The Ups and Downs of Southern California: Mountain Building, Sea Level Rise, and Earthquake Potential from Geodetic Imaging of Vertical Crustal Motion

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Imaging Vertical Land Motion for Earth Science

<u>The Global Explosion of GPS data</u>

- Processing the Earth's GPS Networks
- Data Products
- **Plug and Play GPS** for Earth Science

<u>Sierra Nevada Uplift</u>

- Imaging **Vertical Land Motion** (VLM)
- Emblematic of many problems and opportunities we have in tectonic geodesy

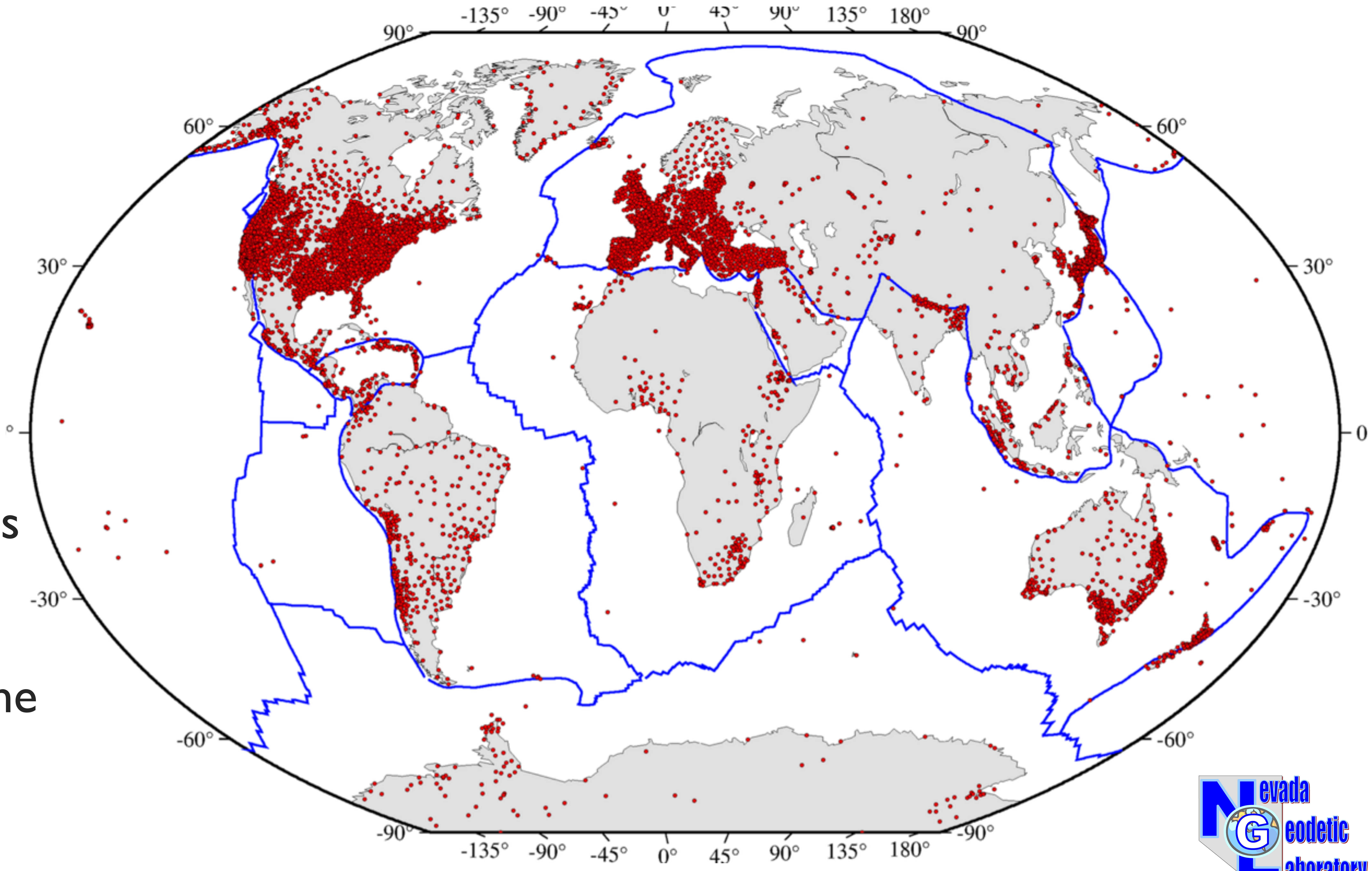
<u>Southern California</u>

- A four-technique study for the SCEC Ventura Special Fault Study Area/ Western Transverse Ranges
- Separation of tectonic and non-tectonic signals

Explosion: Global GPS Networks

- We have a lot of data to constrain VLM on Earth
- Exceeded 15,000 stations in NGL archive this week
- Hundreds of individual networks
- Processed uniformly at NGL using GIPSY/OASIS and JPL products
- Time series duration as long as 20 years
- Latency as low as 2 hours
- All solutions open access online
- http://geodesy.unr.edu

Distribution of GPS stations in NGL archive



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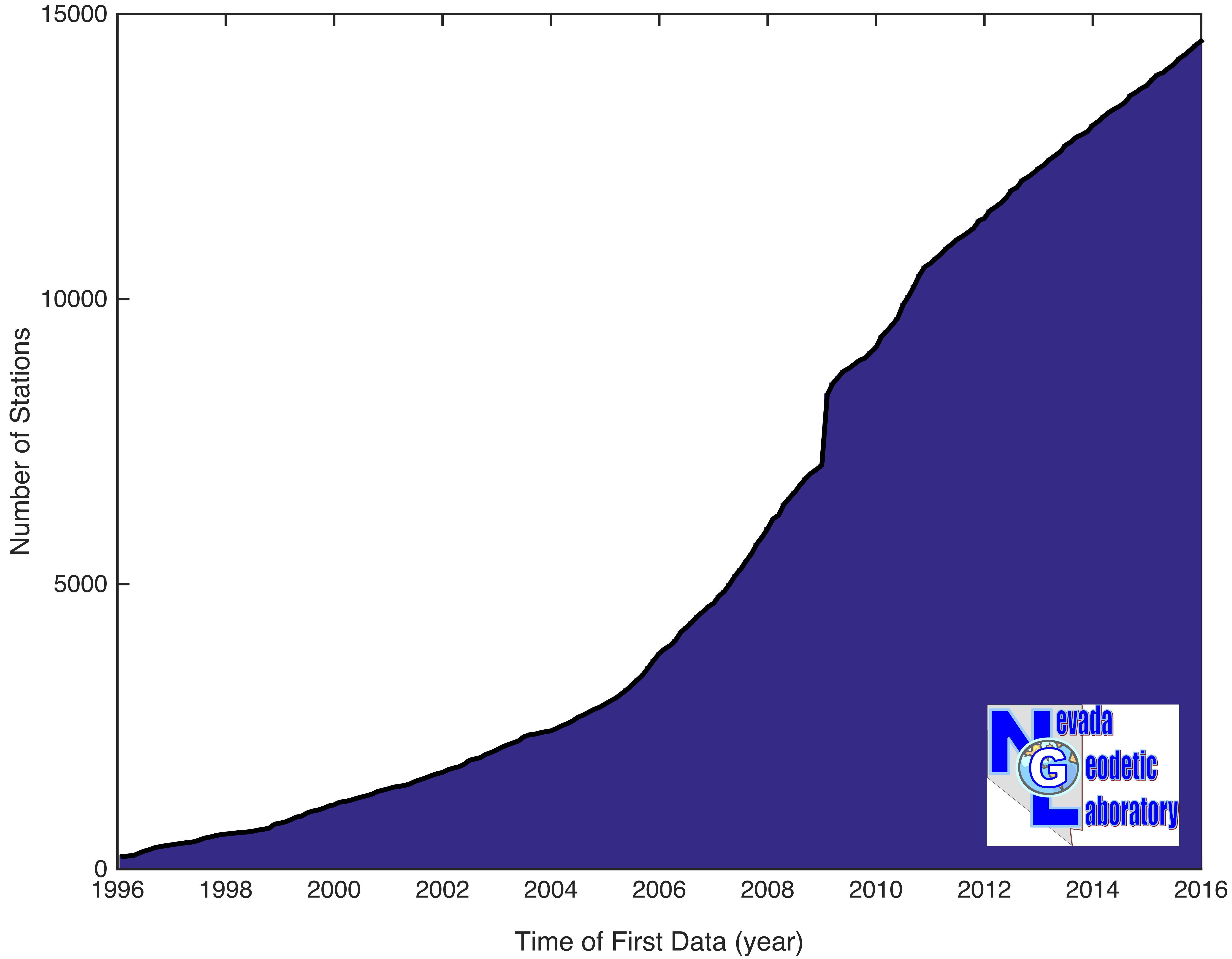
Number of GPS stations in NGL archive over time



Plug and Play GPS for Earth Science

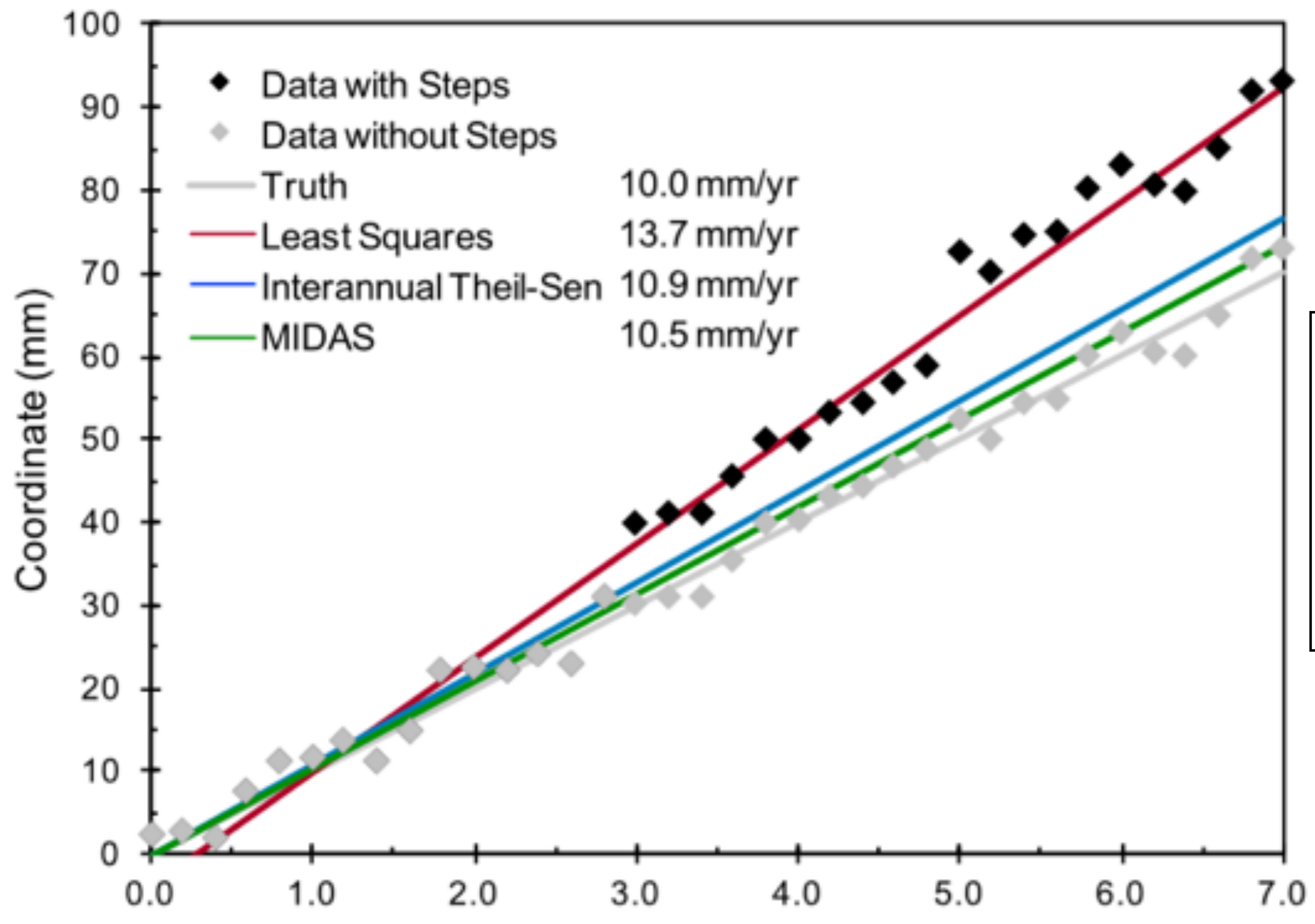
- **Goal**
  - Remove: barriers to maximize proliferation and scientific impact of GPS networks
  - Provide: FREE GPS data processing service. Minimizes effort of network operators who contribute data.
  - Promote: Open data and products sharing for science and society
  - Maximize: Discovery of data for scientific applications
  - *Now operational and accepting networks!*
- **Who is involved? The Plug and Play Players**:
  - A collaboration between UNAVCO and UNR
  - Plus *beta testers* and *unfunded collaborators*, e.g. USGS, JPL, … and you!
  - Funded by NASA ACCESS program
  - Project ending but for now we intend to continue processing all continuous stations
- **The Bottom Line**
  - **You should set up a GPS network.**
- **Explore:**
  - http://geodesy.unr.edu/PlugNPlayPortal.php or google "UNAVCO Plug and Play GPS
- **Latest GPS station:**
  - <u>OREO</u> recently installed to monitor an active landslide in northern California

GPS Velocities: MIDAS

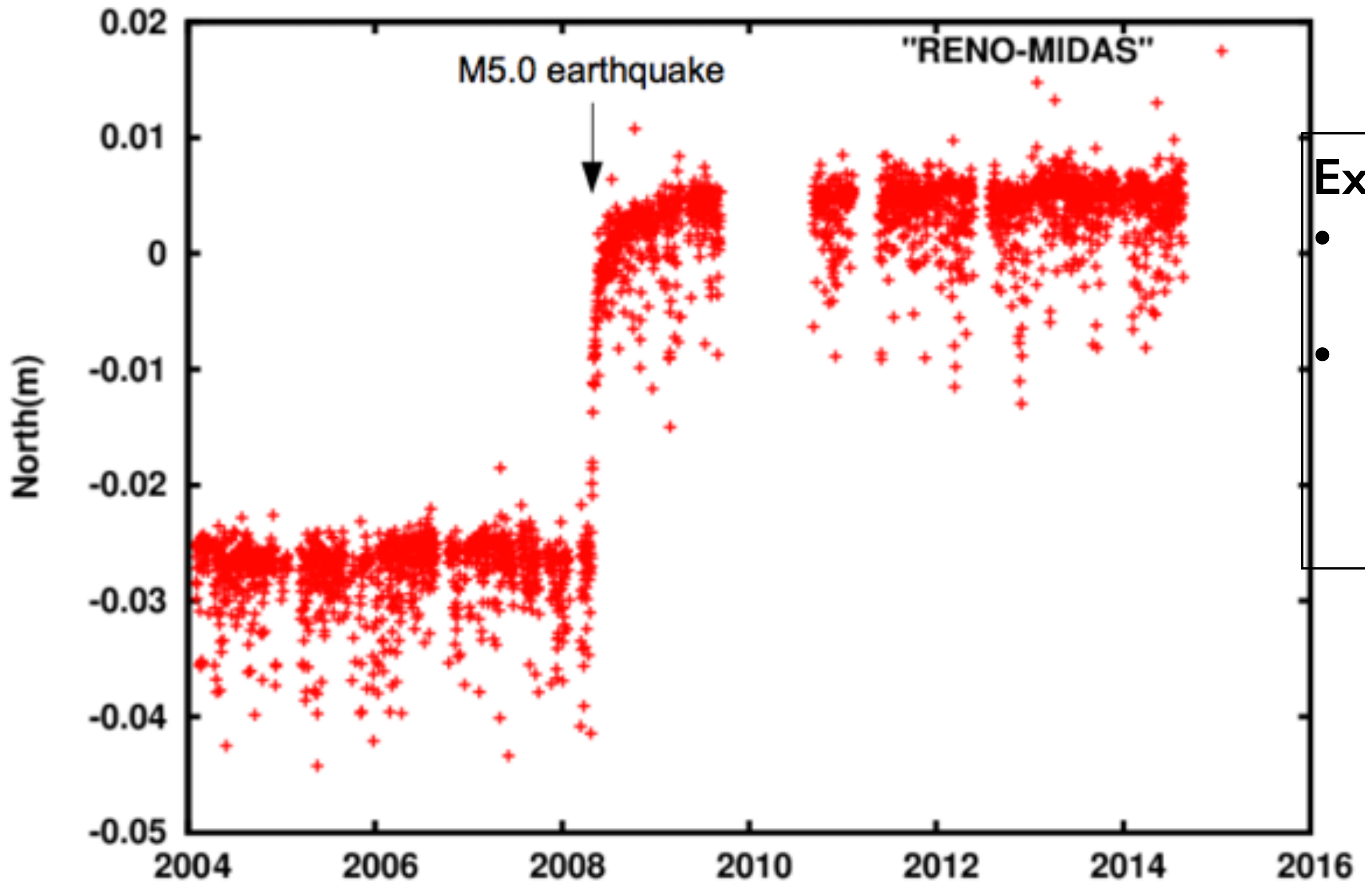
New technique helps isolate the 'long-term' trend in large archives of time series data

- Non-parametric time series trend estimator based on Theil-Sen
- Not least squares: Robust median-based estimate of station velocity
- median trend estimator
- Insensitive to steps, outliers, seasonal terms and heteroscedasticity in noise structure
- Tolerant at up to 29% outliers and steps
- Similar results to least squares in "normal cases"
- More stability in odd cases without detailed parameterization
- Fast algorithm, simple form, suitable for automated large N analyses
- Most accurate method in DOGEx exercise
- All MIDAS rates updated weekly and available at http://geodesy.unr.edu

$$\hat{v} = \mathrm{median}_i \left(x_{i+365} - x_i \right)$$
$$\sigma = 1.4826\,\mathrm{median}_i \left| x_{i+365} - x_i - \hat{v} \right|$$
$$\sigma_v = 1.2533 \frac{\sigma}{\sqrt{N/4}}$$



Example: Synthetic Test
- mystery steps added to linear trend plus noise
- True slope estimated more accurately



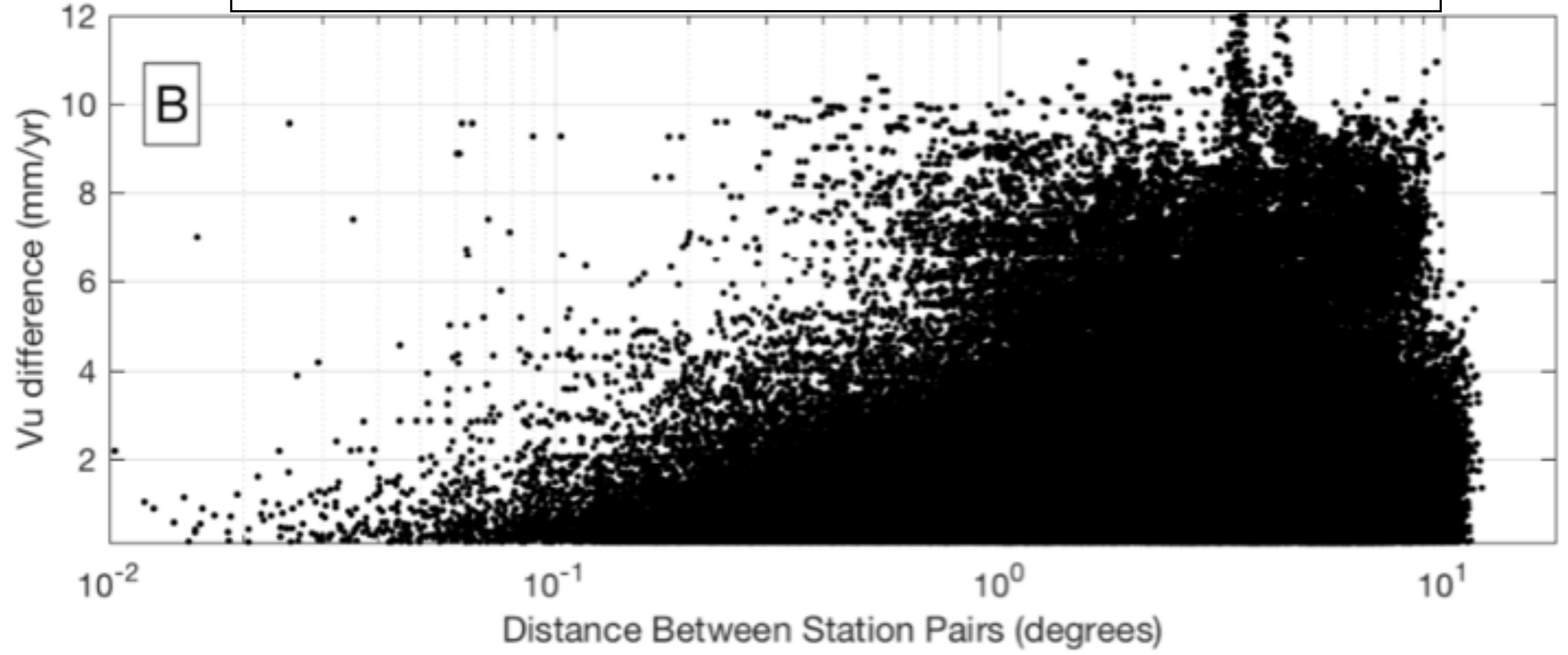
Example: Station RENO
- Detrended using MIDAS rate,
- Accurately estimates pre-seismic trend without knowing when step occurred

Blewitt, G, C. Kreemer, W.C. Hammond, J. Gazeaux, 2015, MIDAS robust trend estimator for accurate GPS station velocities without step detection, *J. Geophys Res.-Solid Earth*, **121**, doi:10.1002/2015JB012552 [available with open access]

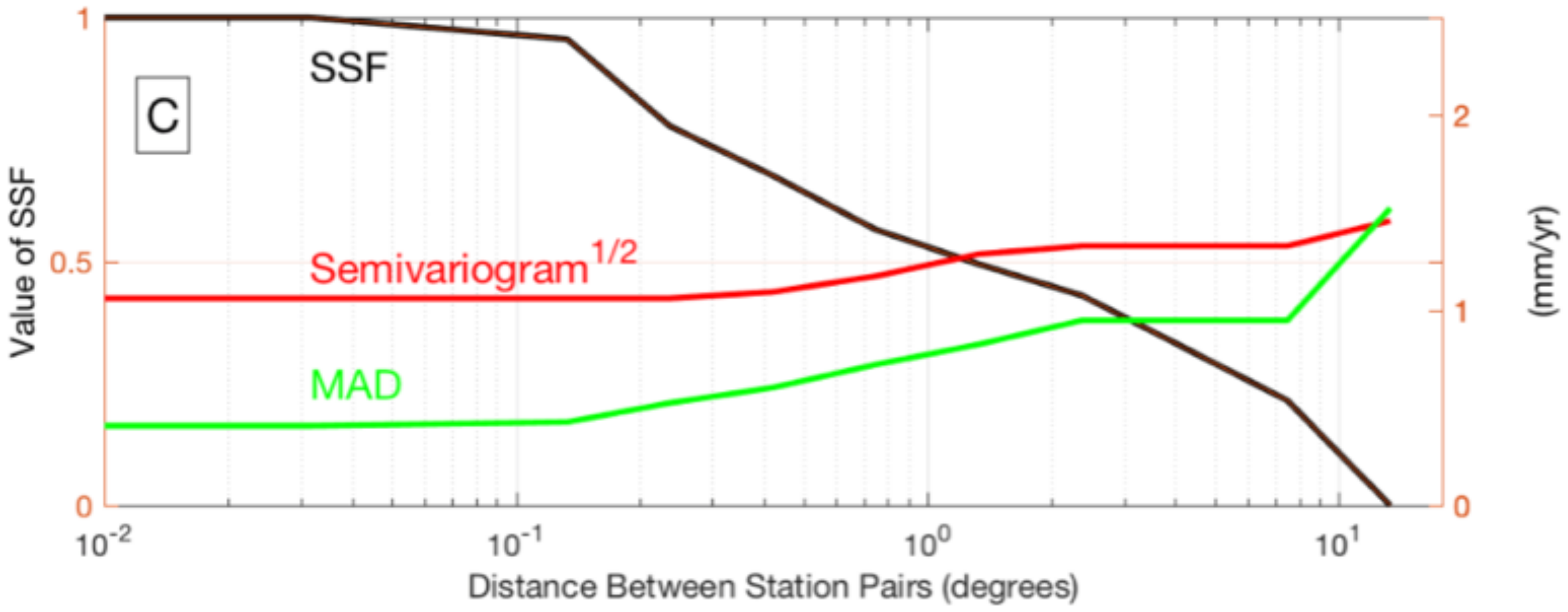
GPS Imaging: How it Works

- Best described as a hybrid between **image processing** and **geostatistical Kriging**
- Uses the data to generate weighting functions
- Image preserves spatial resolution of GPS network (which varies greatly in domain)

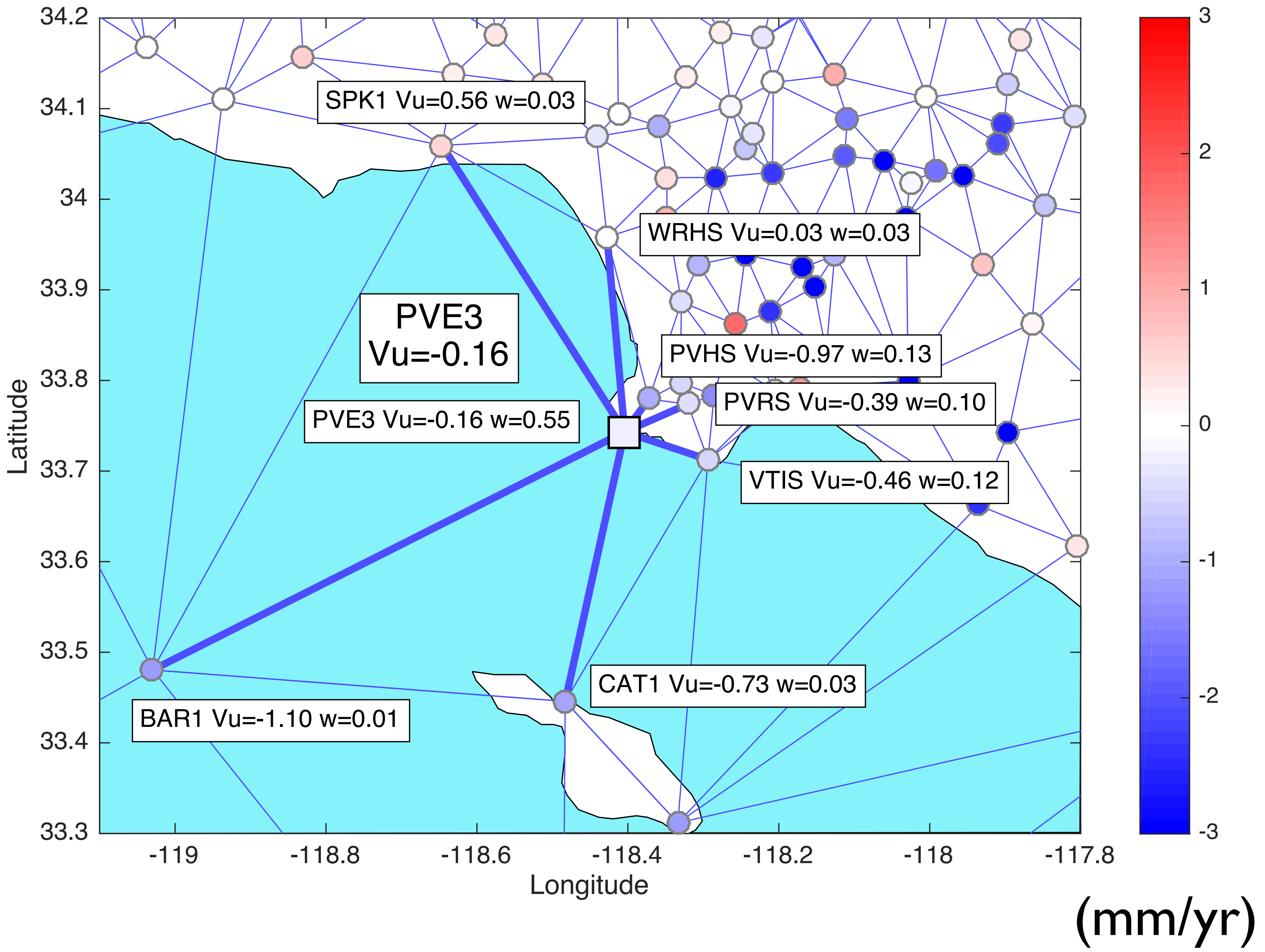
Difference in vertical velocities as a function of inter-station distance



Empirical Spatial Structure Function



Weighted median filter on Delaunay triangulation of GPS station locations



Connected GPS station i gets:

$w_i = ssf(\Delta_i)/\sigma_i$

at evaluation point:

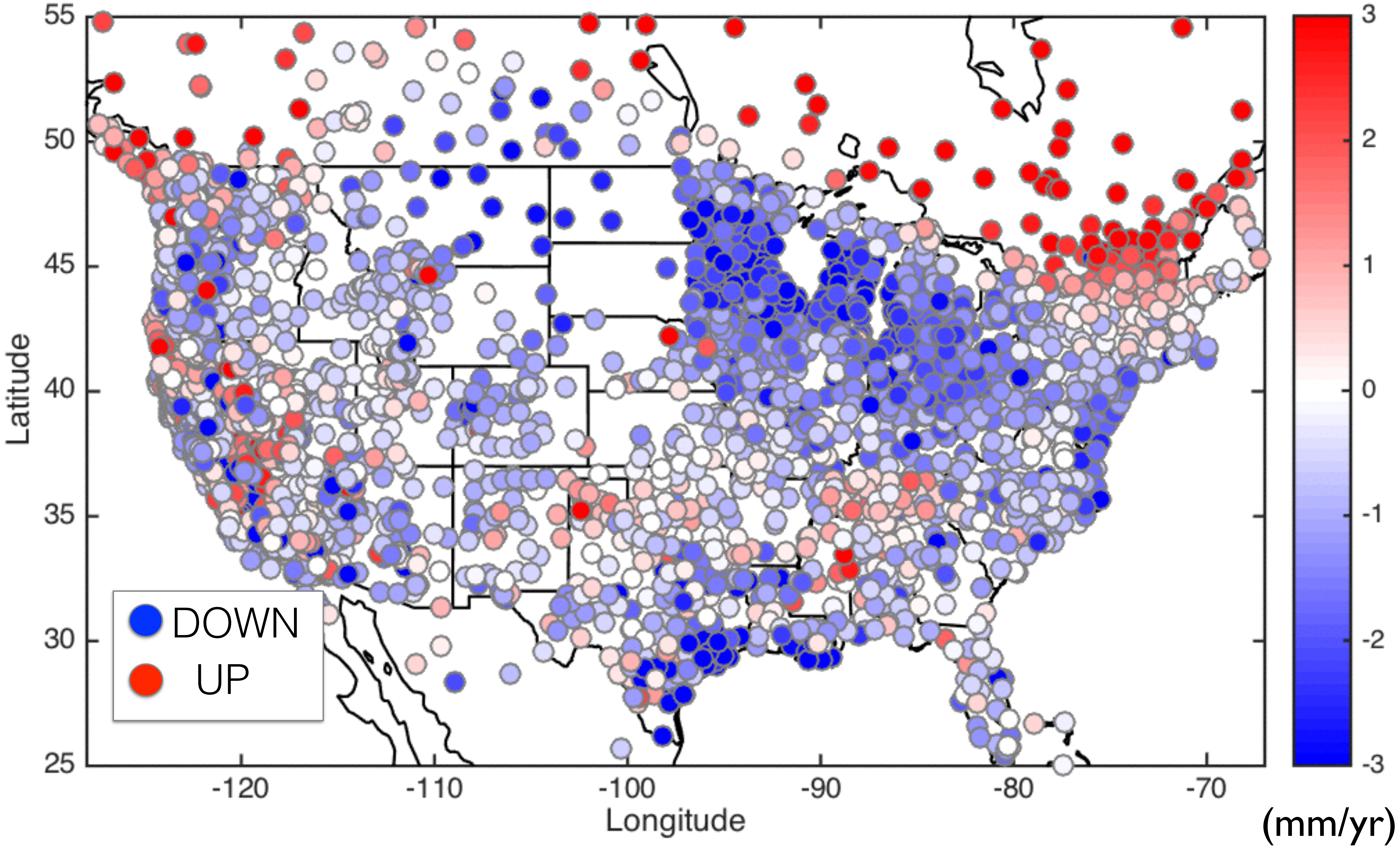
$v = \text{weighted median}(v_i, w_i)$

GPS Imaging North America Vertical Velocity

This method helps isolate the signals from large scale processes such as tectonics and GIA
Deemphasizes signals present only at single stations

- MIDAS addresses robustness in the time series
- GPS Imaging address the spatial part
- Use 5 year time minimum duration time series
- Weighted **median-based** geographic spatial filtering (despeckling) applied
- Insensitive to outliers
- Preserves <u>edges in field: No classical smoothing</u>
- Suitable for focusing on signals that are consistent at multiple stations
- Emphasizes signals with wavelength greater than the station spacing, removes speckle noise
- Efficient: Helps cope with data from 1000s of stations

MIDAS Vertical Rates: North America



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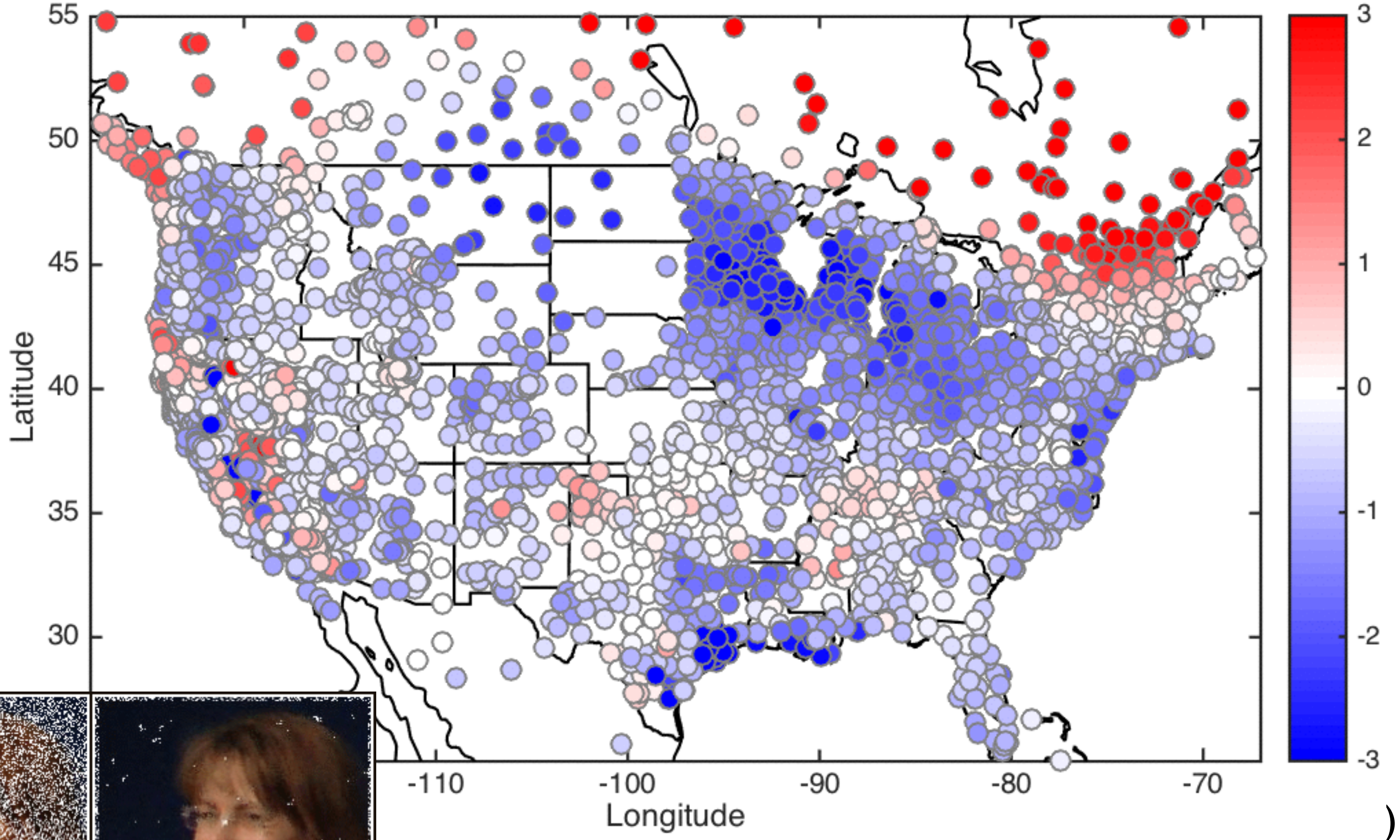
MIDAS Vertical Rates: Median Filtered



Example benefit of median spatial filtering
a photograph with lots of speckle noise

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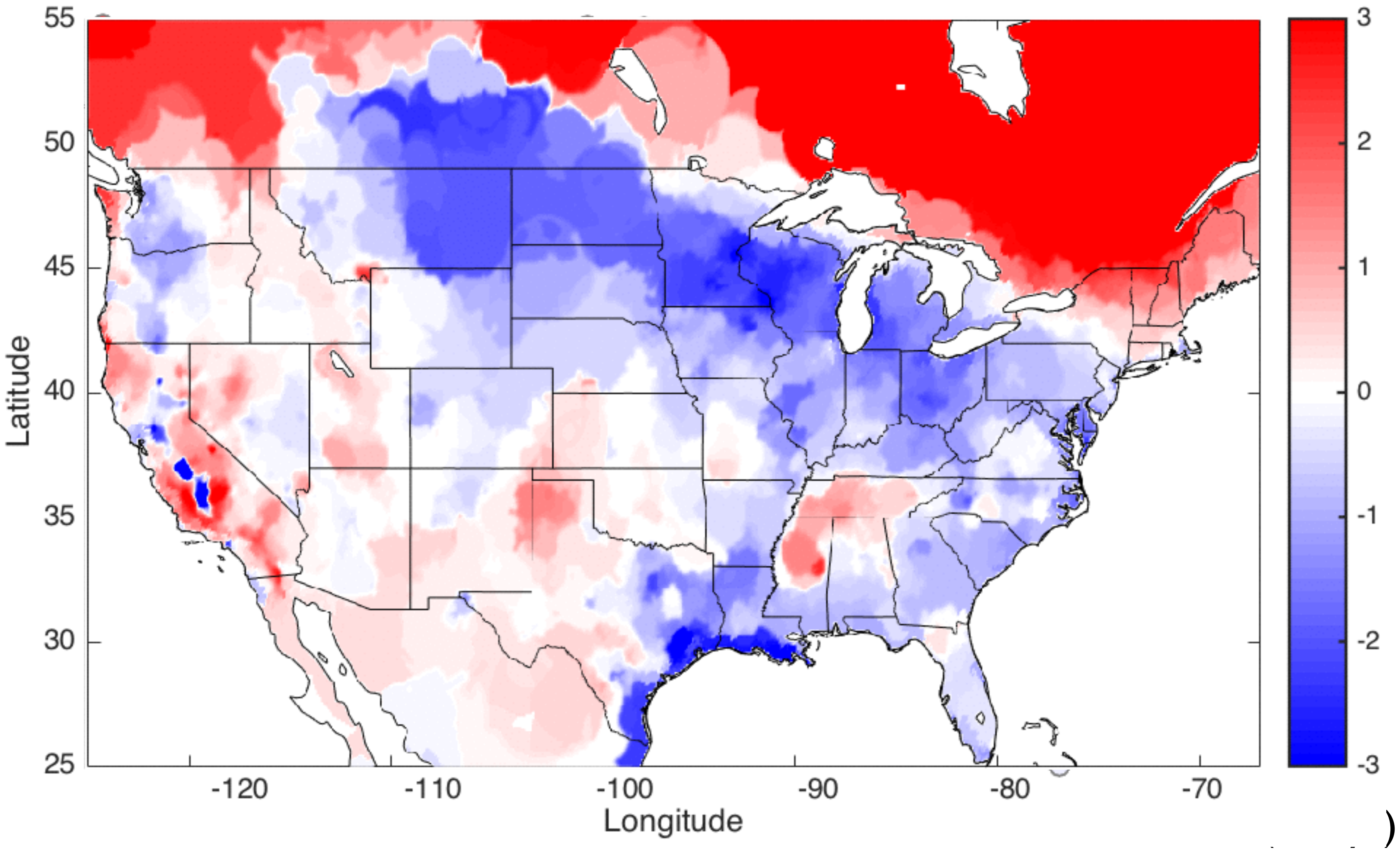


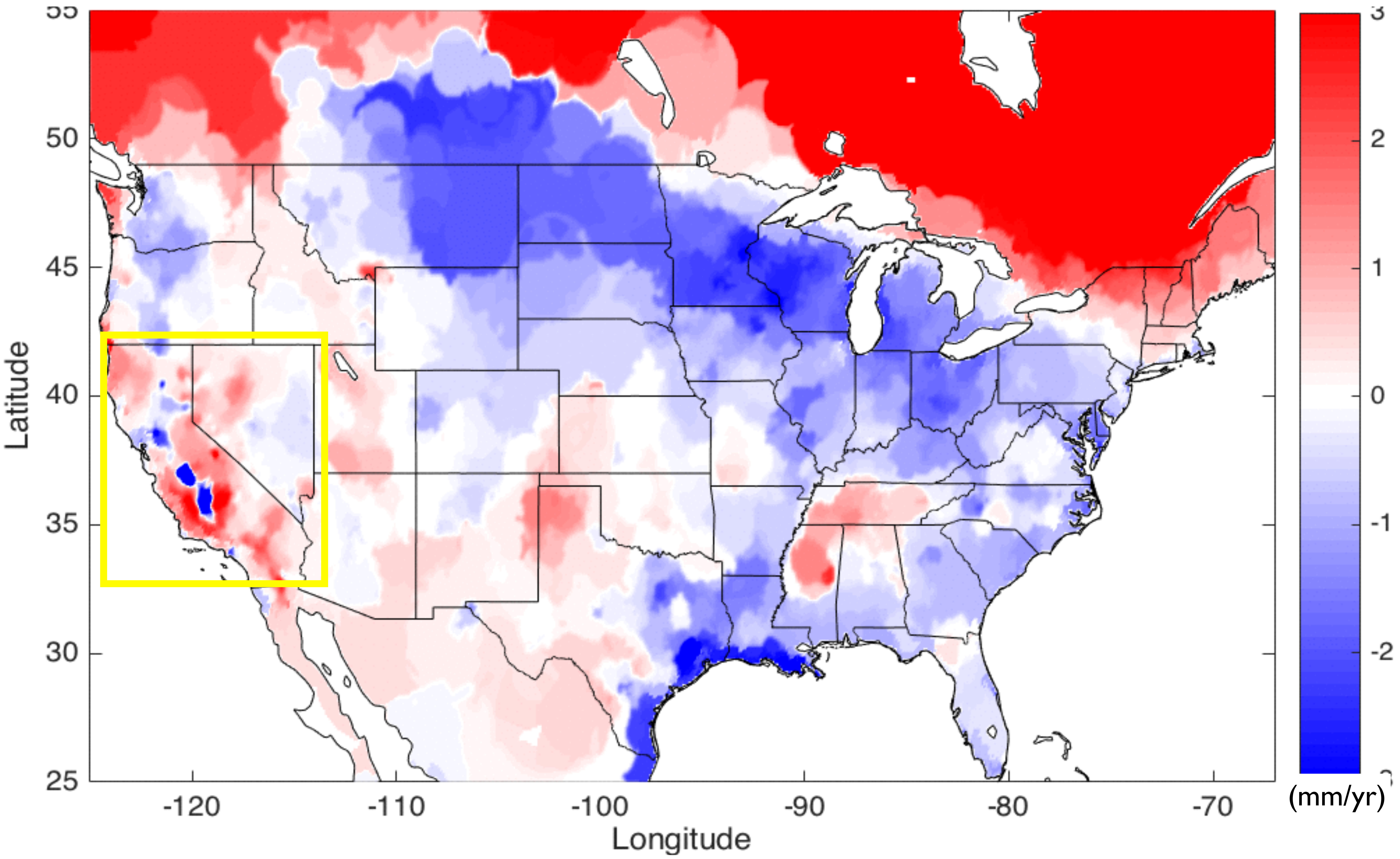
GPS Imaging North America Vertical Velocity

Seeing, for example:

- GIA very well
- Fore-bulge collapse
- Drives subsidence along east coast 1-2 mm/yr (important for sea level rise there)
- Location of hinge line bounding uplift and subsidence well resolved
- Gulf coast subsidence, a combination of pumping, sediment loading

- Technique enhances signals with geographic coherence that are detected in many stations

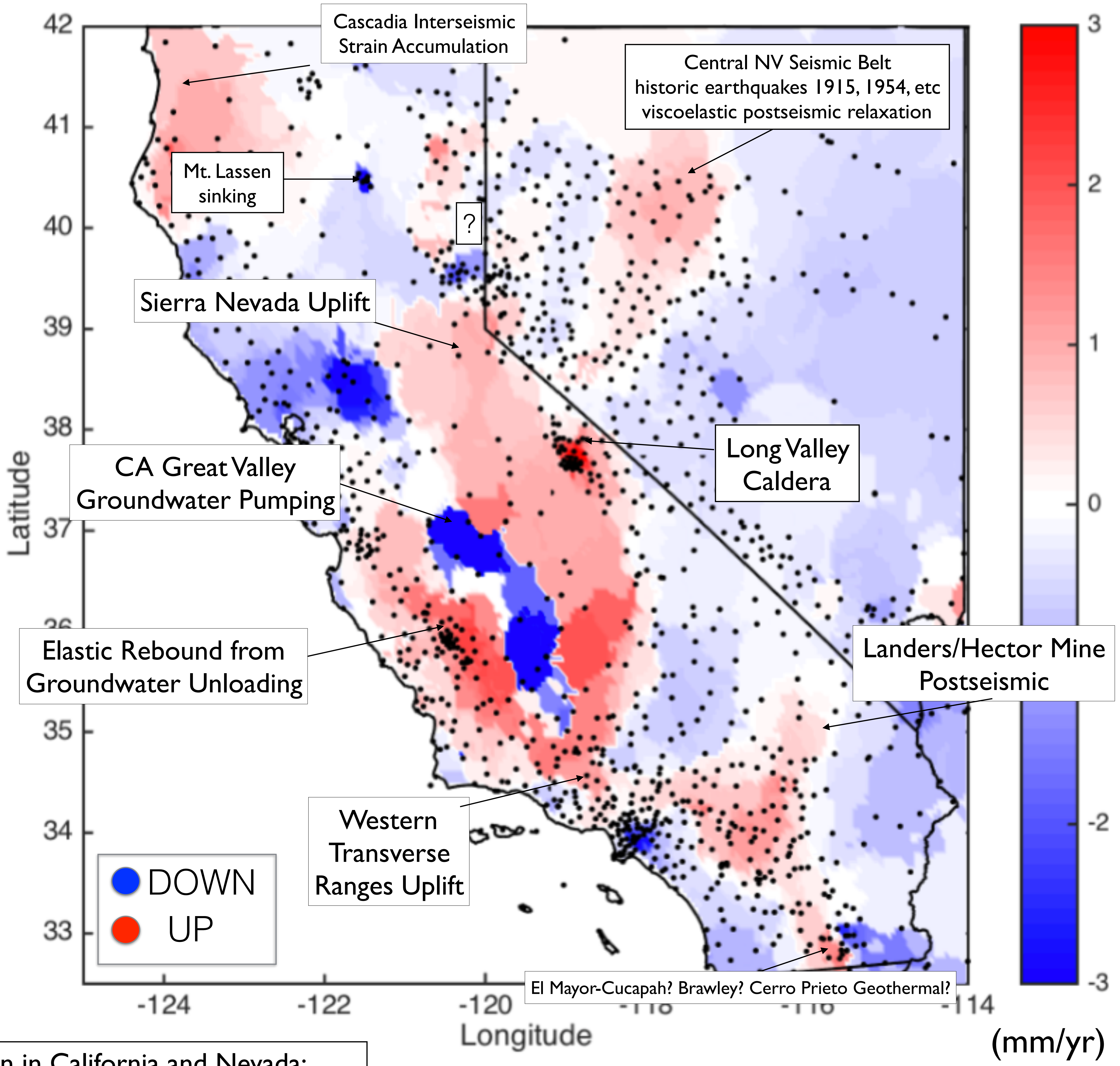
- GPS Imaging sees surface manifestation of mantle flow



GPS Imaging of Vertical GPS Velocity: Sierra Nevada

Structure and Source of VLM

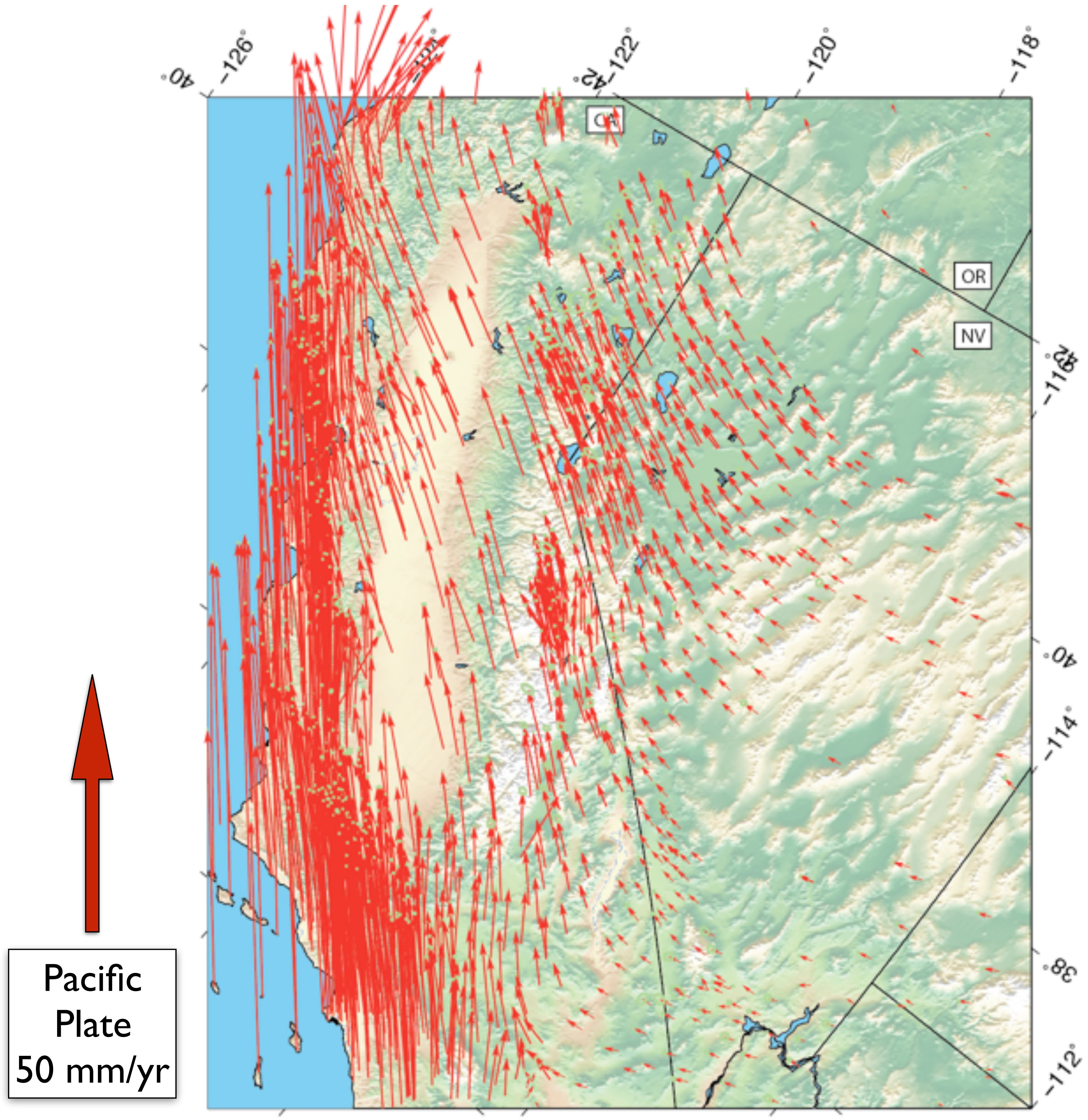
- Details of intriguing geographic clustering of vertical rate signals
- Volcanos, up & down
- CNSB and LH Postseismic
- Cascadia interseismic strain accumulation
- Inland penetration of NW CA uplift
- Groundwater pumping in Central Valley
- Elastic rebound around Central Valley from groundwater unloading (Amos et al., 2014 *Nature*)
- Uplift of the Sierra Nevada and Klamath Mountains
- Preservation of edges important here
- Sharp boundary on east edge of Sierra Nevada/Great Valley microplate



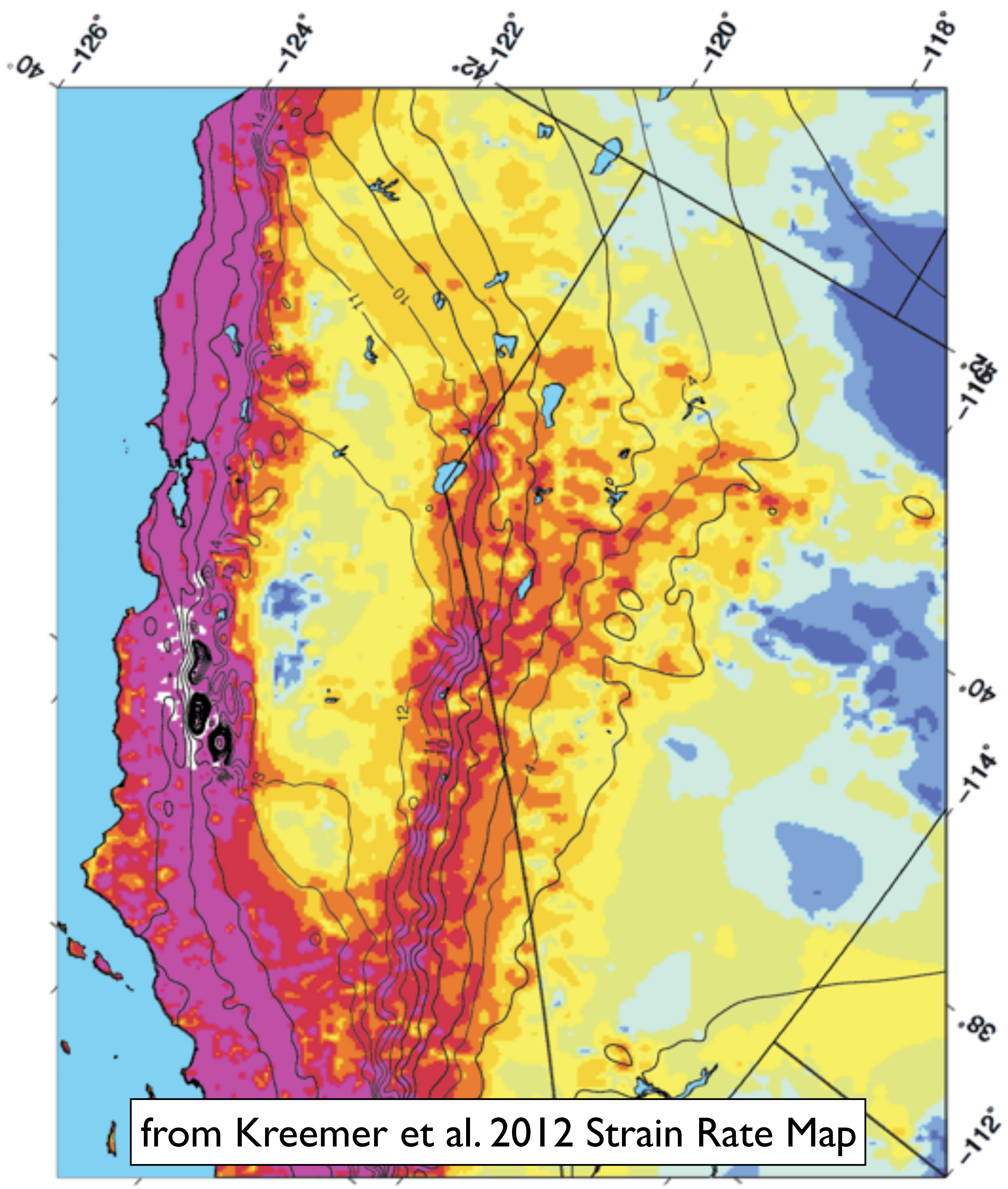
Hammond, W.C., G. Blewitt, C. Kreemer, 2016, GPS Imaging of vertical land motion in California and Nevada: Implications for Sierra Nevada uplift, *J. Geophys Res.-Solid Earth*,, in review

Geodetic Context of Vertical Rates Across CA/NV

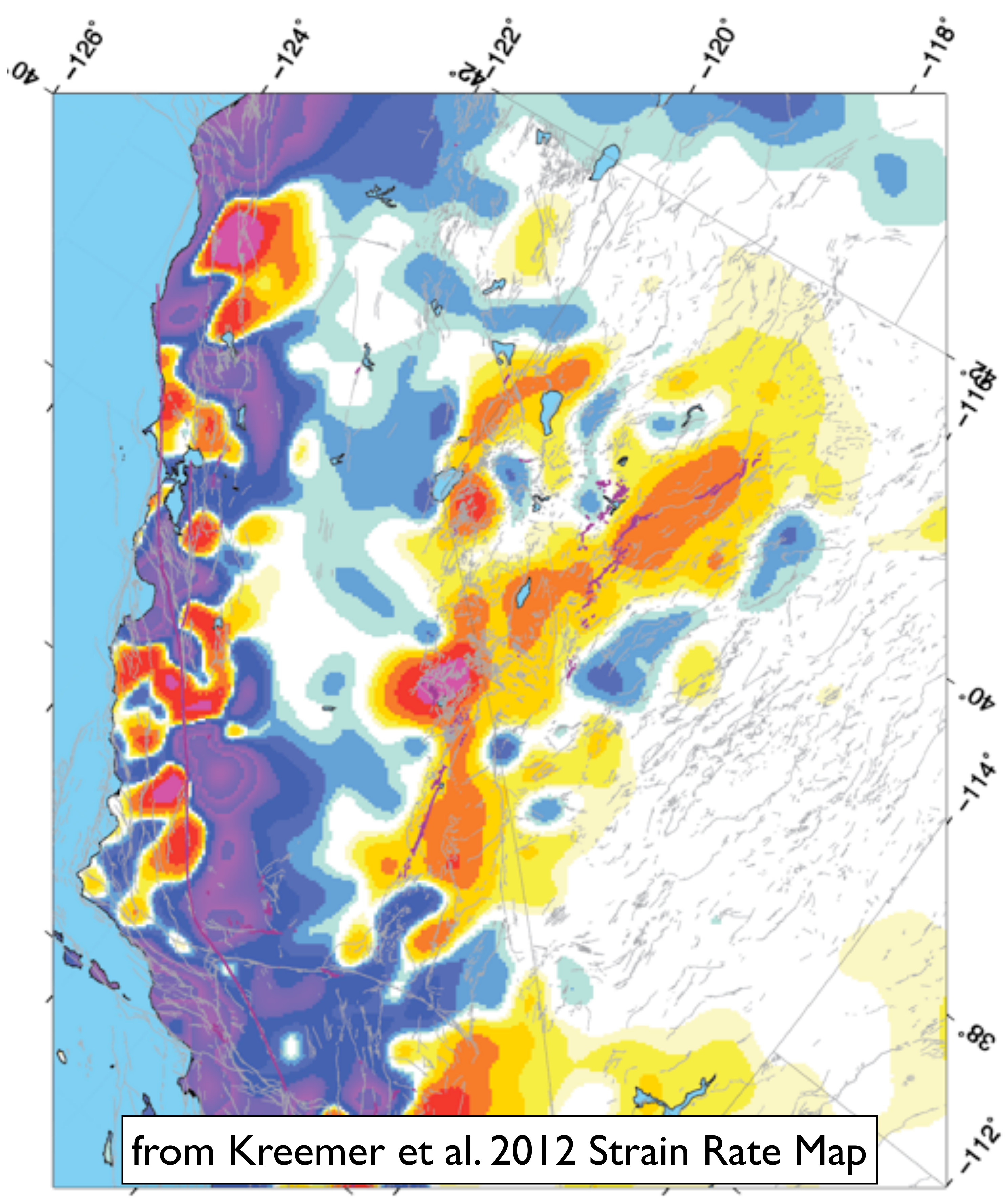
Velocity



Strain Rate - Magnitude



Strain Rate - Dilatation



- Correlation between big changes in: strain rats, dilatation rate, uplift rate
- Need to understand this transition better… Is GPS Imaging well resolved there?

Assess the Resolution the GPS Rate Field

Assess network's ability to resolve structure in the vertical rate field

- +/- 3 mm/yr blocks smoothed
- Sample field at stations
- Add noise consistent with
  - MIDAS uncertainty now
  - Expected uncertainty in near future
- Returning input structure well except where GPS network is sparse
  - East Nevada
  - Western Arizona

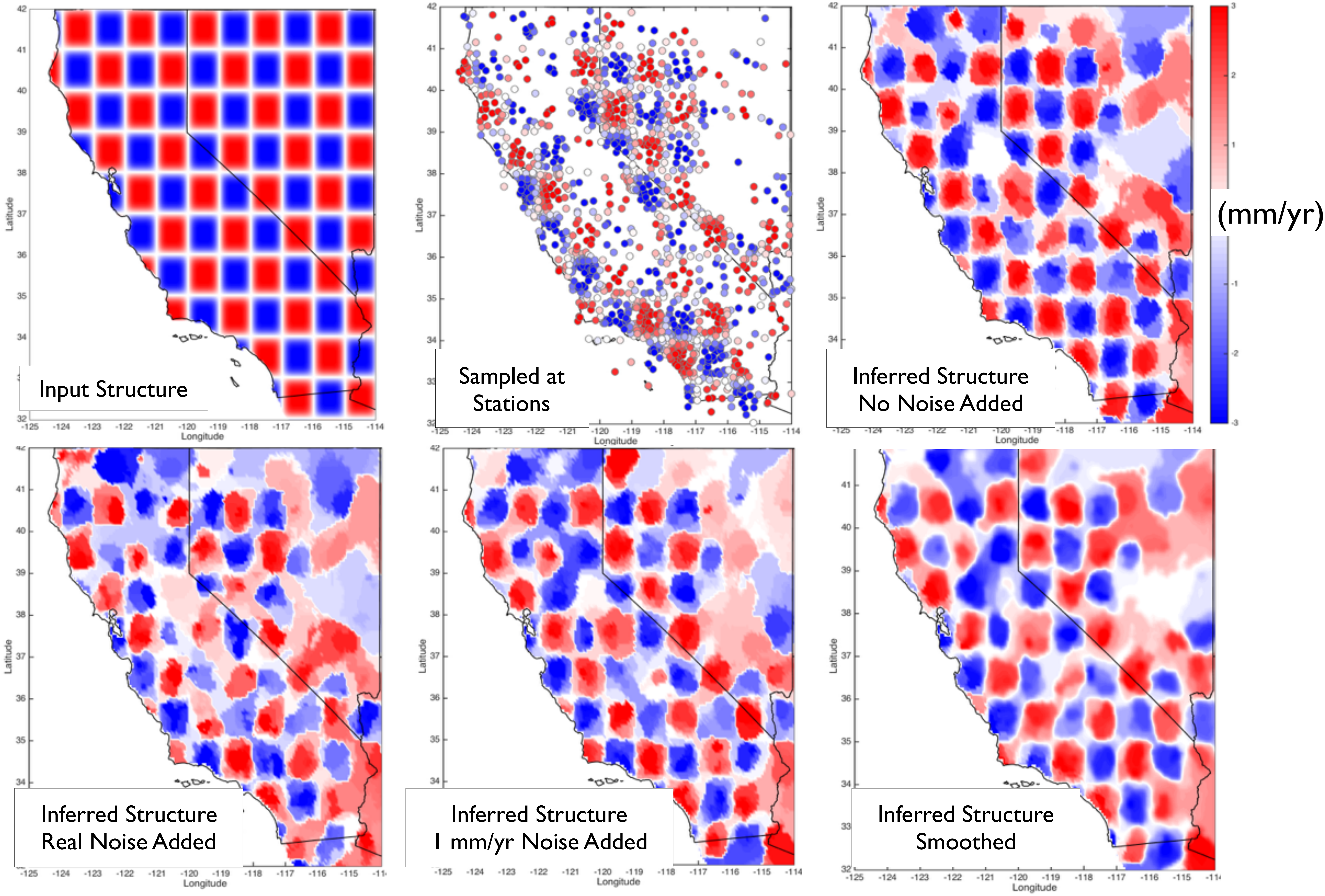
Bottom Line

- Resolution is reasonable near Sierra Nevada east edge and many other places

Recommend future GPS locations

- East Nevada
- Sierra Nevada/Great Valley middle latitudes

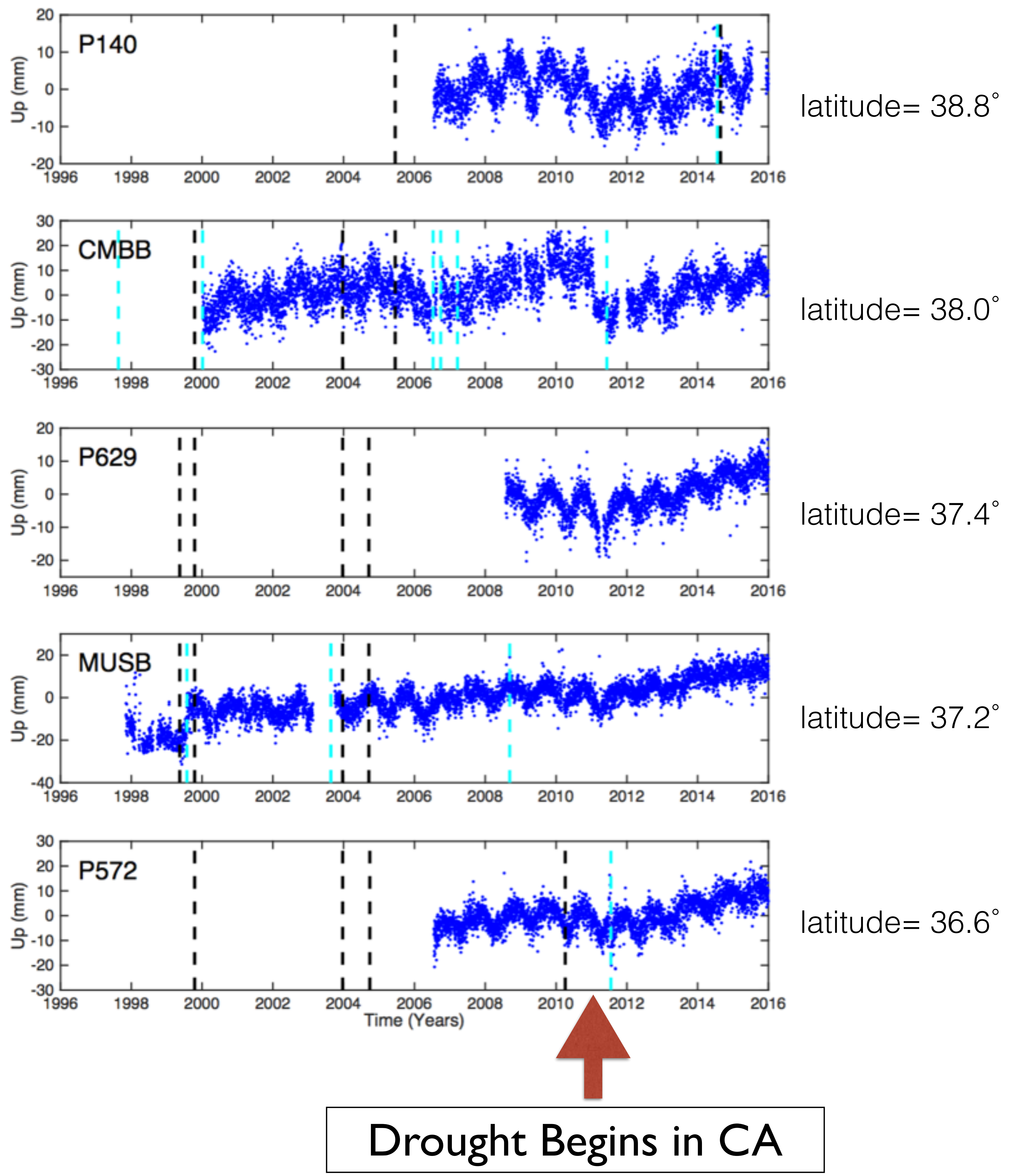
Checkerboard Tests



Sierra Nevada Uplift Over Time

Which signals vary over time?

- We expect that ***tectonic*** uplift of Sierra Nevada would be constant over time of GPS observation.
- But we observe some time dependence of GPS uplift rates.
- Furthermore, this signal is latitude dependent. Stations in southern Sierra show clearer, more consistent uplift.
- All stations show accelerated uplift when drought starts in California (after winter of 2010/2011).
- This correlation suggests that much uplift related to H_2O unloading owing to drought in southwest US, loss of ground and surface water
- So we ask the data how do the signals change with time? What does GPS Imaging say?



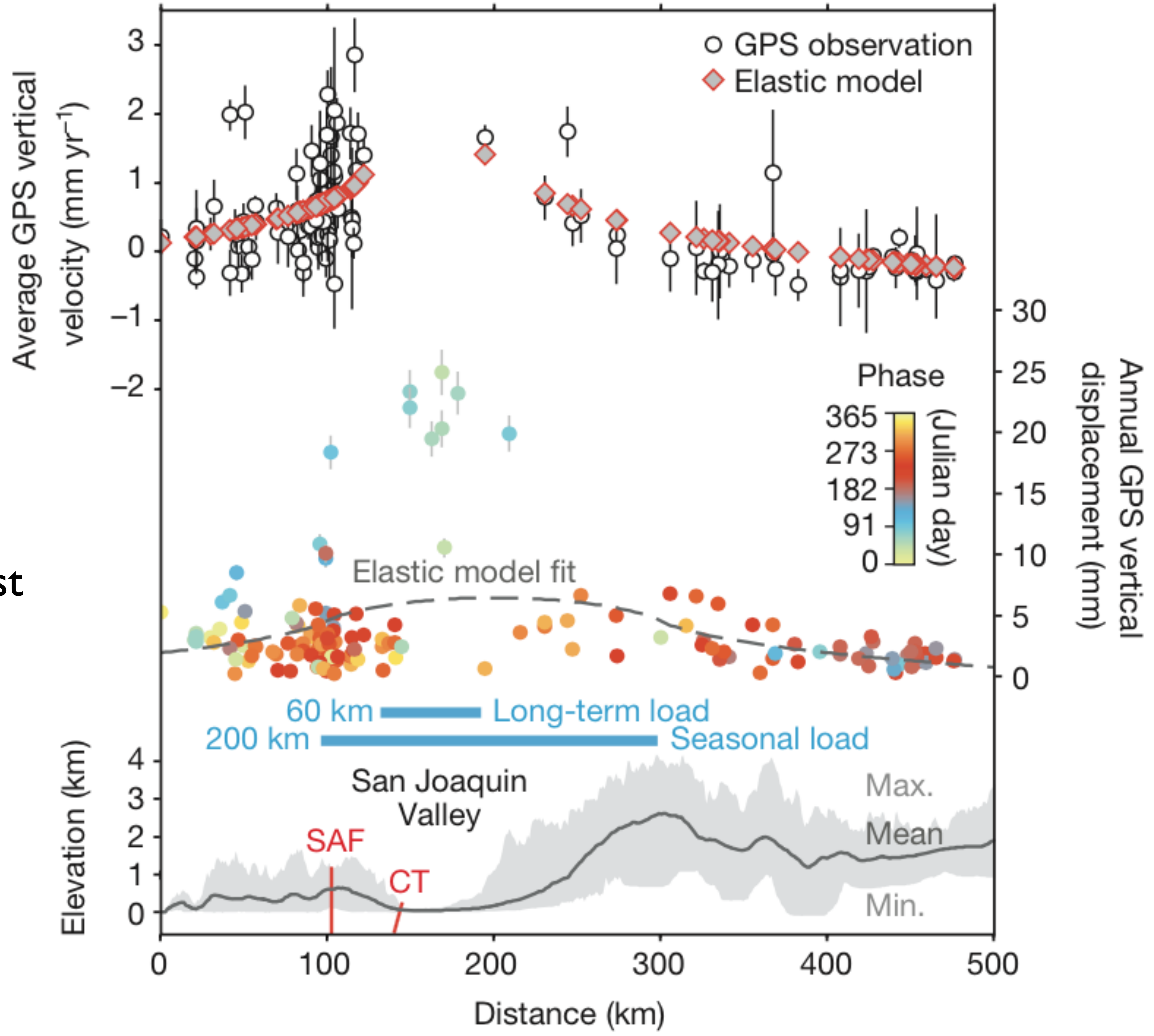
Trends and Seasonality of Uplift

Uplift Trends

- Fits model of elastic rebound
- Mass loss in San Joaquin Valley
- Unloading from 2d load

Seasonal Uplift

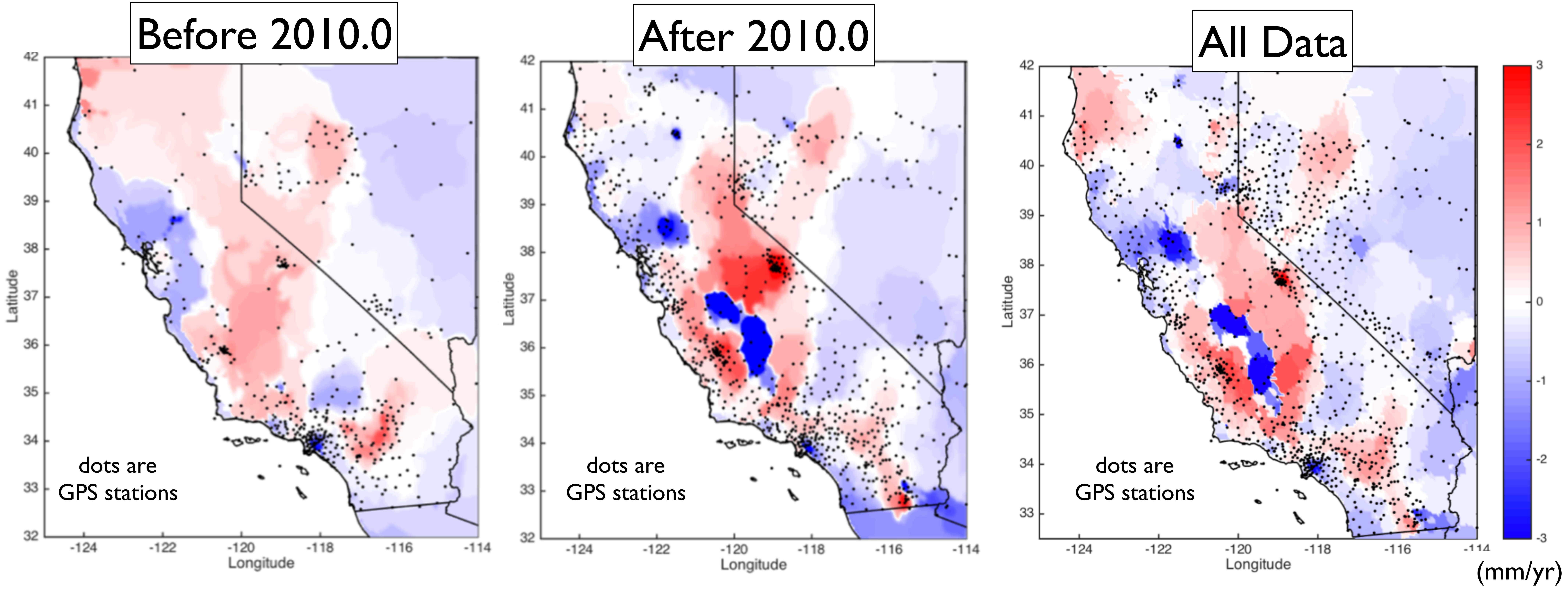
- Same sense as trend
- Though source a bit wider in east-west direction
- Red up in summer-autumn/dry season
- Blue up in winter-spring/wet season



Amos et al., 2014, *Nature*

Sierra Nevada Uplift Over Time

- Looking for time invariant signal of tectonics
- Use time series 5 years or longer duration
- Network not good enough before 2010 to constrain shapes



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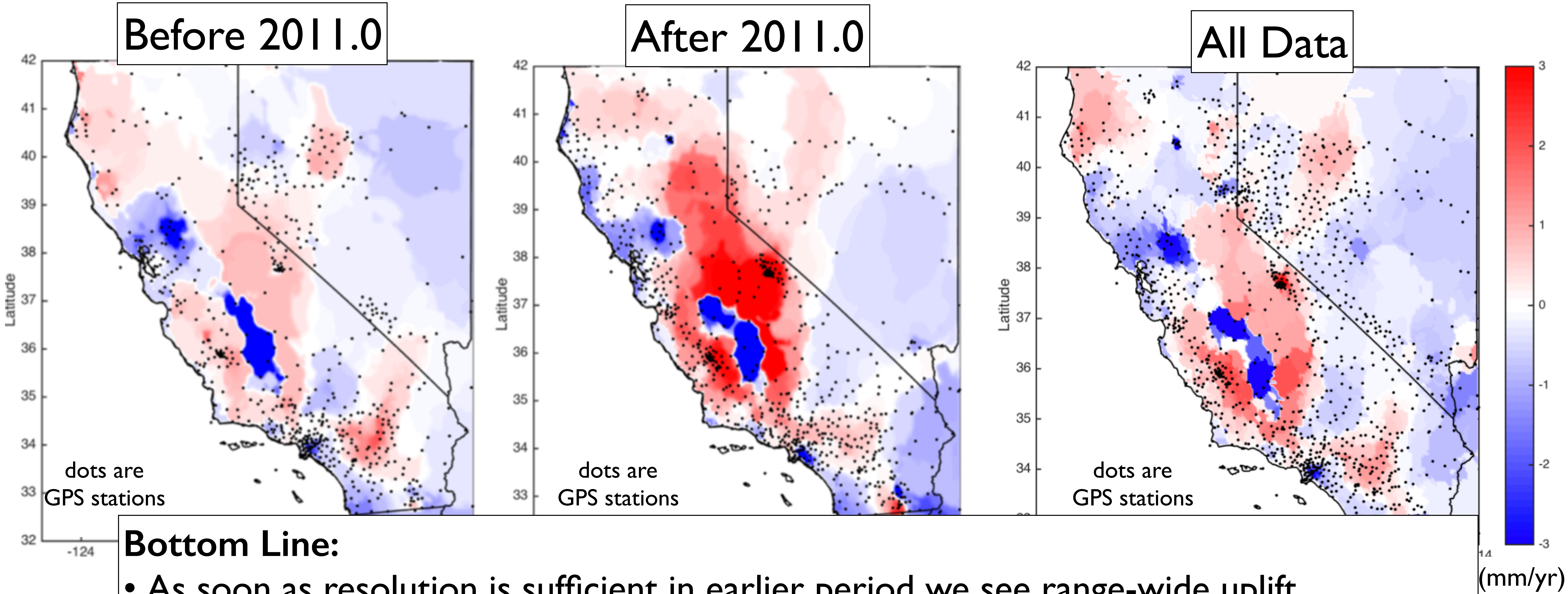


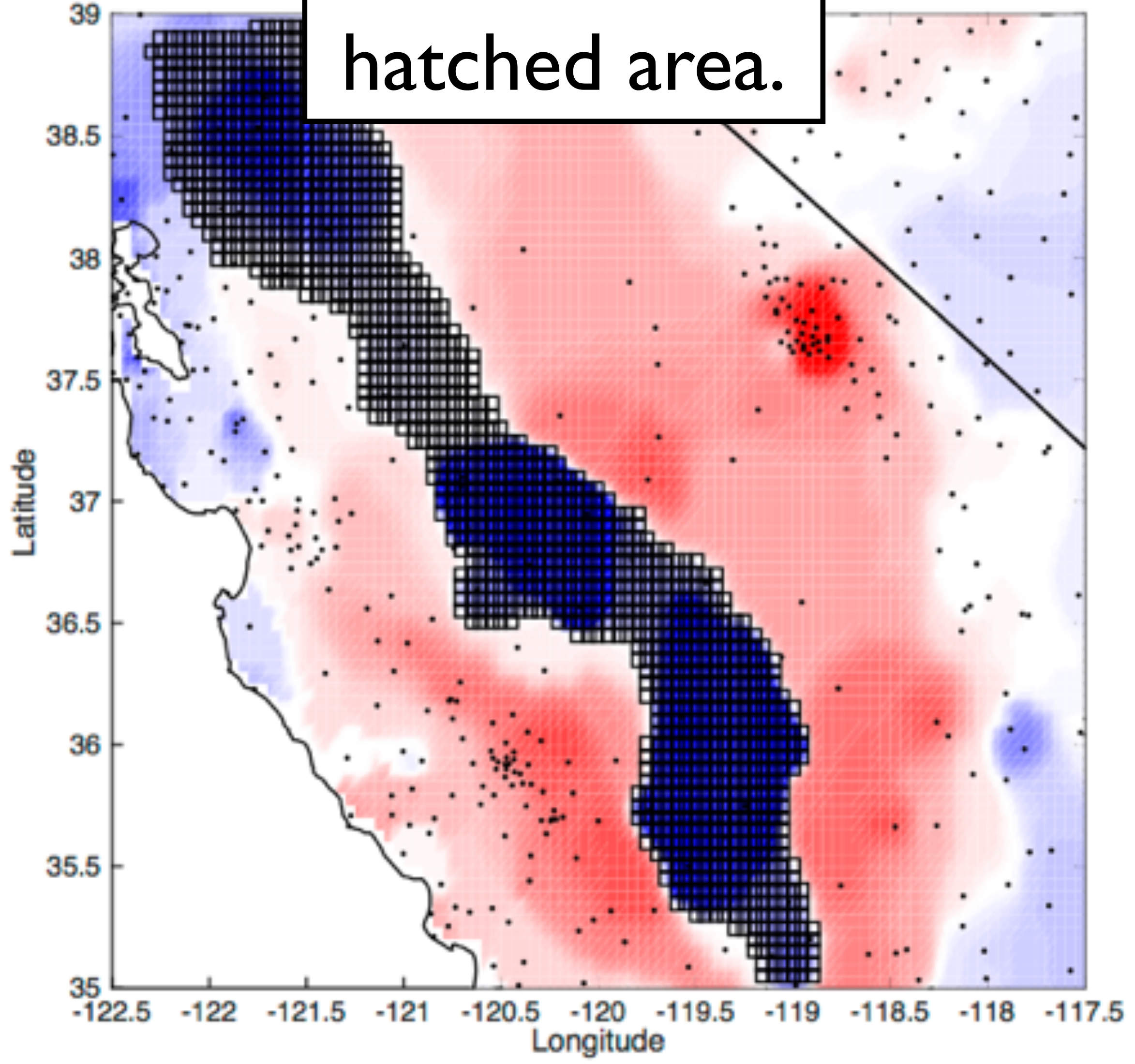
Bottom Line:

- As soon as resolution is sufficient in earlier period we see range-wide uplift
- Uplift rates increase after 2011
- East boundary of Sierra uplift seems well resolved and constant when network is good
- But is it tectonic uplift?

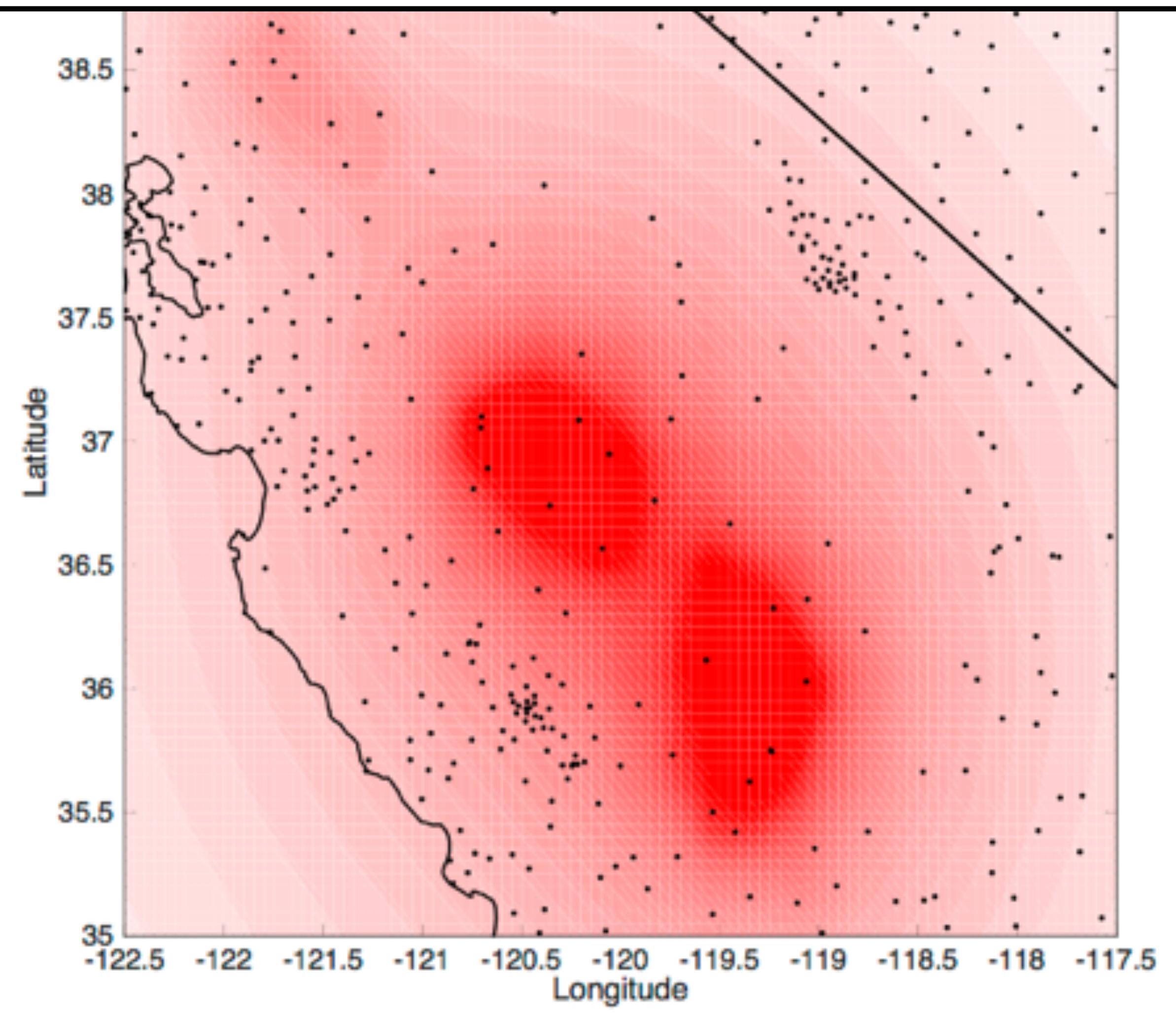
Does the Uplift Look Like an Unloading Signal?

Simple model: Apply load rate proportional to vertical rate
(Negative pressure change from water loss in CA Central Valley)

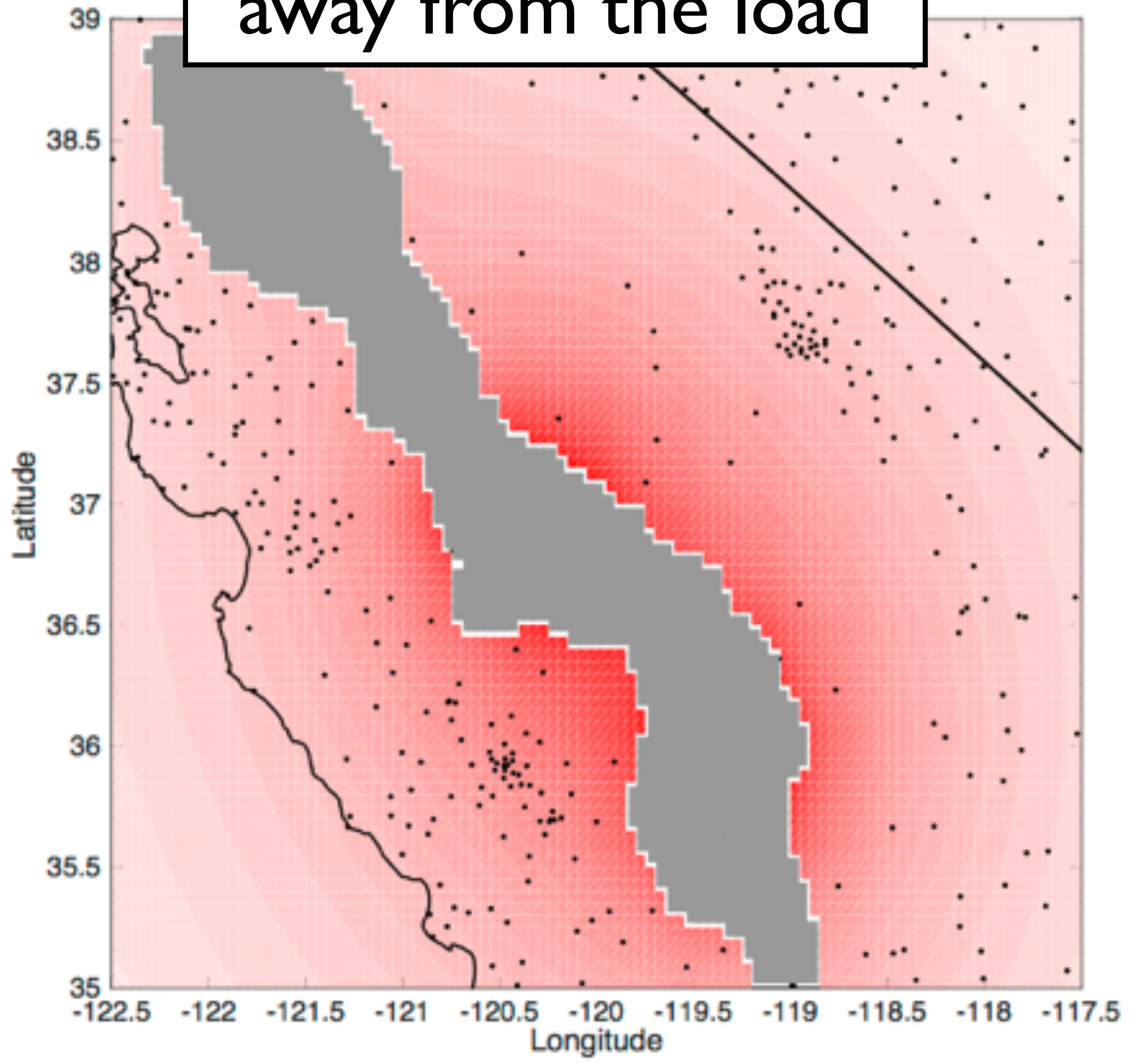
The Load
from GPS.
hatched area.



The Modeled Response
scaled to match signals in Sierra Nevada



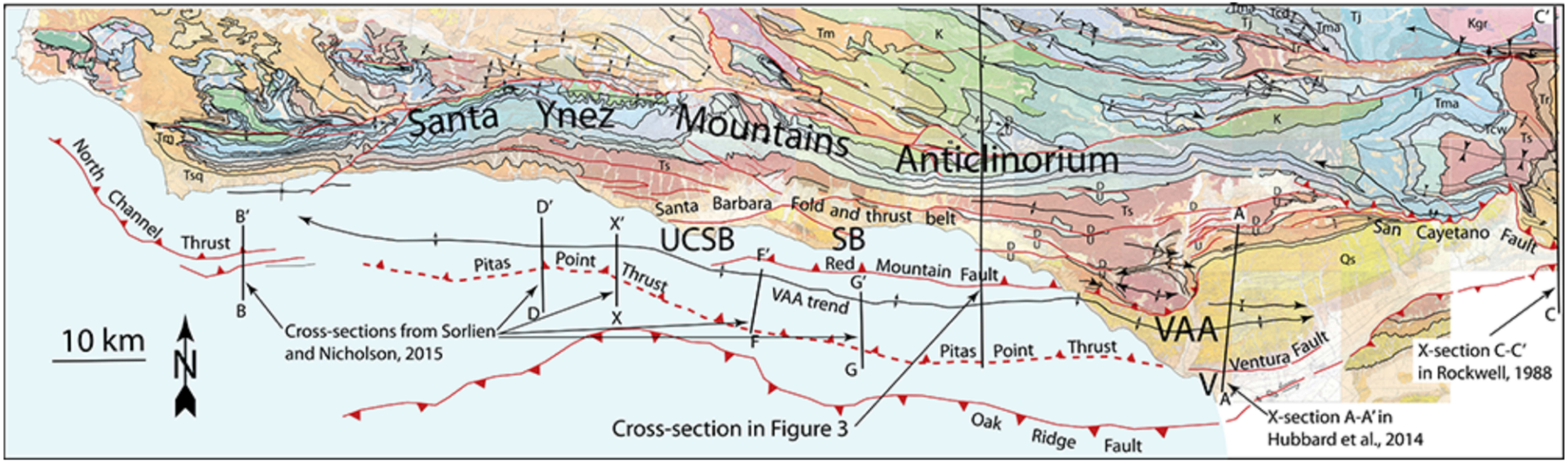
The Response
away from the load



- Use geodetic image as proxy for H_2O load location and magnitude
- Load elastic half space with rectangular load array (Becker and Bevis, 2004)
- Response of groundwater unloading tapers quickly, asymptotically from Central Valley and does not terminate at edge of microplate.
- Edge in rate field not consistent with loading, **unless possibly the plate is broken**
- Consistent with rigid microplate, deformable Walker Lane
- Suggests vertical motion is a sensitive plate boundary strength-change-o-meter

Western Transverse Ranges

SCEC Ventura Special Fault Study Area



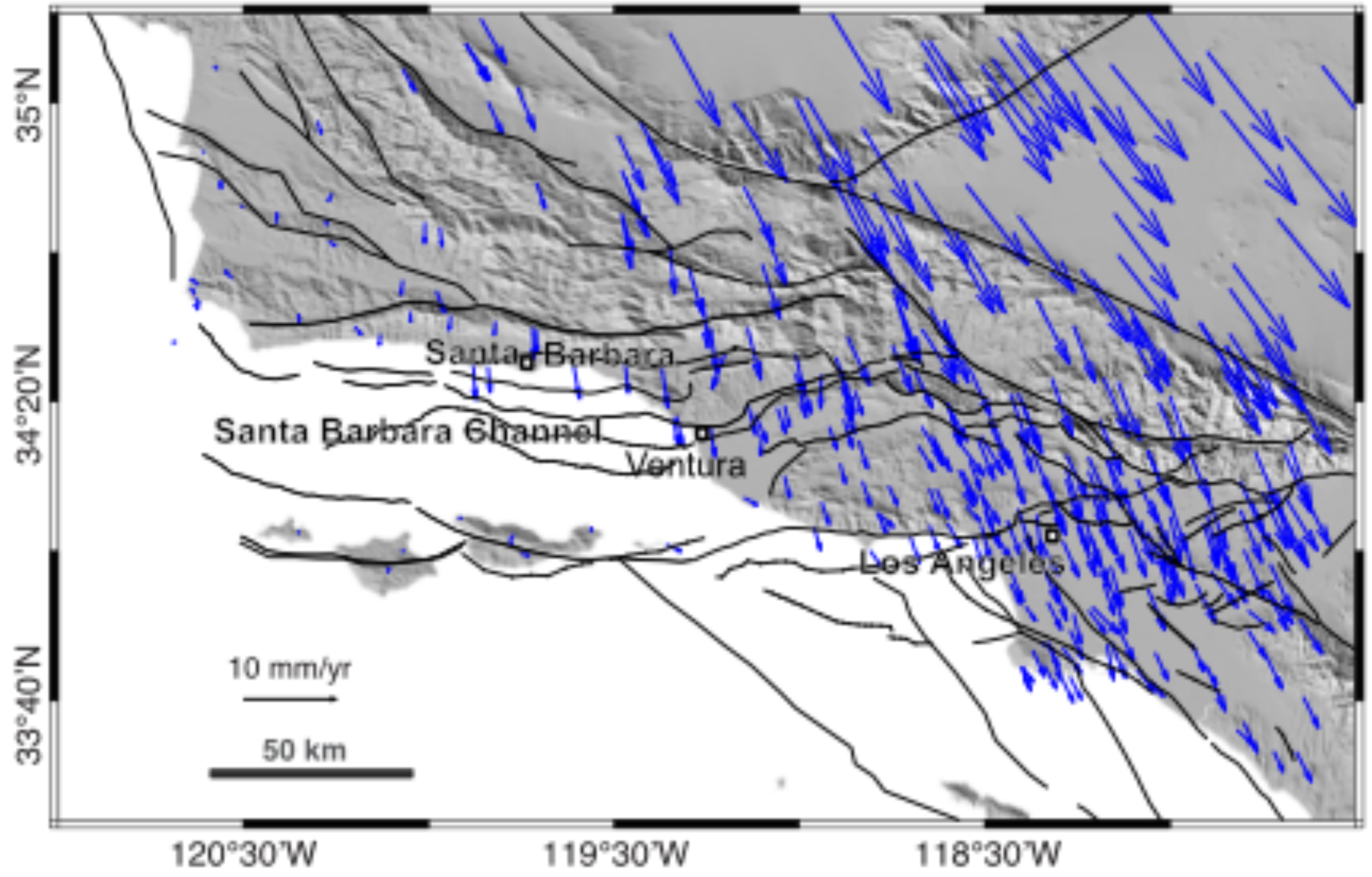
Which faults are the most active? Have the highest contemporary slip rates?

How big will the earthquakes be?

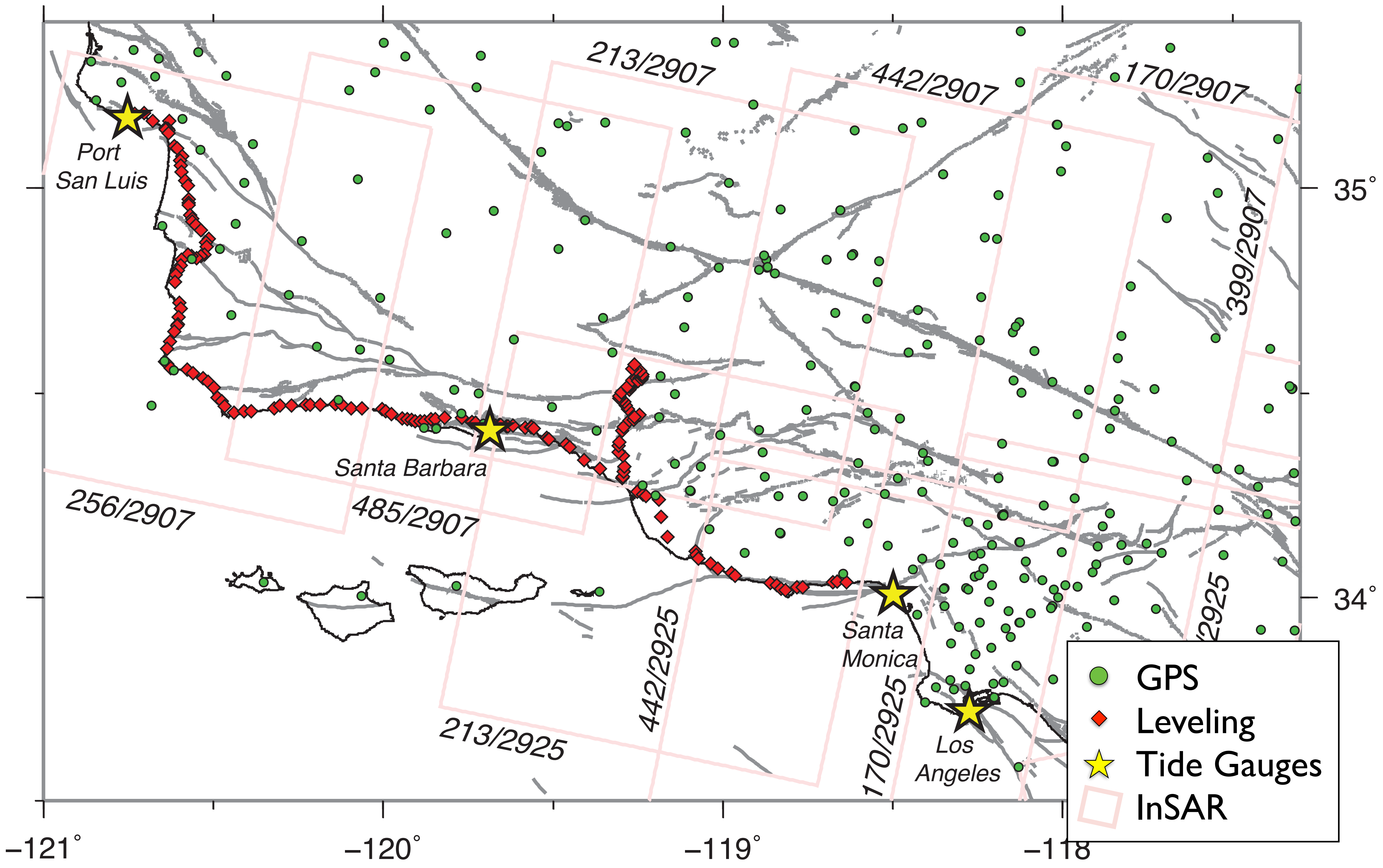
How big a tsunami?

A Four-Technique Study of Uplift

Horizontal GPS: 10 mm/yr Contraction



GPS + Leveling + Tide Gauges + InSAR



Background: 10 mm/yr of contraction across WRT. Thrust faults.

Should be able to observe vertical motion but it has been difficult up to now.

What signal is there in the vertical?

What does GPS Imaging say?

What if we throw everything we have this problem?

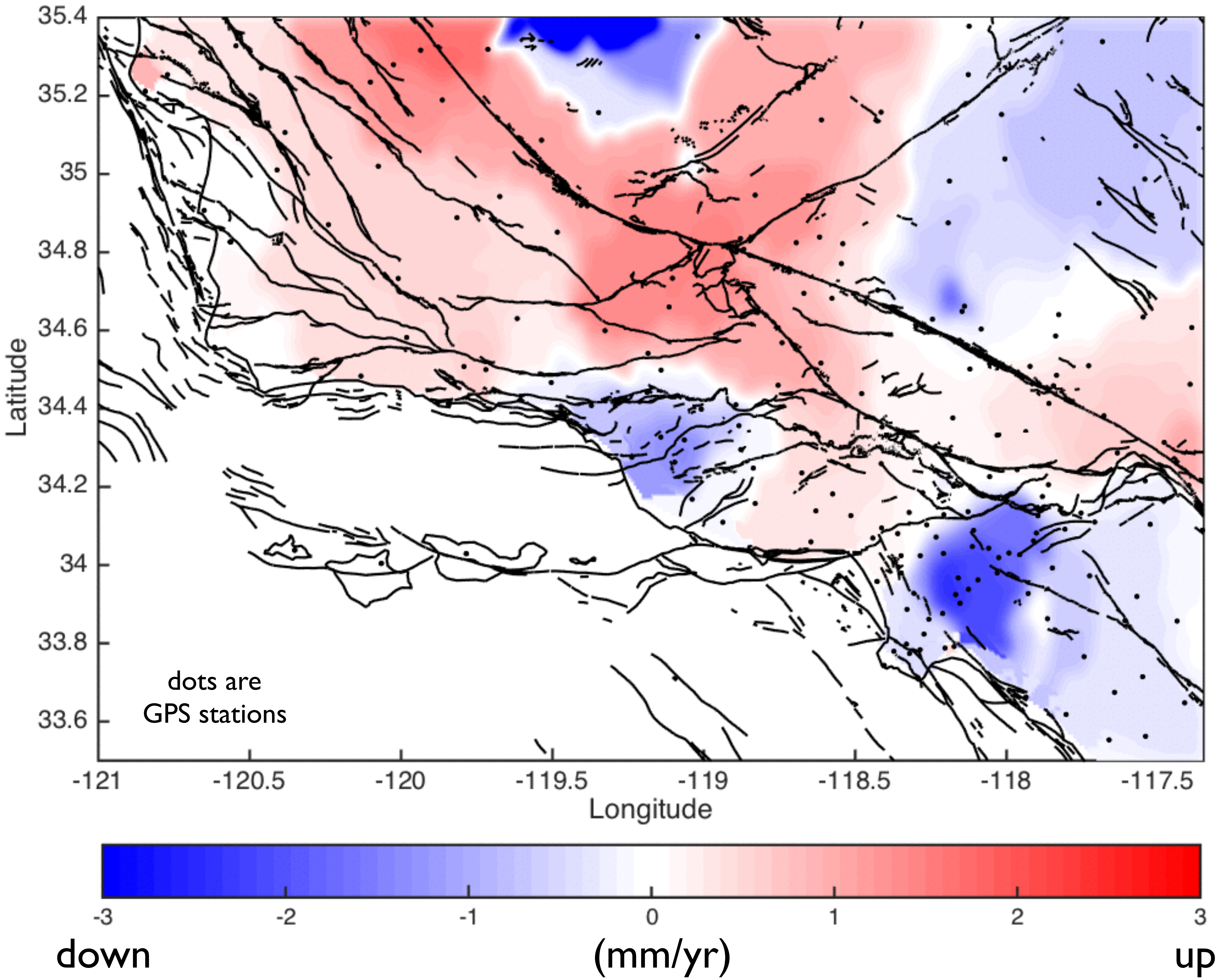
GPS Imaging Western Transverse Ranges

GPS(-Only) Imaging

Close up of Western Transverse Ranges

Signals:

- Central Valley subsidence
- Peripheral elastic unloading from groundwater extraction
- Western Transverse Ranges uplift
- San Andreas/San Gabriel Uplift
- Subsidence in Ventura/LA Basins
- Landers/Hector Mine Postseismic uplift to the east



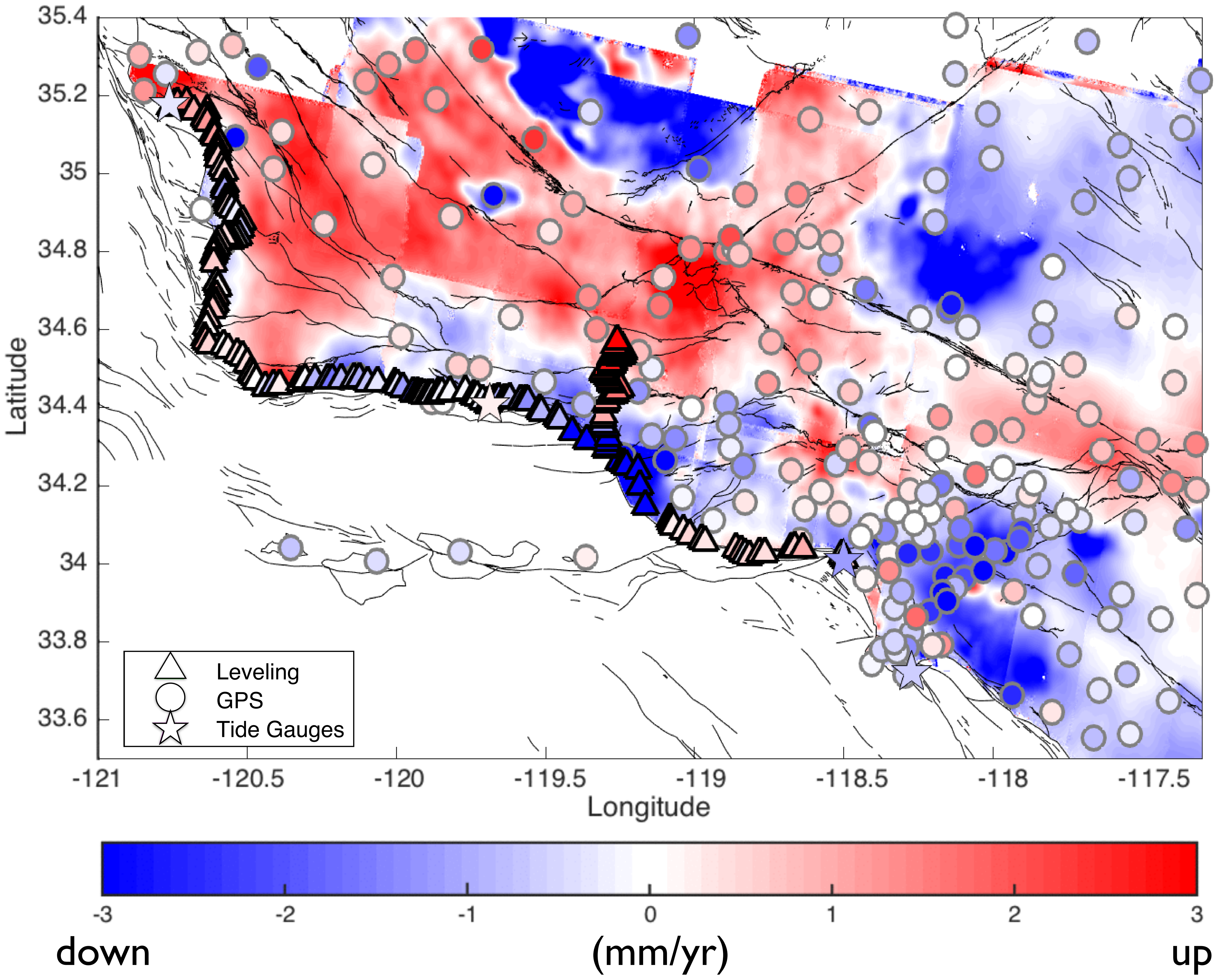
GPS+ Imaging of Vertical GPS Velocity: WTR

Alignment Technique:

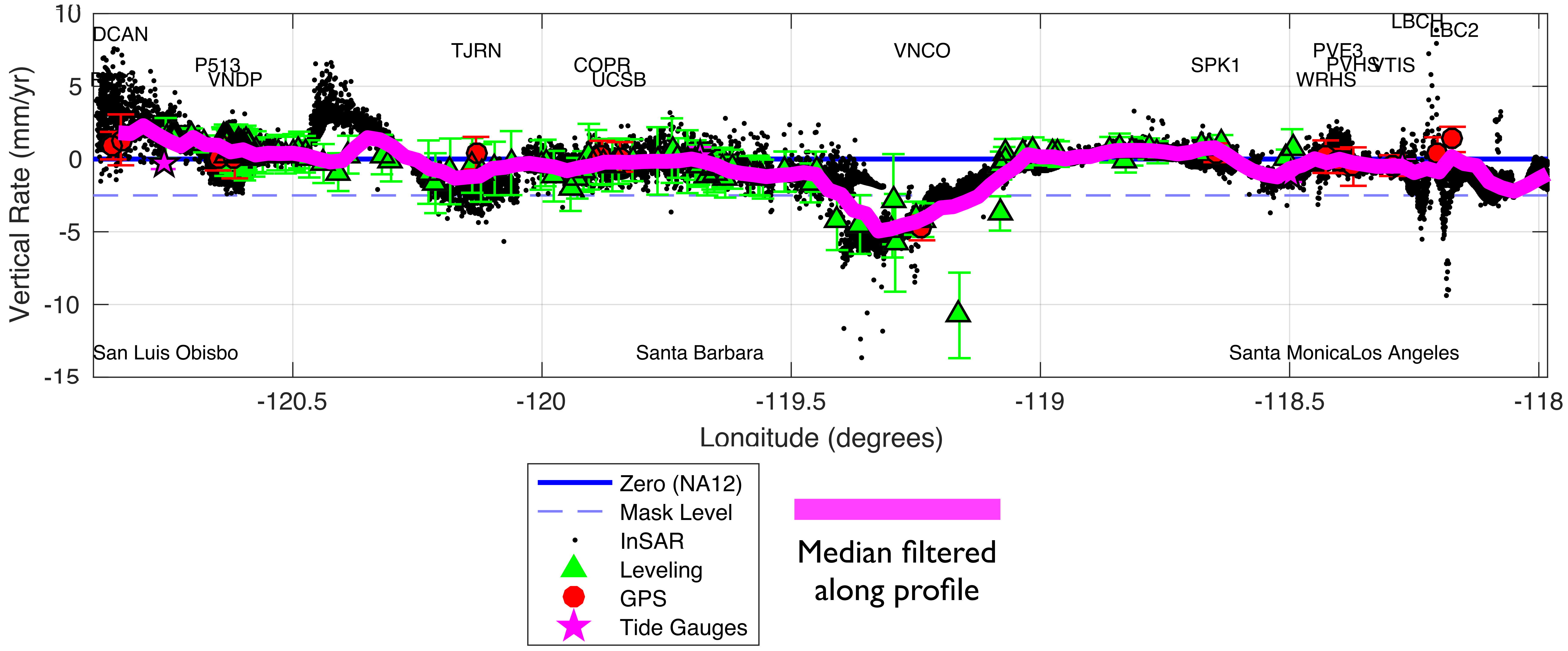
Shift & flip tide gauges
Leveling tied to tide gauges
Align to GPS
Wrap InSAR to GPS+Leveling+Tide Gauges

GPS+InSAR+Tide Gauges+Leveling Imaging

- Each technique has strengths and weaknesses
- By aligning techniques to common GPS frame, we combine the strengths of the individual but mitigate weaknesses
- Leveling 30-60 yrs, tide gauges 80+ yrs
- Improved resolution
- Better control on San Gabriel uplift
- Groundwater basins
- Sees groundwater and tectonic signals
- Works well where GPS networks are dense +other techniques present
- Seams between InSAR scenes



Uncertainties: Coastal Profile

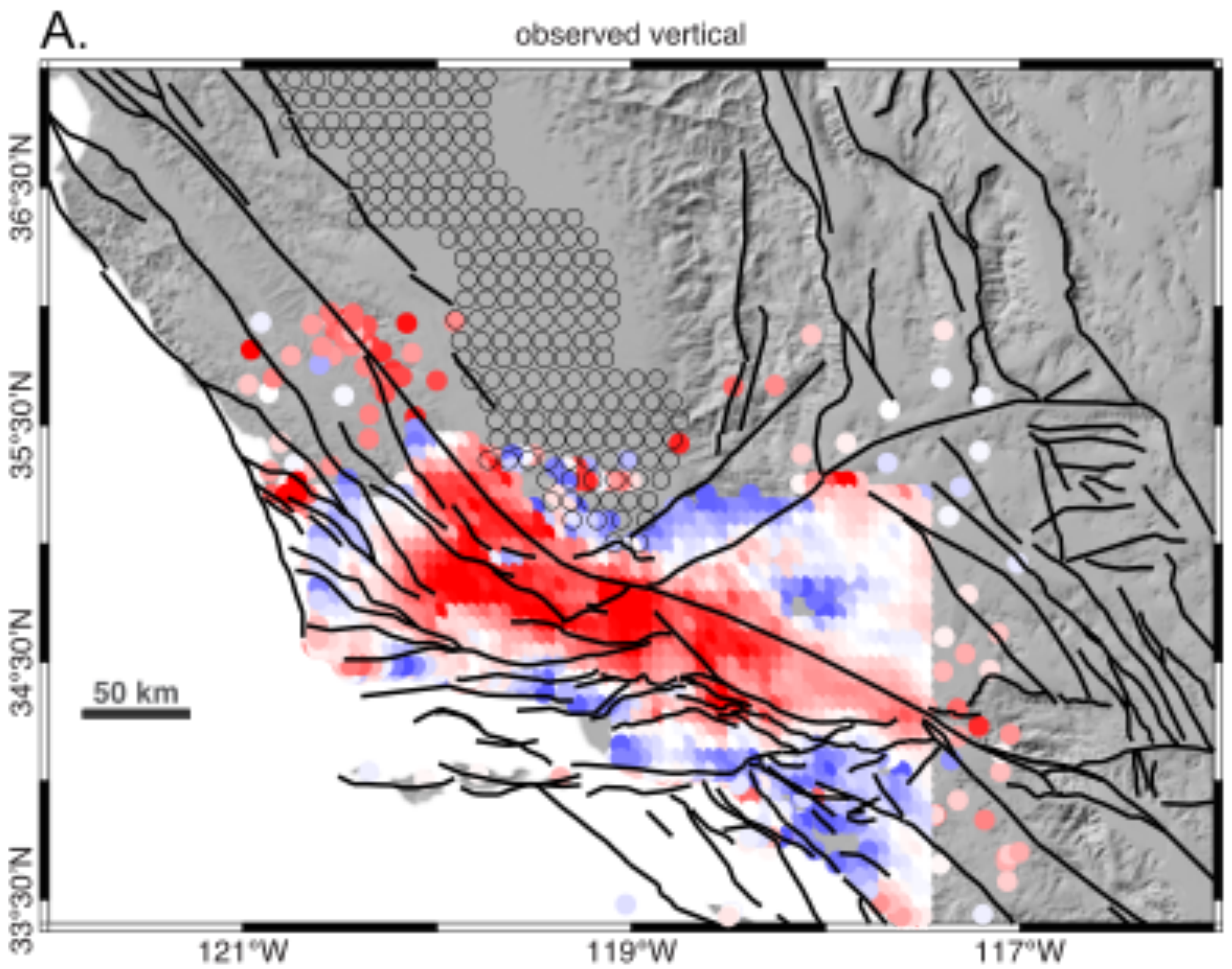


- Vertical rates along coastal profile (San Luis Obisbo to Los Angeles)
- Alignments show internal agreement to ~1 mm/yr RMS
- InSAR a little unstable in a few places where GPS coverage sub-optimal
- Median filtered (robust) profile insensitive to outliers
- Best explanation of the data along coast of S. California
- **Sea Level:** Tide gauges implies 0.99+/-0.31 mm/yr regional geocentric sea level rise San Luis Obisbo to Los Angeles

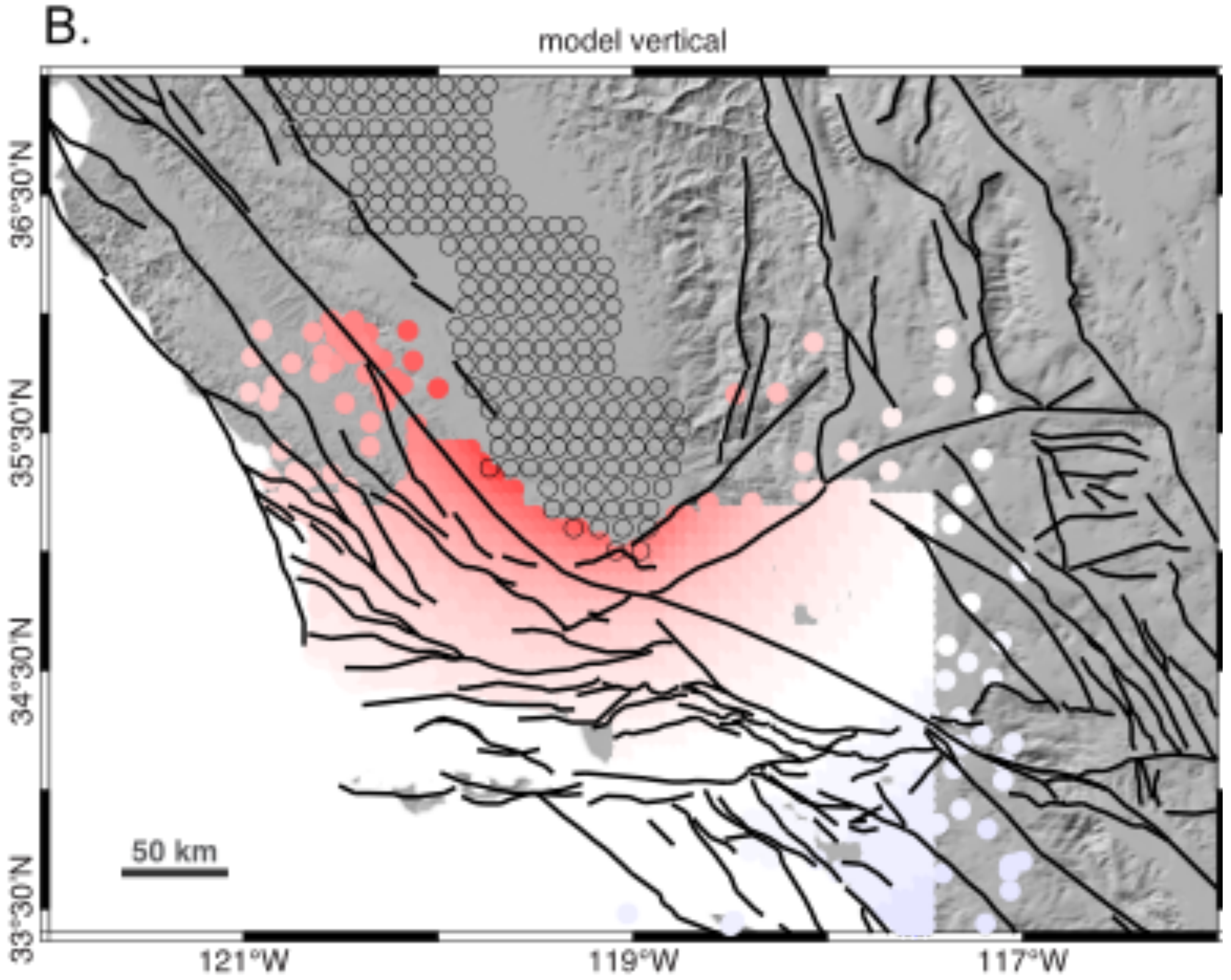
Constraining Tectonic Models Using VLM Data

First remove the expected signal from groundwater pumping

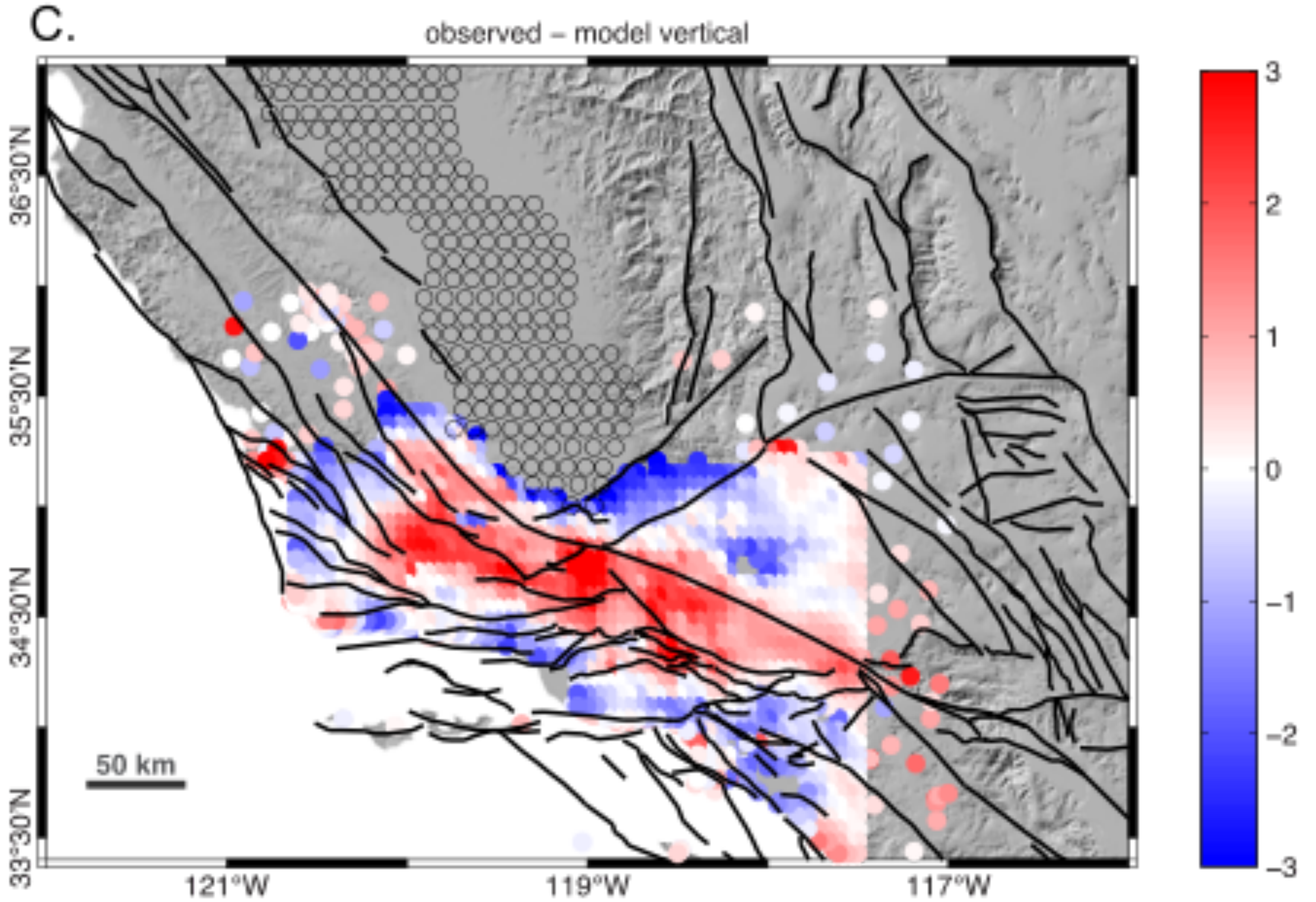
Vertical Rates Observed



Vertical Rates from Groundwater Unloading Modeled



Vertical Rates Corrected for Groundwater Unloading

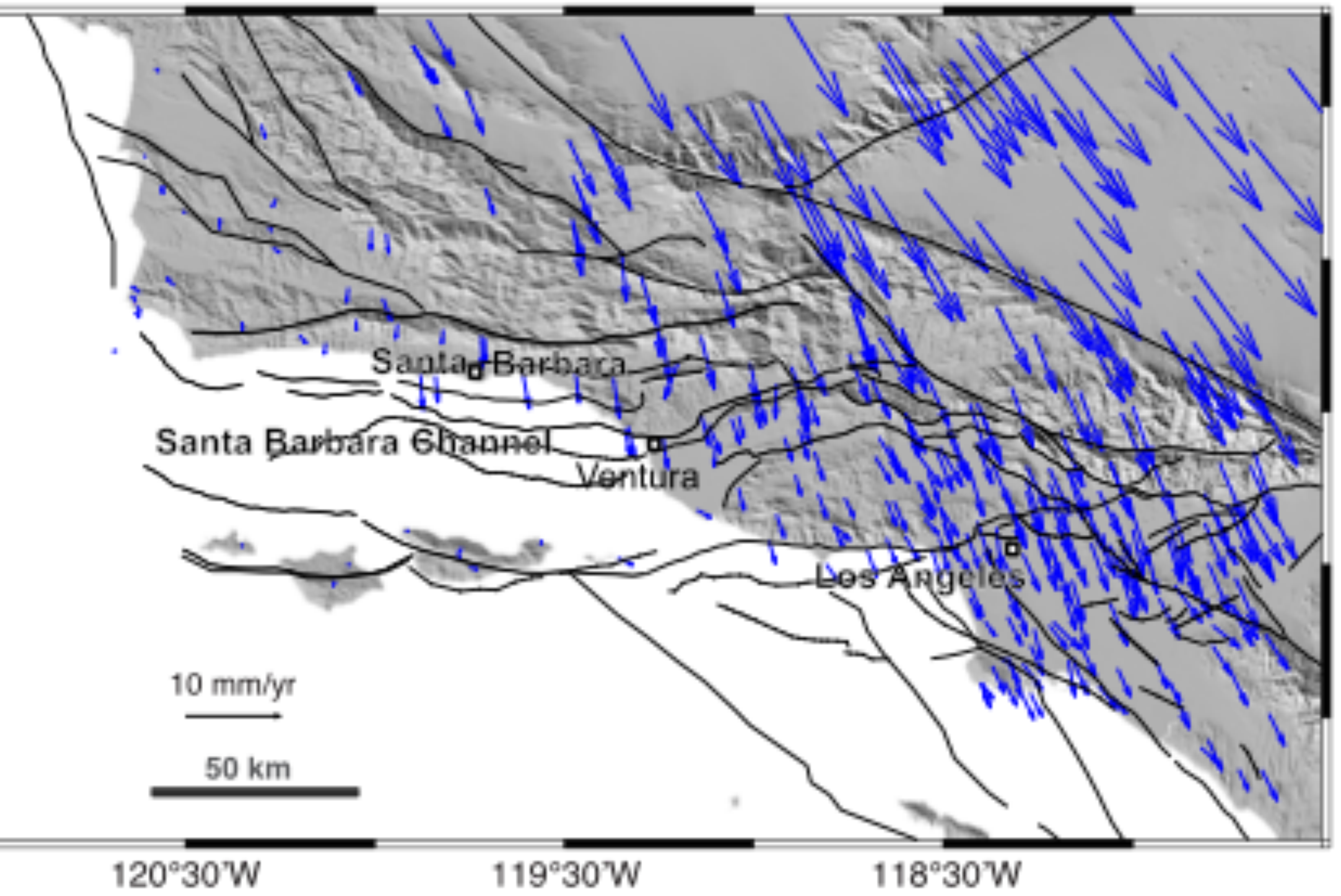


(mm/yr)

Kaj Johnson et al., 2016 in prep.

Constraining Tectonic Models Using VLM Data

Geodetic Vertical Rates



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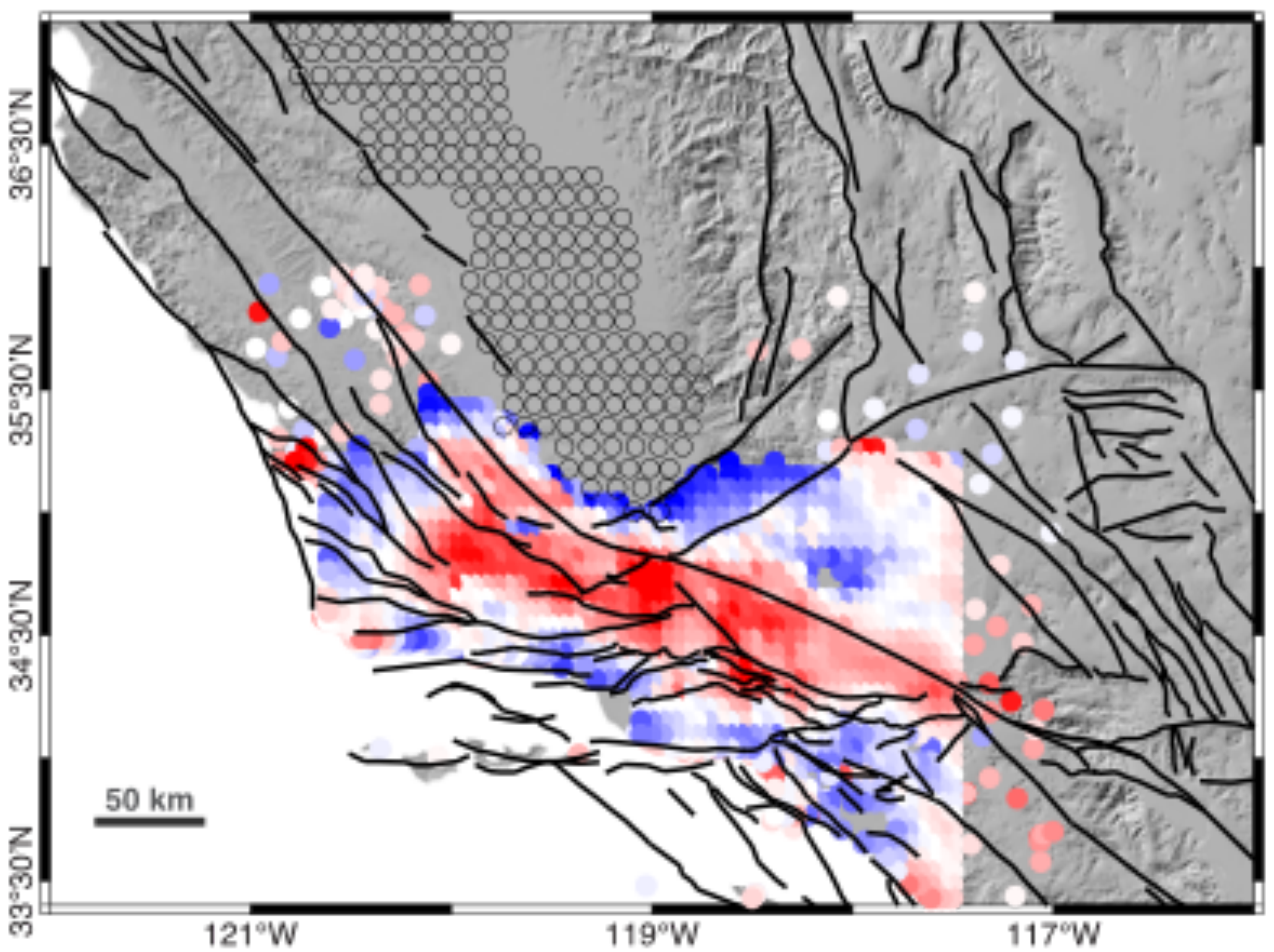
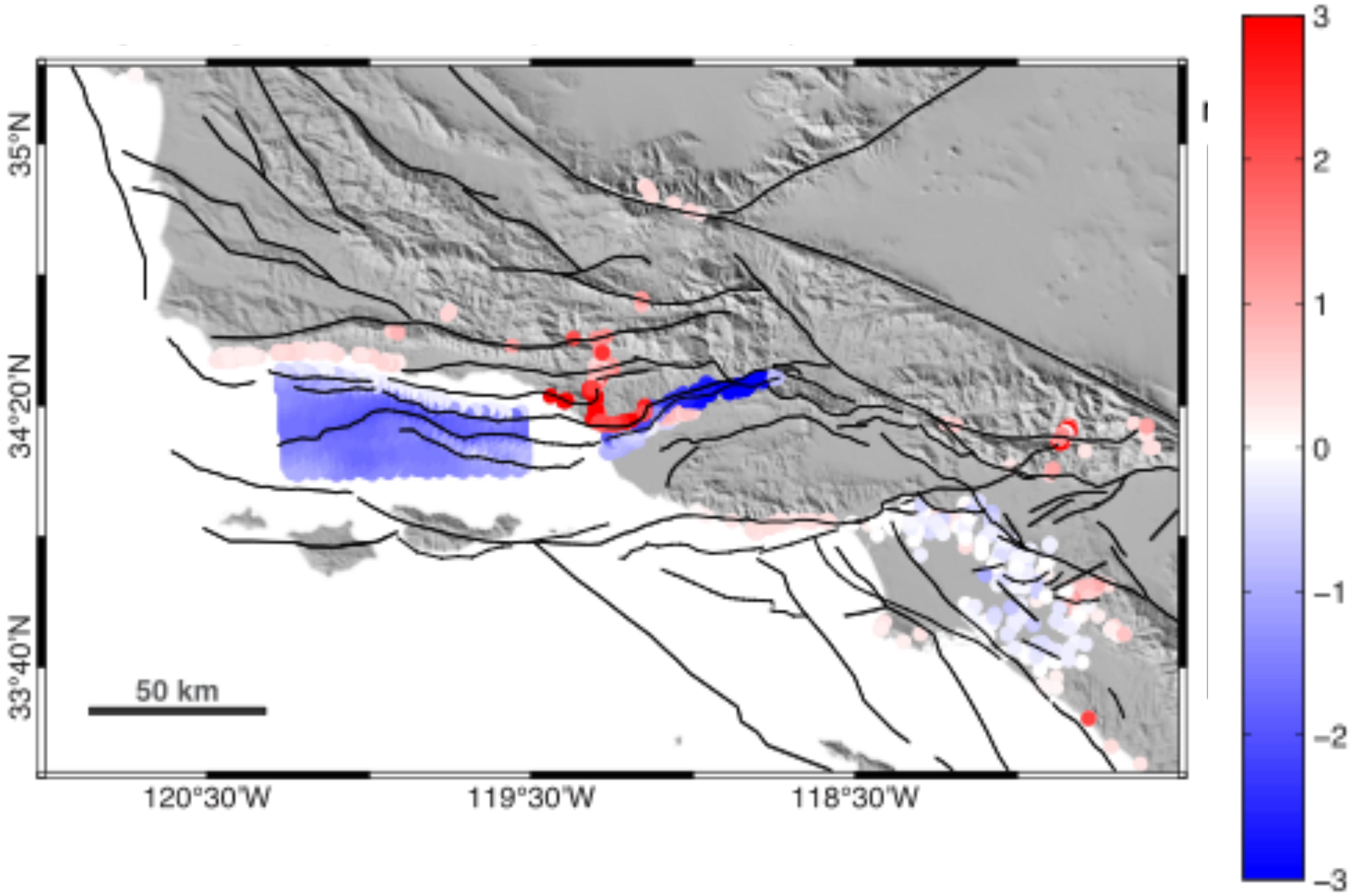


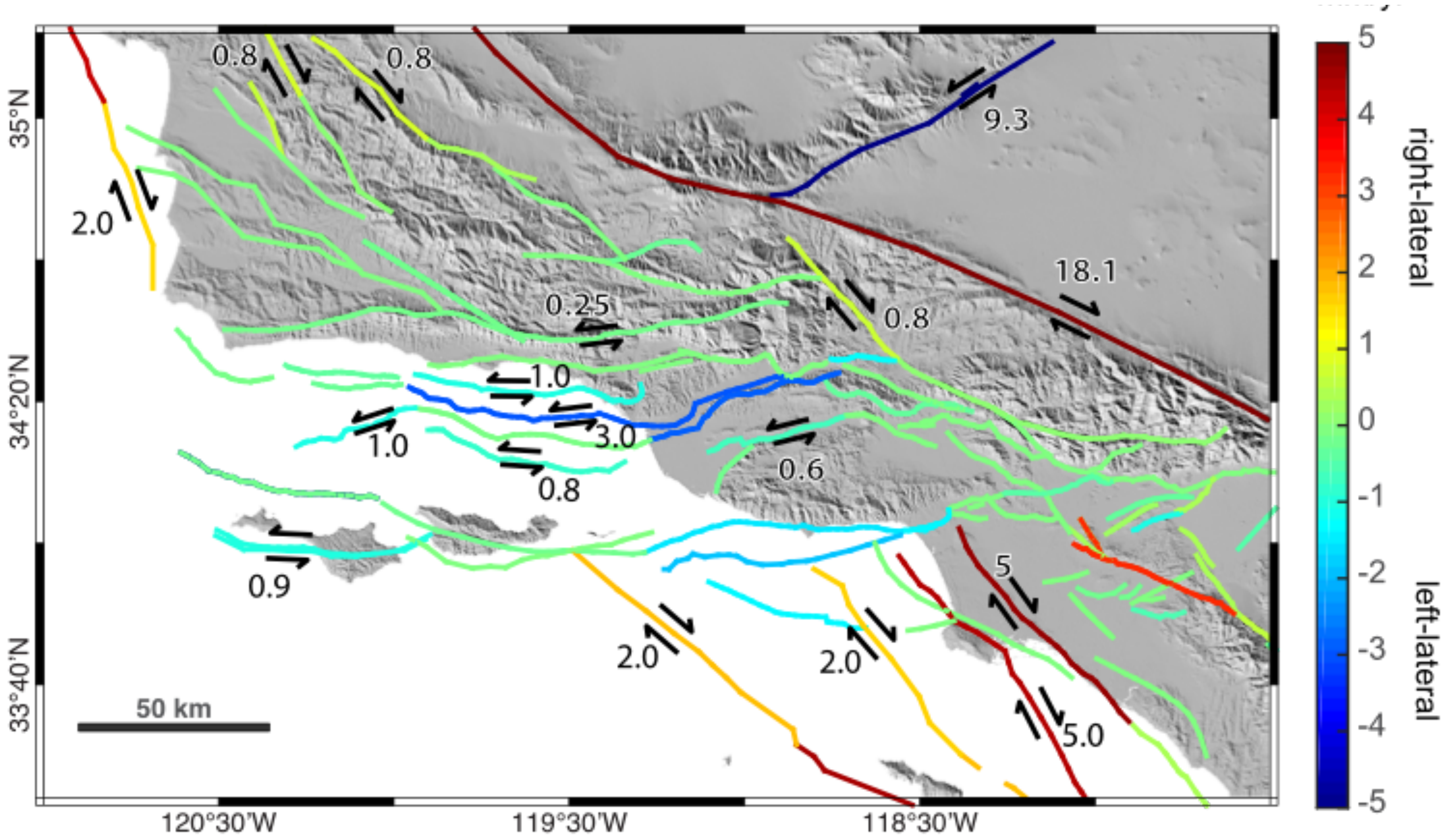
Geologic Vertical Rates



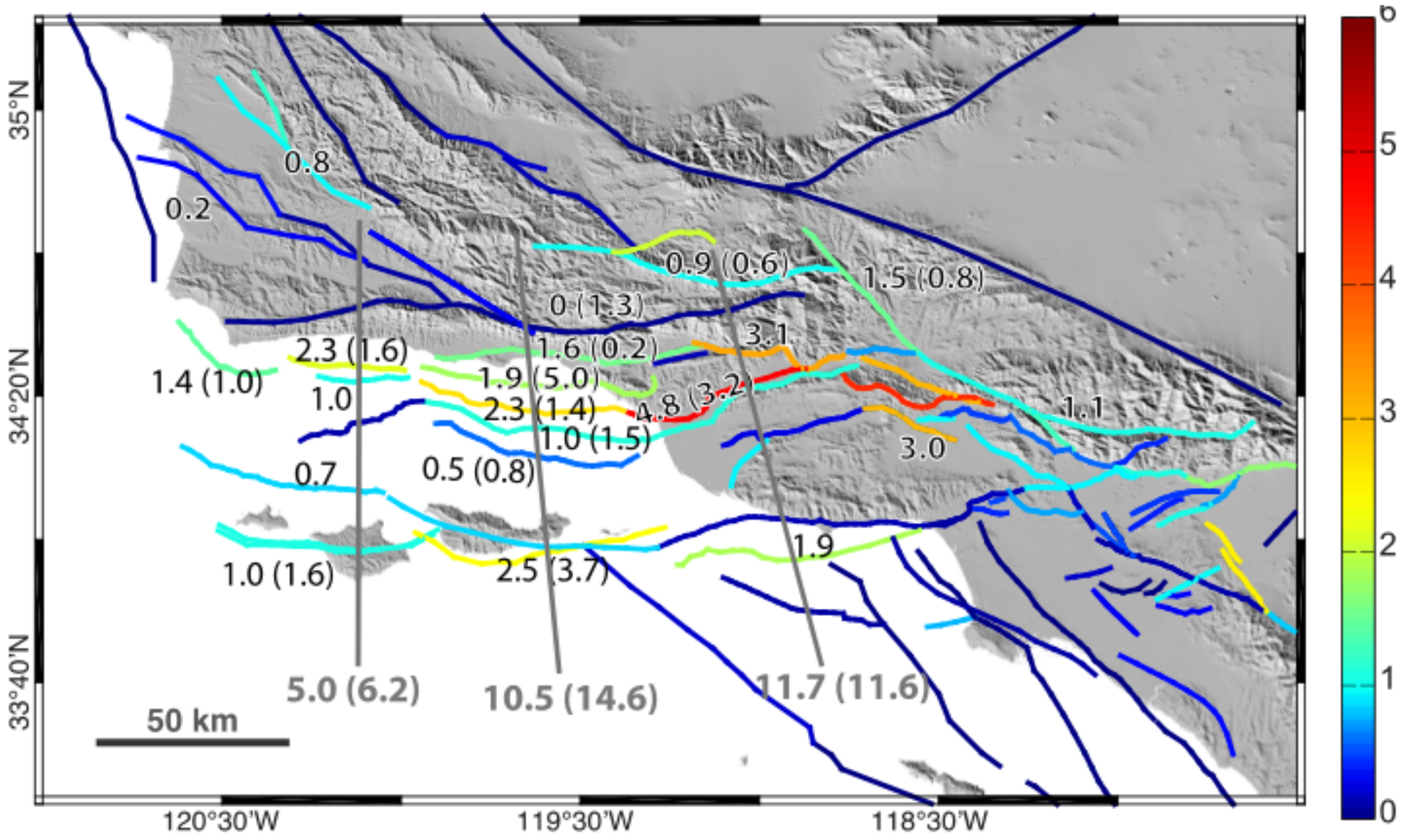
Kaj Johnson et al., 2016 in prep.

Constraining Tectonics Using VLM Data

Strike Slip Rates



Reverse Rates



- Vertical rate field less smooth, helps locate slip on reverse faults
- Highest reverse rates on Red Mountain and San Cayetano
- More distributed offshore as strain is spread among multiple faults

Kaj Johnson et al., 2016 in prep.

Conclusions

- Expansion of GPS networks and new algorithms allows spatially continuous imaging of uplift and subsidence in California.
- Plug and Play gates are open, will hopefully throw more fuel the explosion of GPS networks on Earth
- Sierra Nevada uplift is time-variable but a long-term component possibly tectonic signal exists.
- Owens Valley marks a sharp contrast in vertical rate, and may indicate a broken plate
- In Southern California GPS Imaging resolves Western Transverse Ranges and San Gabriel Mountains uplift, both ~2 mm/yr.
- These constraints are improving models of fault slip rates and seismic hazard.

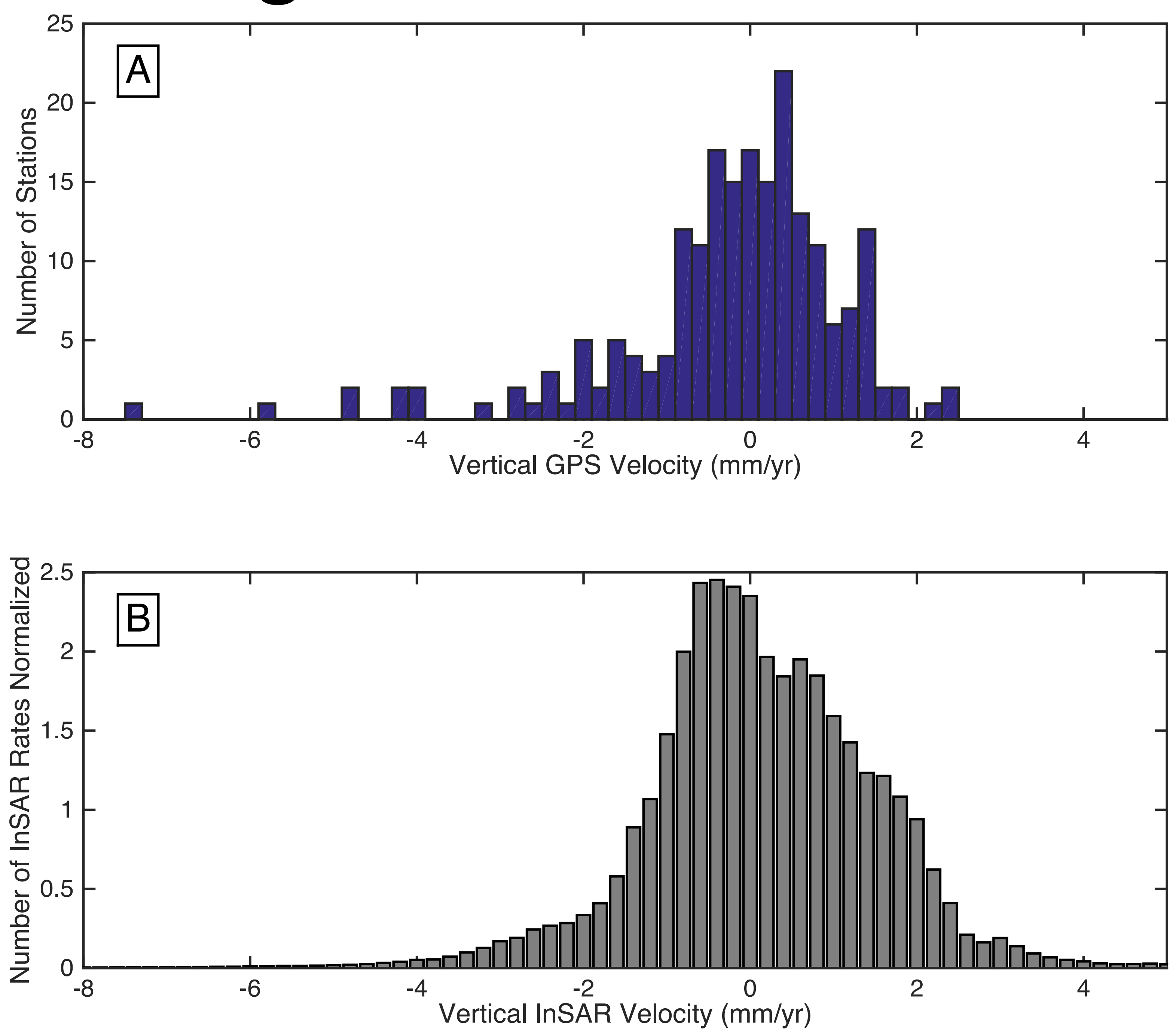
Separate Tectonic vs. Non-Tectonic Motion

An attempt based on signal characteristics

Histograms of Vertical Rates

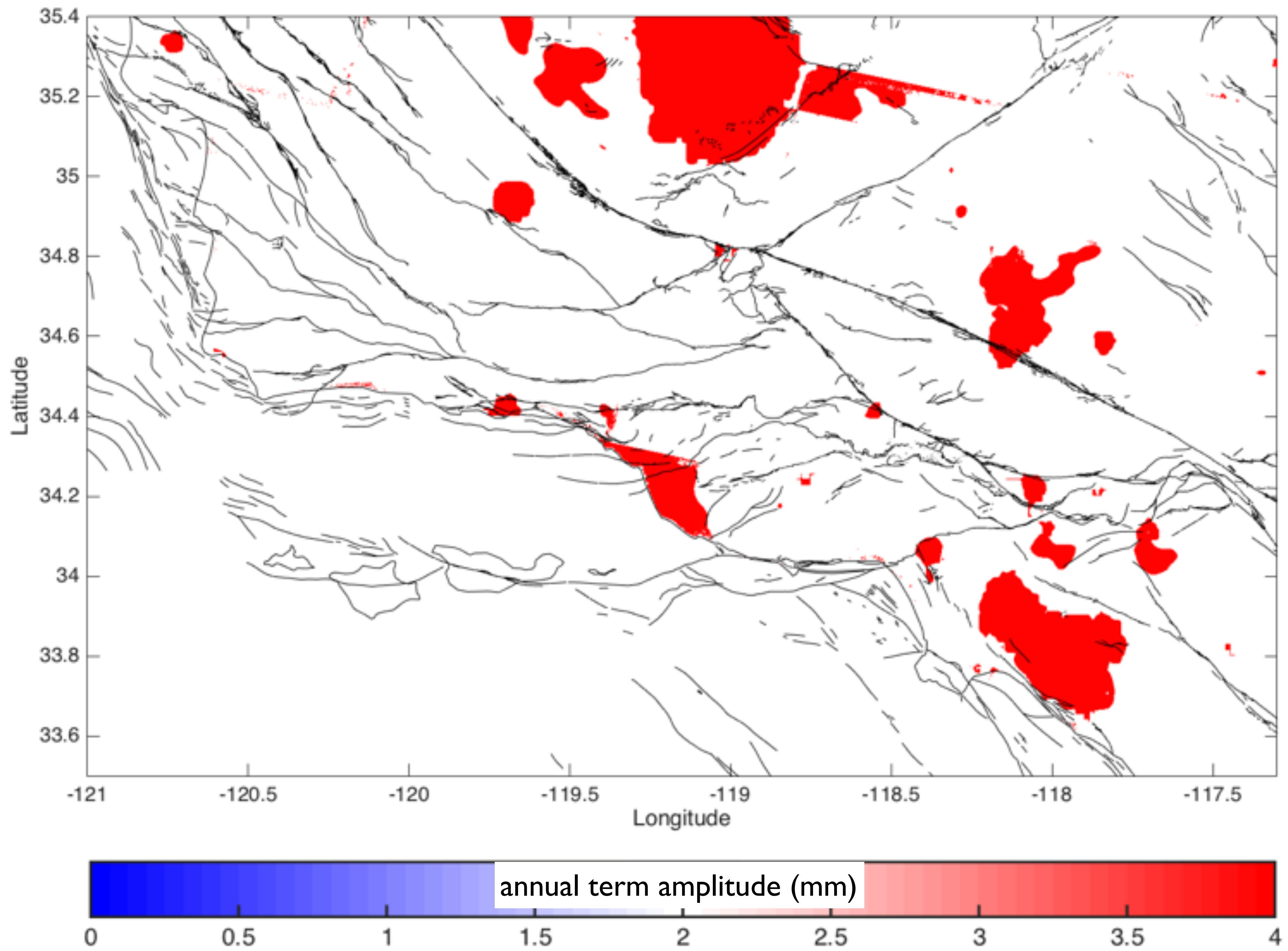
GPS

InSAR



- Nice similarity
- Long tail on left
- Characteristic of non-tectonic motion

Mask



- Subside more quickly than -2.5 mm/yr
- Seasonal terms from InSAR SBAS analysis > 2.0 mm
- Interpolation (using GPS Imaging) of GPS annual terms > 2.0 mm