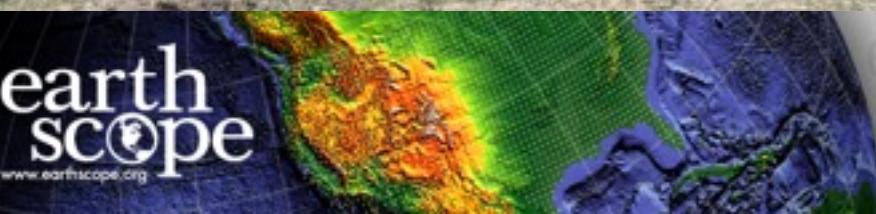


# GPS Imaging of Vertical Motion in California and Nevada

- Update on NGL GPS data products
- MIDAS velocity field now available online
- GPS Imaging of vertical rate field
- CA/NV/Sierra Nevada uplift and subsidence
- Integration of InSAR/GPS/tide gauges/leveling data in Southern California for vertical motion studies

Bill Hammond, Geoff Blewitt,  
Corné Kreemer

Nevada Geodetic Laboratory  
Nevada Bureau of Mines and Geology  
University of Nevada, Reno  
Reno NV, 89557  
[whammond@unr.edu](mailto:whammond@unr.edu)





# Plug and Play GPS for Earth Scientists:

## Providing Immediate Access to Low-Latency Geodetic Products for Rapid Modeling and Analysis of Natural Hazards

- MAGNET plus all continuous networks of which we are aware and provide open access to data
- >14,000 stations and growing
- Data processed with GIPSY/OASIS from JPL
- Products include:
  - Time series
    - IGS08+NA12 frames
    - text+graphic formats
    - xyz+enu,
    - station pages
  - QA files for trouble shooting
  - Solutions from final, rapid and ultra rapid solutions
  - NEW:
    - MIDAS velocity field online IGS08, NA12 frames
    - Browse with maps, station text lists, GSAC search tools, data holdings files updated daily
    - Steps database from equipment and earthquake steps (127,000 records)
    - handy tools, e.g. decimal year date conversion

<http://geodesy.unr.edu>  
<https://www.unavco.org/>

The screenshot shows the Nevada Geodetic Laboratory website. The header features a banner image of a GPS station in a desert landscape with the text "Nevada Geodetic Laboratory". Below the banner is a navigation menu with links: Home, People, Contact, About us, Links, Vacancies, Site Map, News Archive, MAGNET, Acknowledgements.

The main content area is divided into several sections:

- Current Research:** Great Basin Strain, Basin and Range Dynamics, Aquifer Deformation, Geothermal Energy, Global Tectonics, Reference Frames, Global Strain Rate Map, Yucca Mountain GPS, Publications.
- MAGNET GPS Network:** Network Information.
- People:** Geoff Blewitt, Hans-Peter Plag, Bill Hammond, Corné Kreemer, Elliot Klein, Bret Pezomero, Jayne Bormann, Jay Goldfarb, Yang Zhang.
- Opportunities:** Students, Postdocs.
- Latest News:**
  - [December 14, 2015] New Steps Database Product Available! (Text about online database of potential step discontinuities in GPS time series.)
  - [October, 2015] A wave of new papers published by the Nevada Geodetic Lab! (Text about a new set of peer-reviewed publications.)
  - Dornellen, A., L. Grant Ludwig, J.W. Parker, J. B. Rundle, J. Wang, M. Pierce, G. Blewitt, and S. Hensley, 2015, Potential for a large earthquake near Los Angeles inferred from the 2014 La Habra earthquake, *Earth and Space Science*, 2, doi:10.1002/2015EA000113. (PDF)
  - Bird, P., D.D. Jackson, Y.Y. Kagan, C. Kreemer, and R.S. Stein, 2015, GEAR: A Global Earthquake Activity Rate model constructed from geodetic strain rates and smoothed seismicity, *Bulletin of the Seismological Society of America*, 105, 2538-2564. (PDF)
  - Keiding, M., C. Kreemer, C.D. Lindholm, S. Gradmann, O. Olesen and H.P. Kariuk, 2015, A comparison of strain rates and seismicity for Fennoscandia: depth dependency of deformation from glacial isostatic adjustment *Geophysical Journal International*, 202, 1021-1028. (PDF)
  - Aster, R., M. Simons, R. Burgmann, N. Gomez, W.C. Hammond, S. Holbrook, E. Chaussard, L. Stearns, G. Egbert, J. Hole, T. Lay, S. McNutt, M. Oskin, B. Schmandt, D. Schmidt, J. Vidale, L. Wagner, P. Winberry, 2015, Future geophysical facilities required to address grand challenges in the Earth sciences, *A Community report to the National Science Foundation*. (PDF)
  - Blewitt, 2015, GPS and space-based geodetic methods, in *Treatise in Geophysics*, ed. G. Schubert, 307-333, Elsevier, doi:10.1016/B978-0-444-63802-4.00060-9. (PDF)
  - Blewitt, 2015, Terrestrial reference frame requirements for studies of geodynamics and climate change, *International Association of Geodesy Symposia*, 1-8, doi:10.1007/978-3-319-142. (PDF)
  - Bird, P., and C. Kreemer, 2015, Revised tectonic forecast of global shallow seismicity based on version 2.1 of the Global Strain Rate Map, *Bulletin of the Seismological Society of America*, 105, 152-166. (PDF)
  - Melgar, D., J. Geng, B.W. Crowell, J.S. Haase, W.C. Hammond, Y. Bock, R.M. Allen, 2015, Seismogeodesy of the 2014 Mw6.1 Napa, California, Earthquake: Rapid response and modeling of fast rupture on a dipping strike-slip fault, *Journal of Geophysical Research - Solid Earth*, 120, doi:10.1029/2015JB011921. (PDF)
- Data Products:**
  - Map Browse GPS Stations
  - FTP Access to GPS Data Products
  - GPS Data Processing Strategy
  - MAGNET GPS network
  - Guide to GA Files
  - Publications
  - MIDAS Velocity Fields
    - In NA12 Reference Frame
    - In IGS08 Reference Frame
    - MIDAS README
  - Browse Lists of Stations
    - All Stations Processed
    - Stations with rapid 5 minute sample rate solutions (latency 24 hours)
    - Stations with ultra rapid 5 minute sample rate solutions (latency 1.5 hours)
    - Above lists have links to station pages.
  - Downloadable Lists of GPS Data Holdings:
    - Download List of GPS Station Latitude, Longitude, Height
    - Stations with 24 hour sample rate solutions, final orbits, 2 week latency.
    - Stations with 24 sample rate solutions, rapid orbits, 24 hour latency.
    - Stations with 5 minute sample rate solutions, rapid orbits, 24 hour latency.
    - Stations with 5 minute sample rate solutions, ultra rapid orbits, 1.5 hour latency.
  - The linked text files above are updated daily and include: Station Name, Latitude, Longitude, Height, XYZ coordinates, data begin and end dates, number of solutions and station operator original site name.
- Database of Potential Step Discontinuities:**
  - Link to master steps database.
  - README for steps database.
- Decimal Year Convention:**
  - Click here for explanation and translation file
- System Status Notes:**
  - On November 5, 2015 the name of the decyr file was changed to decyr.txt
  - On October 26, 2015 our data products web server failed, resulting in products being unavailable until October 27. The problem has been corrected. Data products are now back online and being updated at: <http://geodesy.unr.edu>

At the bottom of the page, there is a map titled "GEAR1 forecast of magnitude that has rate of 0.01/year in a local circle of radius 100 km". The map shows a color-coded forecast of seismicity over a region of the western United States, with red and yellow areas indicating higher forecast rates.



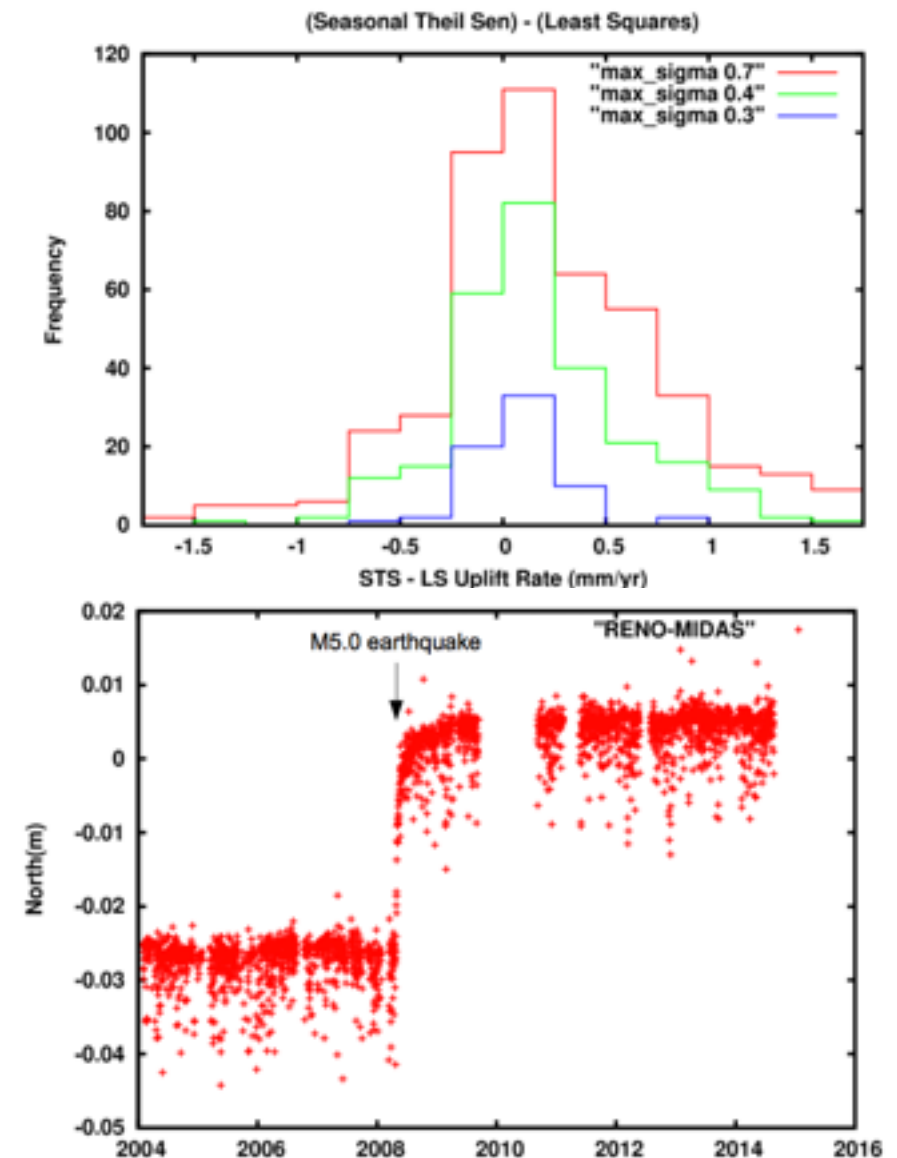
# The MIDAS Non-parametric Time Series Trend Estimator

- Not least squares: Robust median-based estimate of station velocity
- Based on Theil-Sen median trend estimator
- Insensitive to steps, outliers, seasonal terms and heteroscedasticity
- 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
- More accurate than LS methods in DOGEx exercise
- MIDAS rates soon to appear in our data products system

$$\hat{v} = \text{median}_i (x_{i+365} - x_i)$$

$$\sigma = 1.4826 \text{ median}_i |x_{i+365} - x_i - \hat{v}|$$

$$\sigma_v = 1.2533 \frac{\sigma}{\sqrt{N/4}}$$



## Example: Station RENO

- Detrended using MIDAS rate.
- Accurately estimates pre-seismic trend

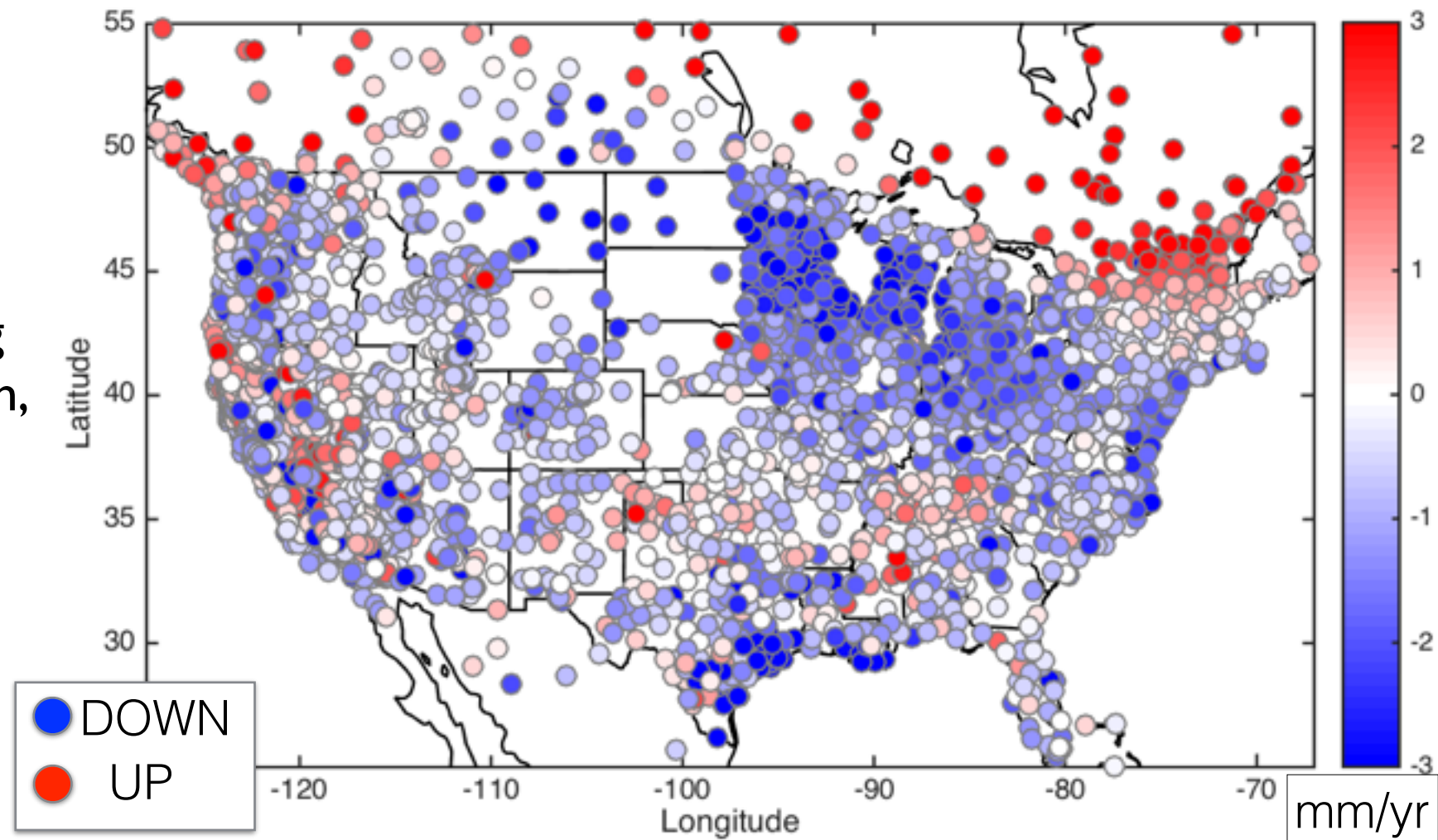


# GPS Imaging of Vertical GPS Velocity: North America

## Vertical Rates from Thousands of Stations

- MIDAS addresses robustness in the temporal part, GPS Imaging tackles the spatial part
- Weighted median-based geographic spatial filtering (despeckling) applied
- Suitable for focusing on signals with wavelength  $>$  station spacing
- “Imaging” step is weighted median, Delaunay-based interpolation
- Not smoothing! Preserves edges in field provided they are supported by multiple stations

## MIDAS Vertical Rates



- Uses 5 year time minimum duration for time series
- NAI2 reference frame.

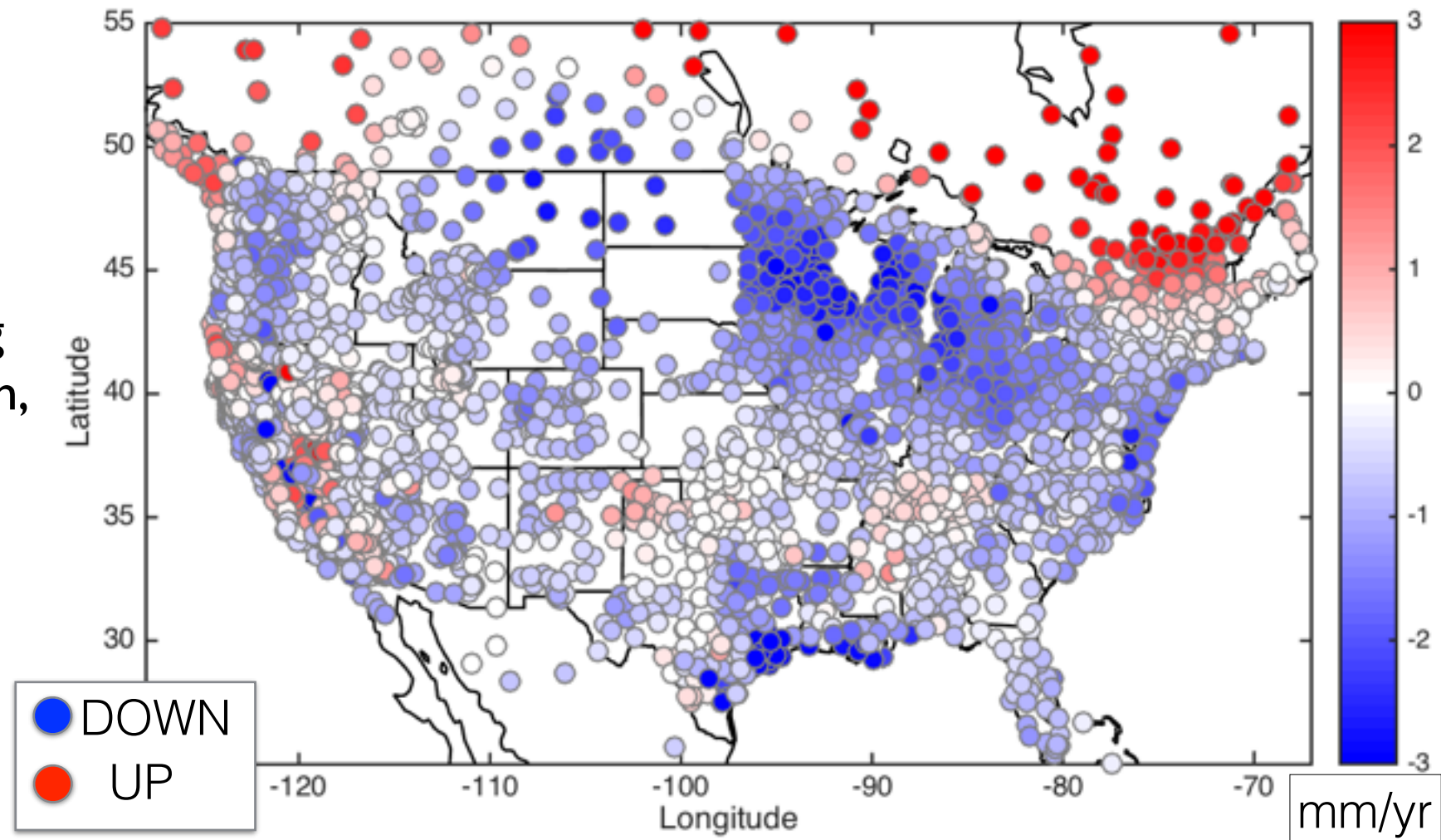
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## MIDAS Rates Despeckled Weighted-Median Spatial Filtered

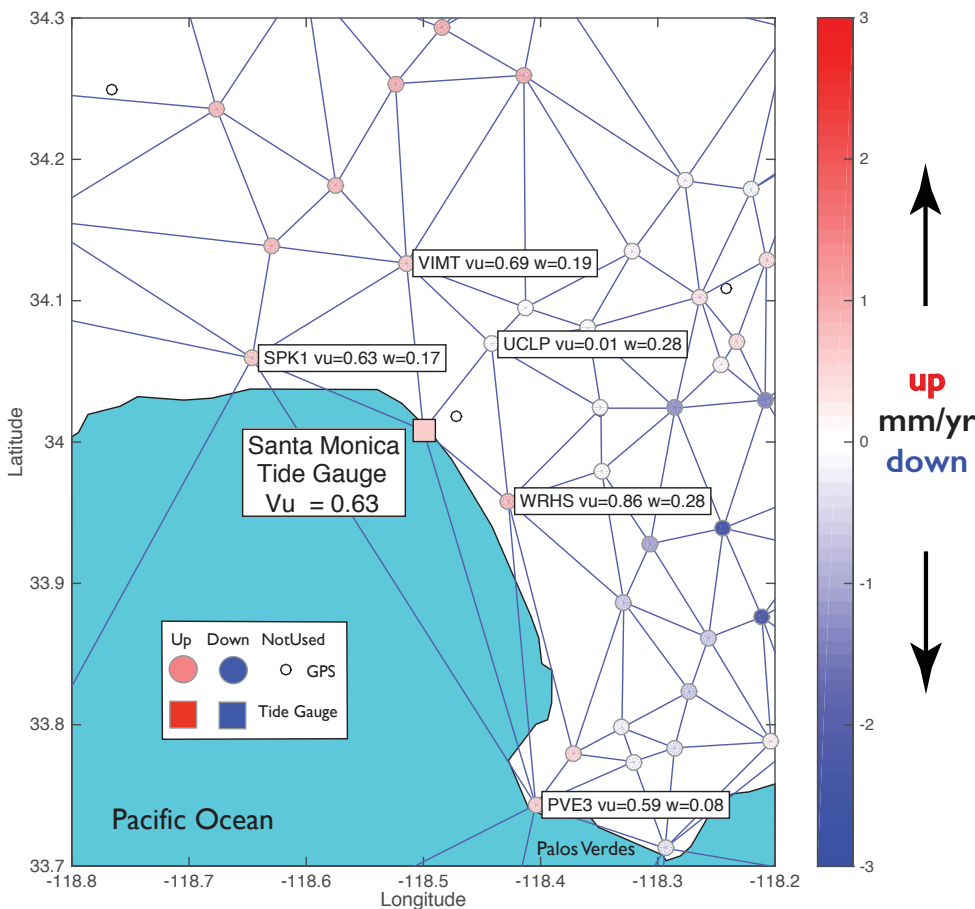


- Uses 5 year time minimum duration for time series
- NA12 reference frame.



# GPS Imaging: How it Works

- Example of a benefit from interdisciplinary studies
- Method designed for robust estimation of vertical land motion at tide gauges from GPS network



connected GPS station  $i$  gets:

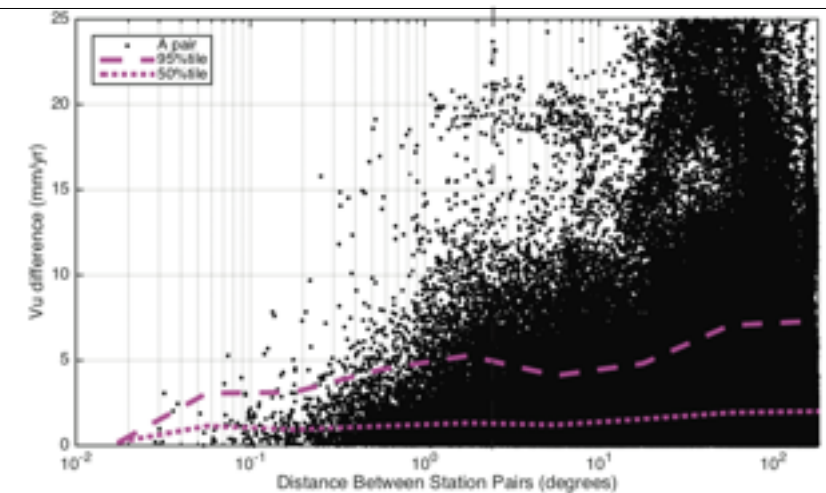
$$w_i = \text{ssf}(\Delta_i) / \sigma_i$$

at tide gauge:

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

- Apply weighted median filter on Delaunay triangulation of GPS station locations with location of tide gauge
- Weights determined with combination of
  - Rate uncertainty
  - Distance from GPS to estimation point
  - Empirical spatial structure function of vertical rate.
- Resolution depends on station density (which varies greatly)
- Apply method to grid points to get image of vertical motion

## Empirical Spatial Structure Function



Difference in vertical velocities  
as a function of station  
separation  
All pairs

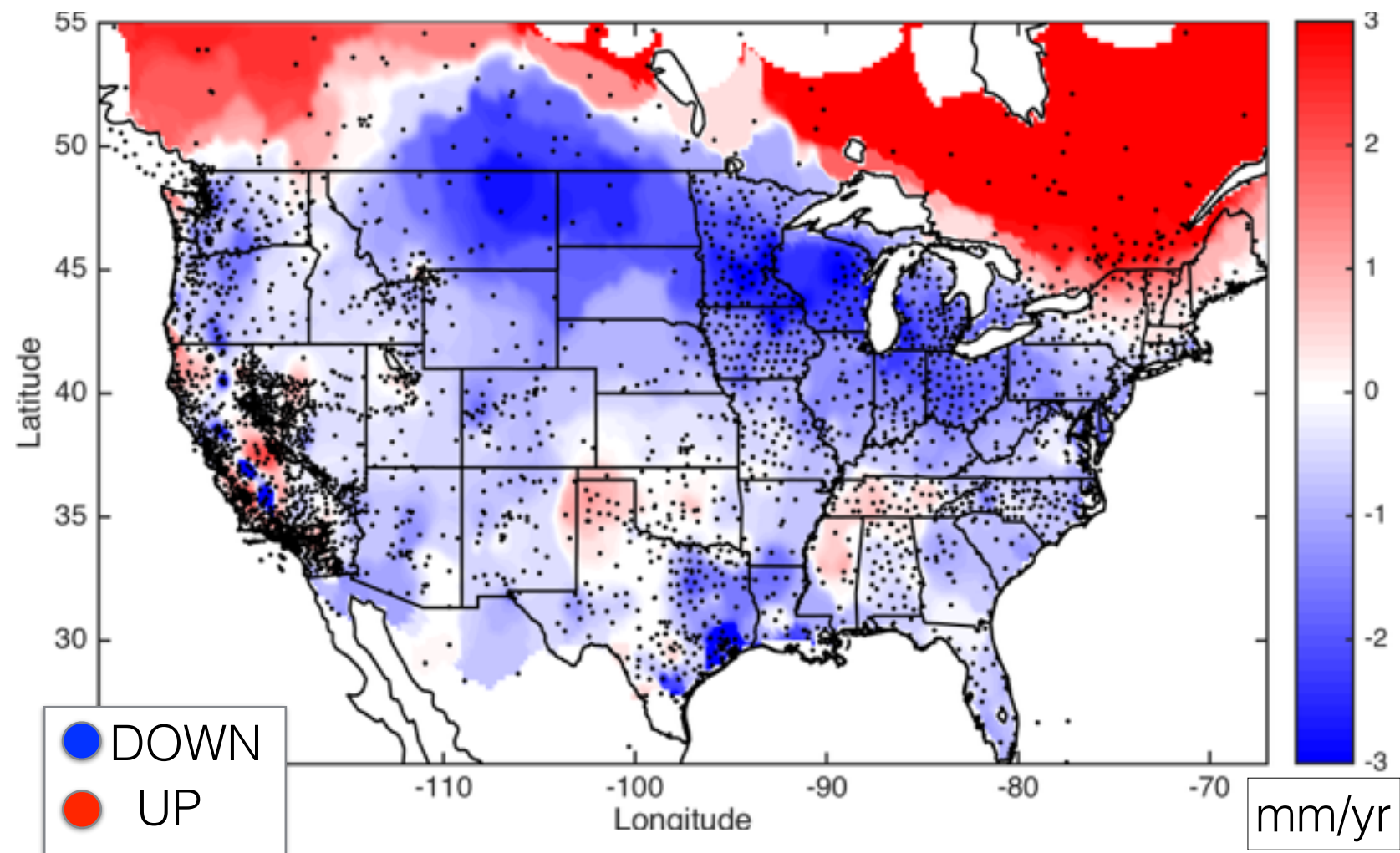
# GPS Imaging of Vertical GPS Velocity: North America

- Final Step: Apply filtering technique to points on grid

Seeing, for example:

- GIA very well
- Location of hinge between uplift and subsidence
- Forebulge collapse south of hinge driving subsidence along east coast 1-2 mm/yr
- Gulf coast subsidence, a combination of pumping and sediment loading
- Technique enhances signals with geographic coherence that are detected in many stations
- GPS Imaging of surface manifestation of mantle flow

## MIDAS Rates with GPS Imaging



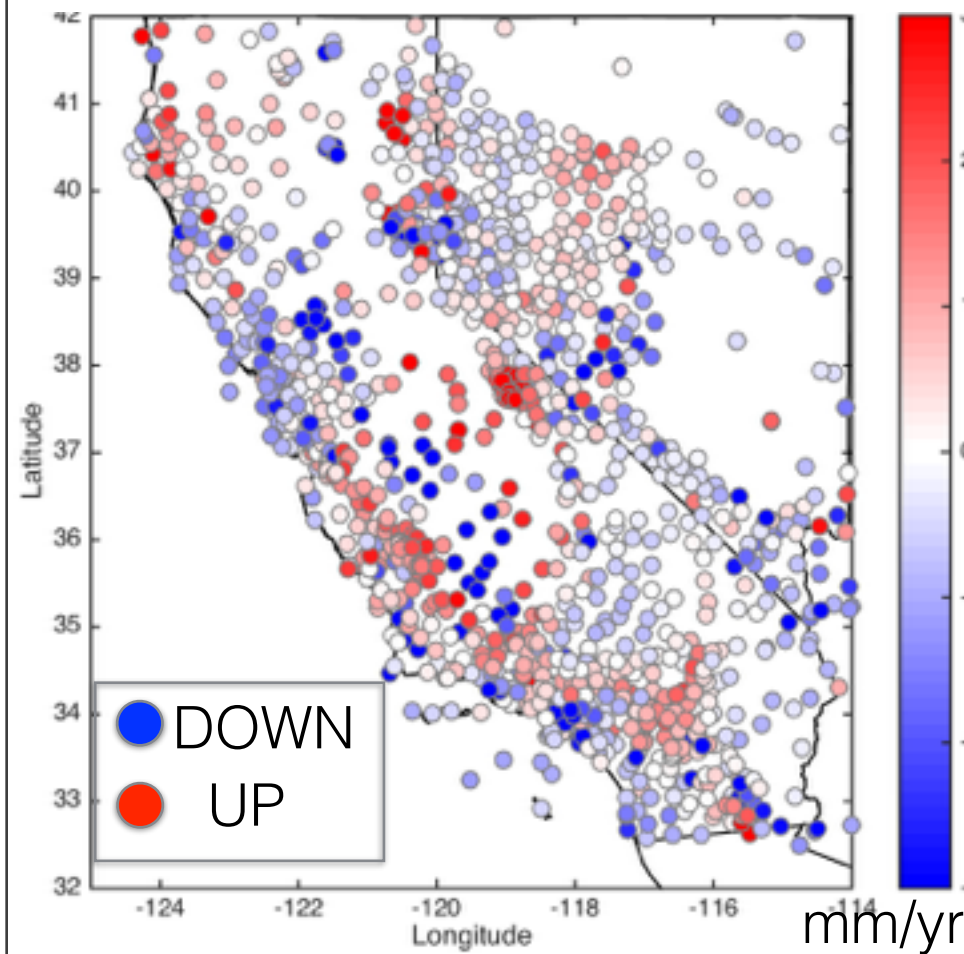
- Uses 5 year time minimum duration for time series
- NAI2 reference frame.

# GPS Imaging of Vertical GPS Velocity: Sierra Nevada

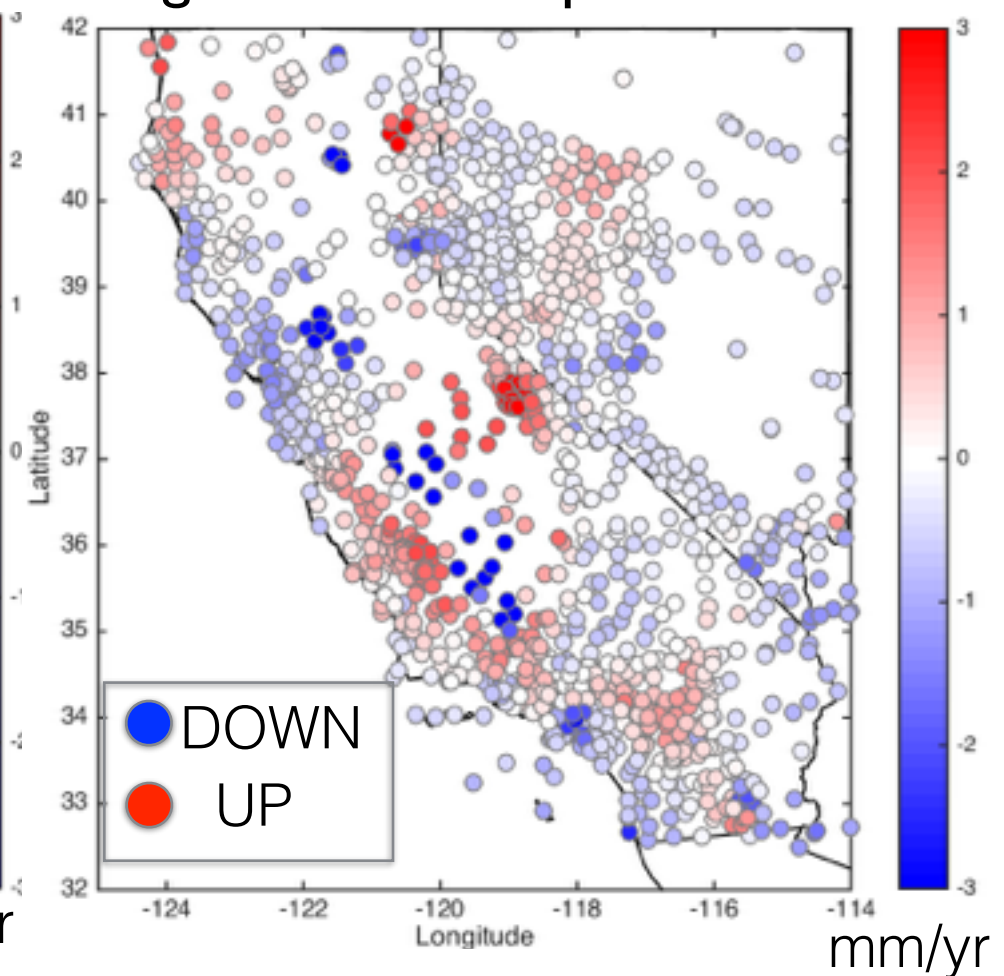
## CA/NV Vertical GPS

- Details of intriguing geographic clustering of vertical rate signals
- Volcanos, up & down
- CNSB and LH Postseismic
- Cascadia interseismic strain accumulation
- GroundH<sub>2</sub>O pumping in CA Great Valley
- Elastic rebound around S. Great Valley
- Uplift of the Sierra Nevada along length of range

MIDAS Vertical Rates



MIDAS Rates Despeckled  
Weighted-Median Spatial Filtered

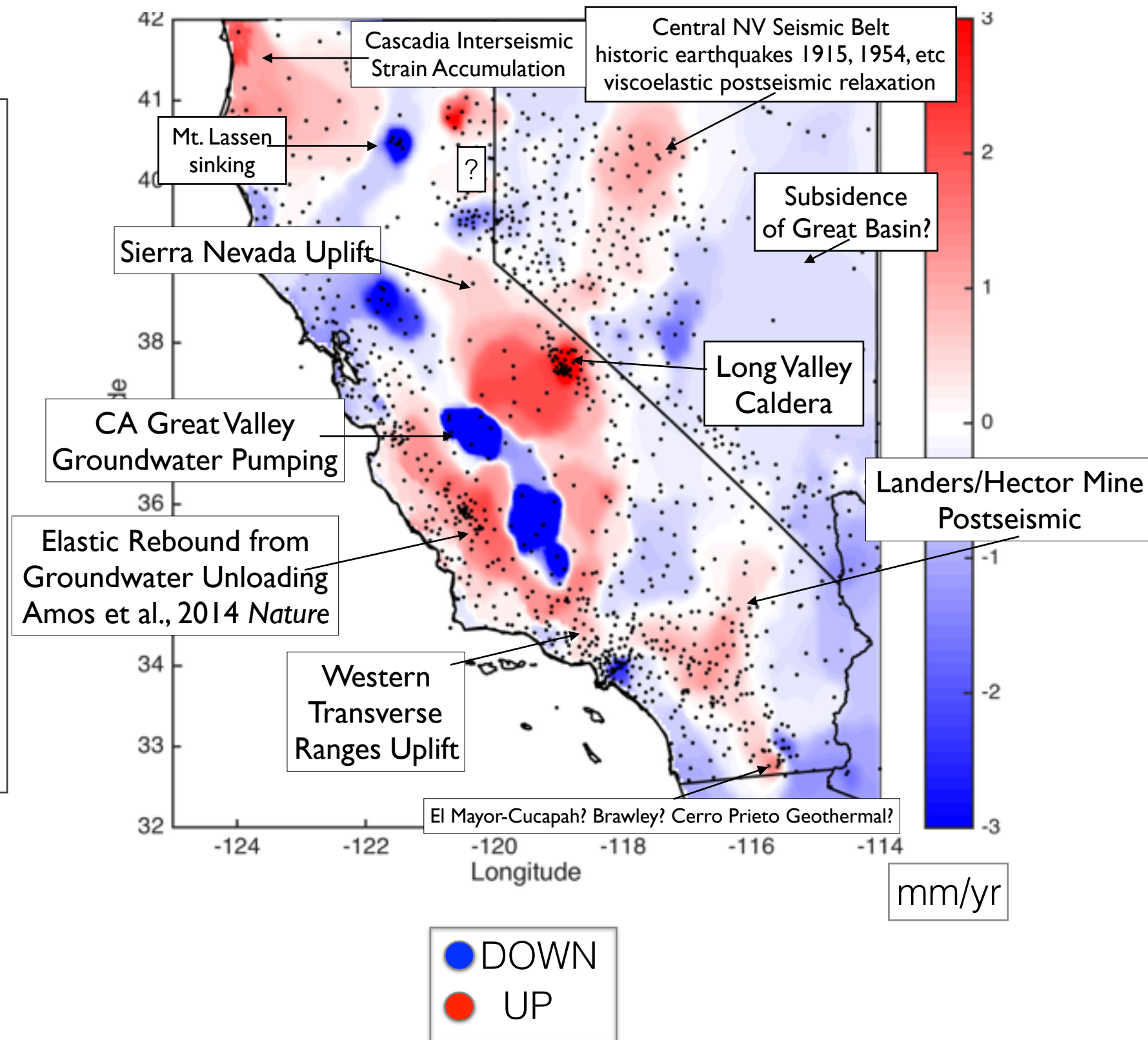




# GPS Imaging of Vertical GPS Velocity: Sierra Nevada

## CA/NV Vertical GPS

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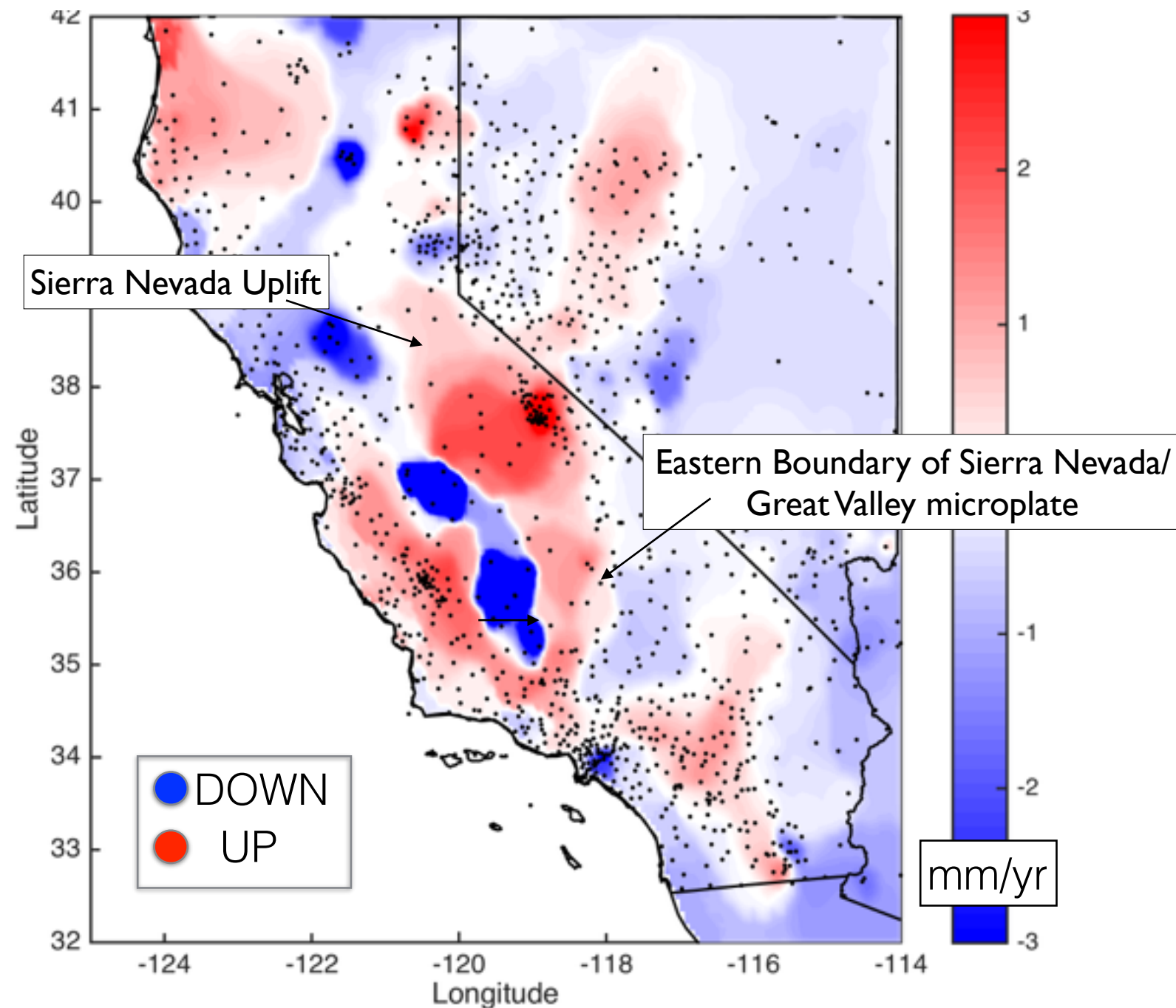


# GPS Imaging of Vertical GPS Velocity: Sierra Nevada

## Do These Images Help Us Measure Long Term Tectonic Uplift of the Sierra Nevada? Is there contemporary tectonic uplift?

- Rate of, even existence of contemporary uplift is enigmatic
  - Normal faults slip 0.1 to 2.0? mm/yr in Sierra Nevada/Great Basin Transition, driving generation of relief but possibly uplift of range to a lesser extent
  - Boundary of SN uplift follows eastern boundary of Sierra Nevada/Great Valley Microplate
  - Suggests:
    - Background uplift distinct from Great Basin
- OR
- Lithospheric strength contrast across Sierra/Great Basin transition....
  - Consistent with horizontal GPS data & seismicity. A rigid response to focussed unloading in the San Joaquin valley?

Are these abrupt edges in rate field well resolved? Checkerboard test says yes

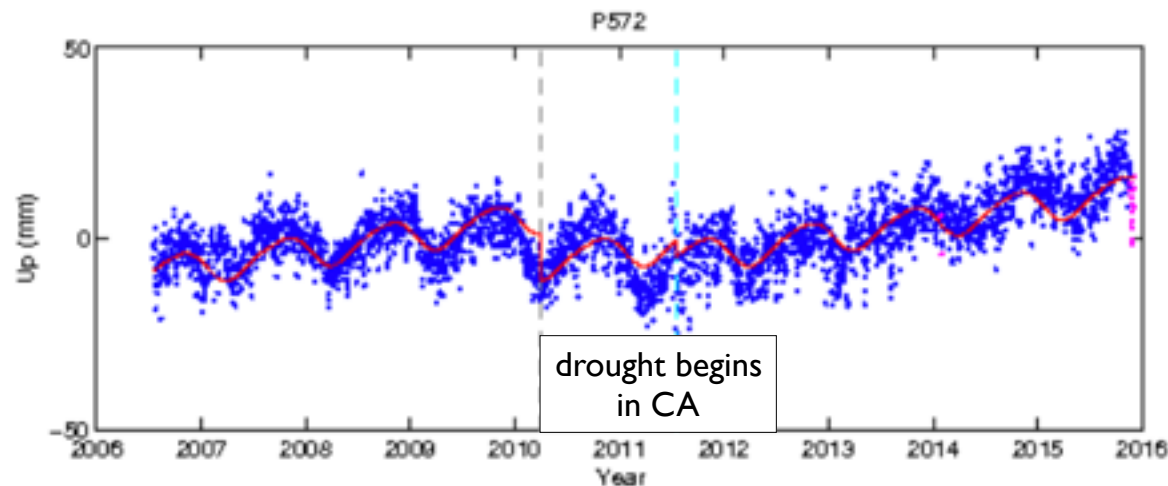




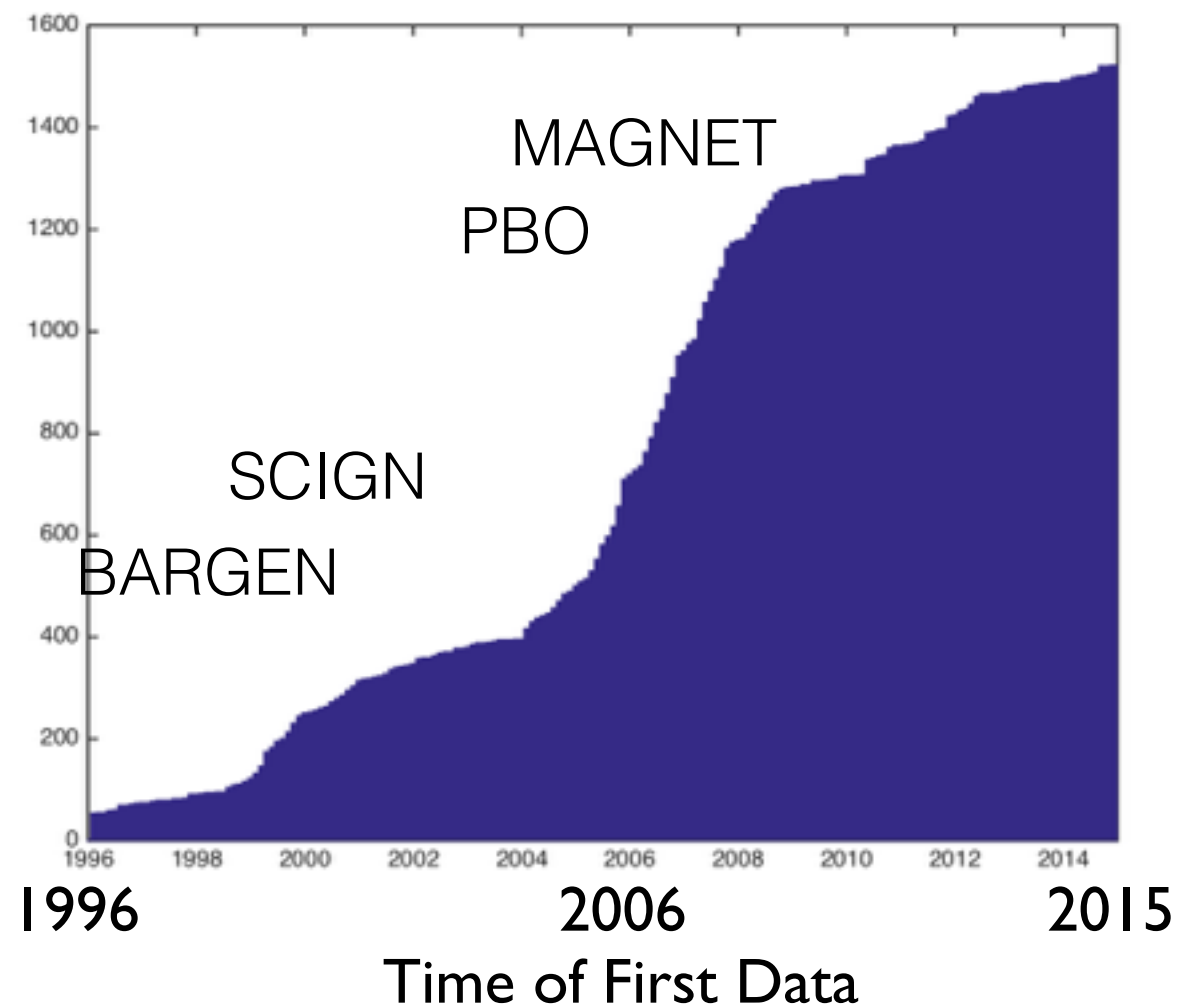
# Sierra Nevada Uplift Over Time

- We expect that *tectonic* uplift of Sierra Nevada would be constant over time of GPS observation.
- So we ask the data how do the signals change with time? Is the Sierra Nevada part constant?

- GPS data show uplift accelerating after 2011
- Related to H<sub>2</sub>O unloading owing to drought in southwest US via loss of ground and surface water



## Number of GPS Stations Over Time in CA/NV area

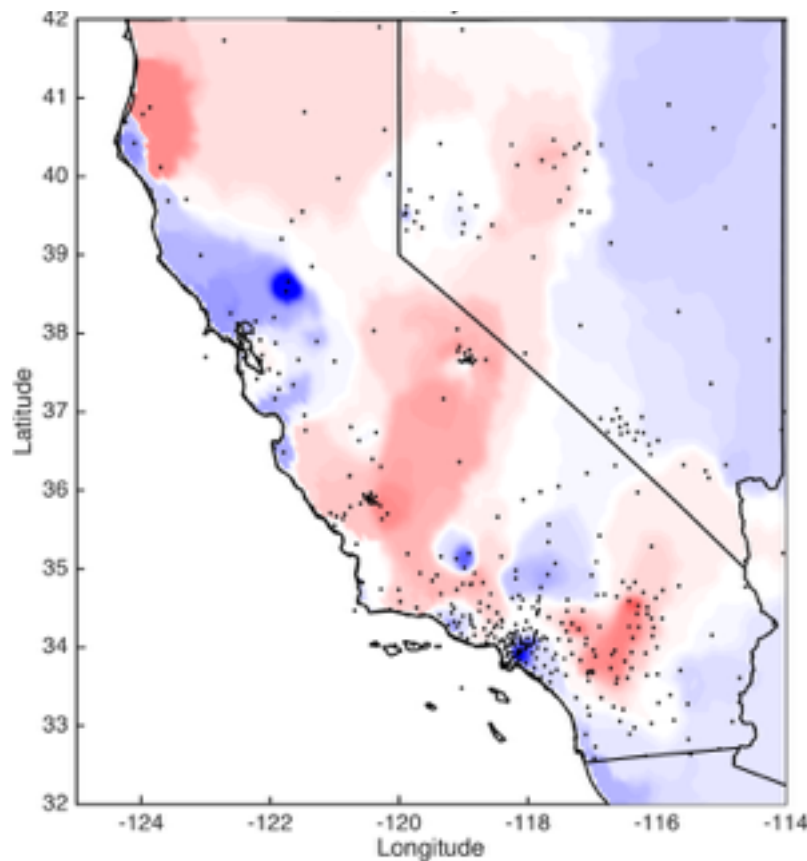


- Prefer 5 years of data to get reliable rate
- Network not as strong prior to 2010

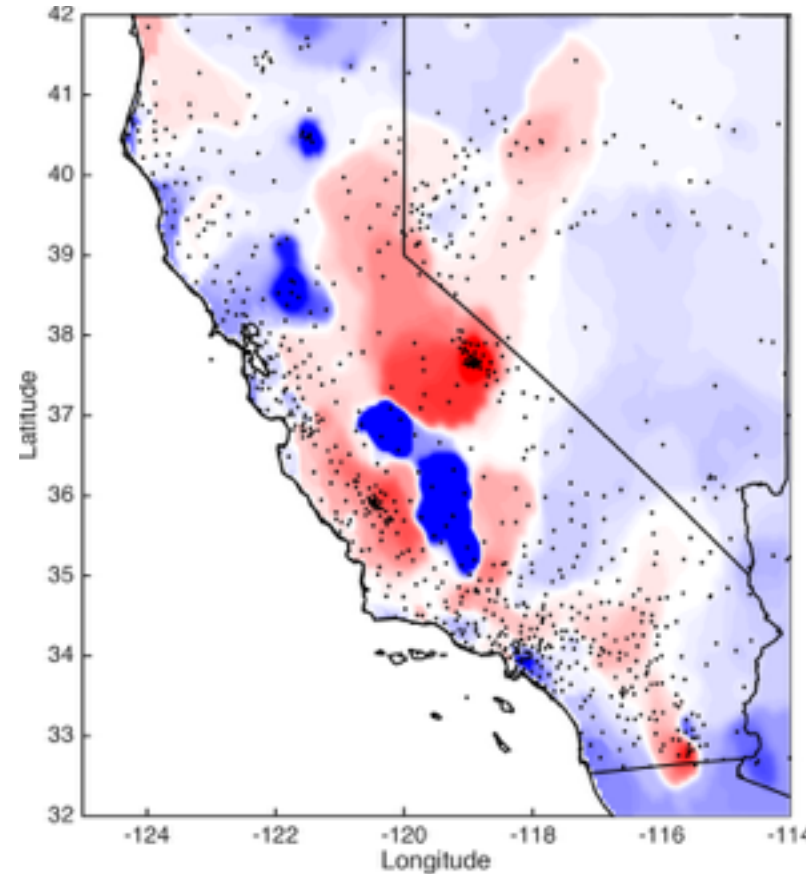
# Sierra Nevada Uplift Over Time

- Looking for the time invariant of signal of tectonics
- Dots show GPS locations
- Use any time series 4 years or longer
- Network not good enough before 2010 to constrain shapes

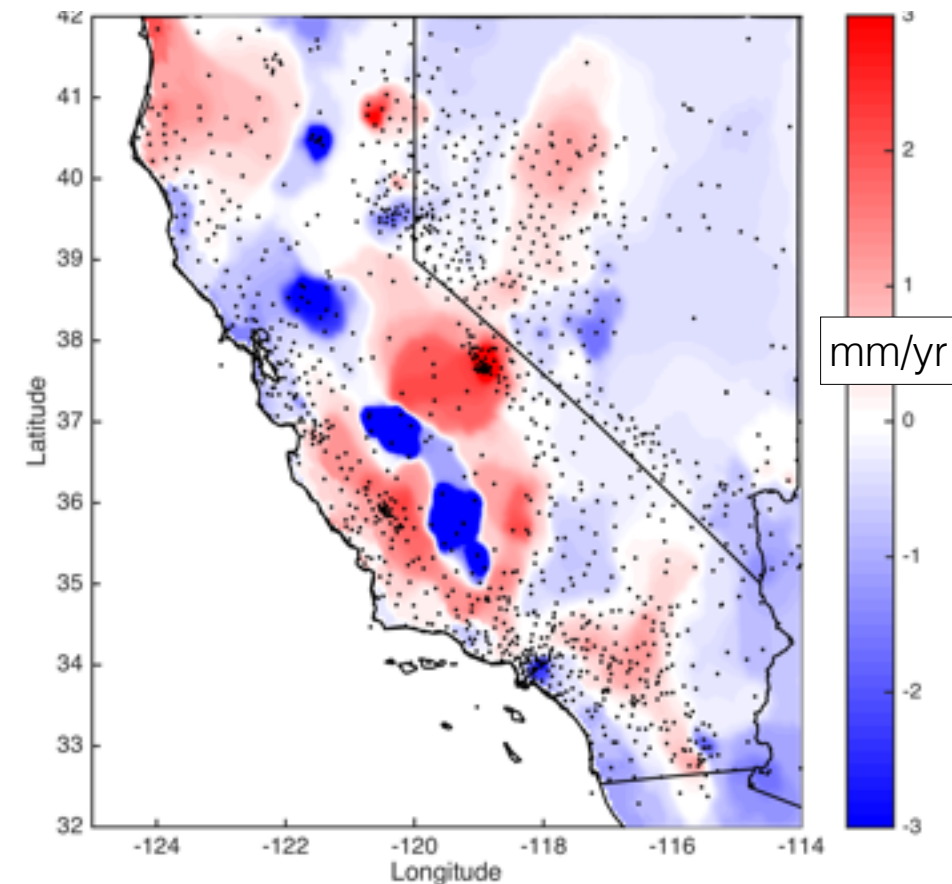
Before 2010



After 2010



All Data



## Bottom Line:

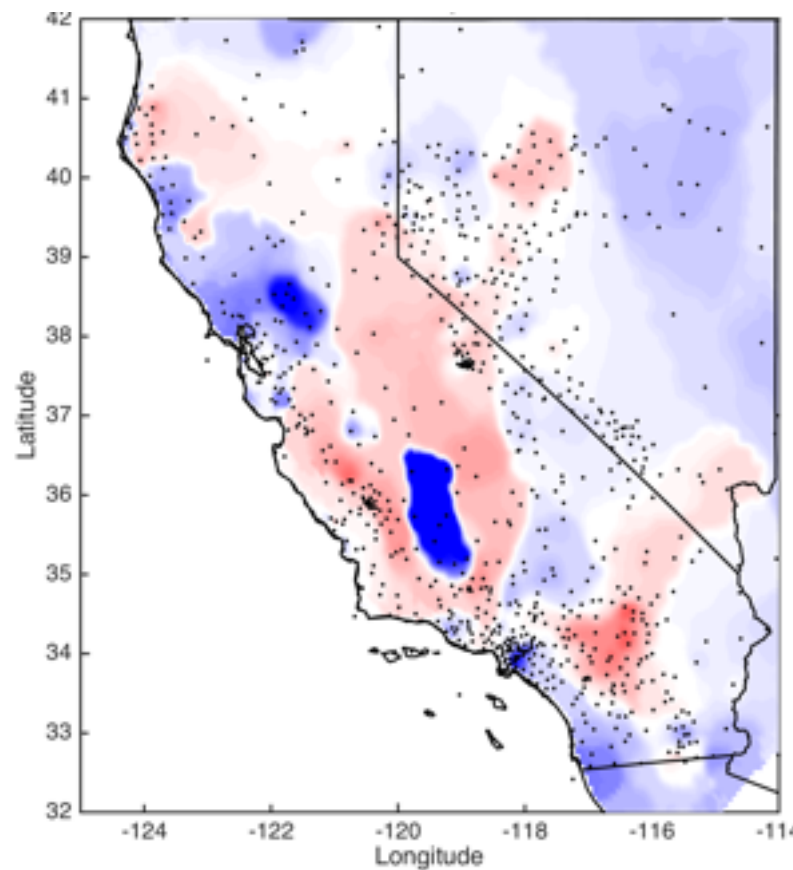
- Uplift rates increase after 2011
- After 2010 the GPS network gets much better for vertical imaging
- East boundary of uplift seems constant when networks is good



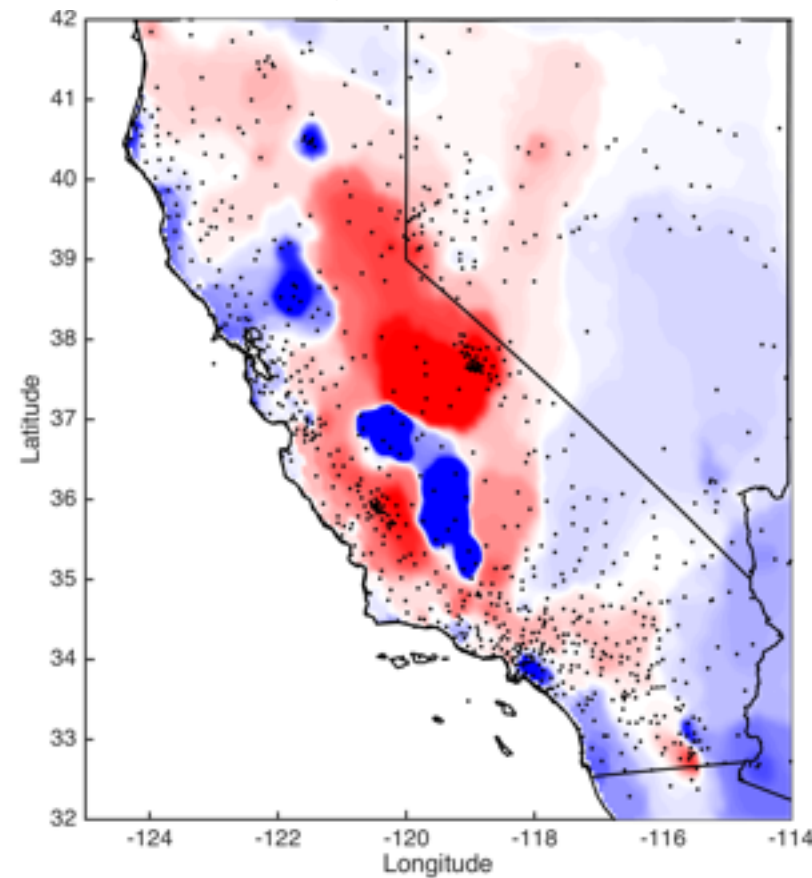
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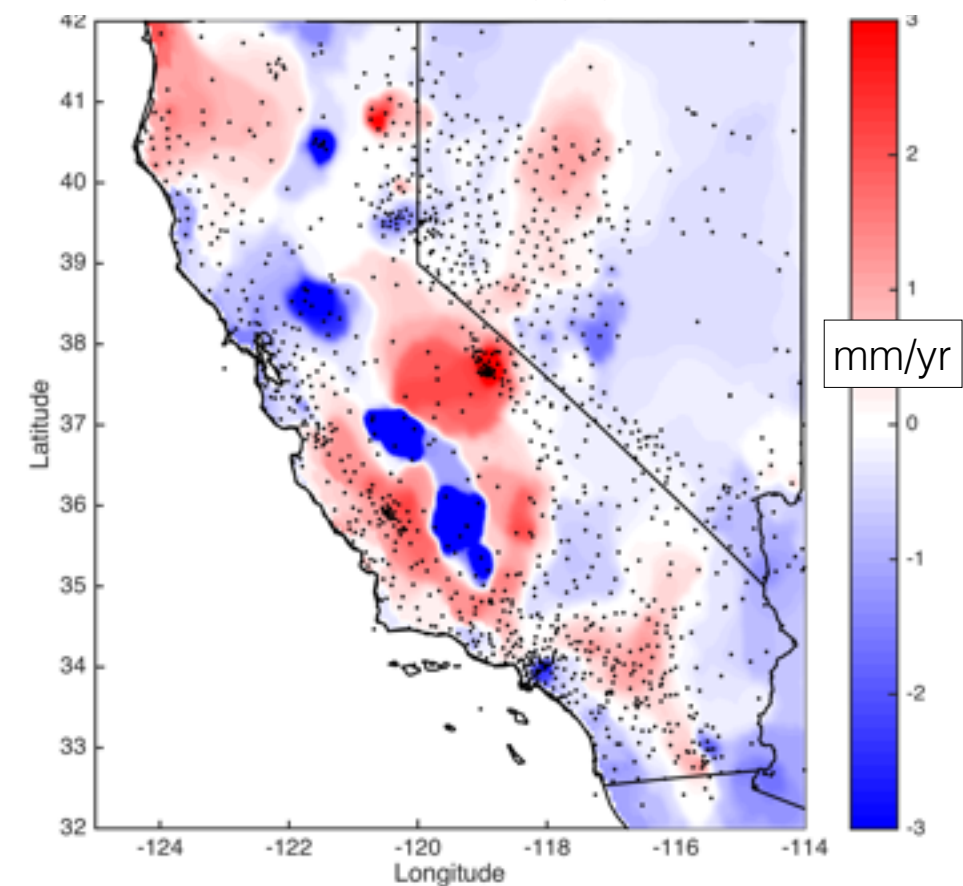
Before 2011



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All Data



## Bottom Line:

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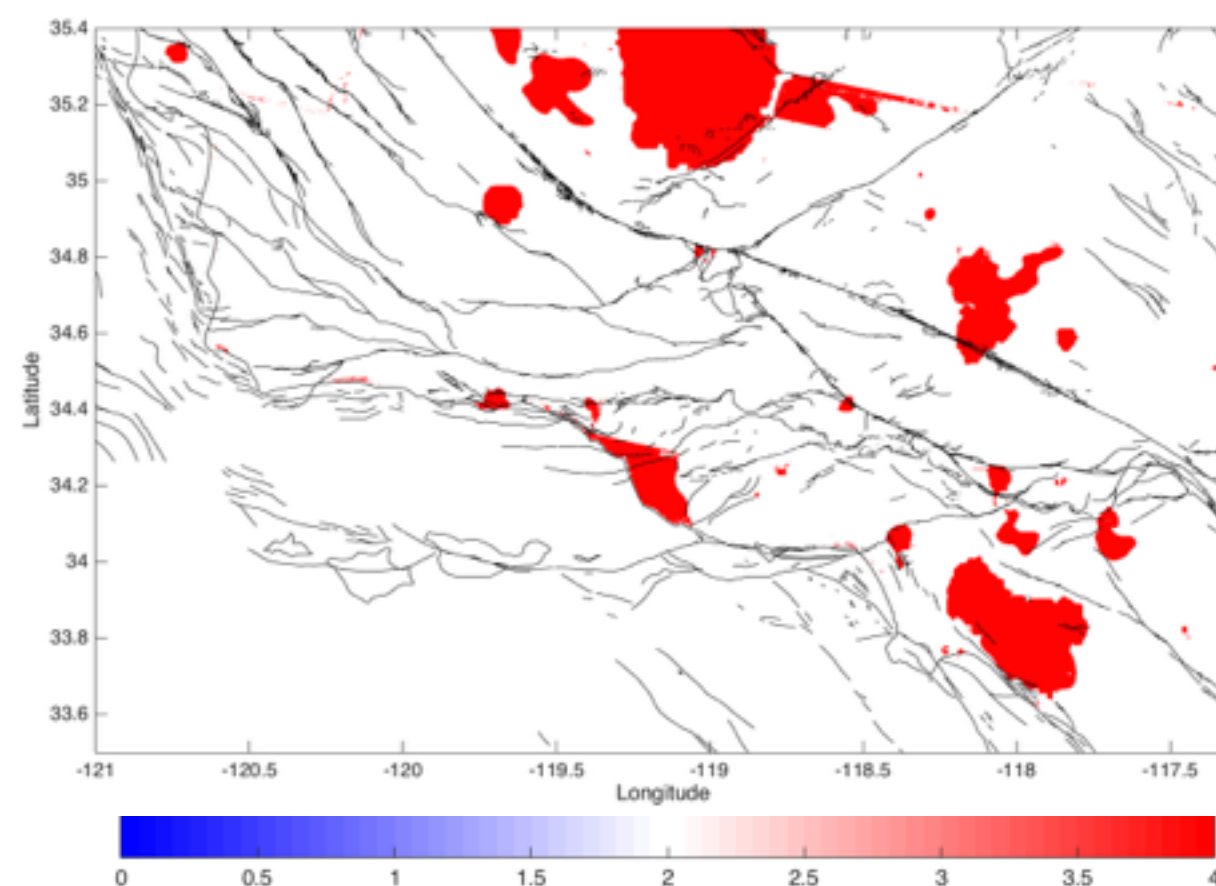
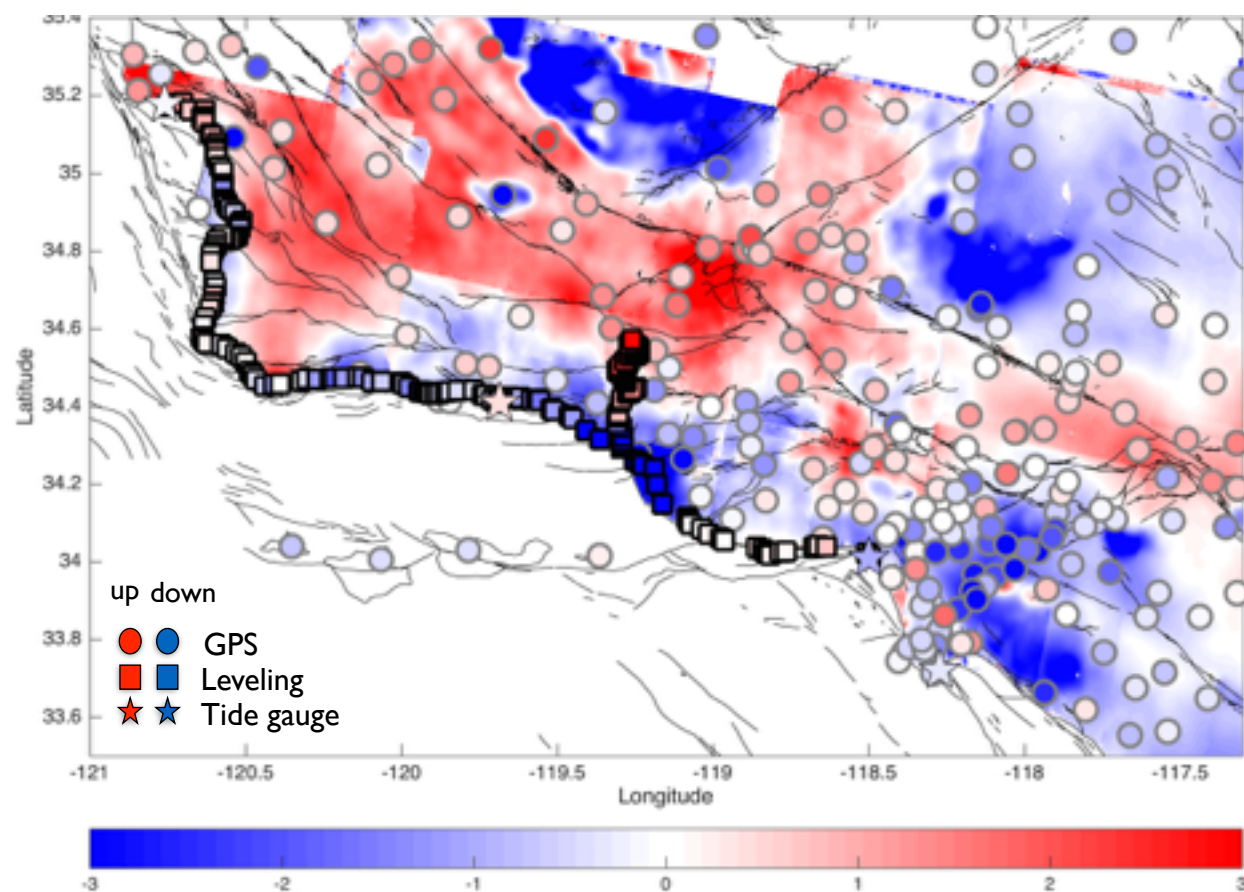
# Southern California Vertical Velocity

## Ventura Area Vertical Tectonic Uplift: A Four-Technique Geodetic Study Combining GPS, InSAR, Leveling and Tide Gauges

William C. Hammond, R. Burgette, K. Johnson, Geoffrey Blewitt

- Integration of GPS vertical rates with InSAR
- SBAS Time series of ERS/ENVISAT data from WinSAR
- Remove horizontal from LOS using crustal strain rate map of Kreemer et al., 2012
- Align InSAR, Tide Gauges, Leveling lines to GPS vertical rate field

- Apply GPS Imaging to the *amplitude* of the annual terms in the GPS time series.



- Agreement between techniques near  $\sim 1$  mm/yr RMS
- Suggest long term signal
- Seams across track/frames apparent, but error is minimized by applying quadratic ramp to align InSAR to GPS+InSAR field

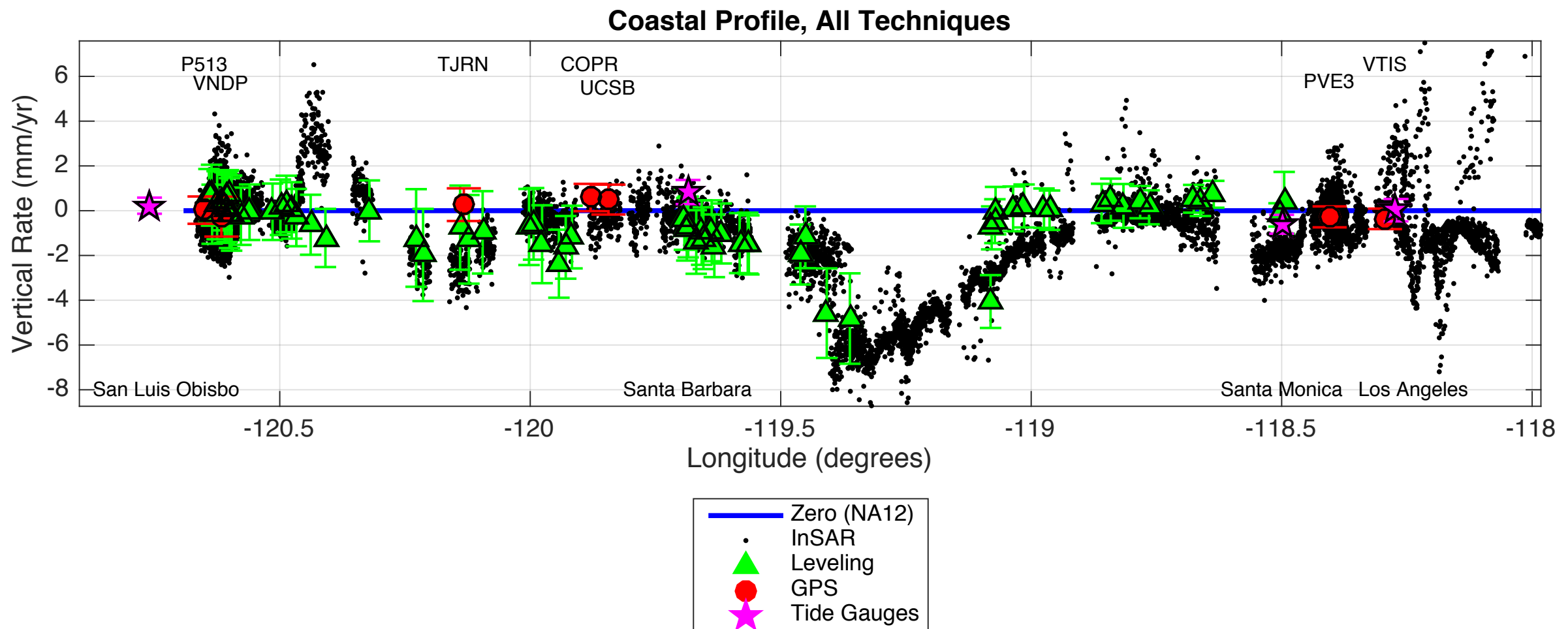
- Generate mask that excludes areas with non-tectonic motion
- Based on vertical rate from InSAR, annual term amplitude from GPS
- Mask out if:
  - Annual amplitude  $> 2.0$  mm or
  - Vertical rate from InSAR less than  $-2.5$  mm/yr



# Southern California Vertical Velocity

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- After alignments techniques agree well (to  $\sim 1$  mm/yr RMS)
- Compared to individual techniques alone, improvement in isolating signal of long term vertical motion
- Using these data to constrain tectonic models/fault slip rates

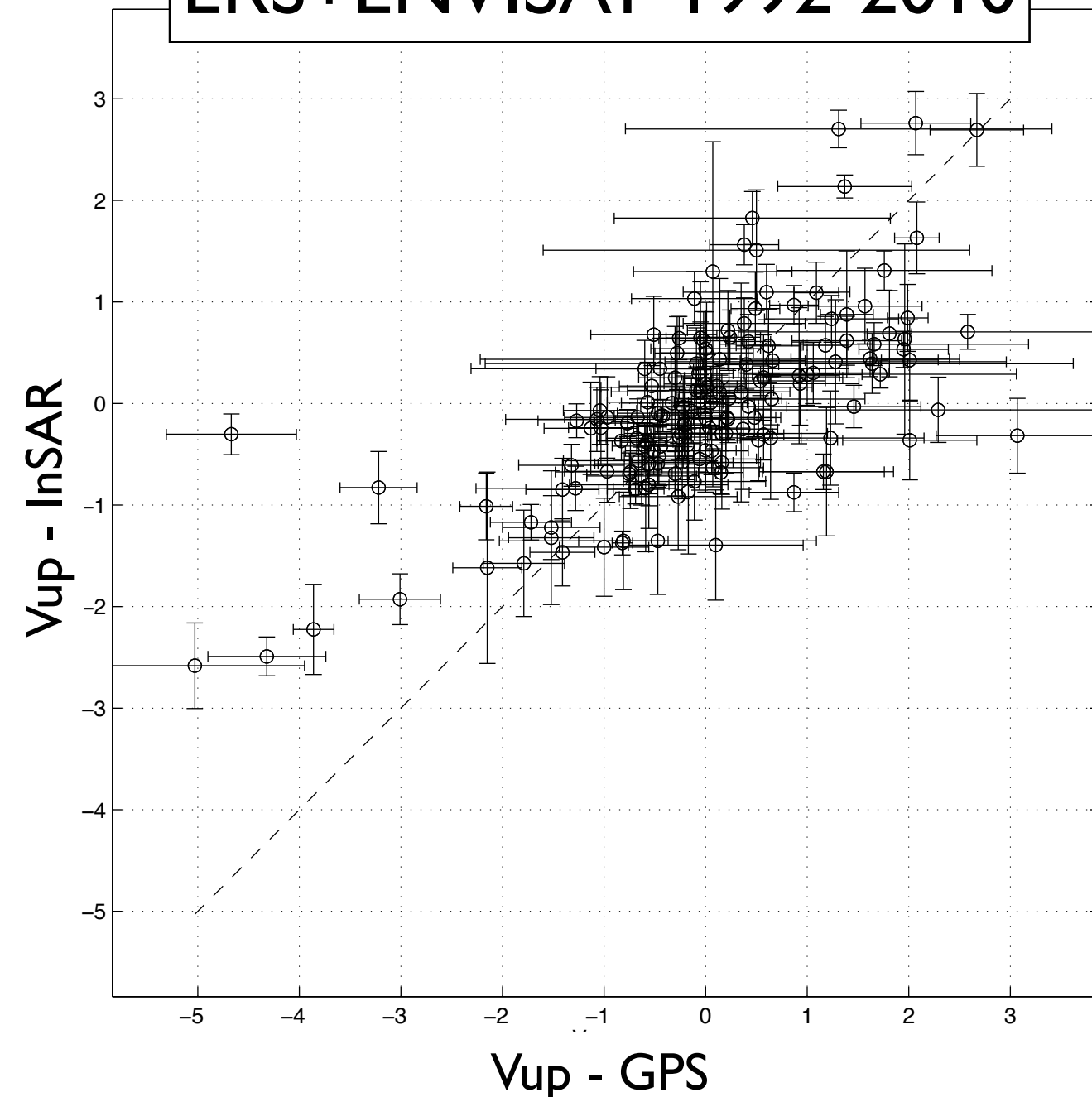
# Misfit between InSAR and GPS Vertical Rate

- Alignment better when using only ENVISAT
- ENVISAT date ranges more similar to time of GPS data acquisition

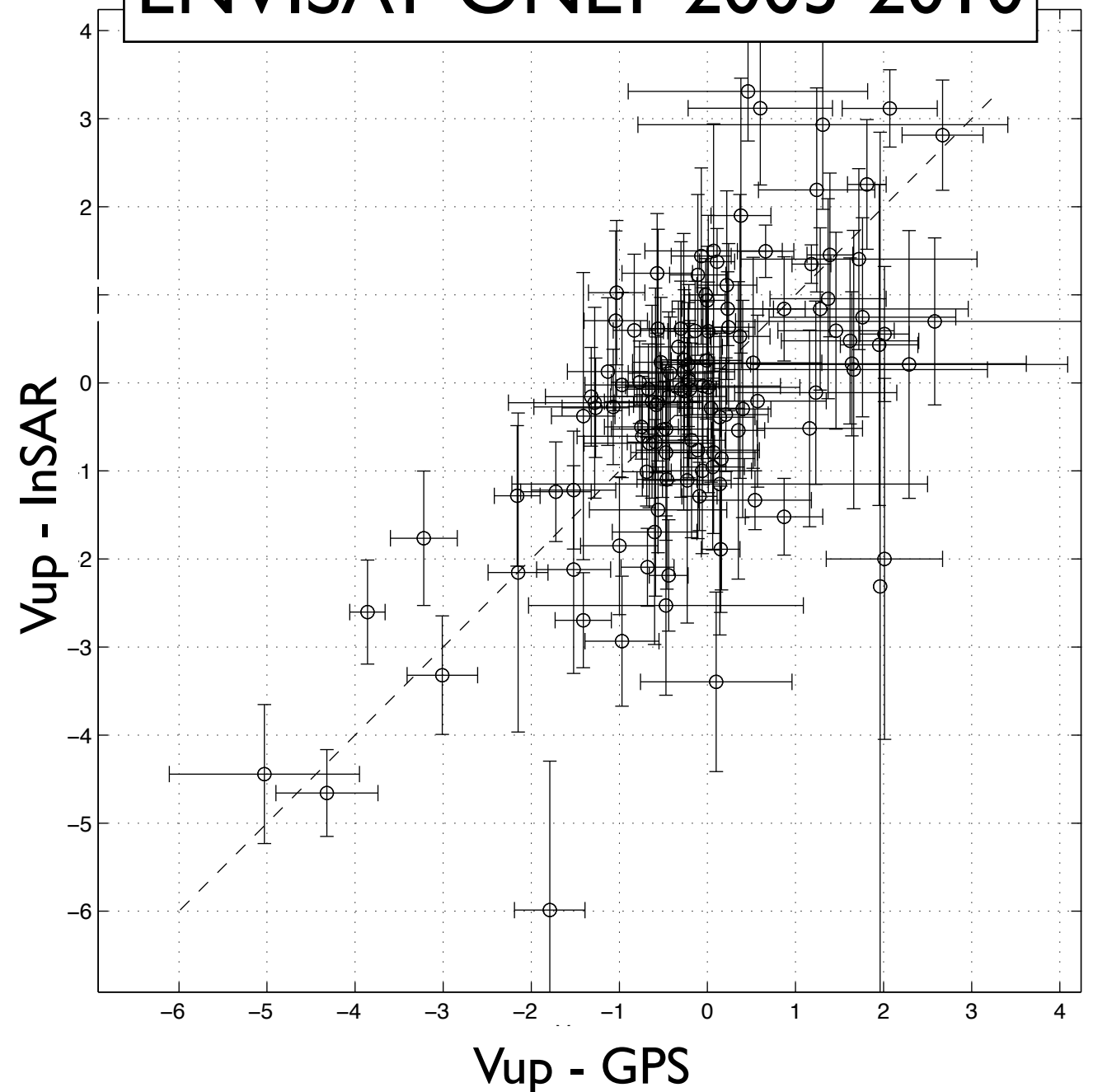
Suggests:

- 1) Misfit is driven by time-variable motion of fastest dropping stations
- 2) Subsidence in rapidly dropping areas is accelerating
- 3) Other areas (near stable GPS stations) have relatively stable constant rates

**ERS+ENVISAT 1992-2010**



**ENVISAT ONLY 2003-2010**







# The End

## Questions?



*Some Things to Work On*



# Resolution Tests

## Checkerboard Tests

- Assess network's ability to resolve structure in the vertical rate field
- $\pm 3$  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
  - Sierra Nevada
  - Latest network development addressing northwest Nevada

Recommend future GPS locations.

- Sierra Nevada/Great Valley middle latitudes
- East Nevada

