Climate modulated water storage, the deformation, and California earthquakes

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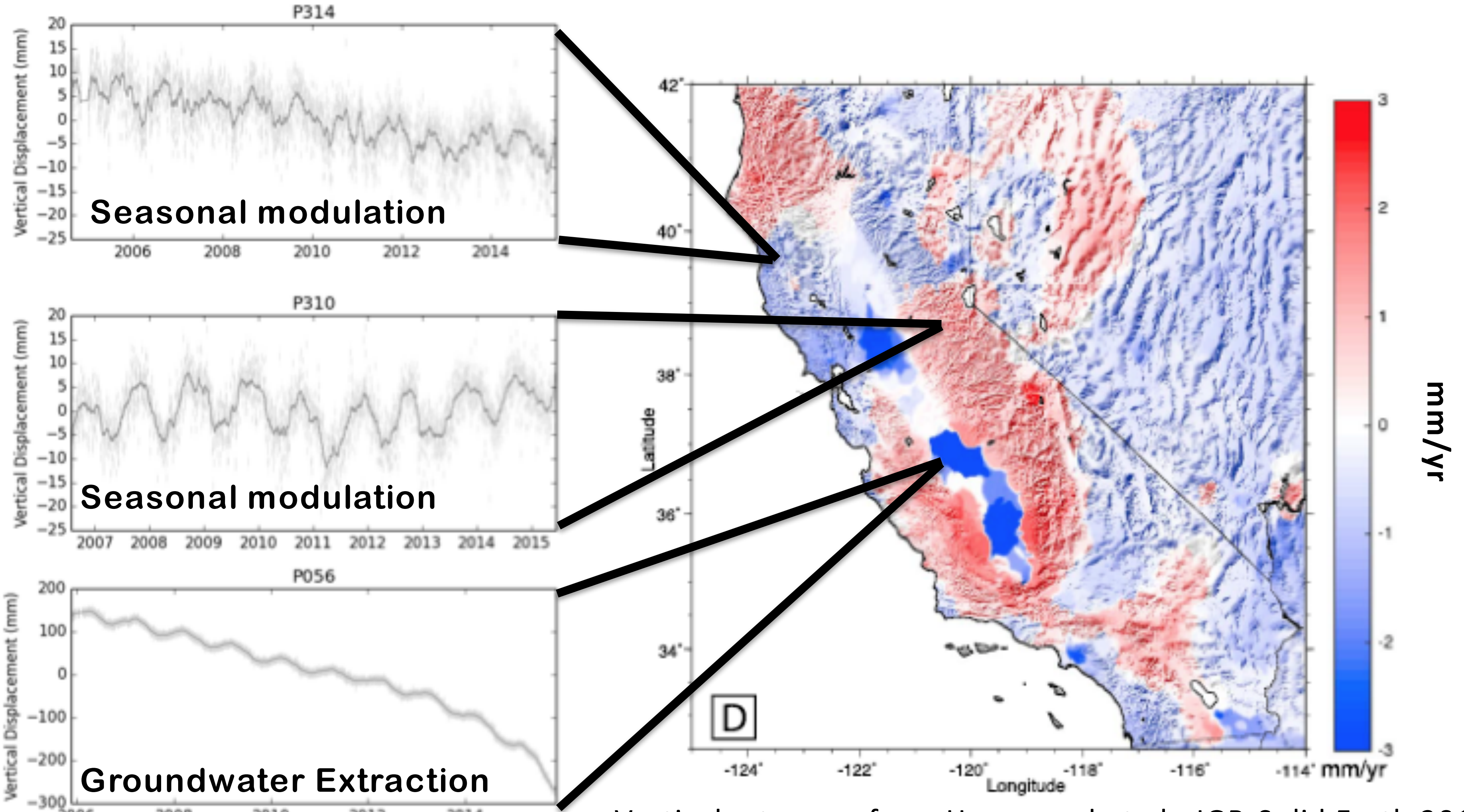
cGPS PBO Station P314 http://www.earthscope.org

Seasonal Displacements

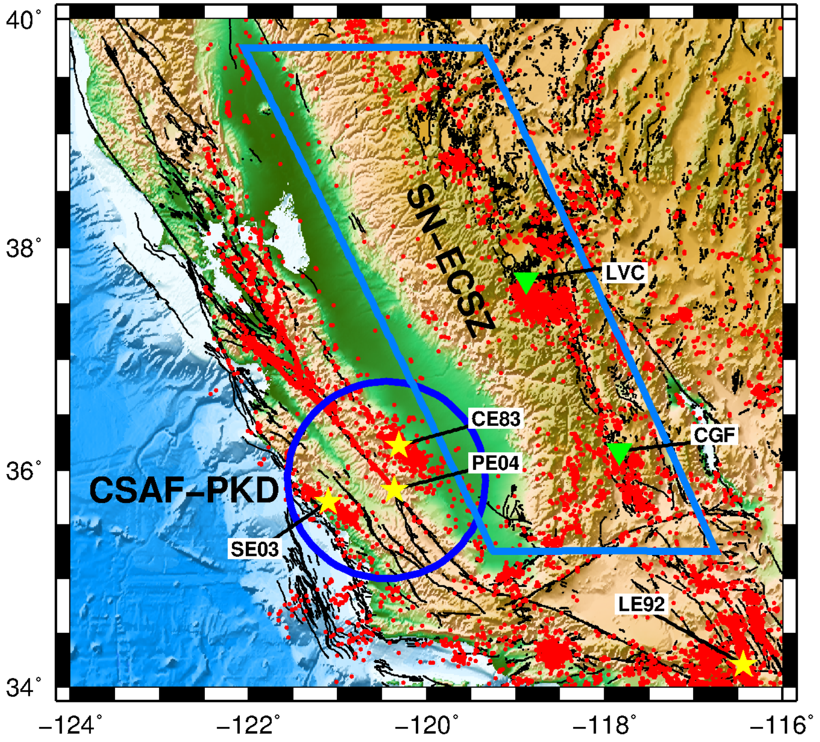
Vertical GPS Time Series



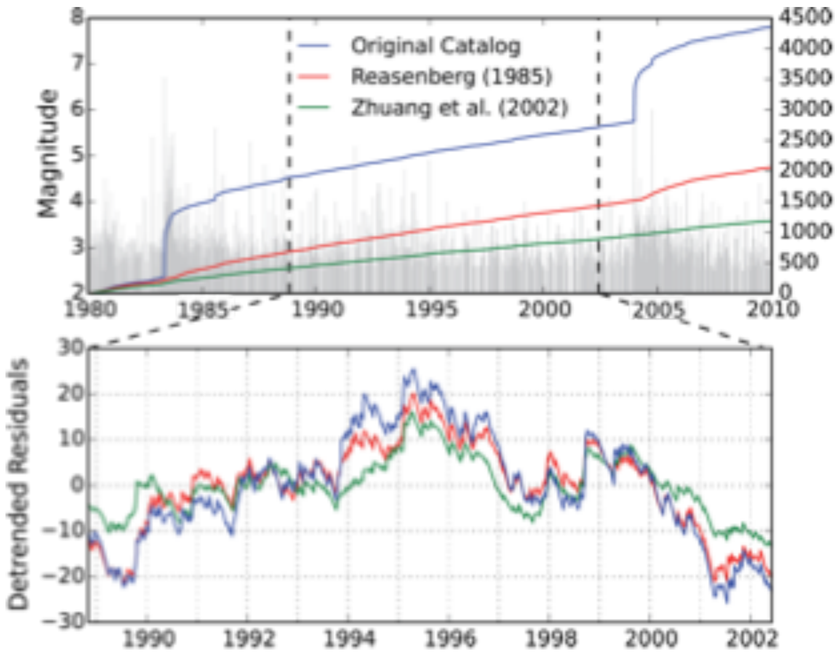
Vertical rate map from Hammond et al., JGR-Solid Earth 2016

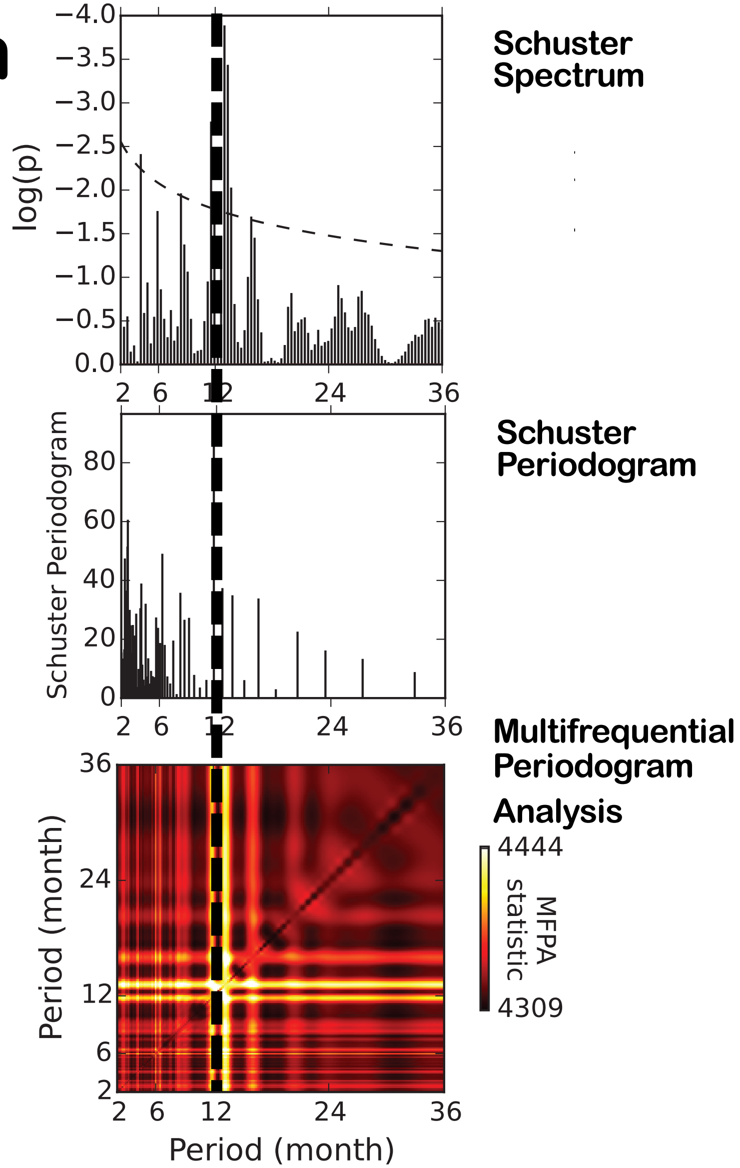
Periodicity in Seismicity Records

Evidence for Stress Modulation



Central Coast Ranges Seismicity
M≥2.5 Declustered and Detrended

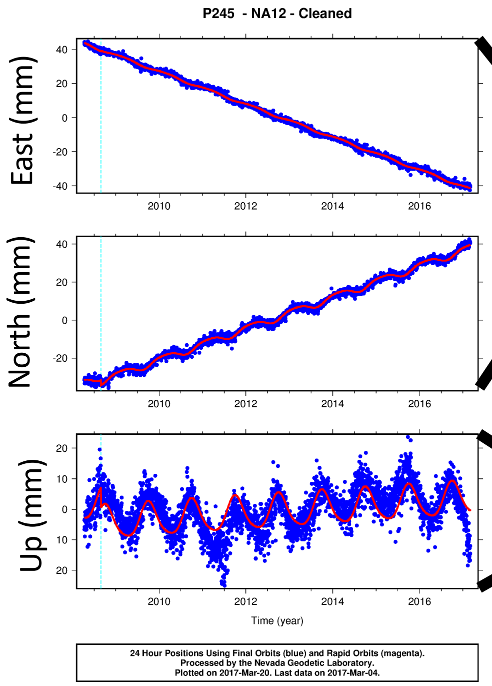




Dutilleul, Johnson, Bürgmann, et al., JGR, 2015

Seasonal Loading and Coulomb Failure

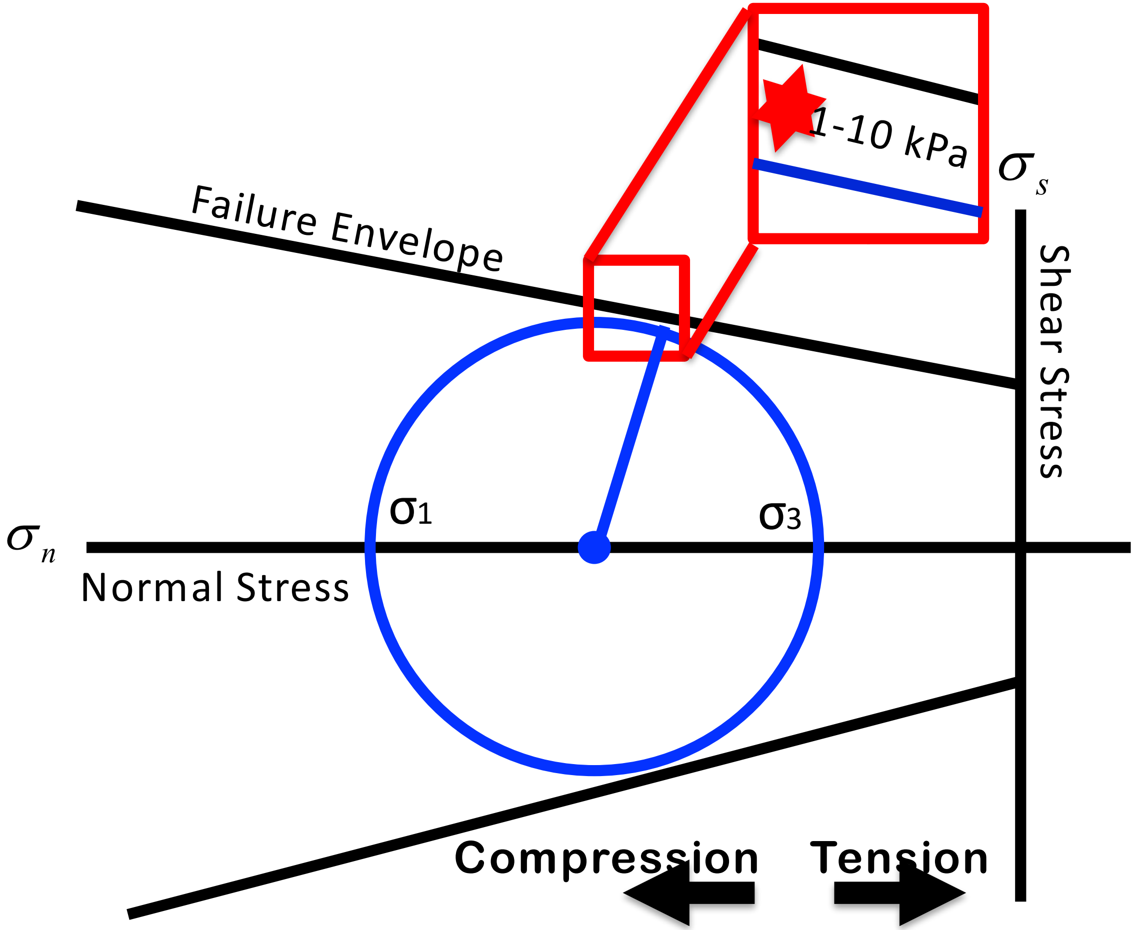
UNR GPS NA12 solution



Stress on faults 1-100 MPa (range of stress drop)

Tectonic Loading
5-50 kPa/yr loading rate

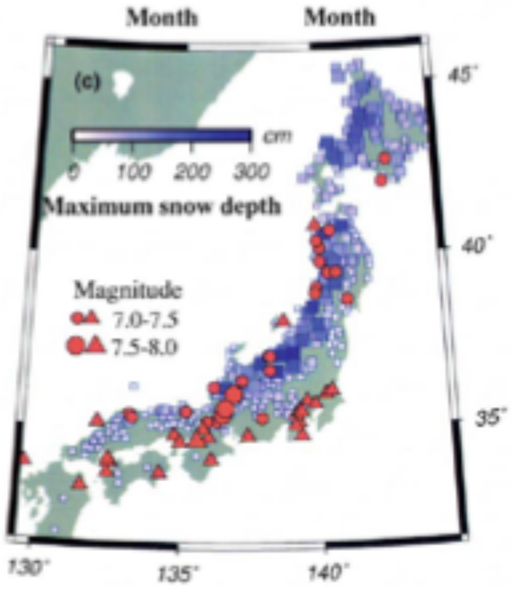
Seasonal Modulation
100 mm water load ≈ 1kPa

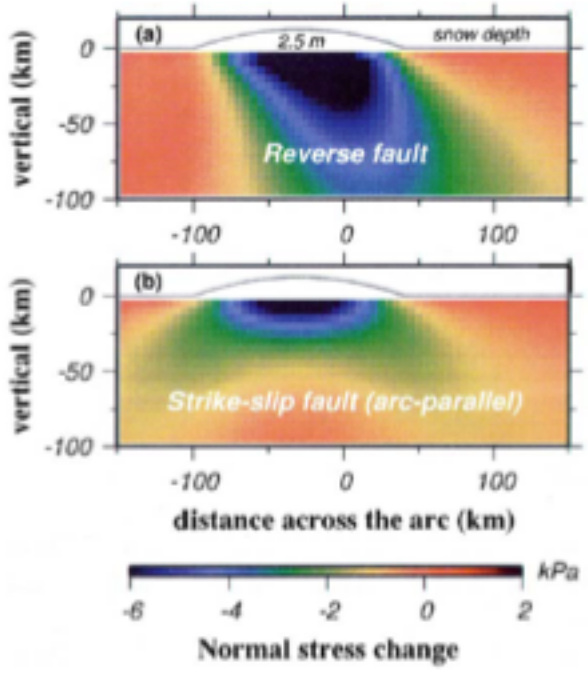


Mechanical Schematic of Critically Stressed Fault

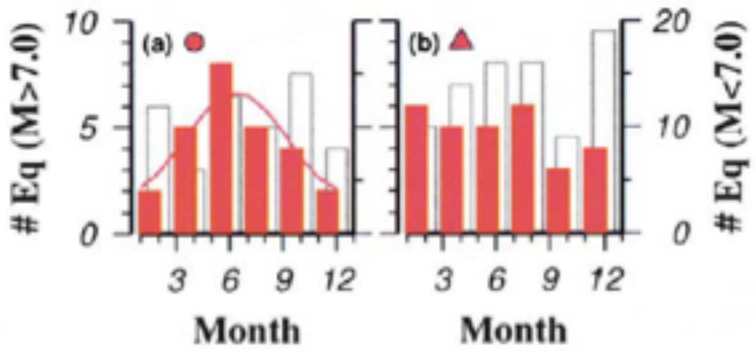
Evidence of Water/Snow Loading and Seismicity

Snow Loading in Japan





Snow Region | No Snow Region

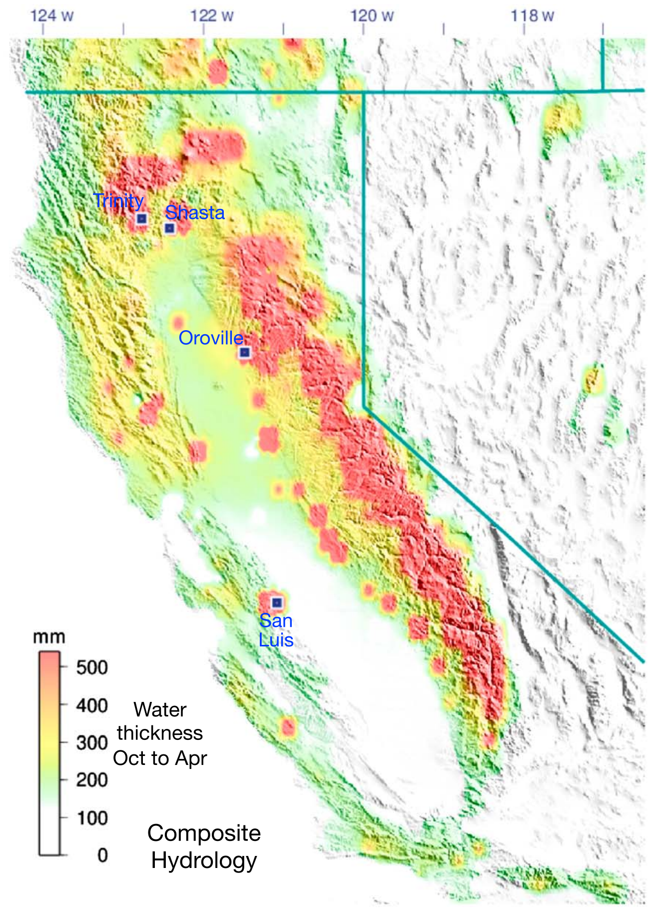


26 Eq's | 58 Eq's

<10kPa Stress Change

Heki, 2003

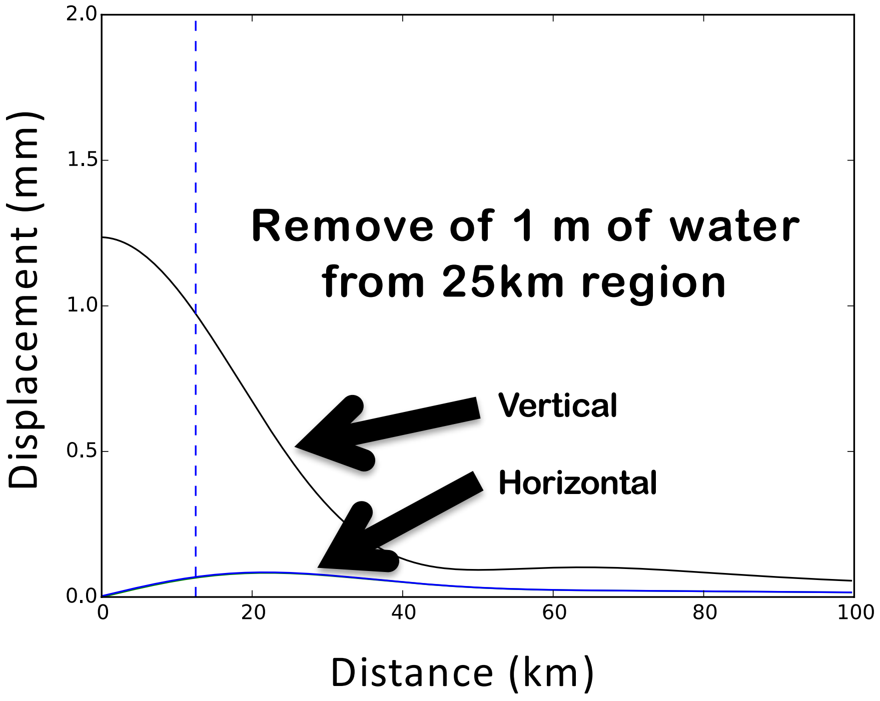
Average Water Thickness in California



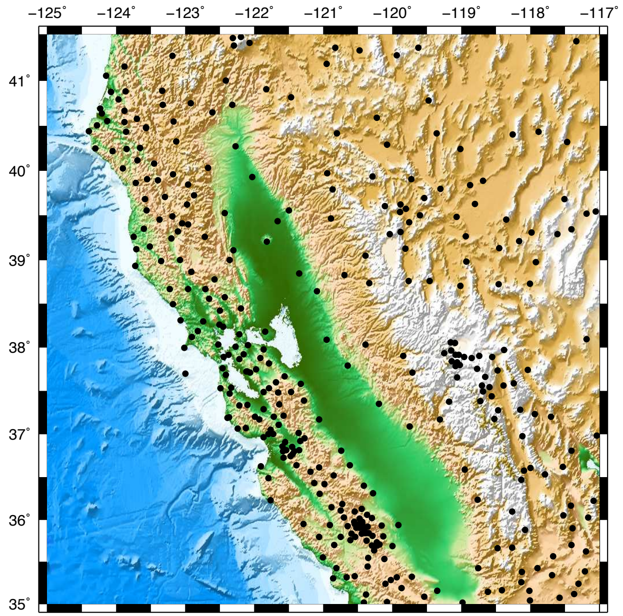
Argus et al., 2014

Elastic Load Model

- **Effective Water Storage estimated from vertical GPS displacement**
- **GPS Stations in the Central Valley omitted**
- **Invert displacement for mass on surface and estimate water storage**



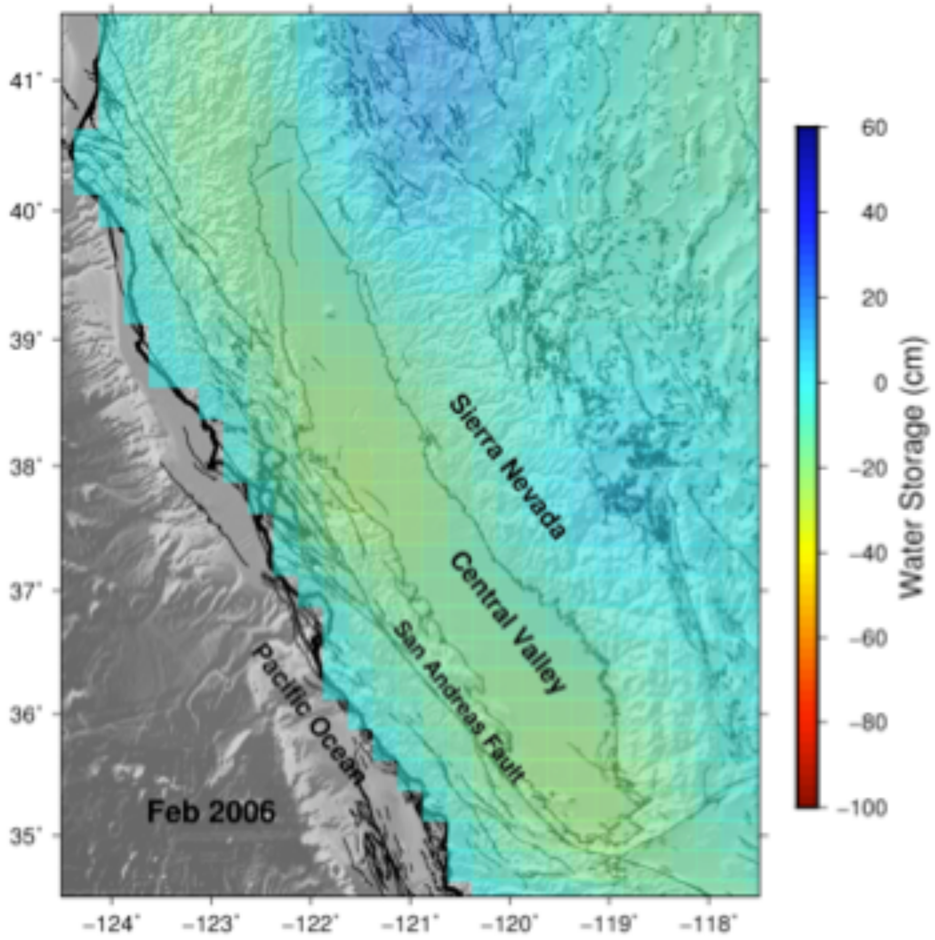
~700 GPS Stations

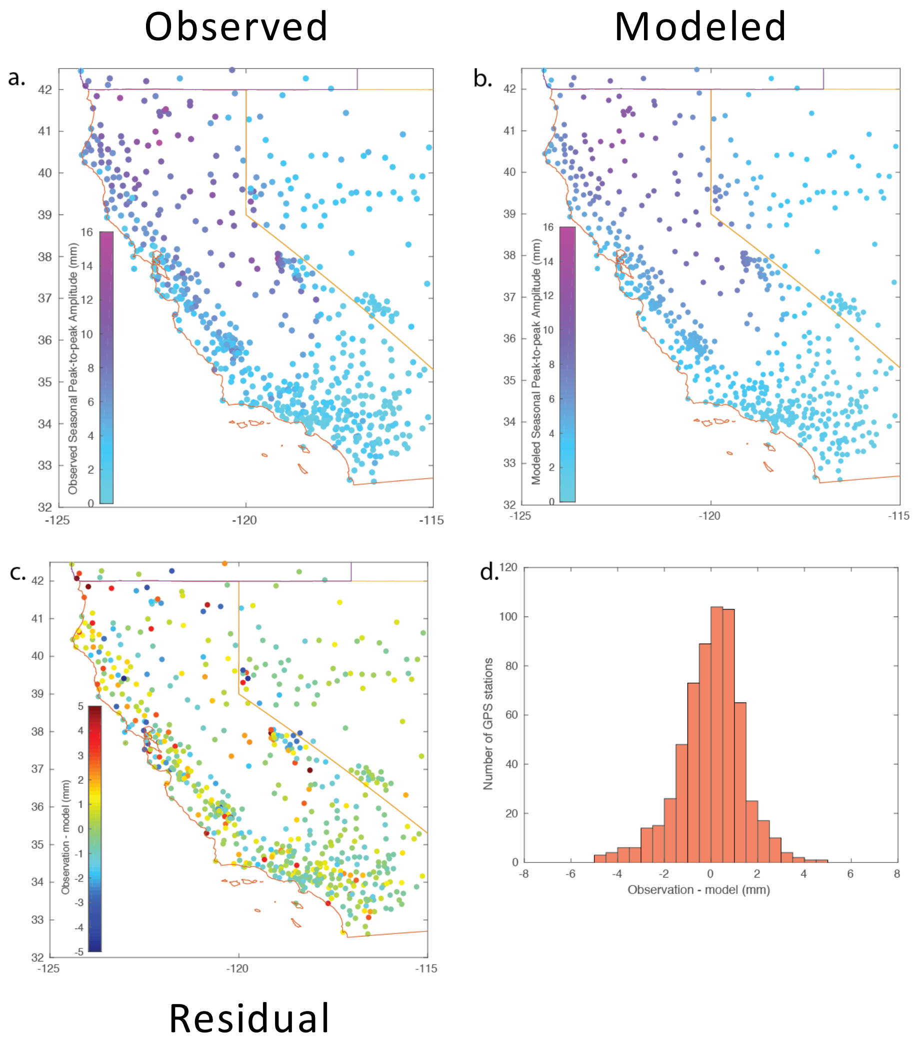


Inversion following *Argus et al., GRL, 2014 and Fu et al., JGR, 2015*

Terrestrail Water Storage

Inverted using vertical GPS displacement following Argus et al. GRL 2014 & Fu et al. JGR 2015

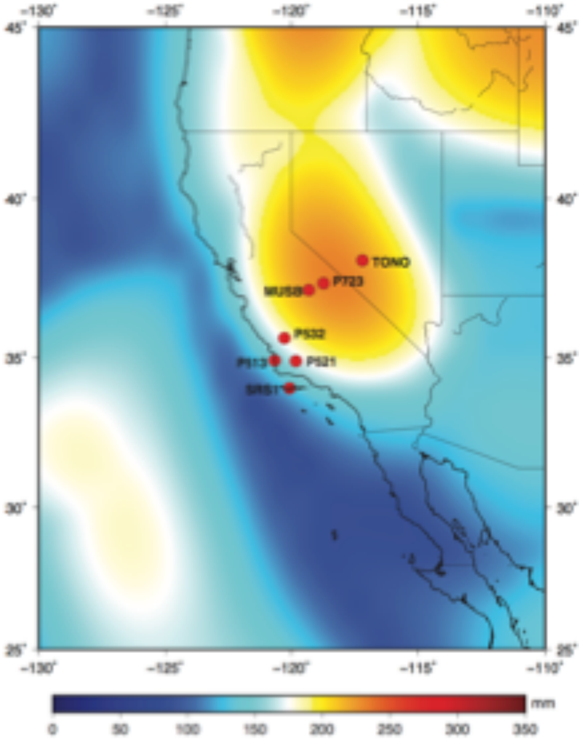


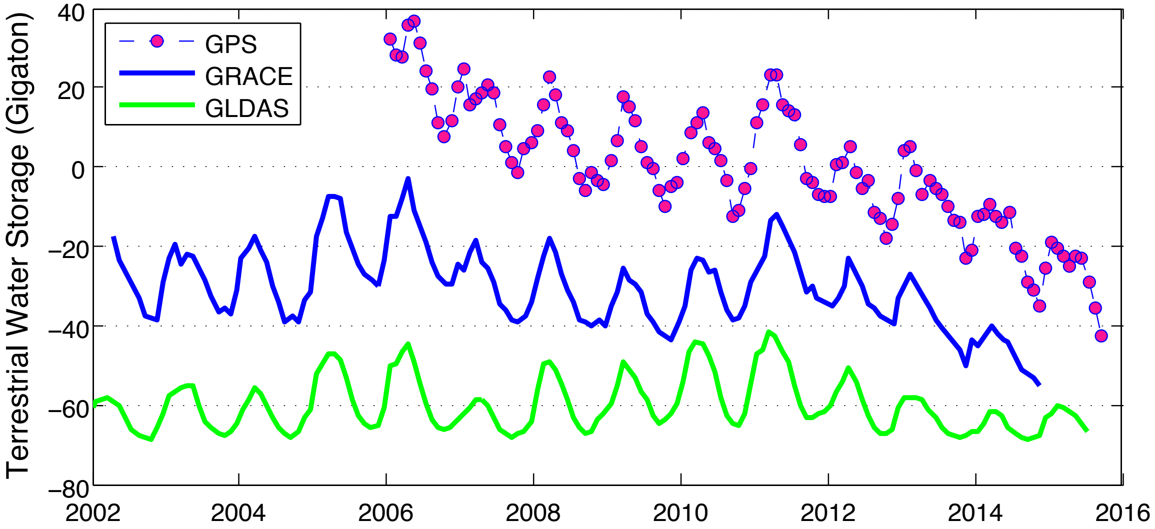


Johnson, Fu, and Bürgmann, Science, 2017

GRACE / GLDAS Comparison

- Gravity Measurements to Infer Water Storage
- Composite models

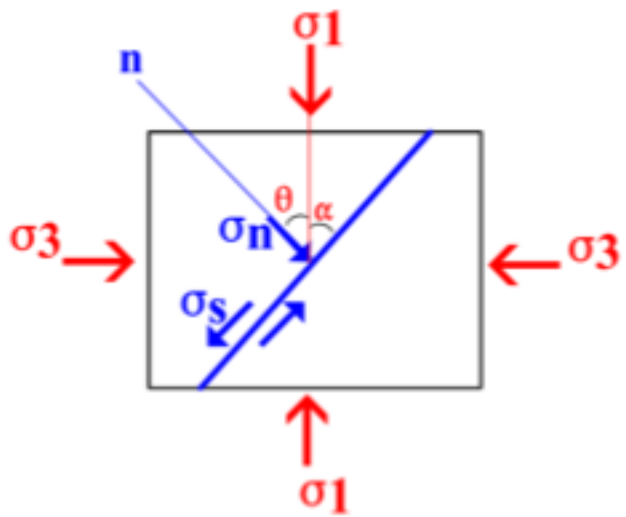




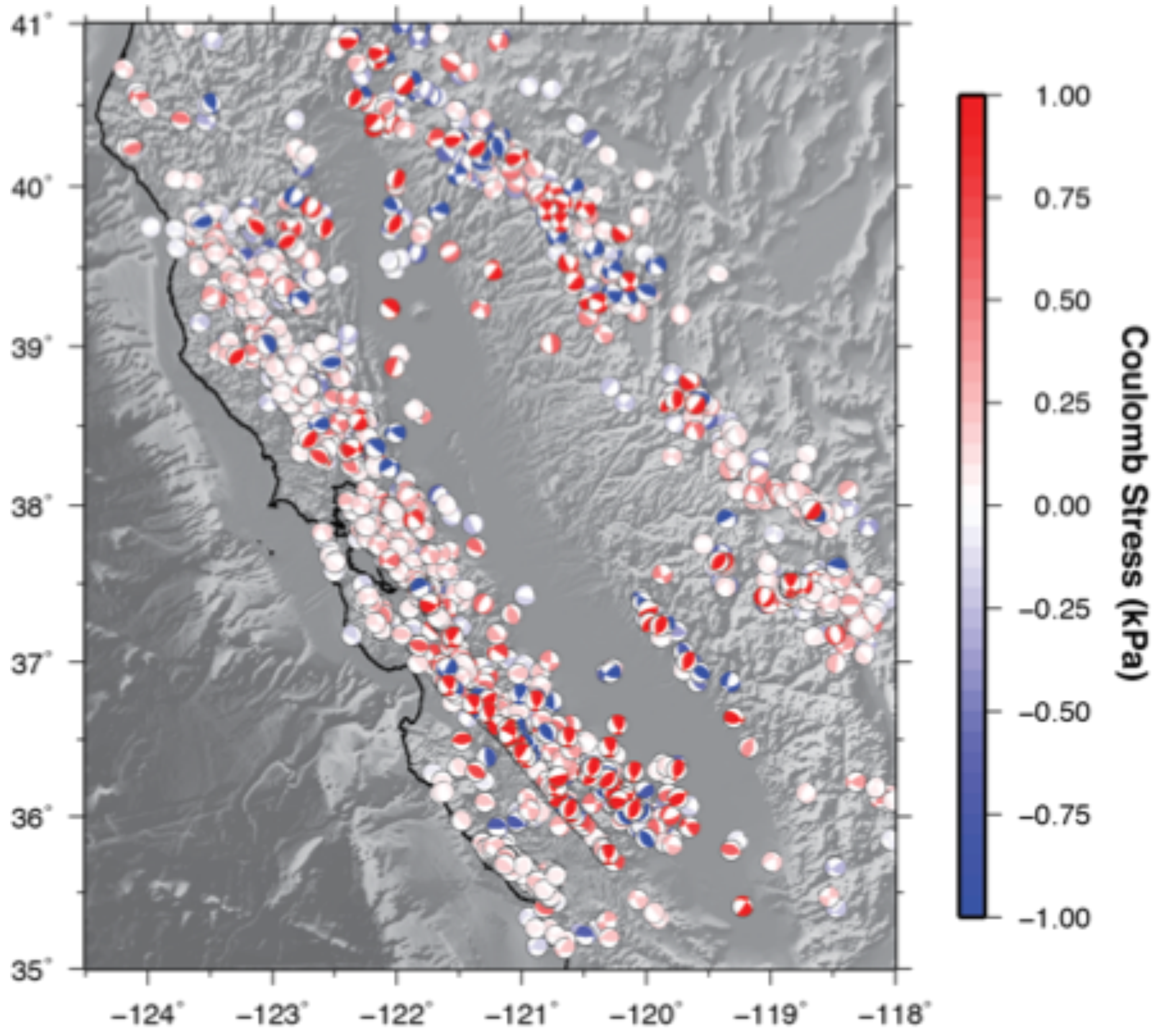
y-axis offset for comparison

Deformation Modeling

- **Linear Elastic**
- **Stress at 8 km Depth**
- **Rotate to Failure Plane**
- **Shear (σS) and Normal (σN)**
- **ΔCoulomb = $\Delta\sigma_S + \mu\,\Delta\sigma_N$**
- **Seasonal stress on focal plane**

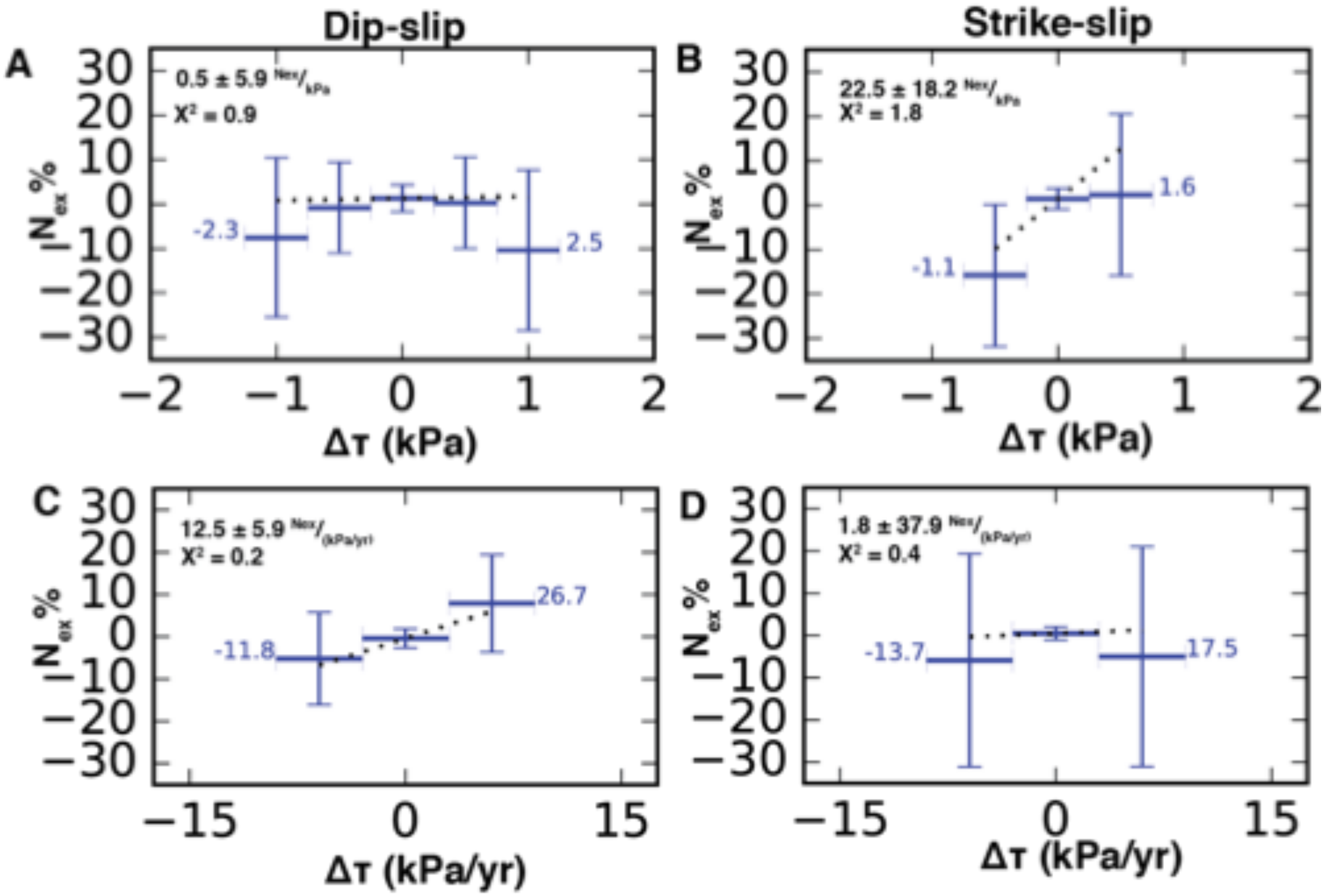


2006-2015 declustered focal mechanisms



Johnson, Fu, and Bürgmann, Science 2017

Percent excess M≥2.0 seismicity
Shear Stress Amplitude and Rate



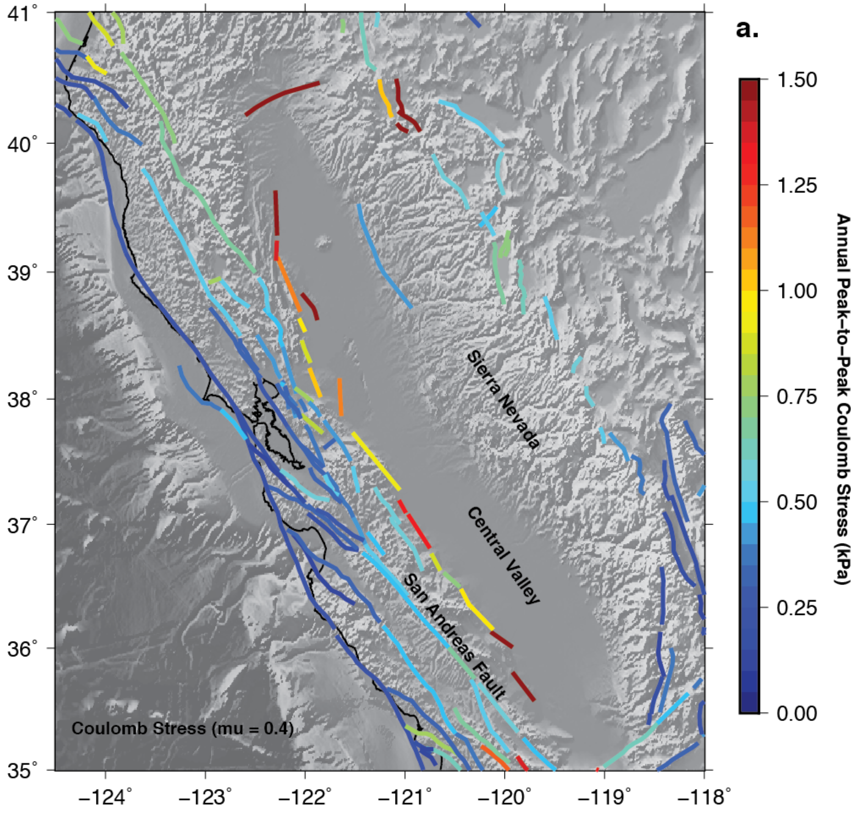
Amplitude

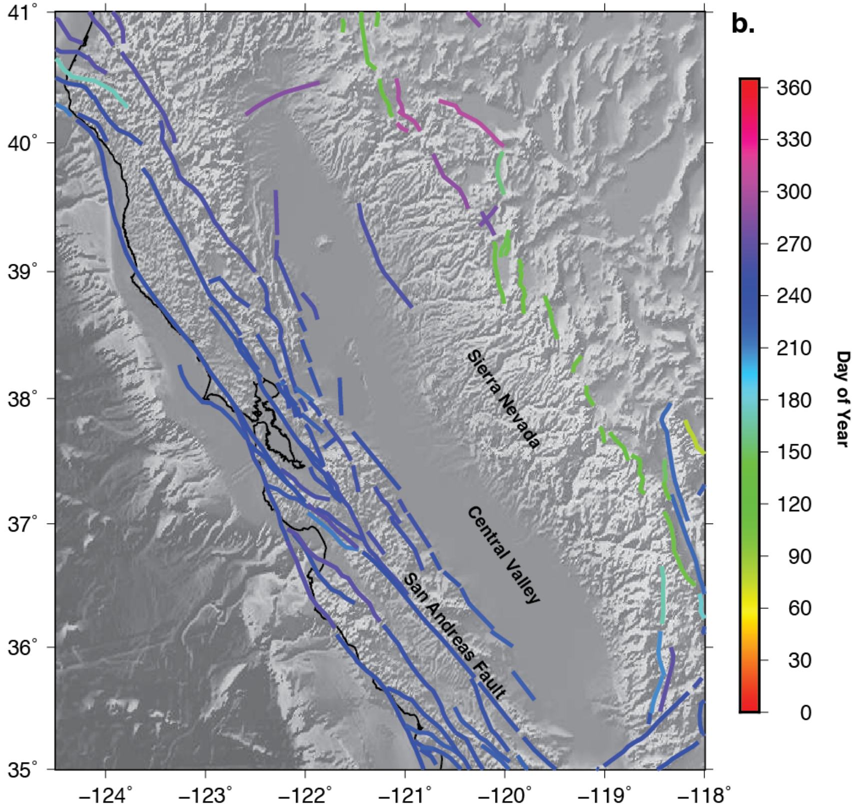
Rate

Johnson, Fu, and Bürgmann, Science 2017

Are Other Loading Sources Contributing to Earthquake Modulation?

- Surface Water
- Atmosphere
- Temperature
- Ocean
- Non tidal Ocean
- Earth Body Tides
- Earth Pole Tides



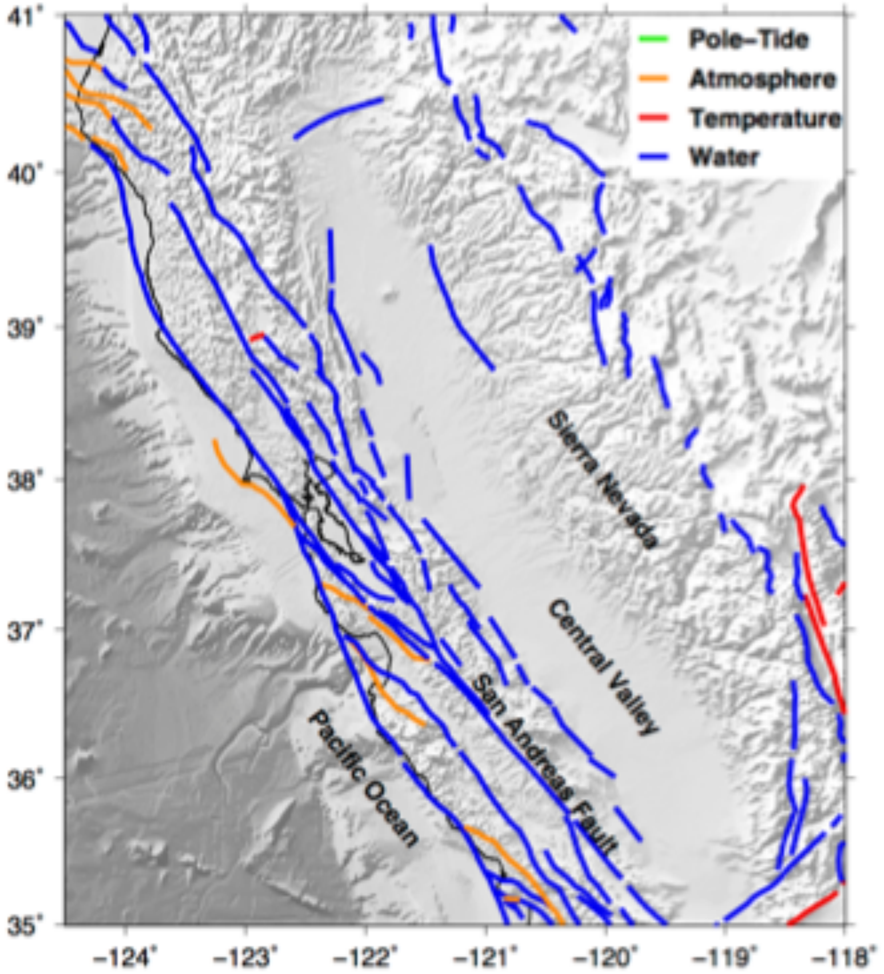


Johnson, Fu, and Bürgmann, JGR 2017

What is the Largest Annual Load?

Table 1
Average Seasonal Peak-to-Peak Stress (Pa) With 1-Standard Error for Each Loading Source

Loading source	Normal	Shear	Coulomb
Atmosphere (annual)	760 ± 225	171 ± 144	371 ± 240
Earth body tide (annual)	2 ± 1	3 ± 1	2 ± 1
Earth body tide (semiannual)	14 ± 12	16 ± 11	14 ± 10
Earth pole tide	125 ± 25	25 ± 10	53 ± 31
Nontidal ocean	44 ± 95	28 ± 58	22 ± 60
Ocean tide	4 ± 3	3 ± 2	4 ± 3
Temperature (annual)	474 ± 204	101 ± 69	133 ± 122
Hydrosphere	2,654 ± 2,764	1,052 ± 1,091	1,477 ± 1,370



Johnson, Fu, and Bürgmann, JGR, 2017

Background Stress Orientation

Invert using high quality focal mechanisms

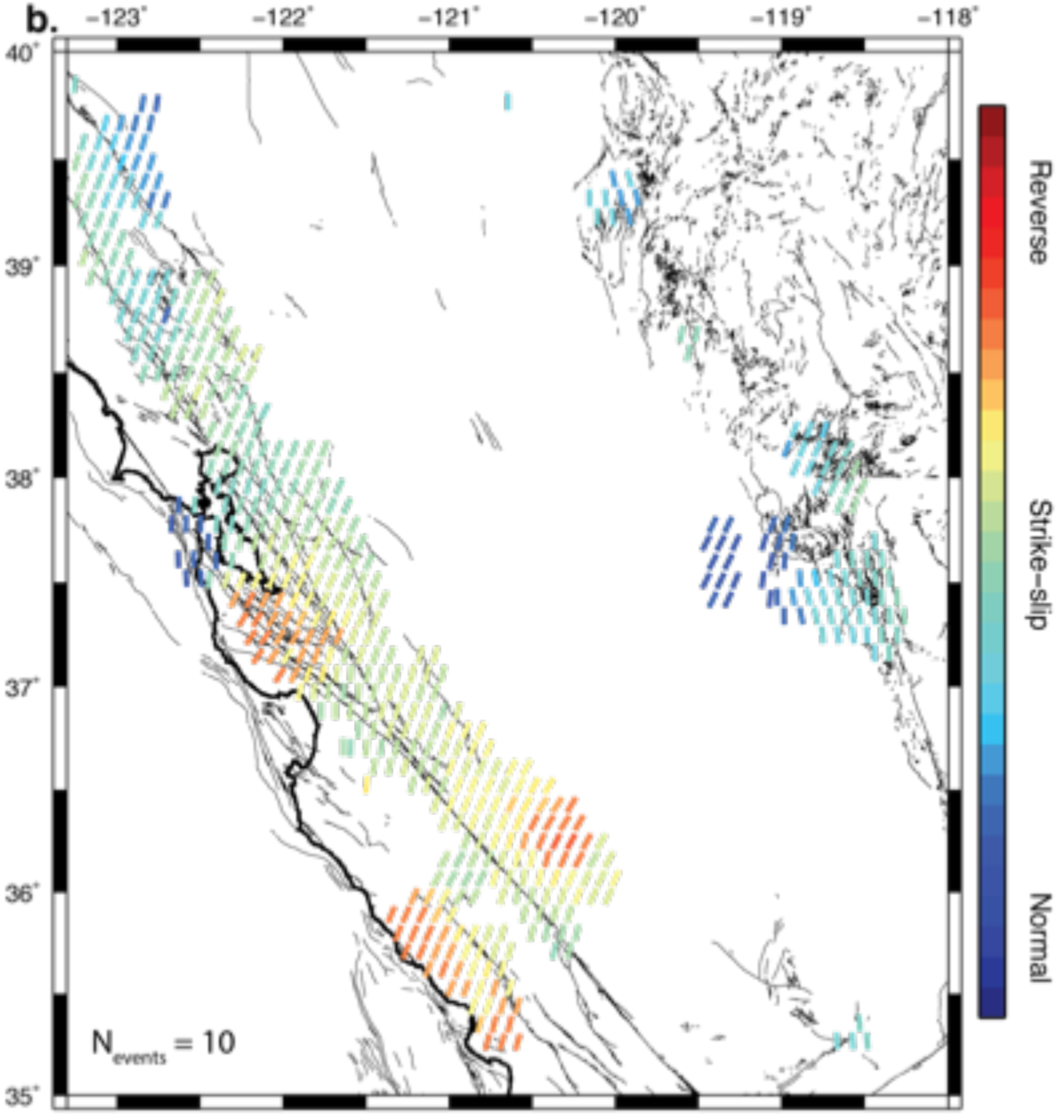
No amplitude information

S_{Hmax} Azimuth shown

Colored by Tensor Shape Describes the Rupture Style

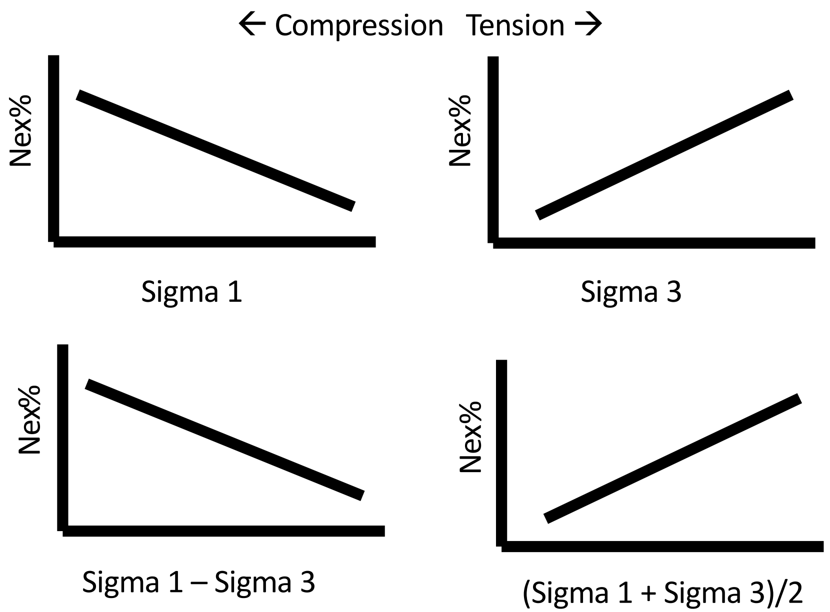
Project Seasonal Stress into Principal Orientations

Test for Excess Seismicity

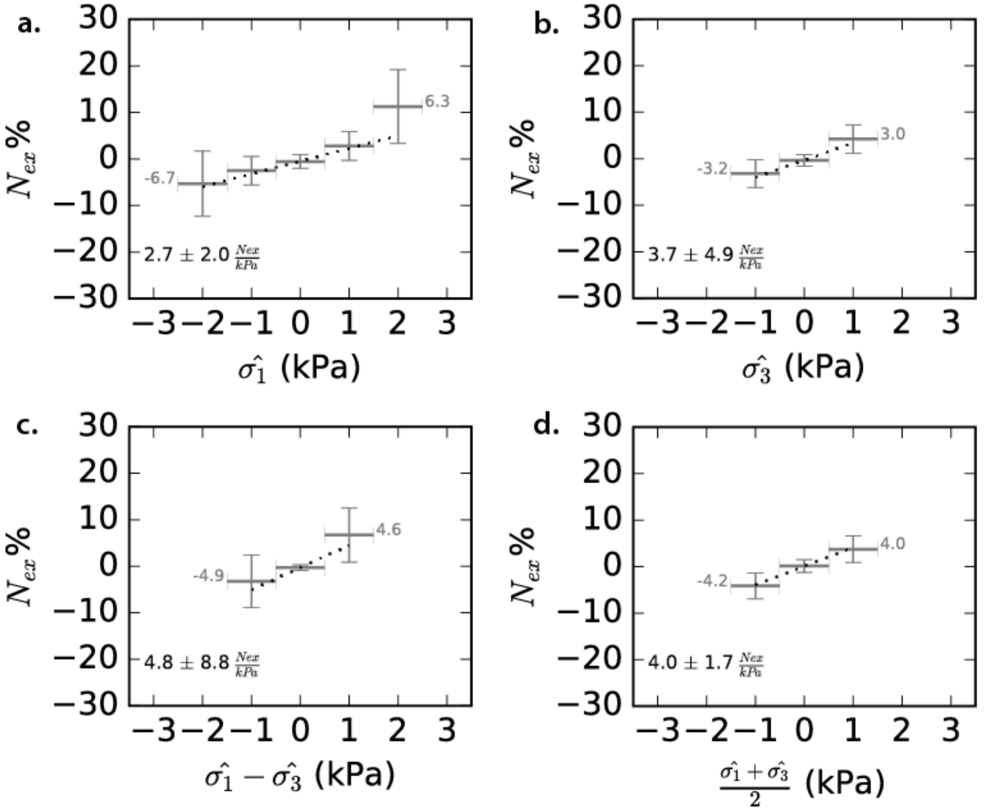


Percent Excess Seismicity

Expected



Sigma-1 & Sigma-3: More events when mean stress decreases

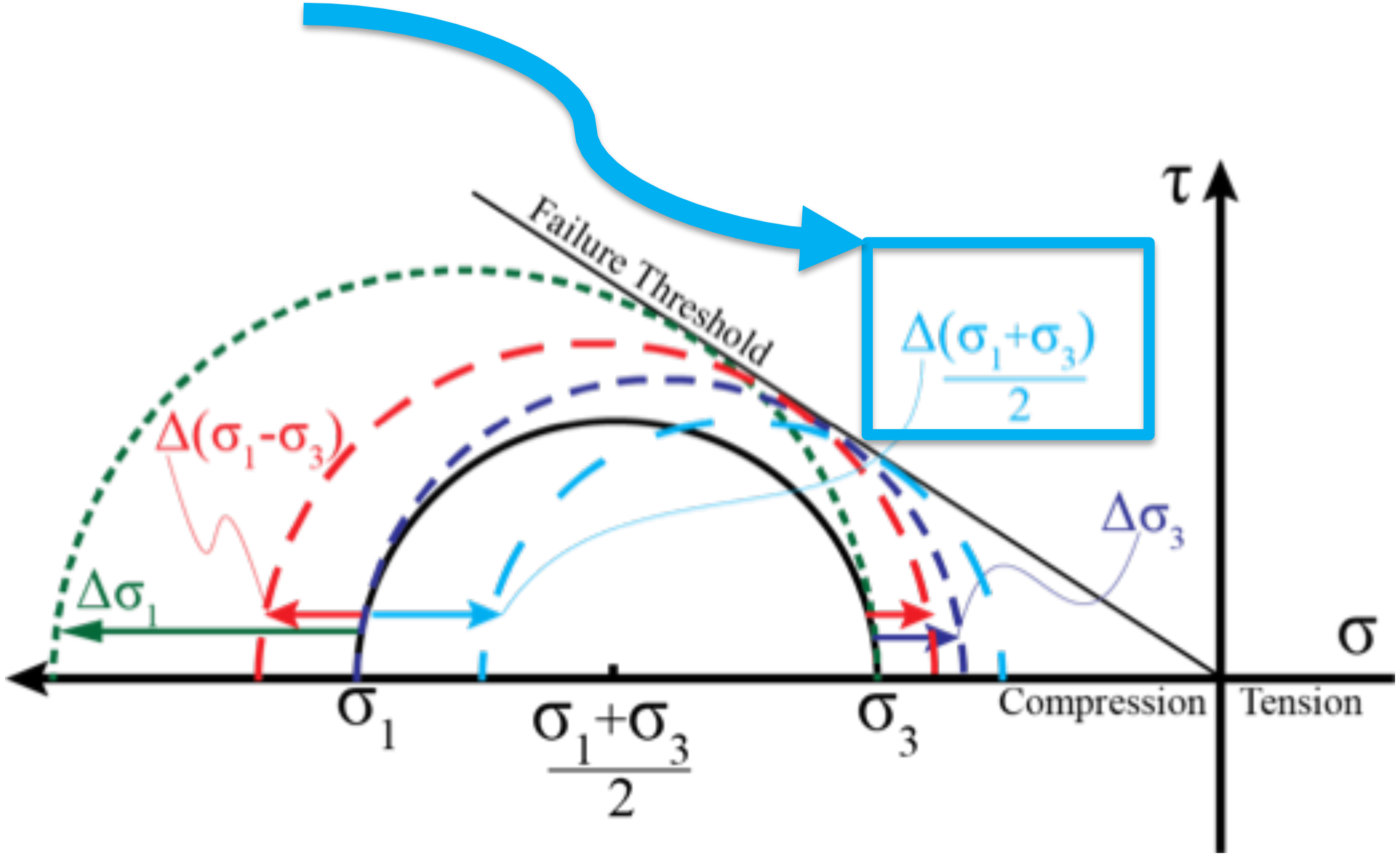


2006-2014 declustered hypocentral seismicity
Principal components derived from focal mechanism inversion
Loading time series projected into ambient stress field
Earthquakes at each inversion point used in calculation
Fault unclamping indicates a correlation

Johnson, Fu, and Bürgmann, JGR 2017

Failure Mechanism

- Change in mean normal stress
  - Possible fluid interaction



1/ Is Seasonal Hydrological Loading Modulating Seismicity?

Are faults responding to stress perturbations with annual periods?
Hydrological loading is a large contributing factor in the modulation of earthquakes from the annual stress cycles

Is the crust critically stressed?
Excess seismicity from a 1-5 kPa

What is the failure mechanism for earthquake nucleation?
Positive correlation with peak stress amplitude suggests an instantaneous threshold failure stress. Positive correlation with peak stressing rate suggests agrees with lab and model results

2/ Are Other Natural Deformation Sources Contributing?

All natural loading cycles should be considered when analyzing seasonal stress cycles. Water is the largest.

Seismicity indicates more events when loading align with ambient background stress orientation.


Thank You
Questions?