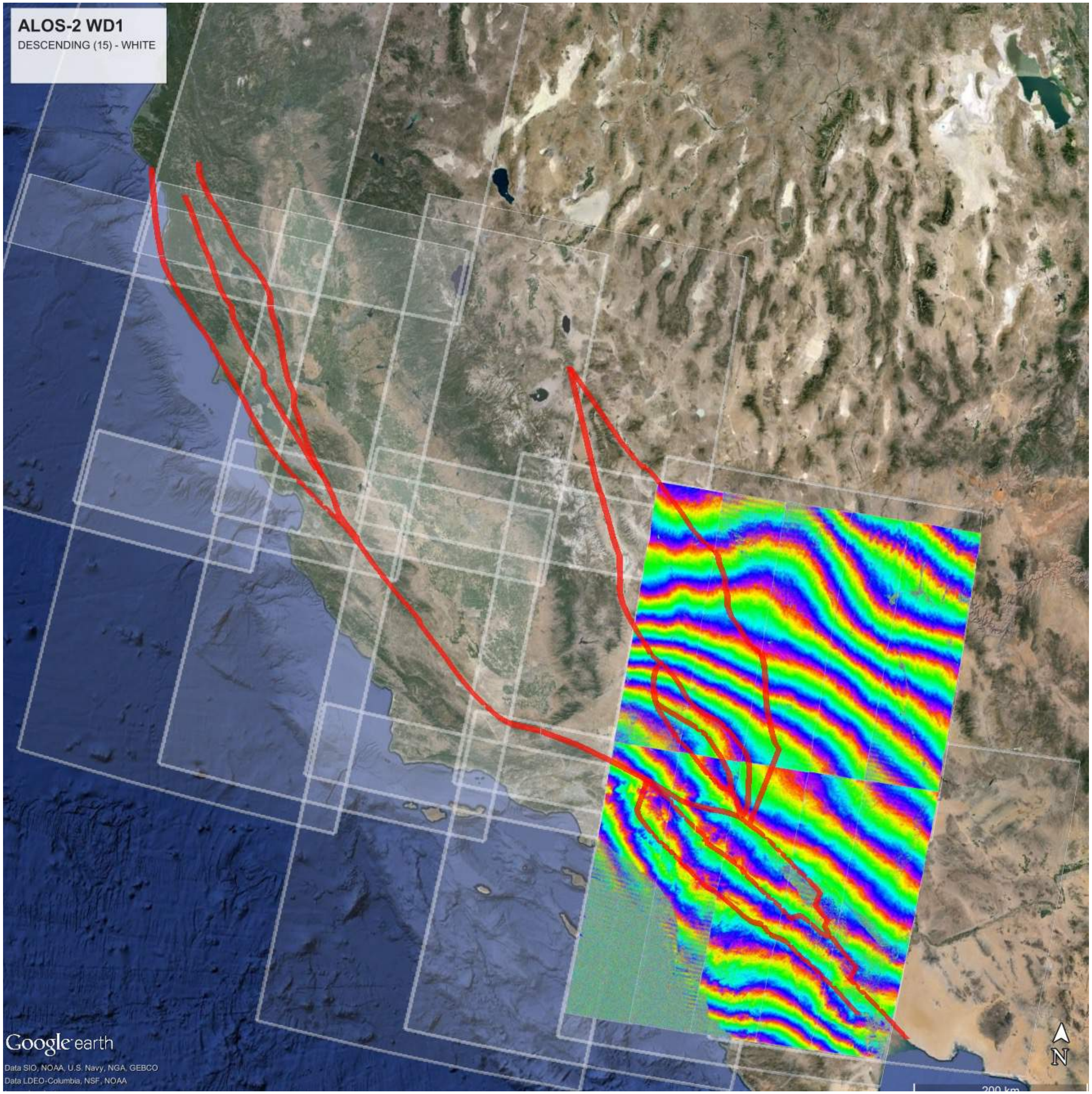
Each interferogram is 250 km by 200 km.



Coverage of the San Andreas Fault System from ALOS-2

Today each frame
has 9 repeats on a
42-day cadence.

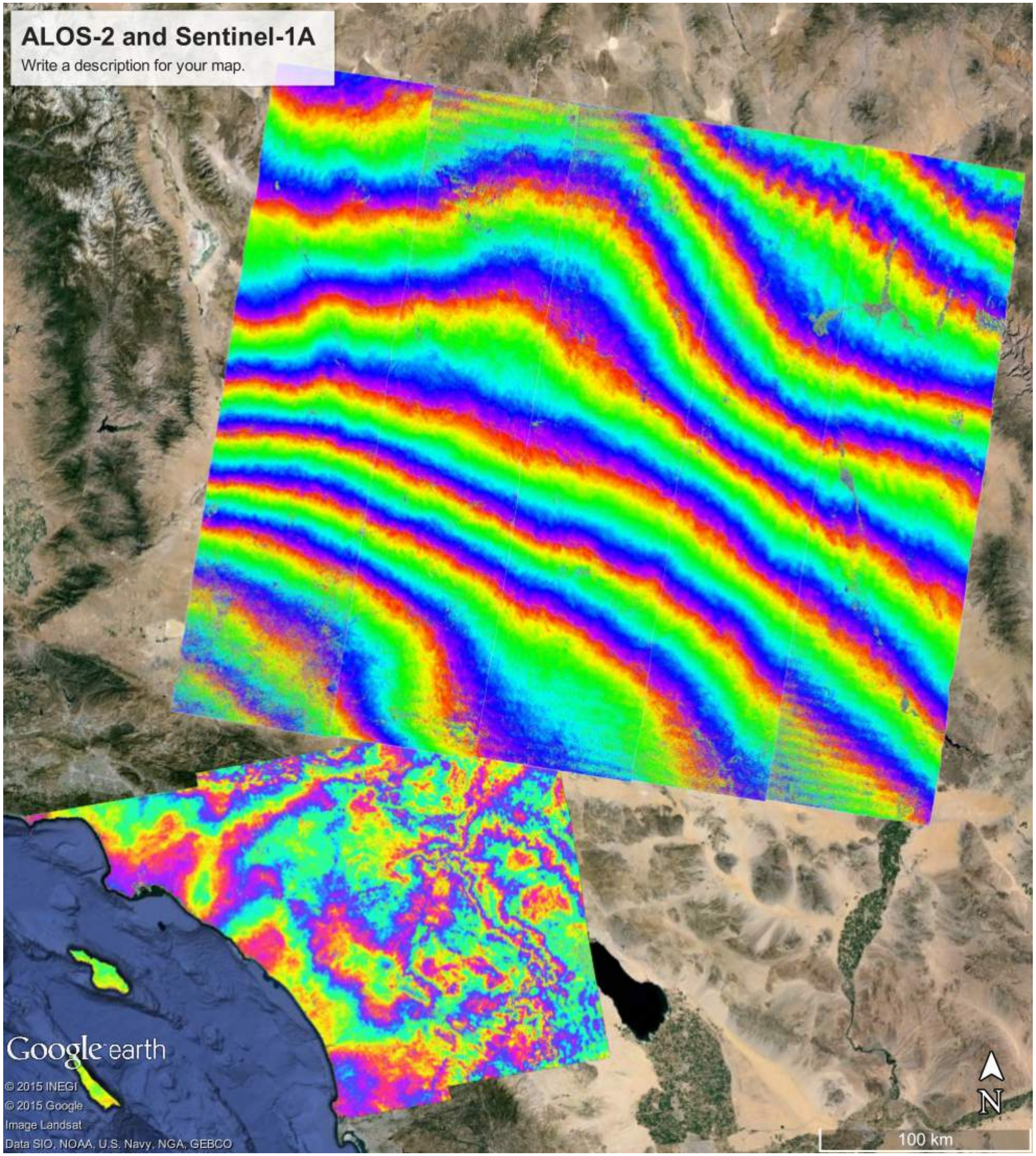
Each ALOS-2 interogram
is 350 km by 350 km



Example interferograms from ALOS-2 and Sentinel-1A.

New processing methods are needed to achieve seamless coverage.

Large trends in ALOS-2 InSAR may reflect spatial variations in ionosphere TEC.

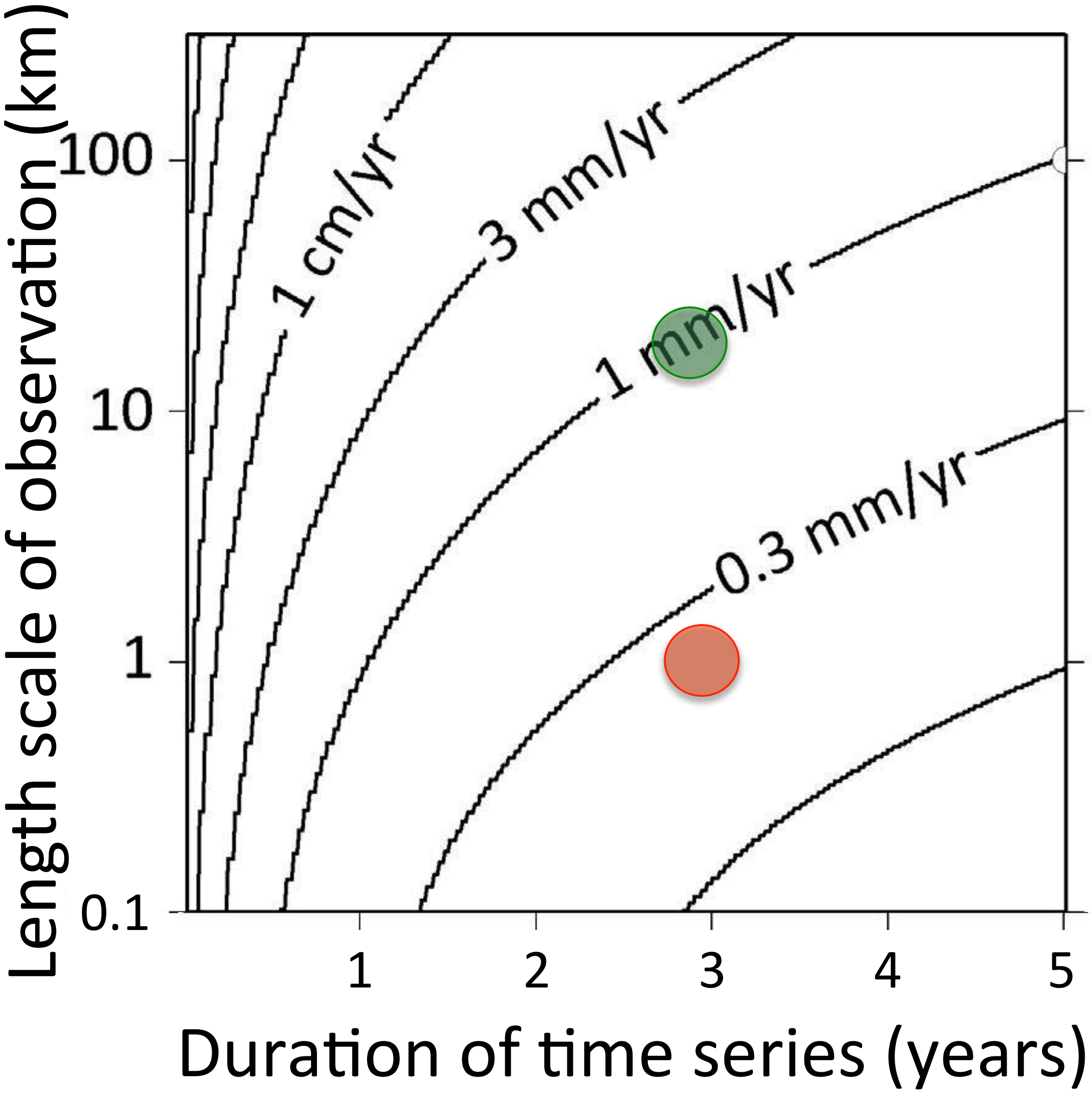


Expected velocity error from Sentinel-1a observations at 12-day intervals. Assumes atmospheric error model of *Emardson et al.,* [2003].

1 mm/yr accuracy can be achieved in 3 years for areas with ~20 km GPS spacing.

250 nanostrain over at 1 km resolution can be achieved in 3 years.

(Tim Wright, personal communication, 2015)

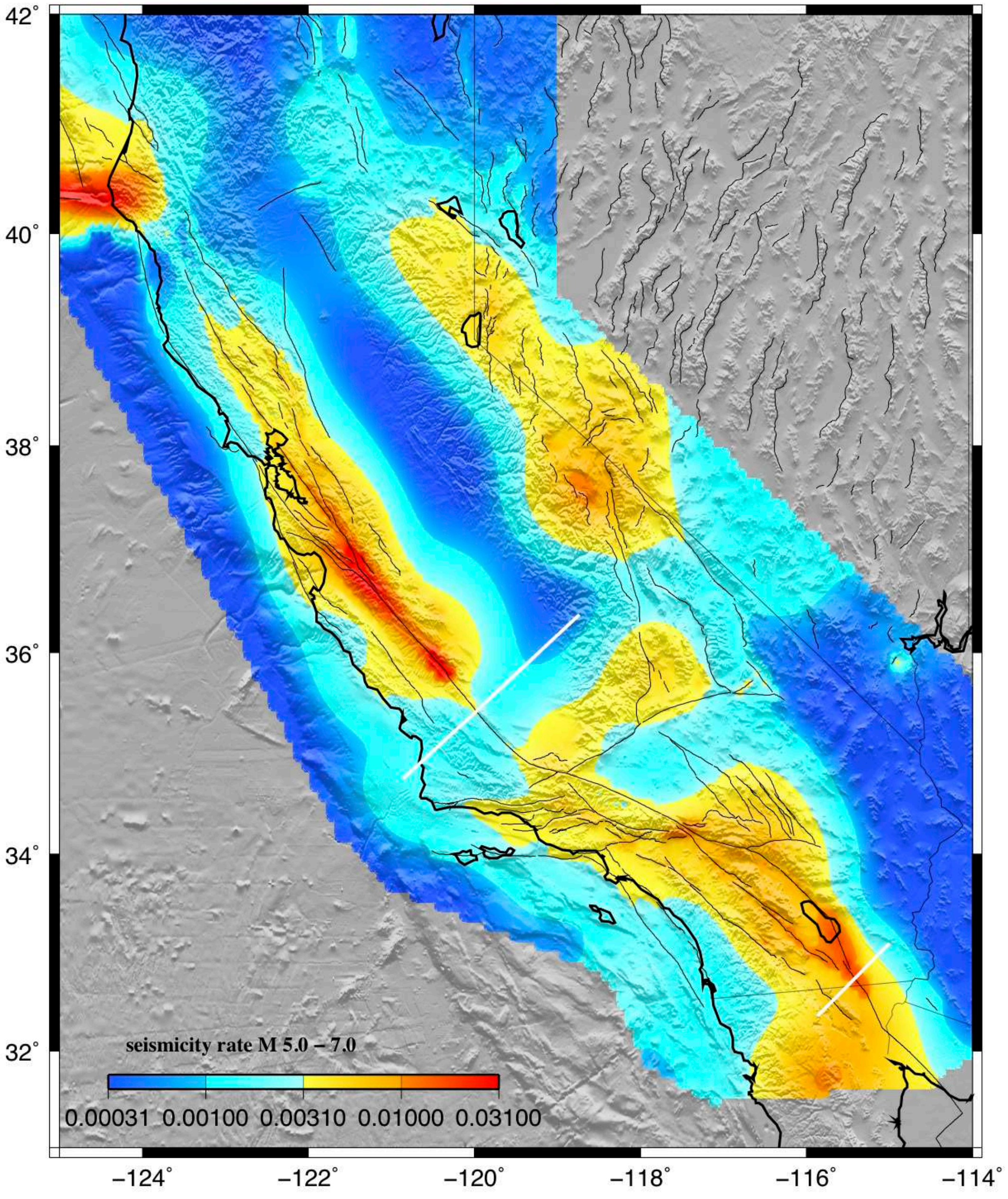


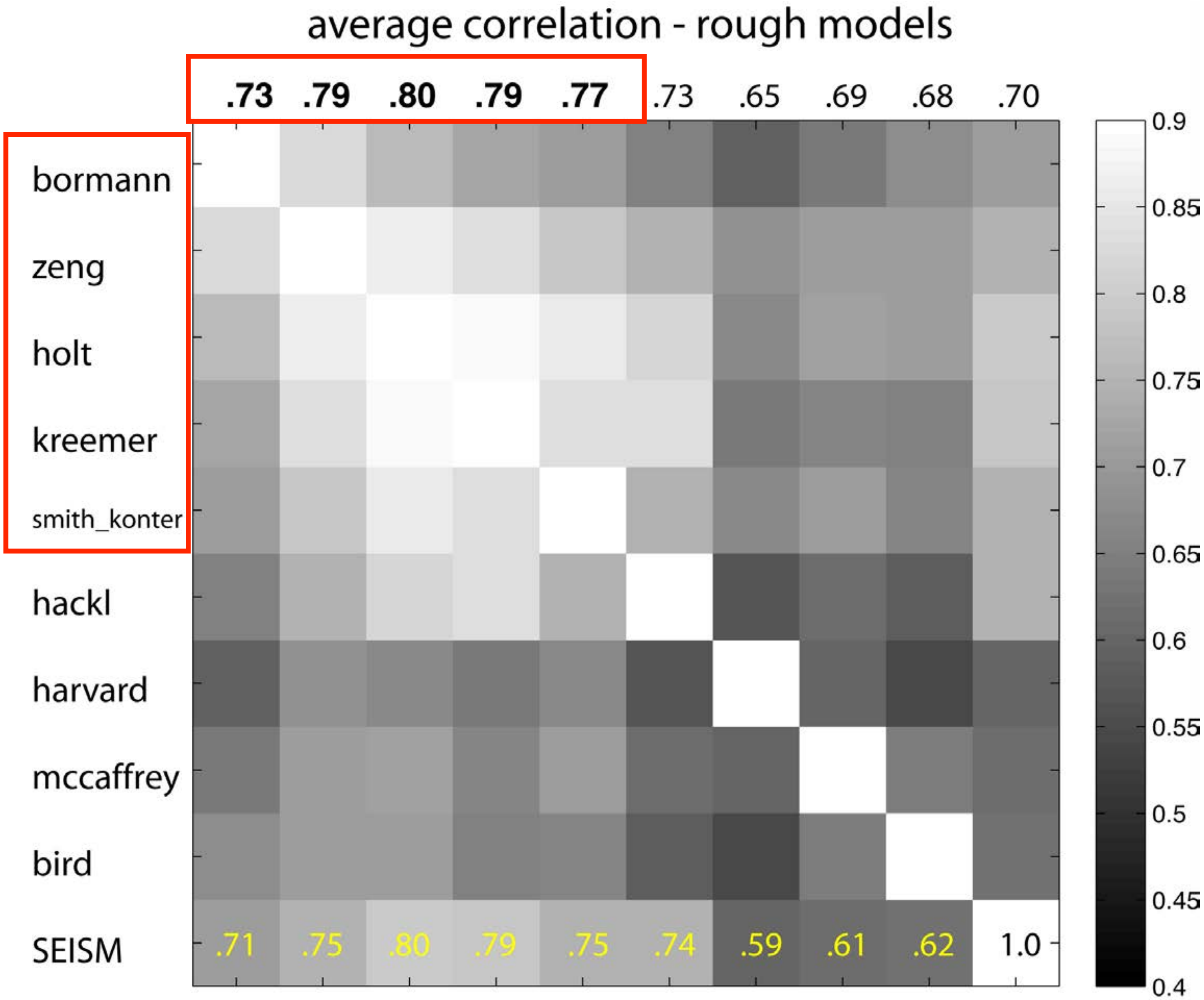
Conclusions

- The current GPS sampling of ~8 km is insufficient for unique recoverly of strain rate. Need a fault model to localize strain and provide direction.
- The 5 “best” models are similar to each other and to the log of the seismicity rate.
- New InSAR satellites will deliver 1 km spatial resolution strain rate maps accurate to 250 nanostrain/yr. Then we won’t need fault models to guide the interpolation.

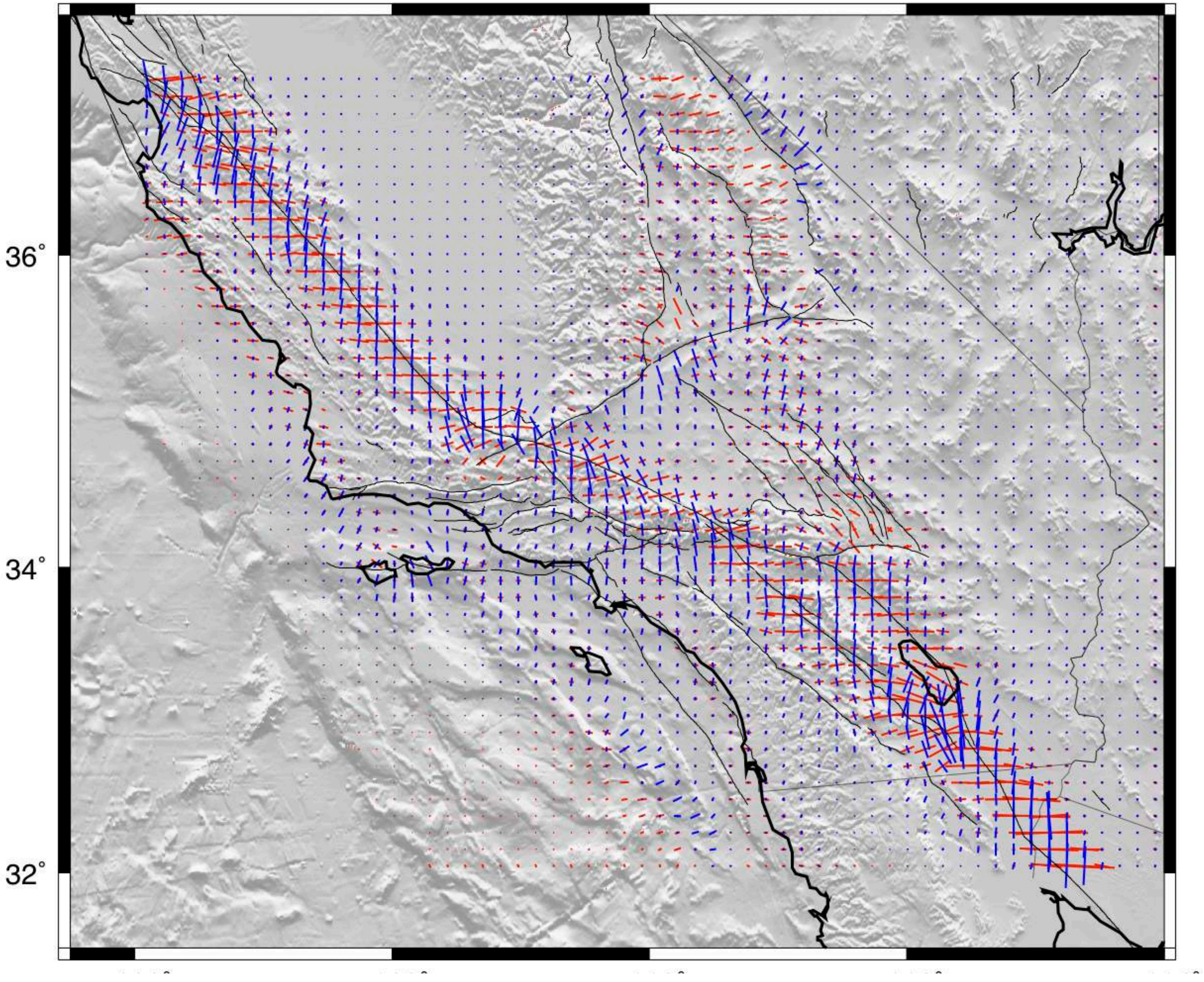
SEISM

The background seismicity model is included to account for M 5.0 - 6.5 earthquakes on faults and for random M 5.0 – 7.0 earthquakes that do not occur on faults included in the model (as in earlier models of Frankel et al., 1996, 2002 and Petersen et al., 1996). We include four different classes of earthquake sources in the California background seismicity model: (1) gridded (smoothed) seismicity, (2) regional background zones, (3) special fault zone models, and (4) shear zones (also referred to as C zones). The gridded (smoothed) seismicity model, the regional background zone model, and the special fault zones use a declustered earthquake catalog for calculation of earthquake rates. Earthquake rates in shear zones are estimated from the geodetically determined rate of deformation across an area of high strain rate. We use a truncated exponential (Gutenberg-Richter, 1944) magnitude-frequency distribution to account for earthquakes in the background models.

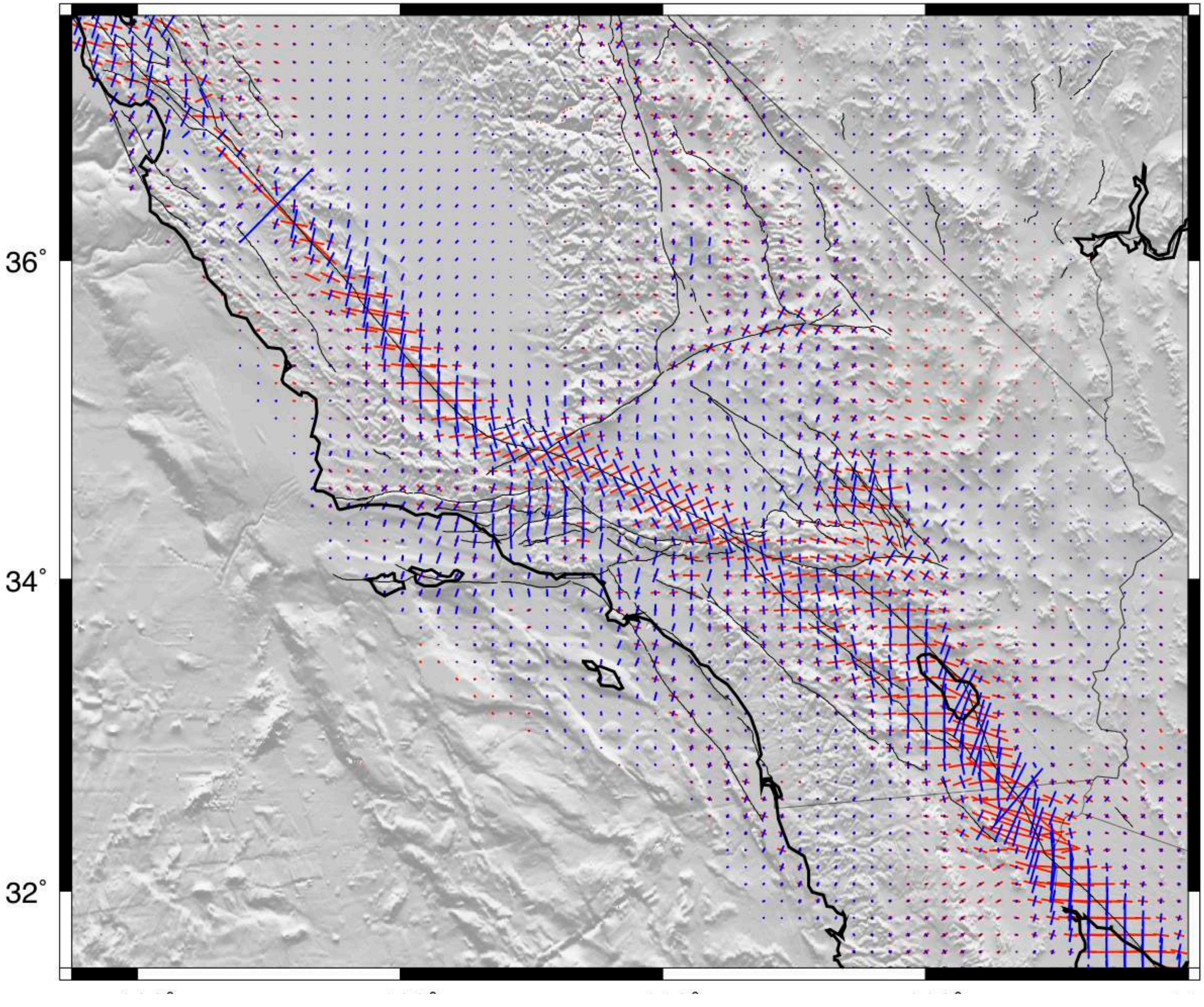



average correlation - rough models
.73
.79
.80
.79
.77
.73
.65
.69
.68
.70
bormann
zeng
holt
kreemer
smith_konter
hackl
harvard
mccaffrey
bird
SEISM
.71
.75
.80
.79
.75
.74
.59
.61
.62
1.0
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4

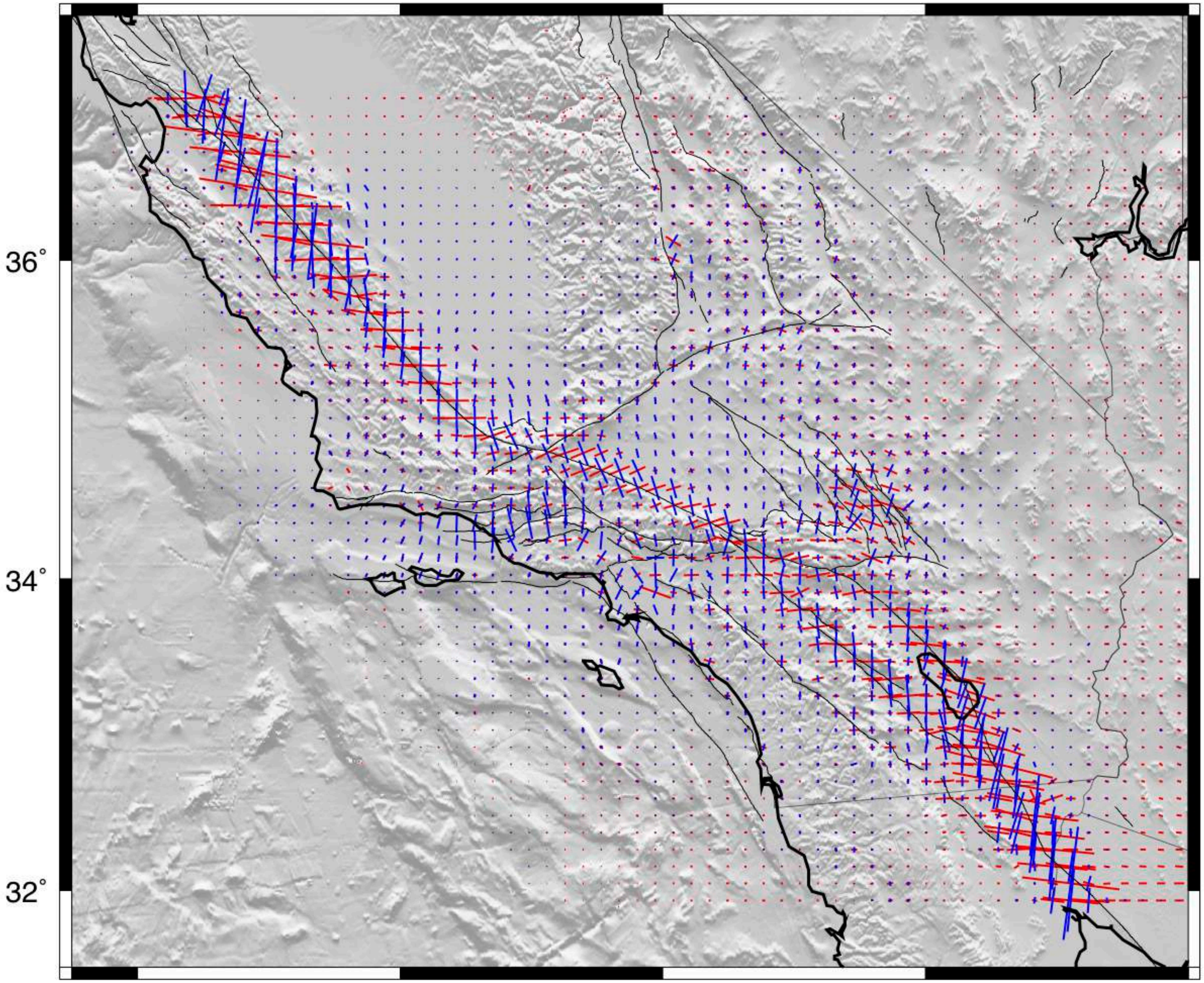
bormann_hammond



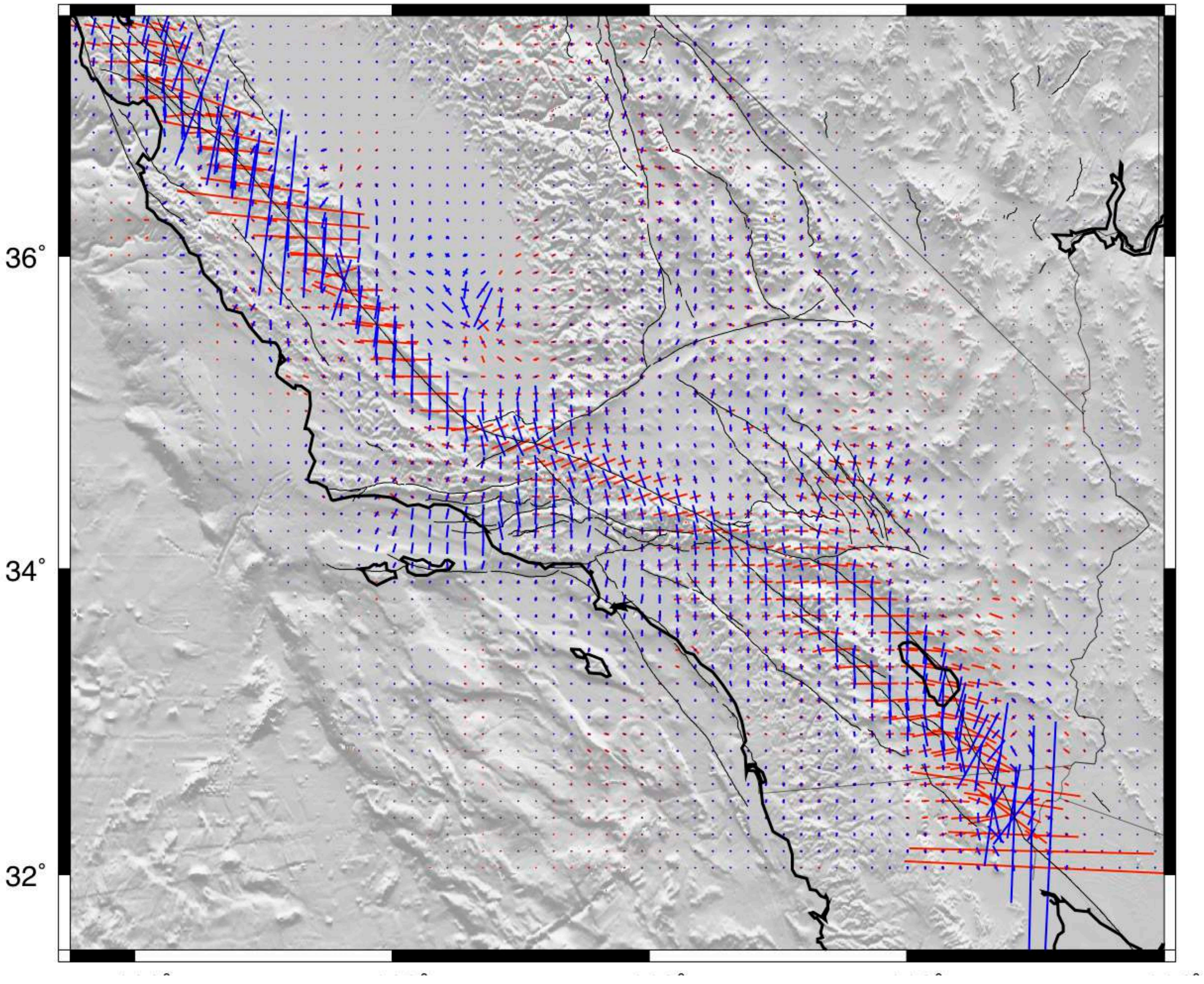
zeng



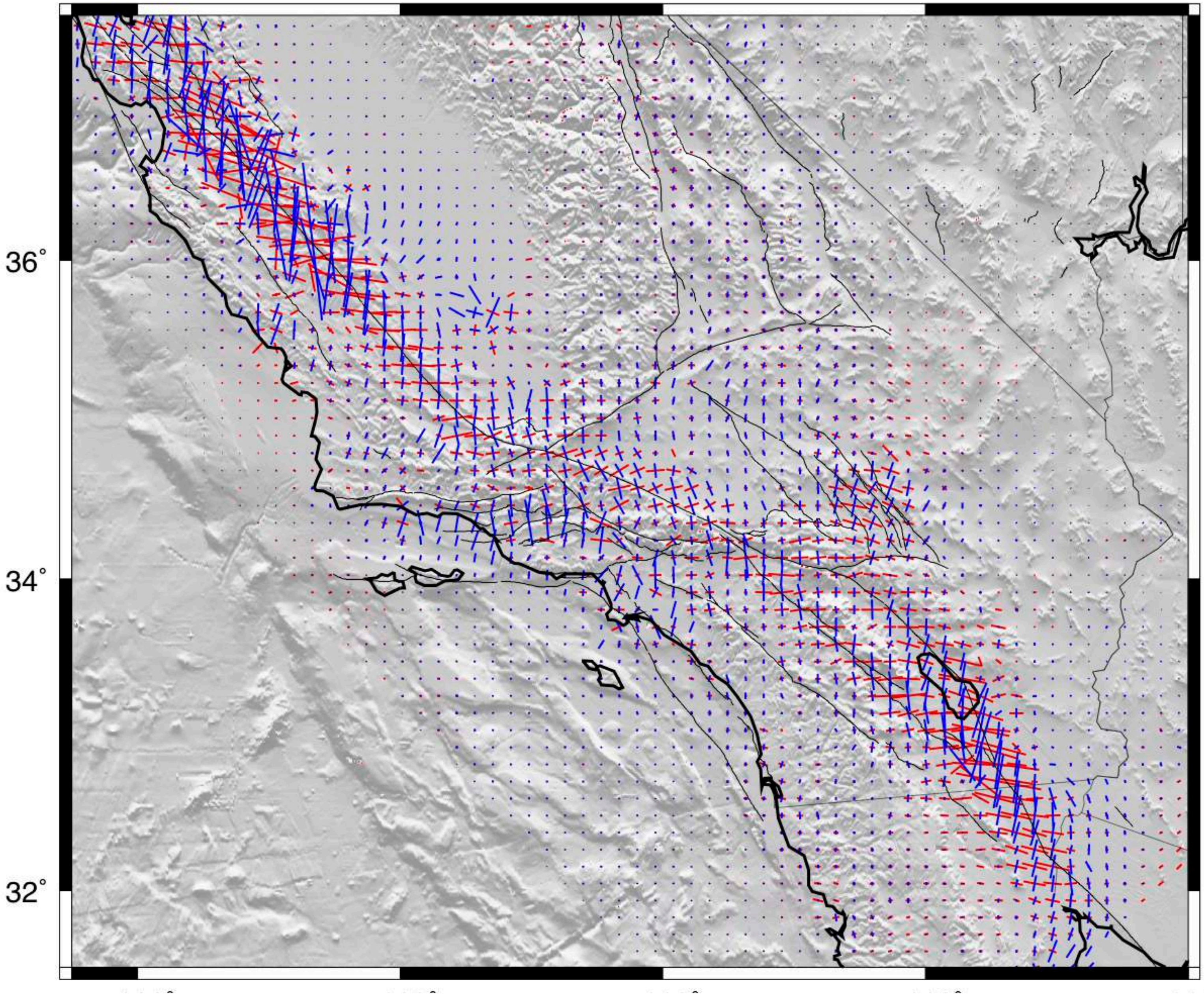
holt

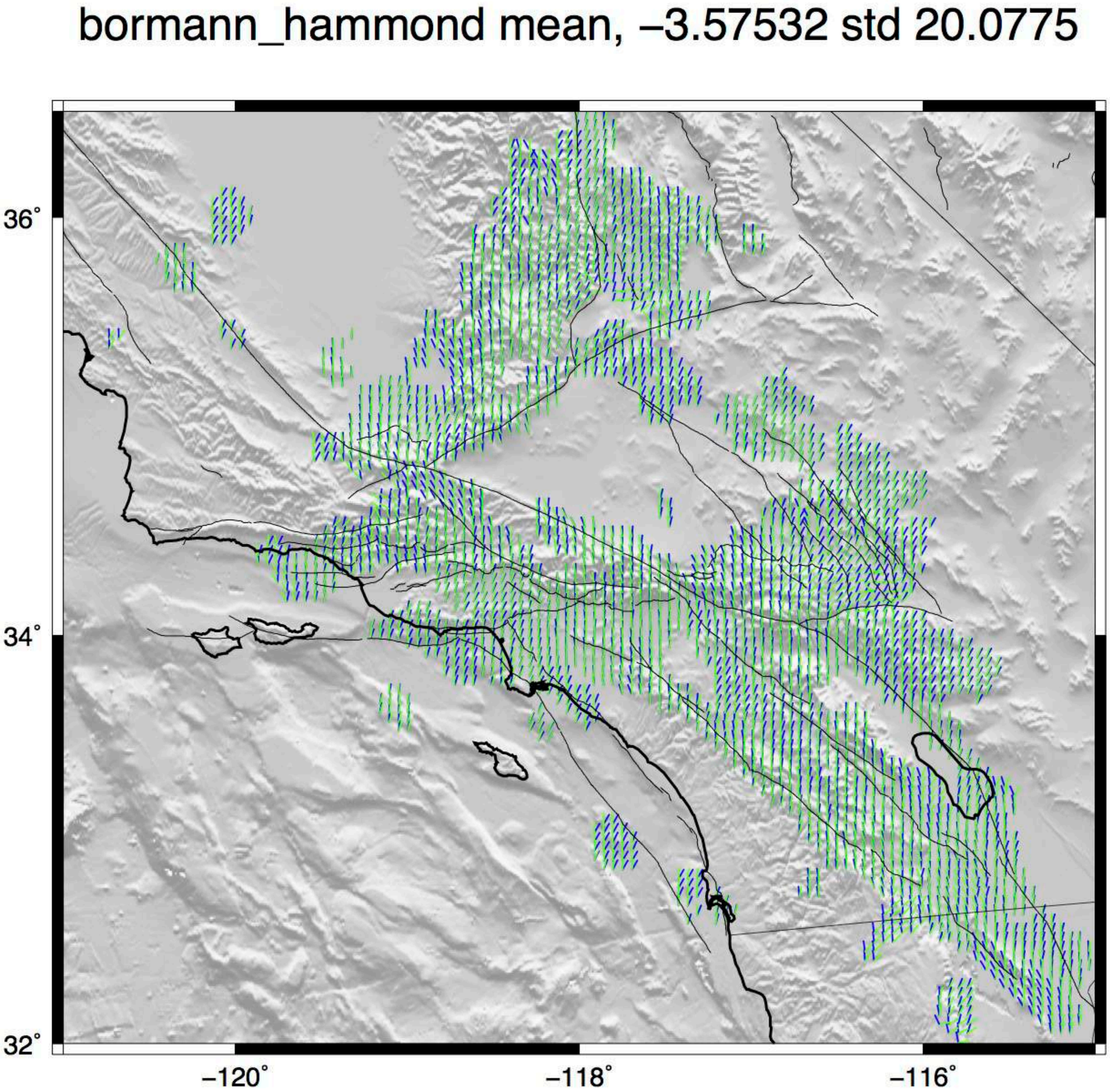


smith_konter



kreemer

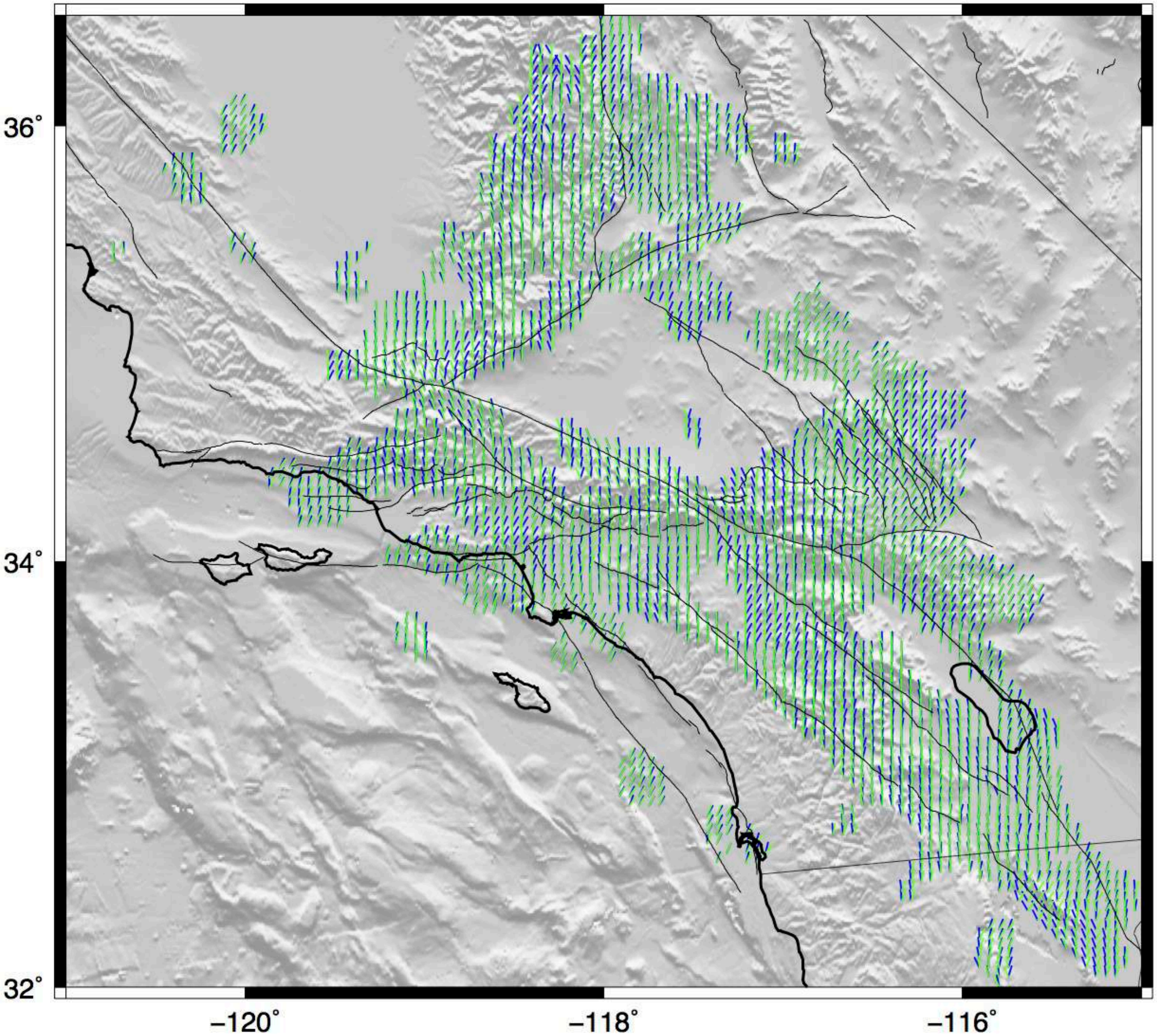




blue – SHmax
green - comp

095 ηs

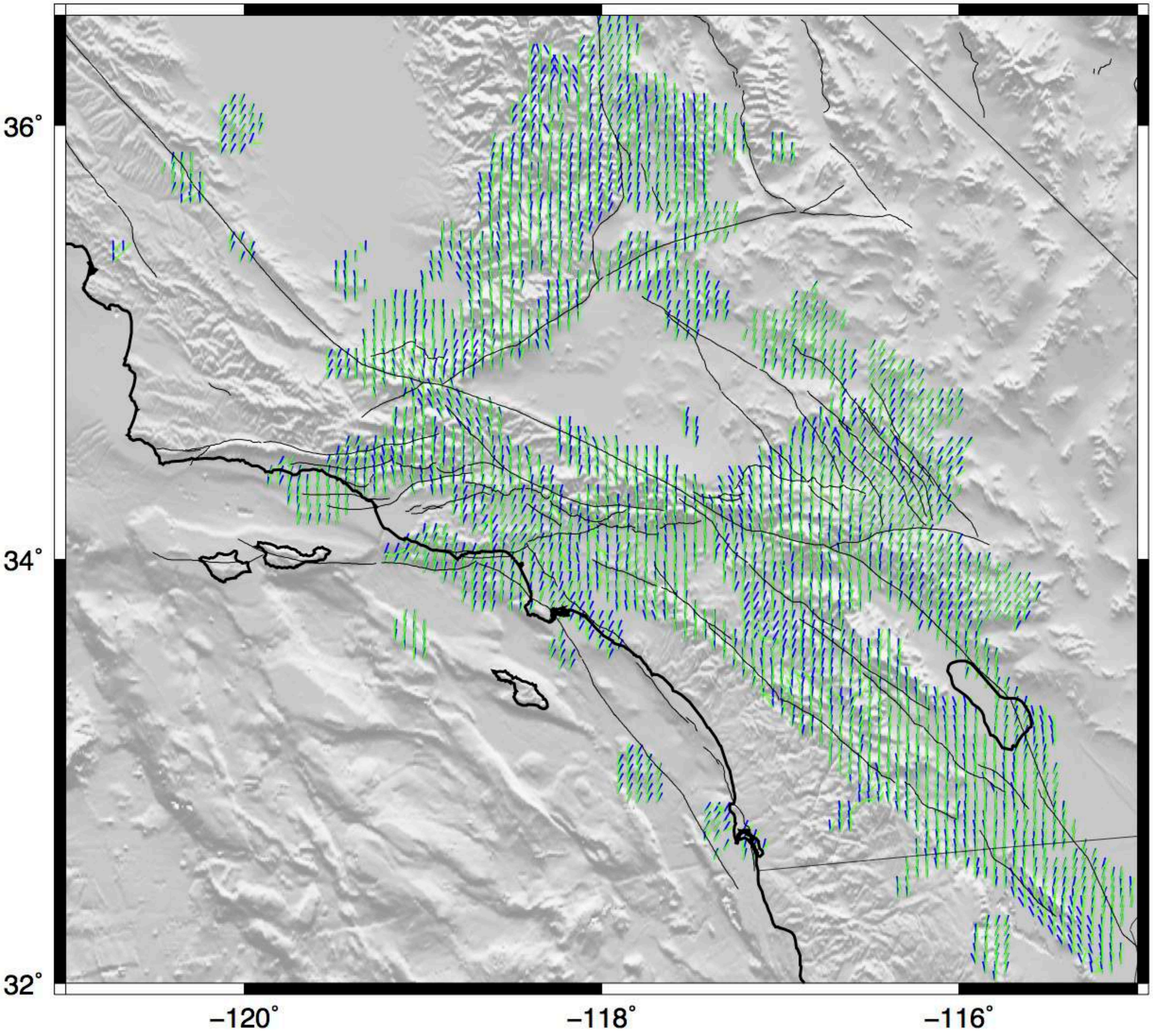
zeng mean, –4.77864 std 17.2355



blue – SHmax
green - comp

111 ηs

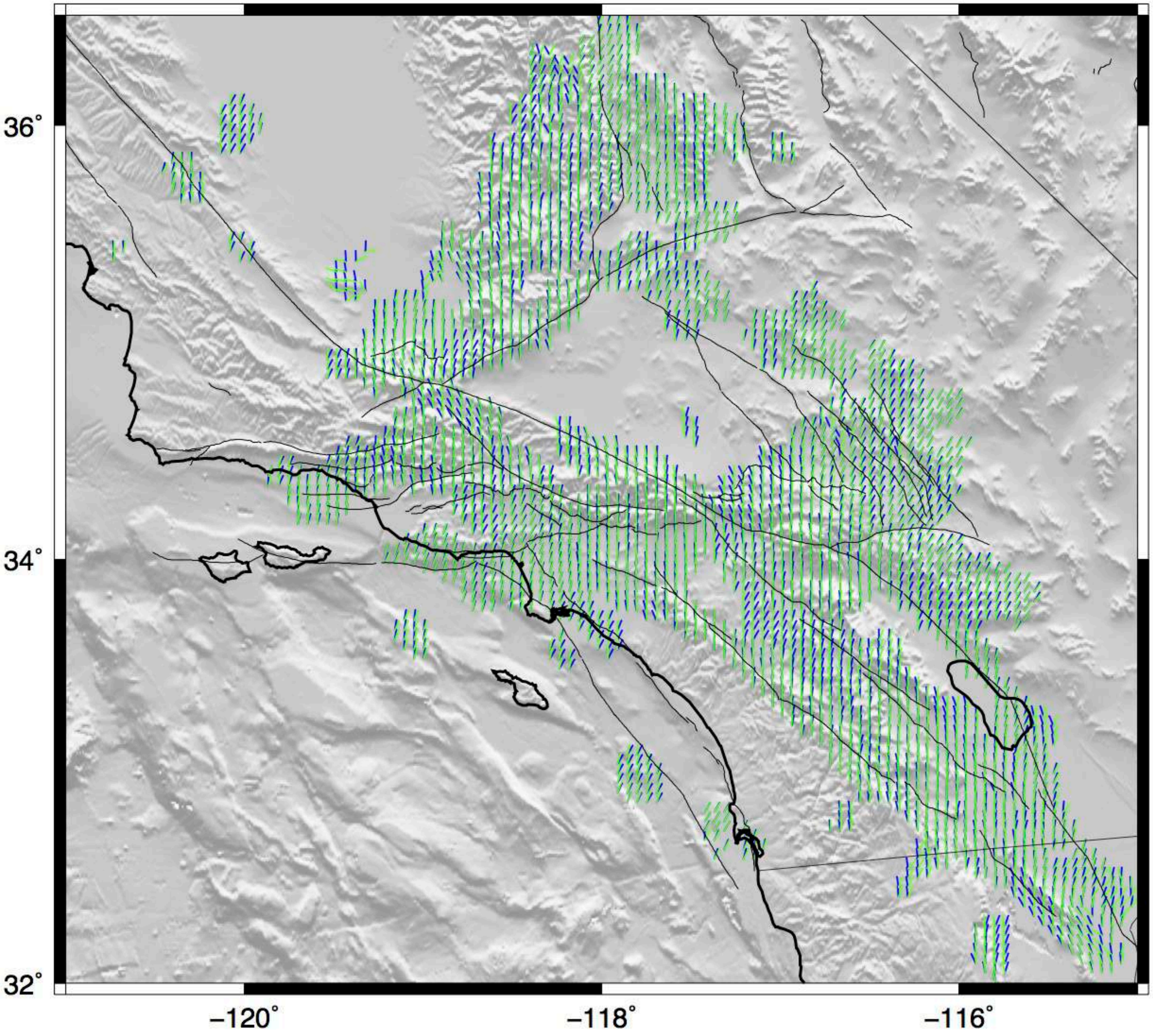
holt mean, –4.41174 std 15.8018



blue – SHmax
green - comp

123 ηs

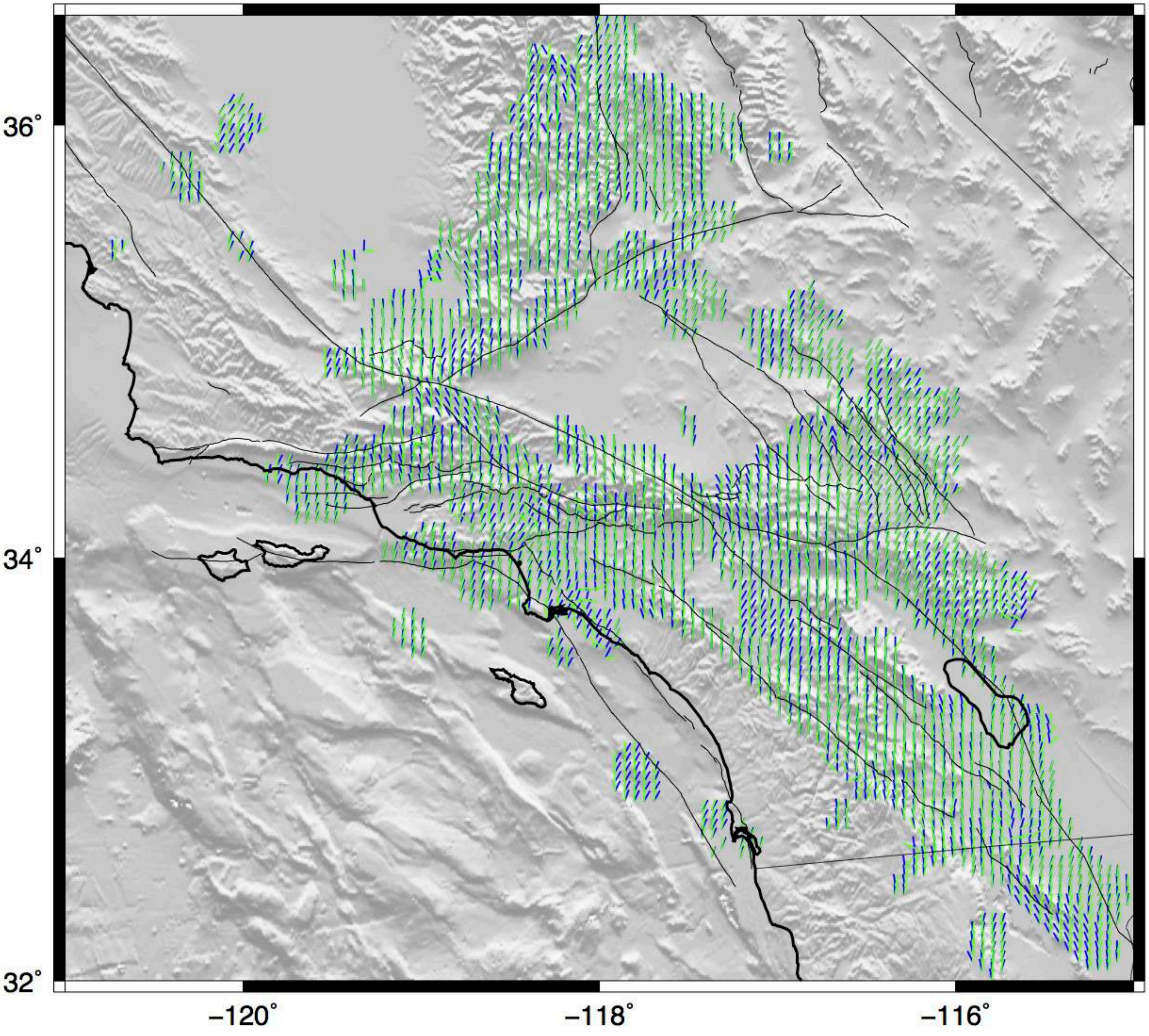
smith_konter mean, –5.13954 std 13.9929



blue – SHmax
green - comp

114 ηs

kreemer mean, –4.71275 std 18.1131



blue – SHmax
green - comp