Seasonal Loading Modulating Seismicity on California Faults

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

University of California Berkeley Seismological Laboratory

UNIVERSITY OF CALIFORNIA, BERKELEY ACTIVE TECTONICS

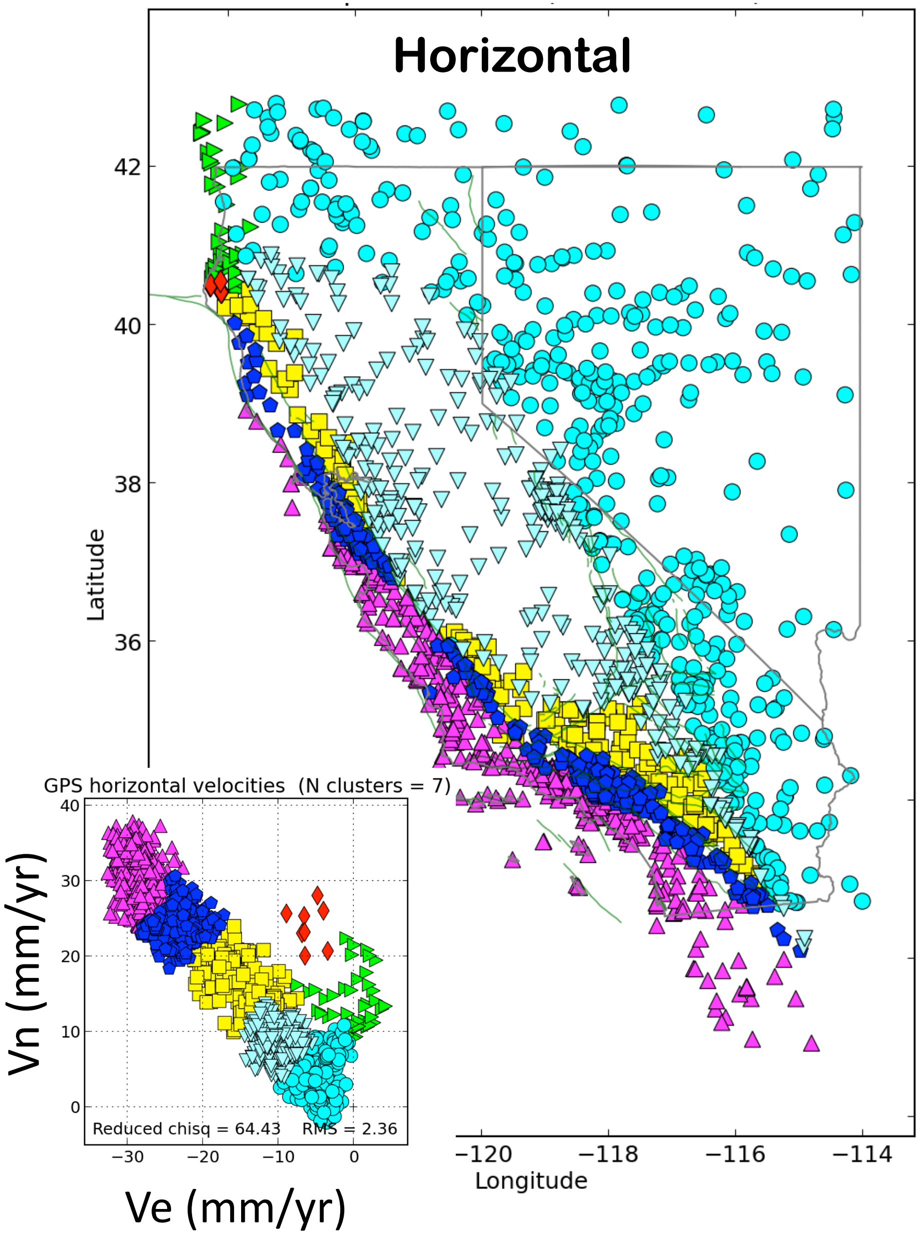
California Deformation and Uplift

NA – Pacific Plate Boundary
Transform faulting / Diffuse extension
Transpressional uplift in Coast Ranges
Sierra Nevada range-front faulting
Mantle upwelling and delamination
Erosional unloading

Eastern Sierra Nevada

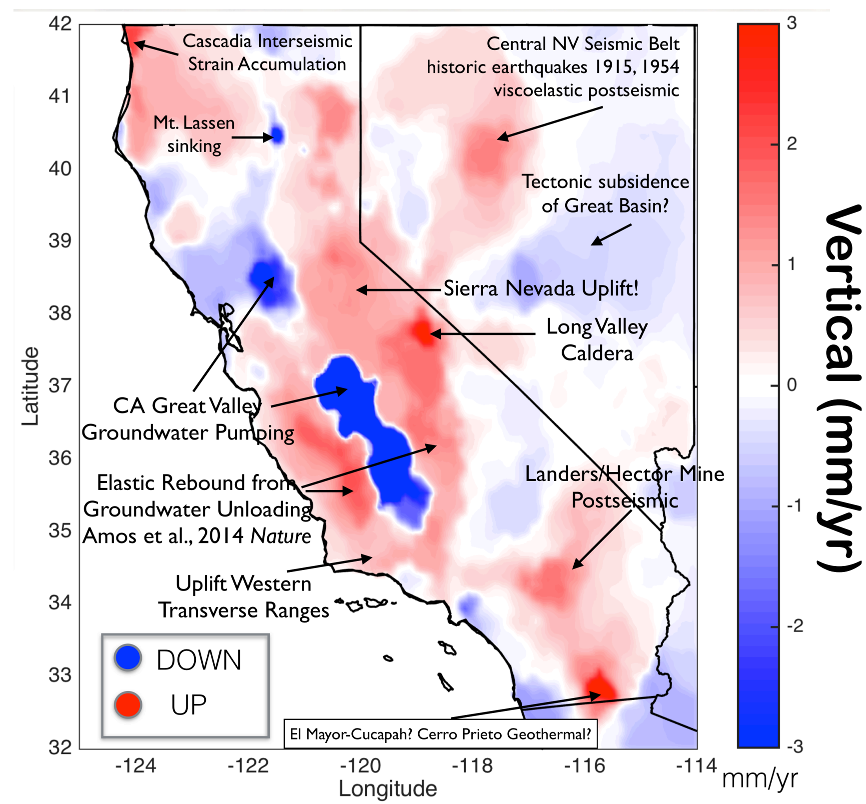
Unruh, 2003

California Deformation and Uplift



Major Features Delineated

- San Andreas Fault system
- Sierra Nevada – Great Valley microplate
- Central Valley pumping
- Long-term post-seismic signal

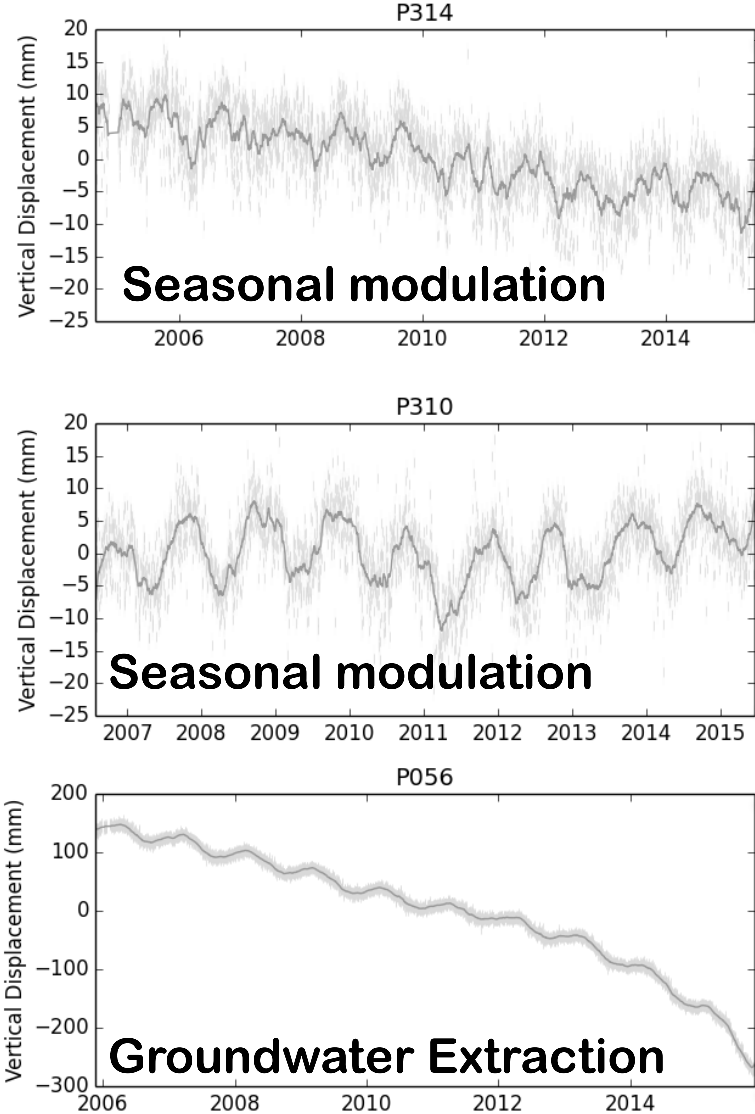


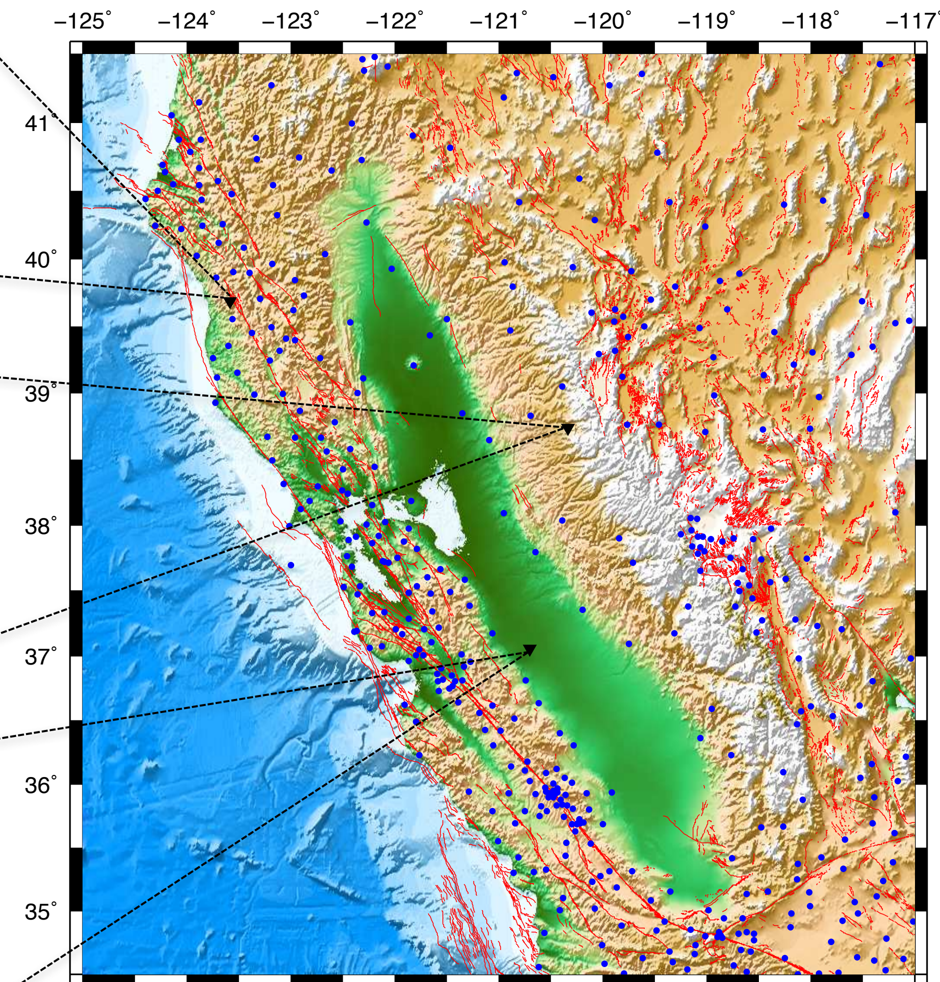
Simpson & Thatcher, USGS

Bill Hammond, UNR, pers. comm. MIDAS vel. solution

Seasonal Deformation

Vertical GPS Time Series



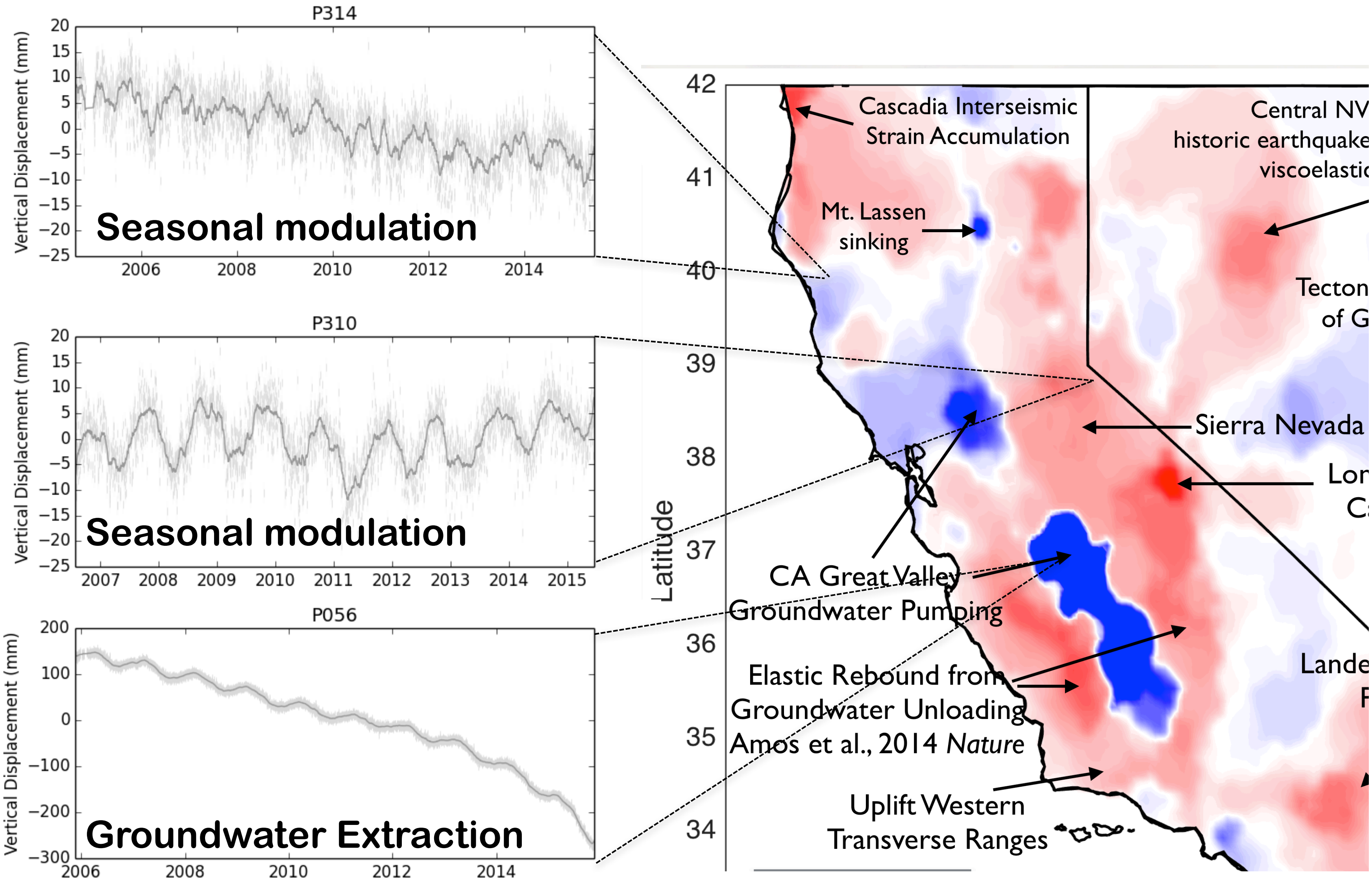


661 GPS Stations

USGS mapped faults

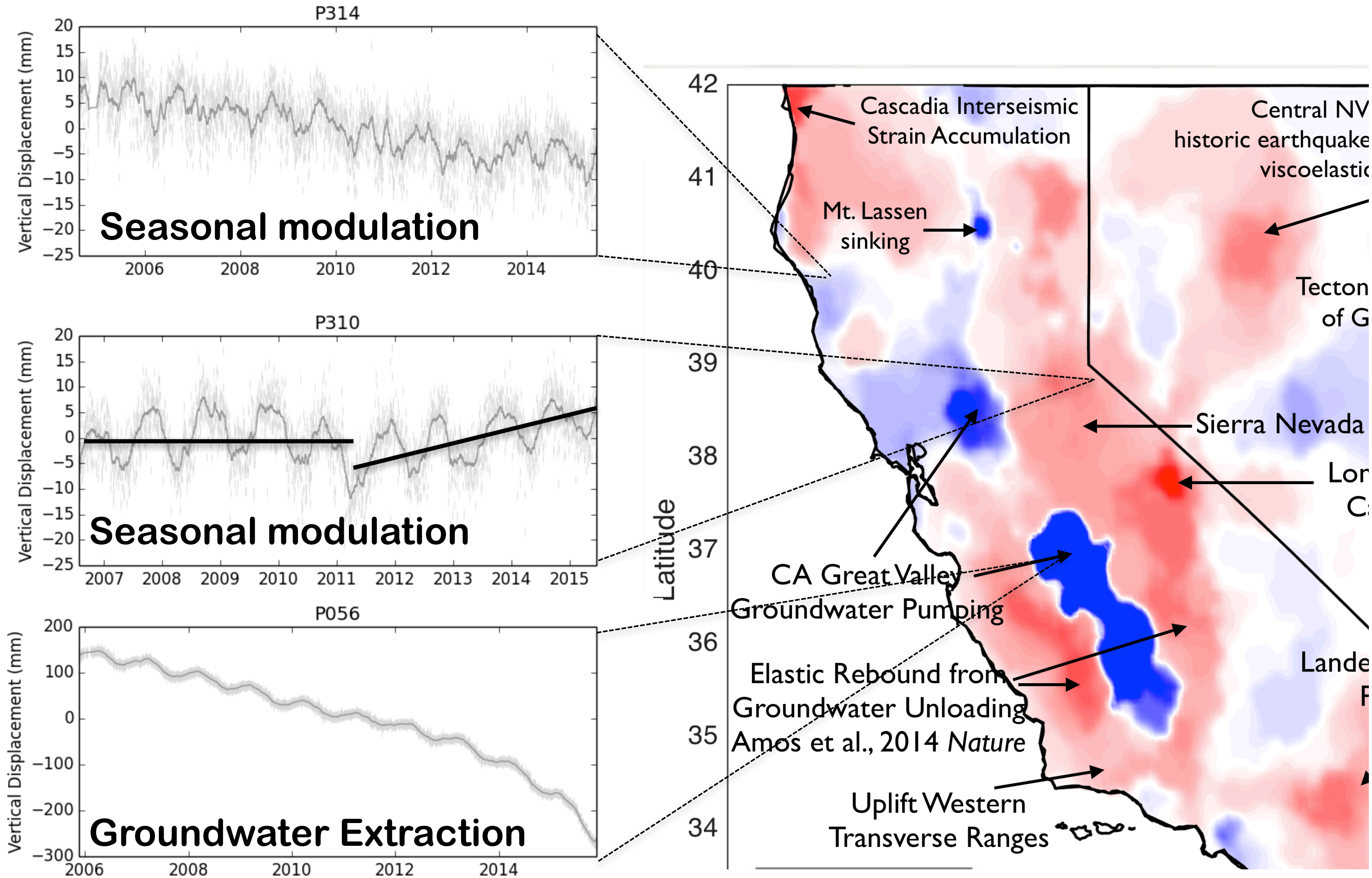
Seasonal Deformation

Vertical GPS Time Series



Seasonal Deformation

Vertical GPS Time Series

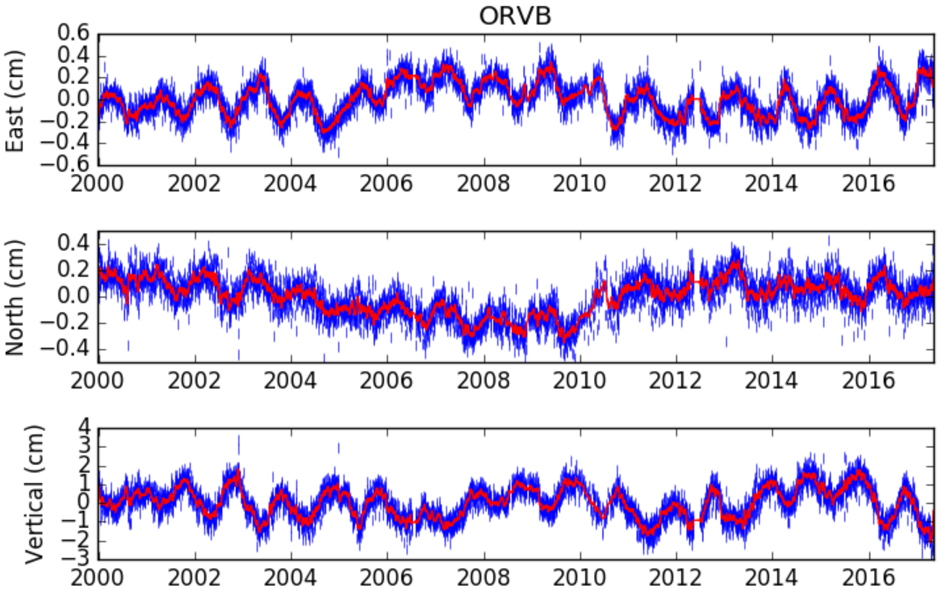


Climatic Changes Observed in Loading

Lake Oroville, 19 August 2014
Drought Crisis

Lake Oroville, 11 February 2017
Dam Crisis ~200k people evacuated

UNR GPS NA12 solution



http://geodesy.unr.edu

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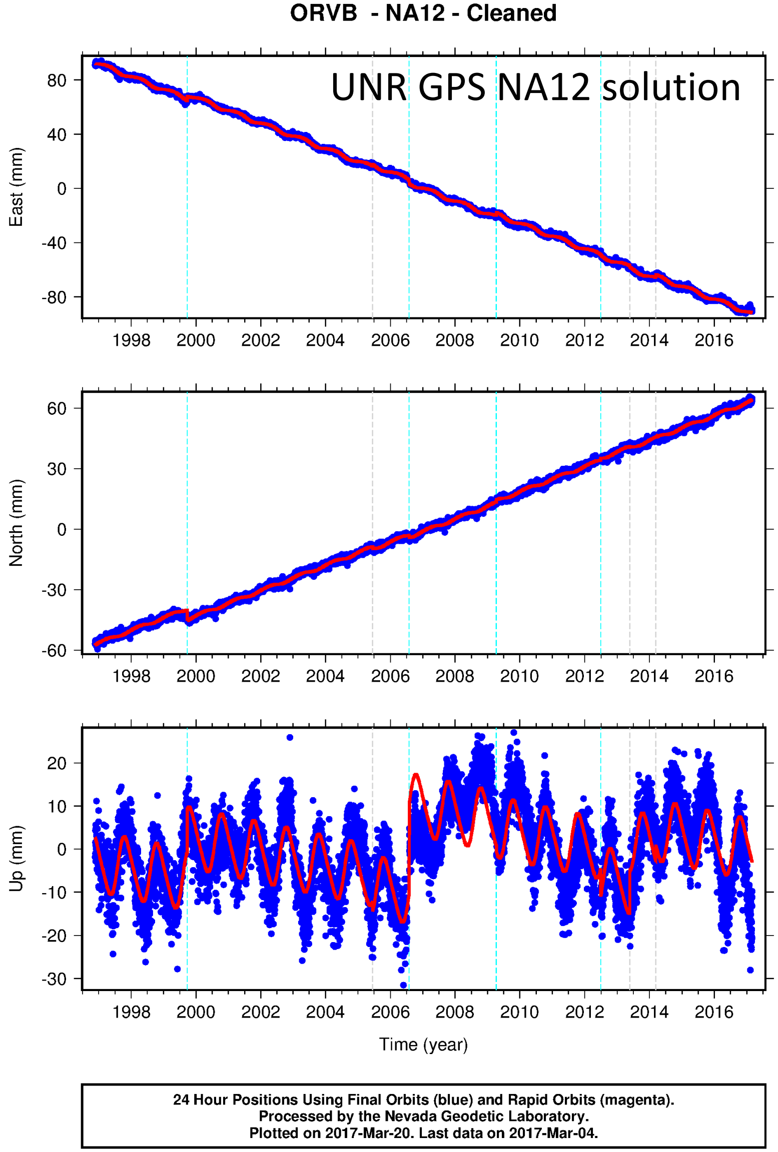


http://geodesy.unr.edu

What do we want to learn?

1/ Is Seasonal Hydrological Loading Modulating Seismicity?

Are faults responding to stress perturbations with annual periods?

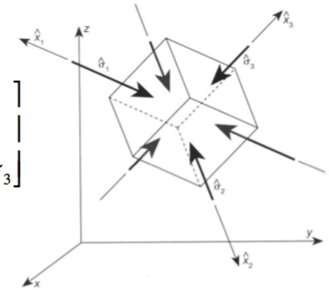
Is the crust critically stressed?

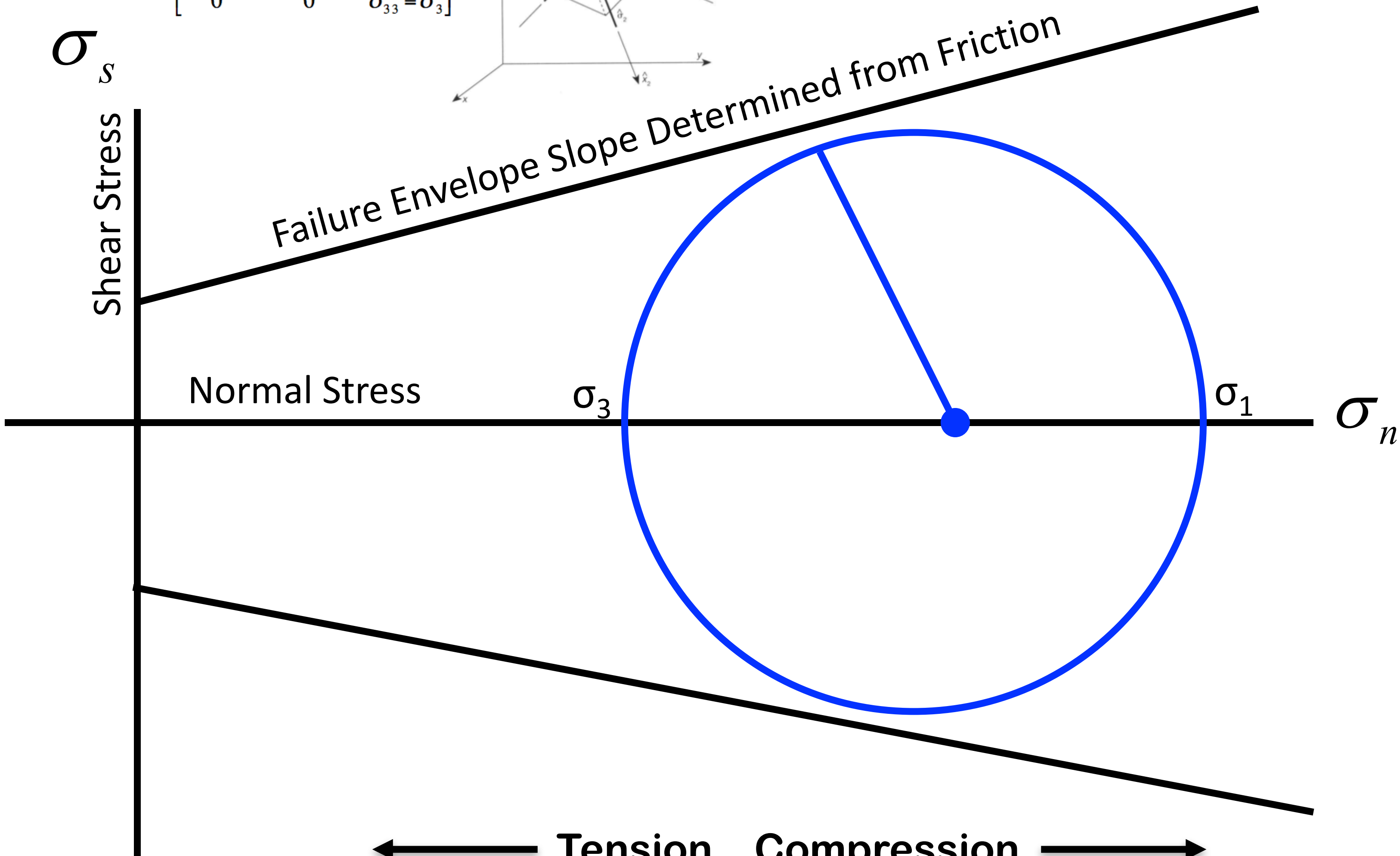
What is the failure mechanism for earthquake nucleation?

2/ Are Other Natural Deformation Sources Contributing?

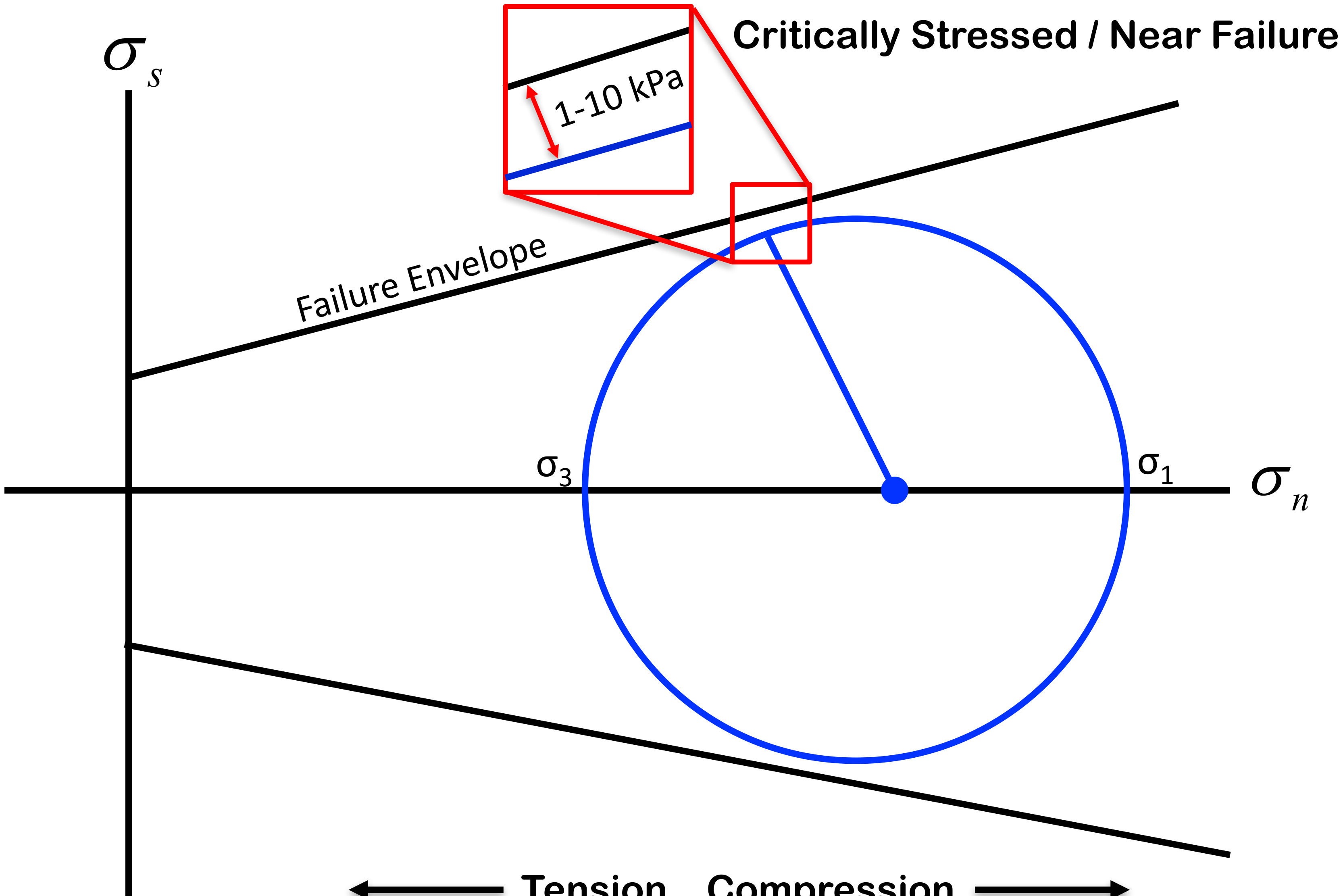
Coulomb Failure and Mohr Circles

$$\sigma = \begin{bmatrix} \sigma_{11} = \hat{\sigma}_1 & 0 & 0 \\ 0 & \sigma_{22} = \hat{\sigma}_2 & 0 \\ 0 & 0 & \sigma_{33} = \hat{\sigma}_3 \end{bmatrix}$$





Coulomb Failure and Mohr Circles



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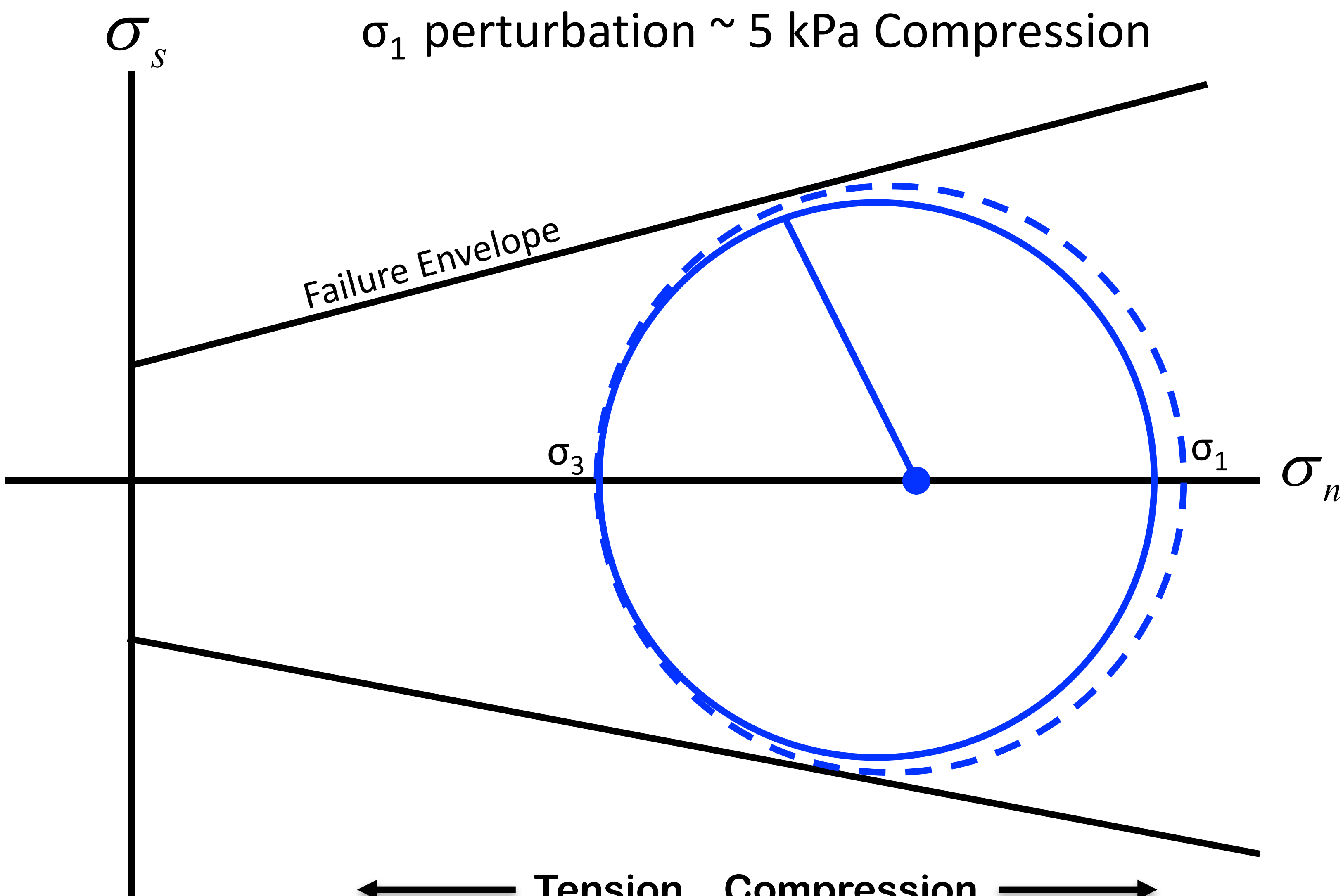

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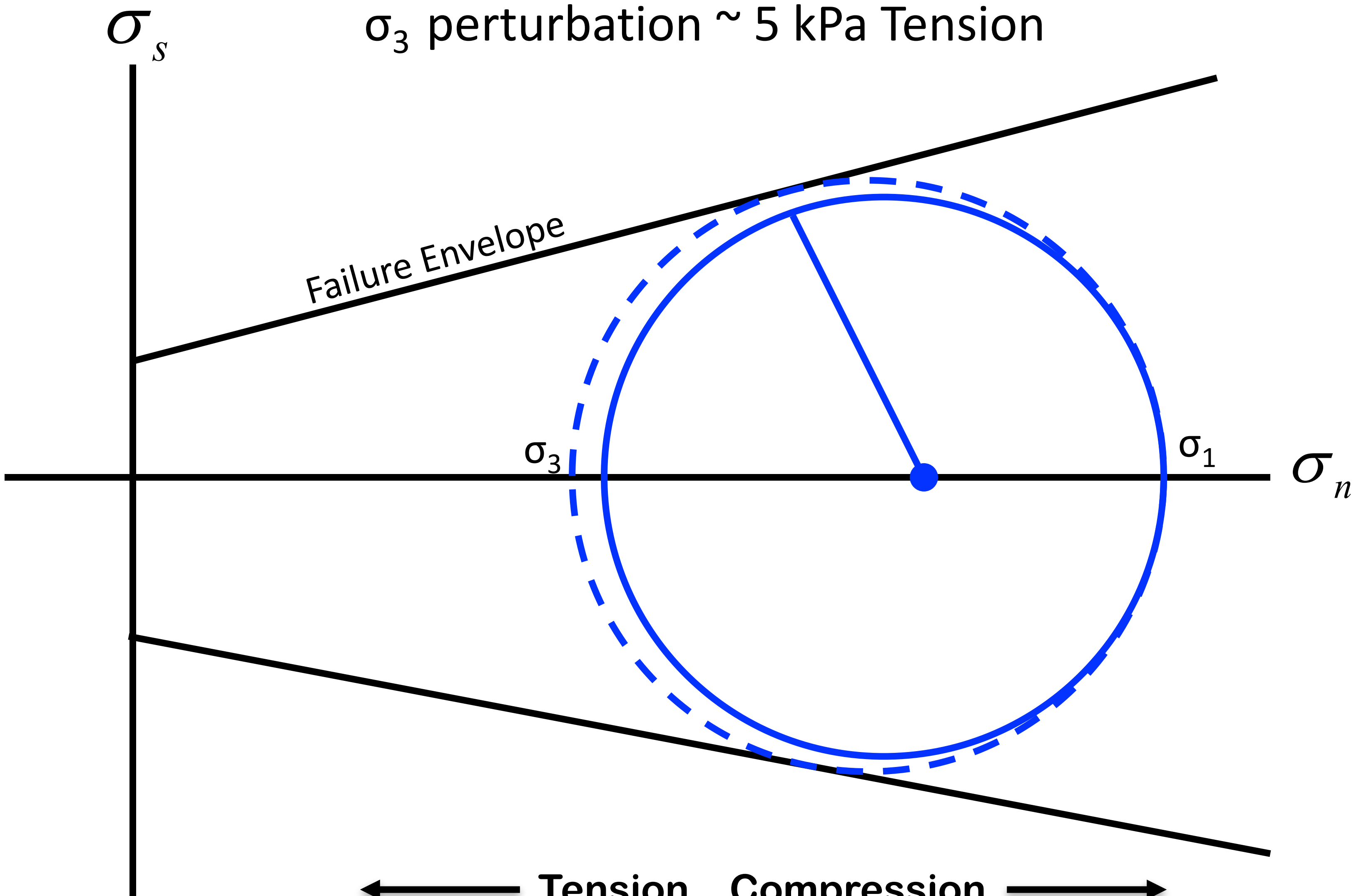
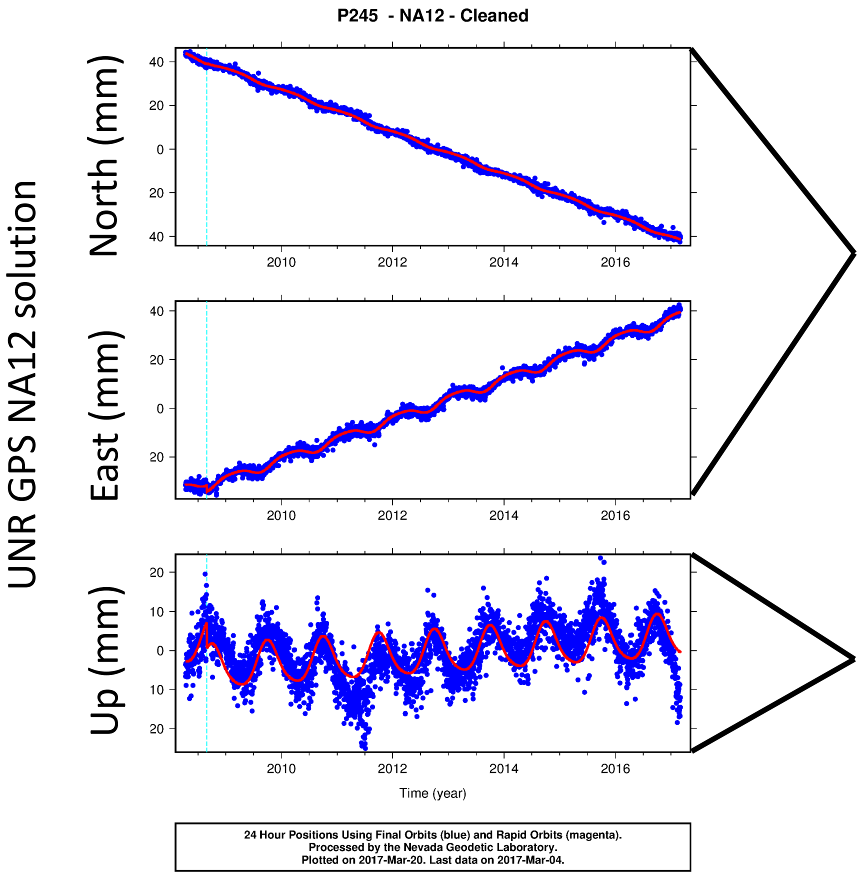


Seasonal Loading



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

Tectonic Loading
5-50 kPa/yr loading rate

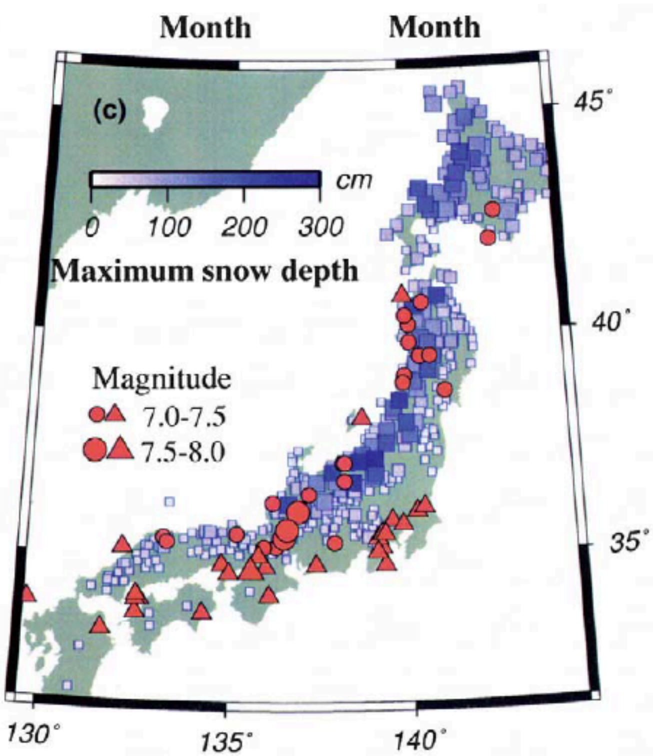
Seasonal Modulation
100 mm water load ≈ 1kPa

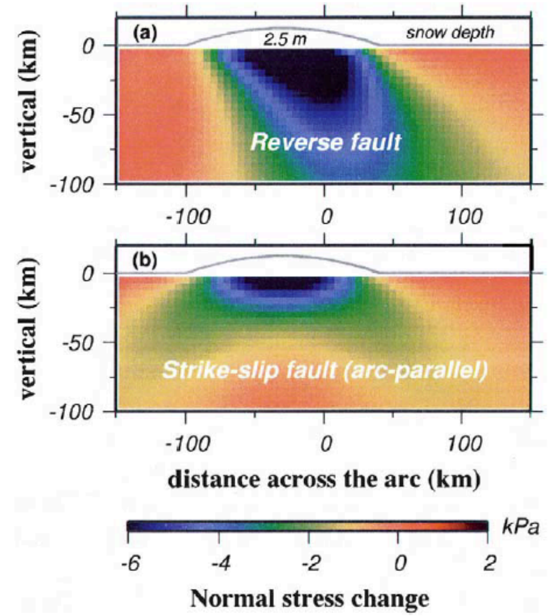
Seasonal Loading Modulating Seismicity on California Faults

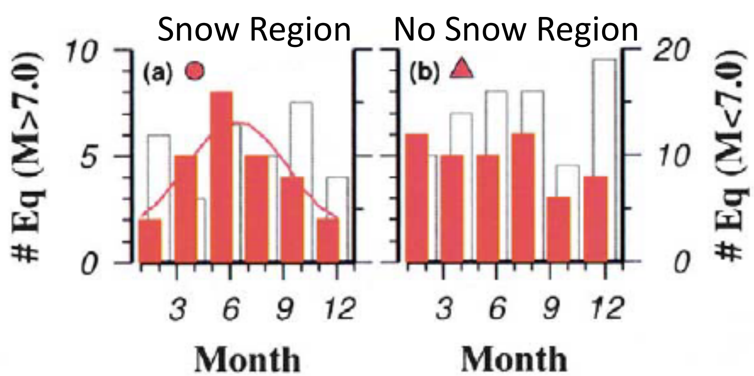
i. Motivation – Annual Loading Cycles
   i. Nepal, Japan, and California
ii. Seasonal Loading and Deformation
   i. Modeling Efforts
   ii. Stress calculations
iii. Stress and Seismicity Analysis
   i. Is Seasonal Hydrological Loading Modulating Seismicity?
   ii. Are Other Loading Sources Contributing?

Water/Snow Loading Examples

- Snow loading in Japan
- Interseismic strain suppressed
- Less M>7 events in winter



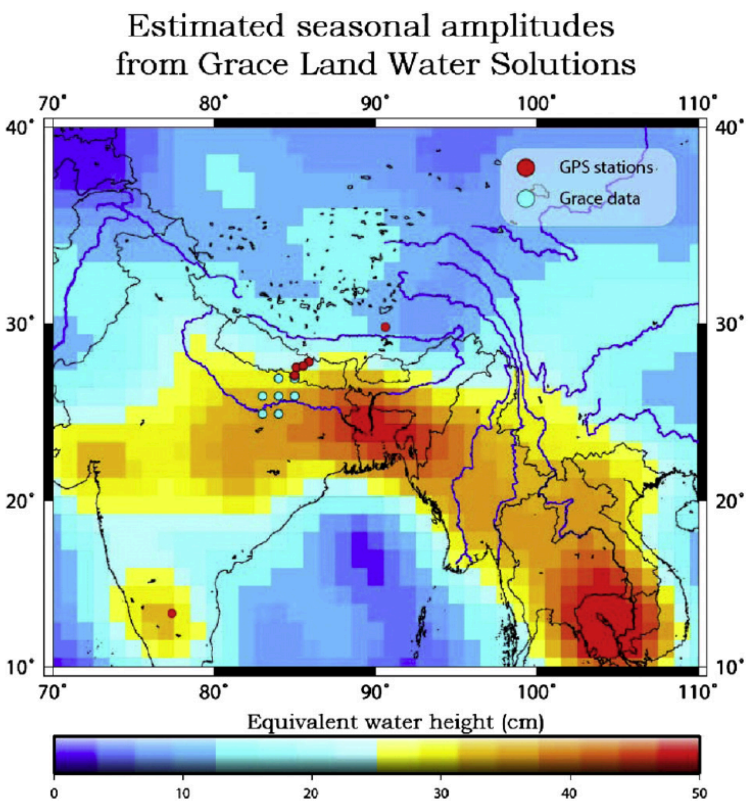


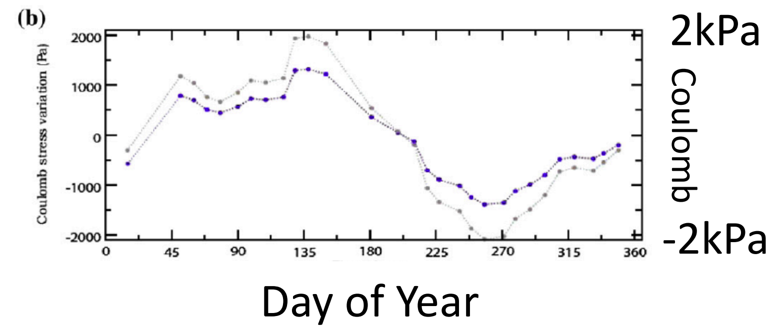


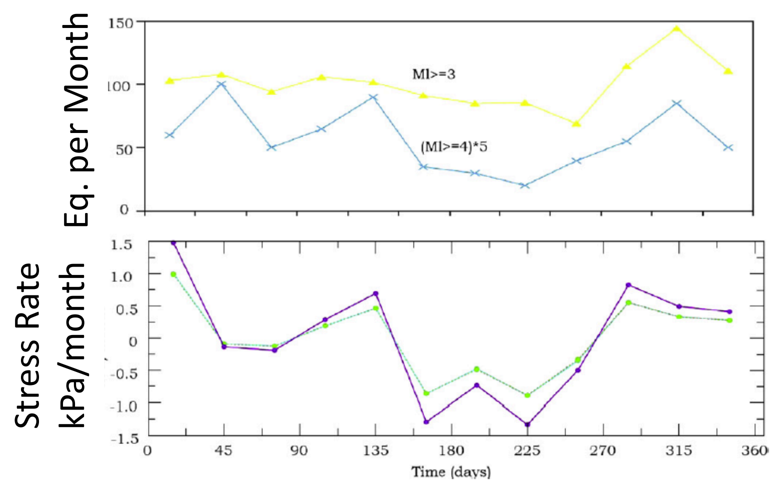
Heki, 2003

Water/Snow Loading Examples

- Gravity inferred seasonal water change in the Ganges Basin
- ~4kPa stress change
- Stacked seismicity



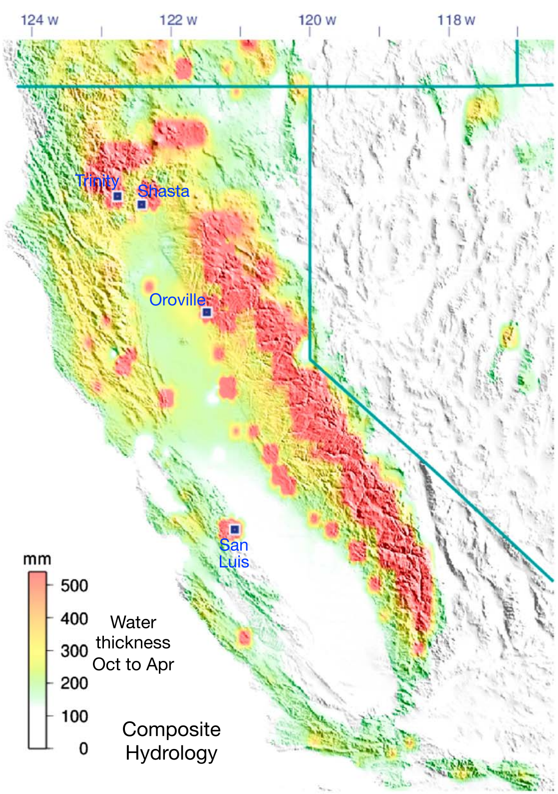




Bettinelli et al., 2008

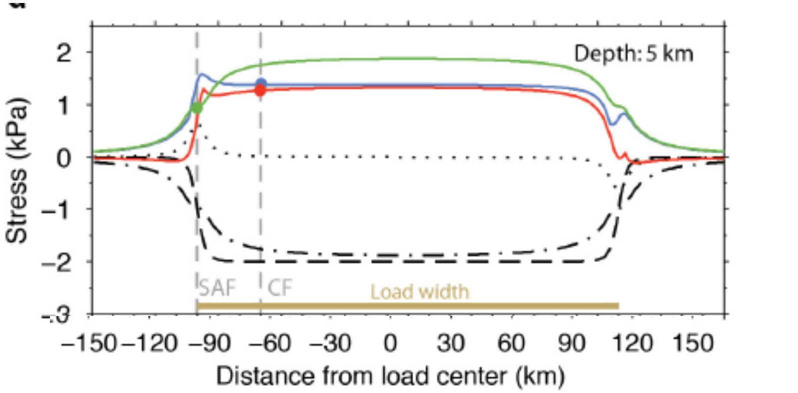
Water/Snow Loading Examples

- **Estimated Water Thickness**
- **Seasonal Deformation in California**
  - **~1.5 kPa Stress Estimate**
- **Stacked seismicity along SAF**



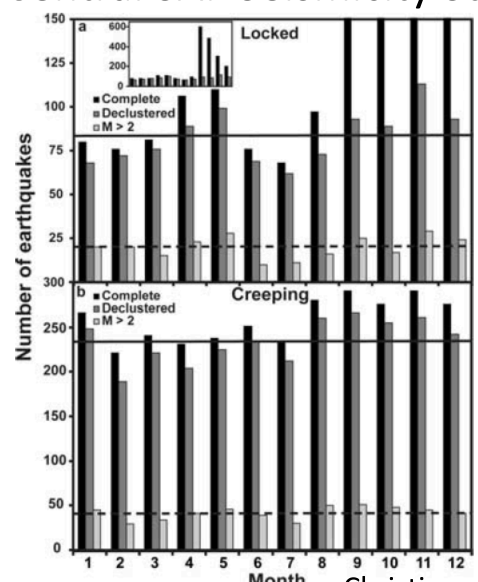
Argus et al., GRL, 2014

Line Load Stress Estimate



Amos et al., Nature, 2014

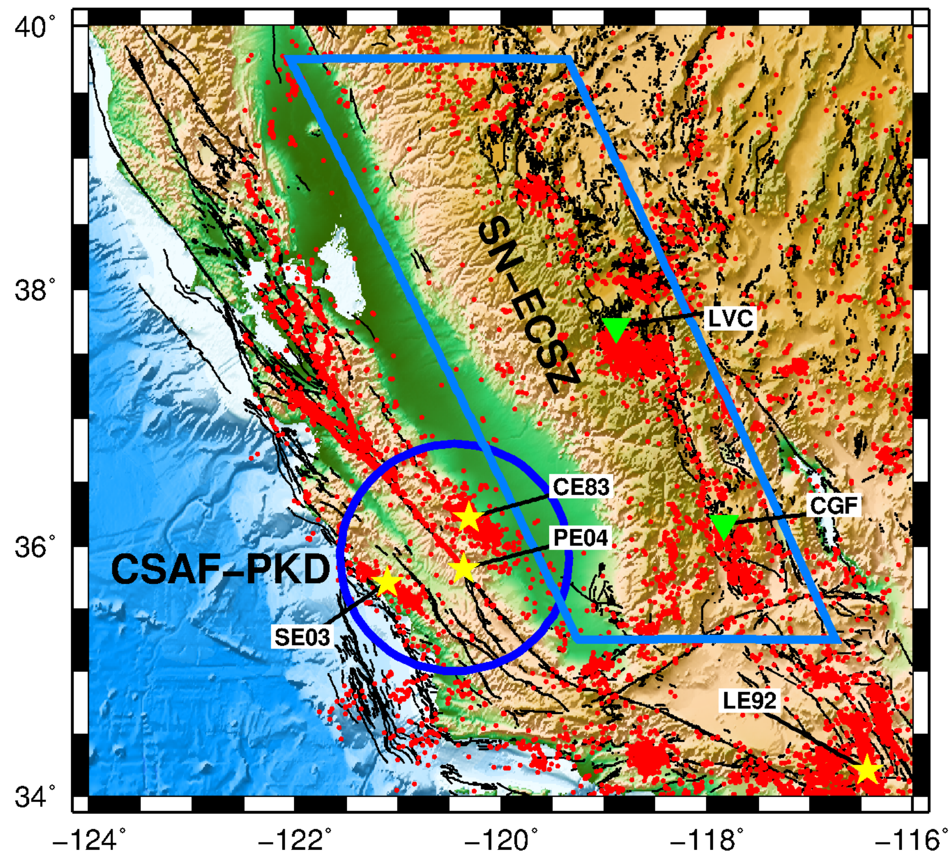
Central SAF Seismicity Stack

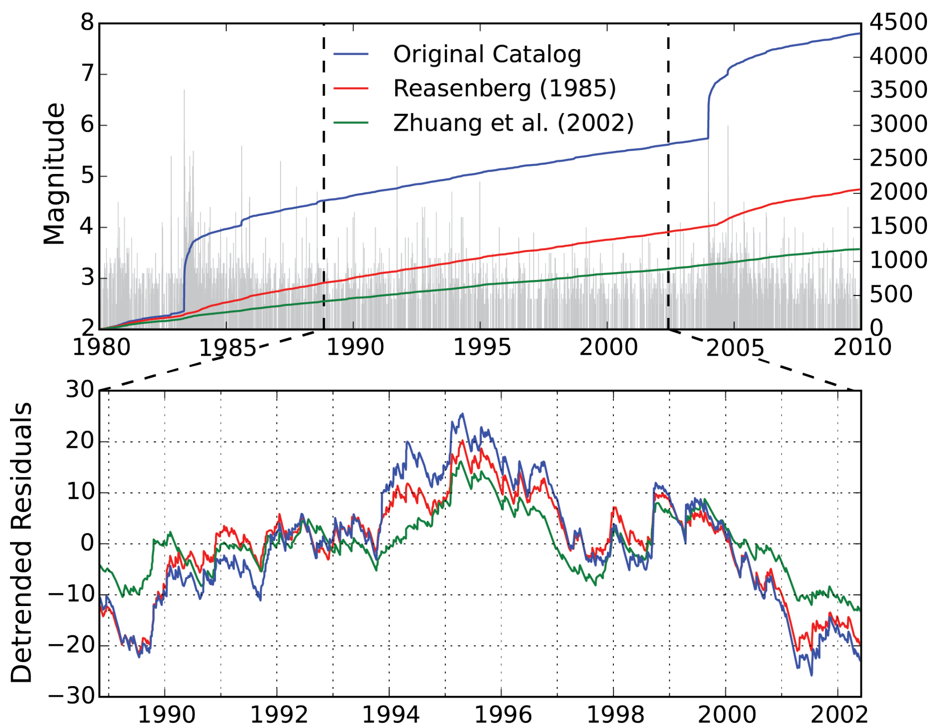


Christiansen et al., GRL, 2007

Periodicity in Seismicity Records

Evidence for Stress Modulation





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

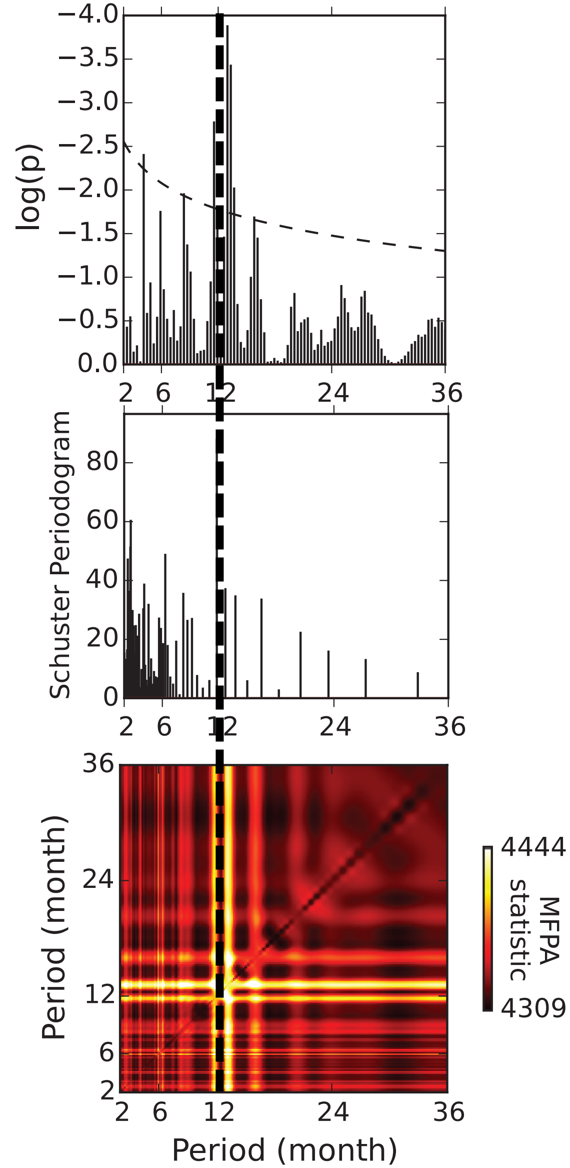
Annual Periodicity

Three Independent Tests

Schuster Spectrum

Schuster Periodogram

Multifrequential Periodogram Analysis



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

Seasonal loading modulating seismicity on California faults

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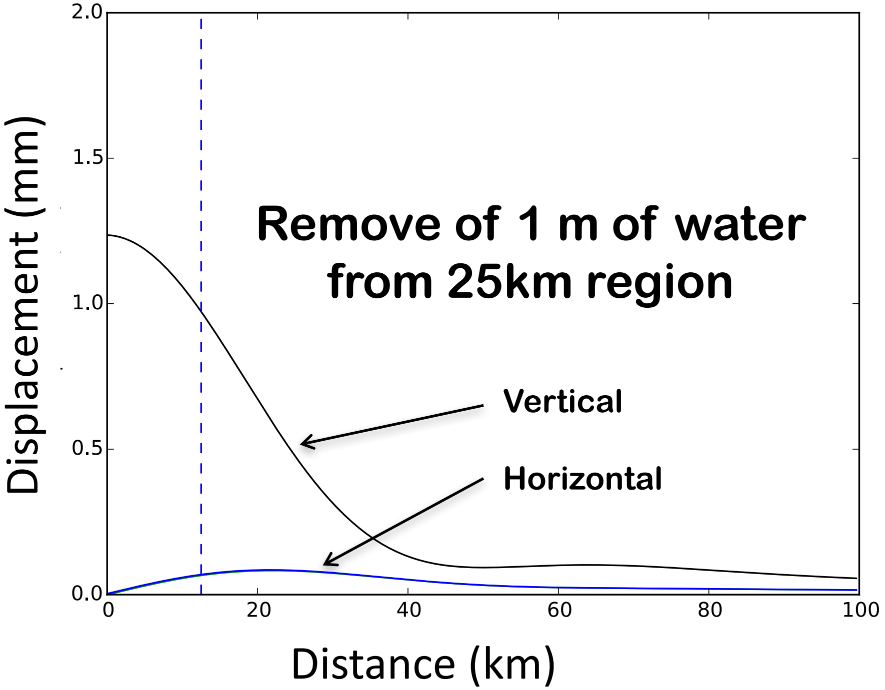
   i. **Nepal, Japan, and California**
ii. **Seasonal Loading and Deformation**
   i. **Modeling Efforts**
   ii. **Stress calculations**
iii. **Stress and Seismicity Analysis**
   i. **Is Seasonal Hydrological Loading Modulating Seismicity?**
   ii. **Are Other Loading Sources Contributing?**

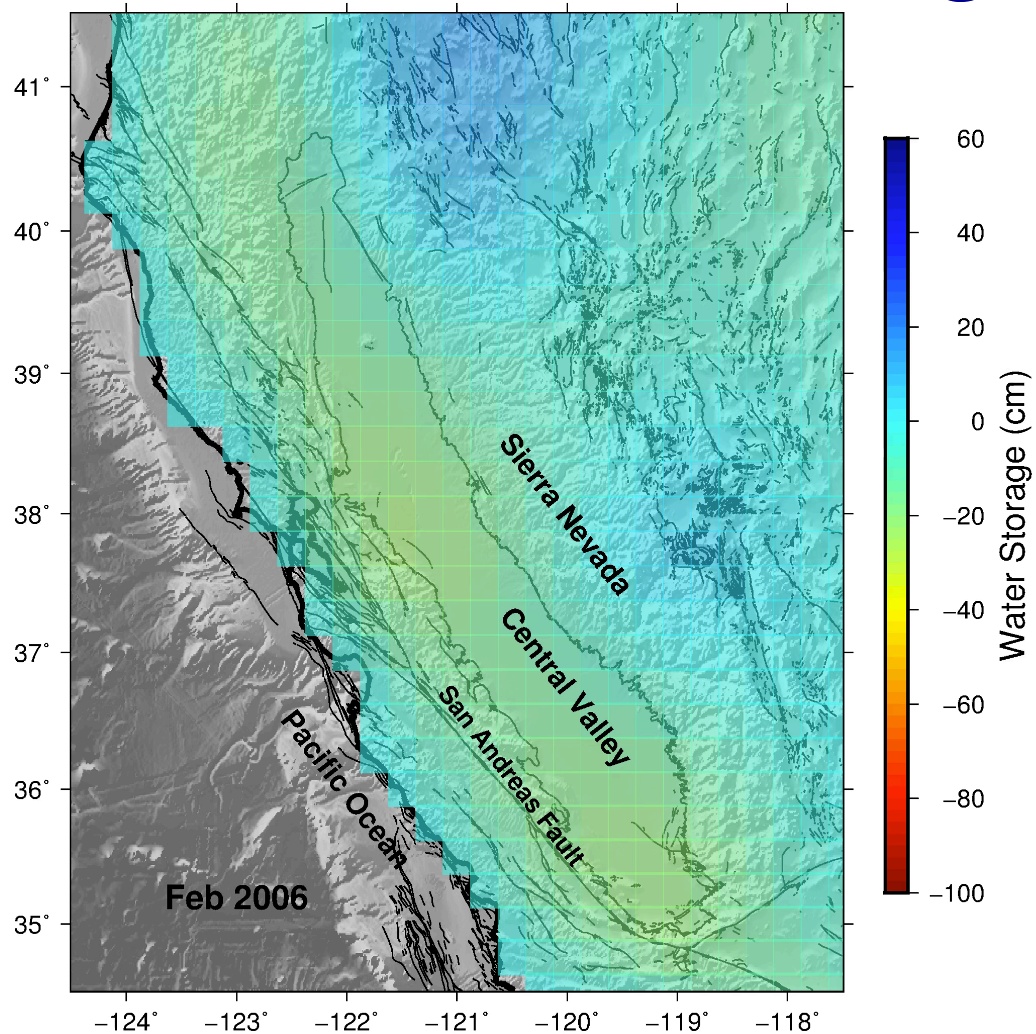
Elastic Load Model

- **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**



Inversion following Argus et al., 2014 and Fu et al., 2015

Effective Water Storage



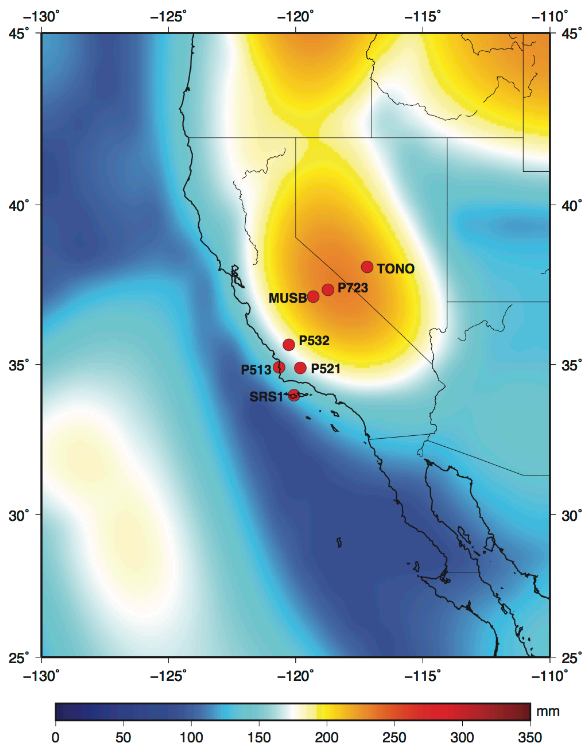
Derived using vertical GPS displacement following Argus et al., 2014 on 0.25˚ x 0.25˚ grid

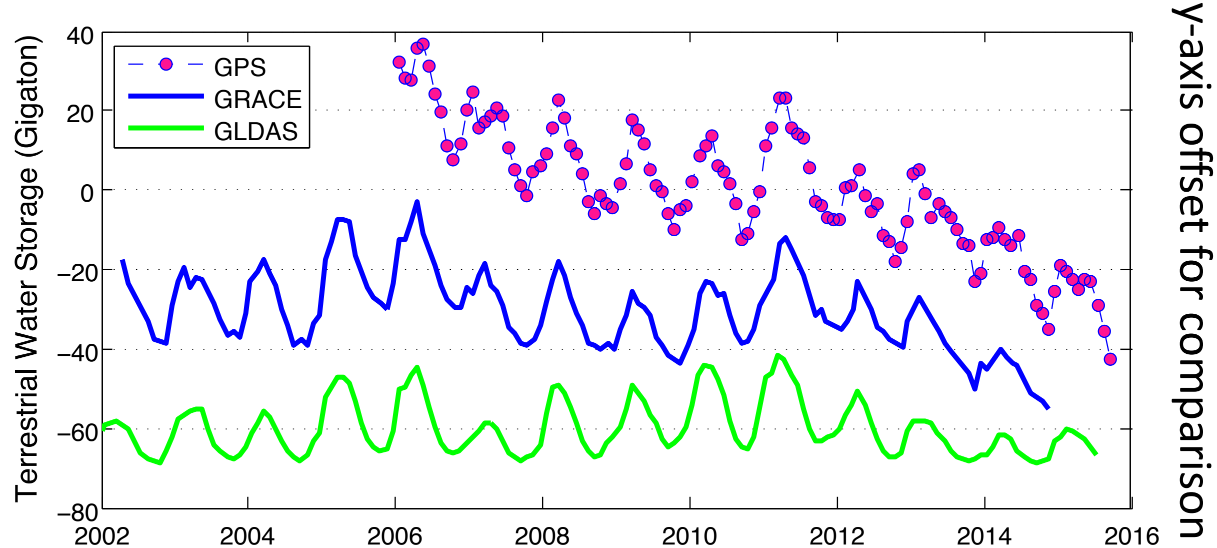
Johnson, Fu, and Bürgmann, Science 2017

GRACE / GLDAS Comparison

- Gravity Measurements to Infer Water Storage

- Composite models

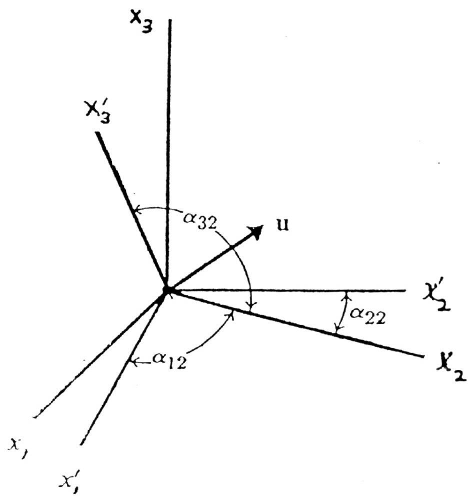


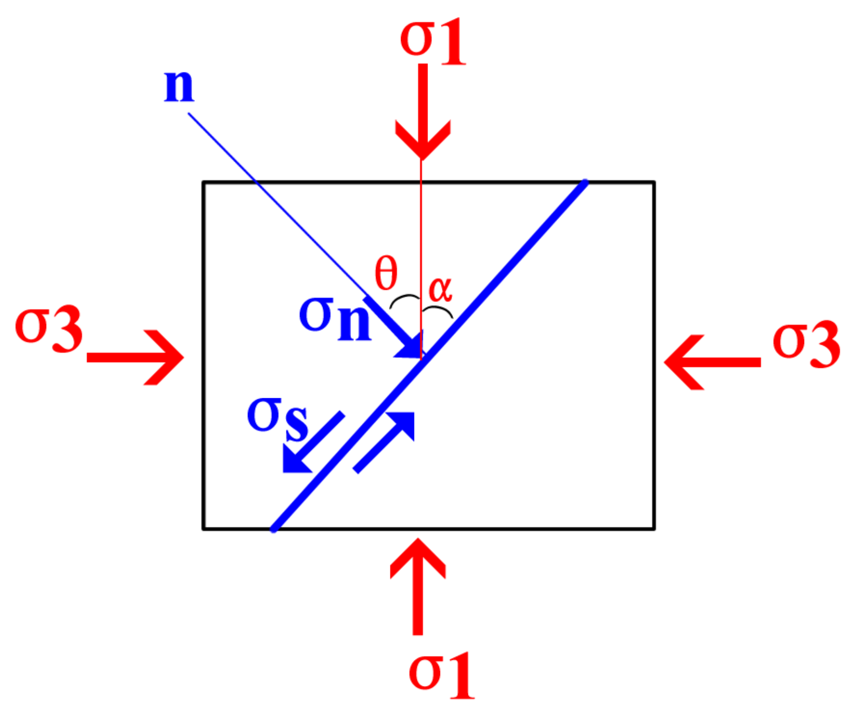


Deformation Modeling

- **Assume Linear Elastic**
- **Calculate Stress at 8 km Depth**
- **Rotate to Failure Plane**
- **Shear (σ_S) and Normal (σ_N)**
- **ΔCoulomb = $\Delta\sigma_S + \mu\, \Delta\sigma_N$**

$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$





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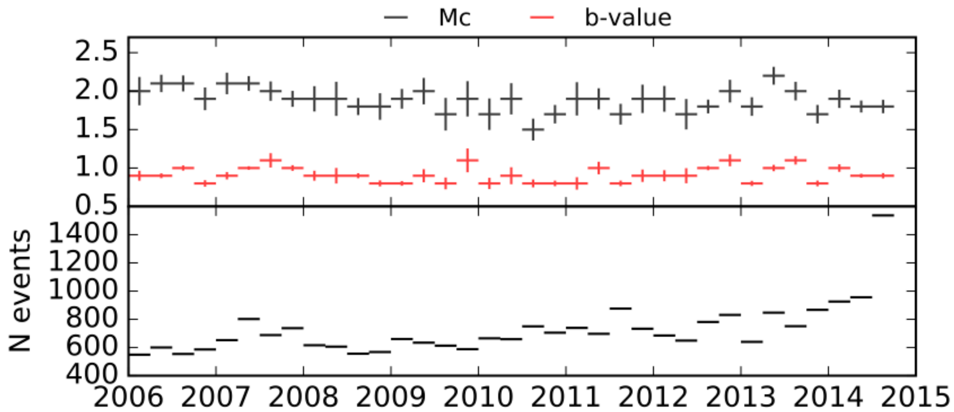
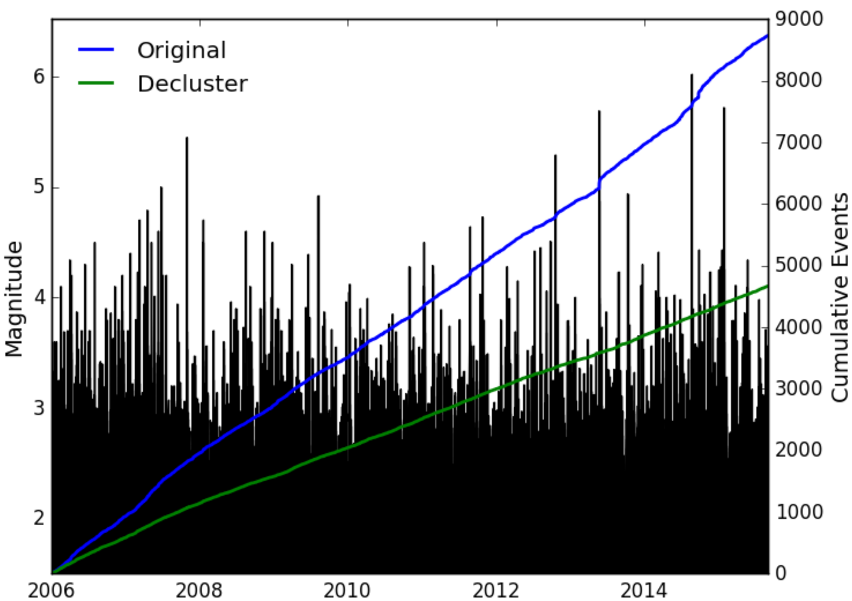
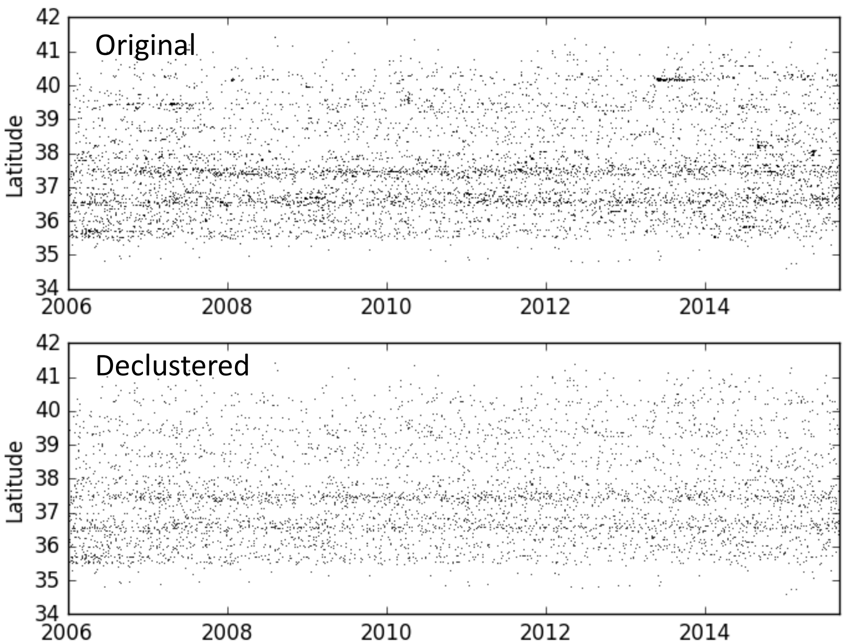
NCSS Focal Mechanisms



ETAS Declustering

2006-2014
Exclude geothermal & volcanic
Mc ~ 2.0 (w/ 0.25 yr window)
ETAS 2D (Zhuang et al., 2002)

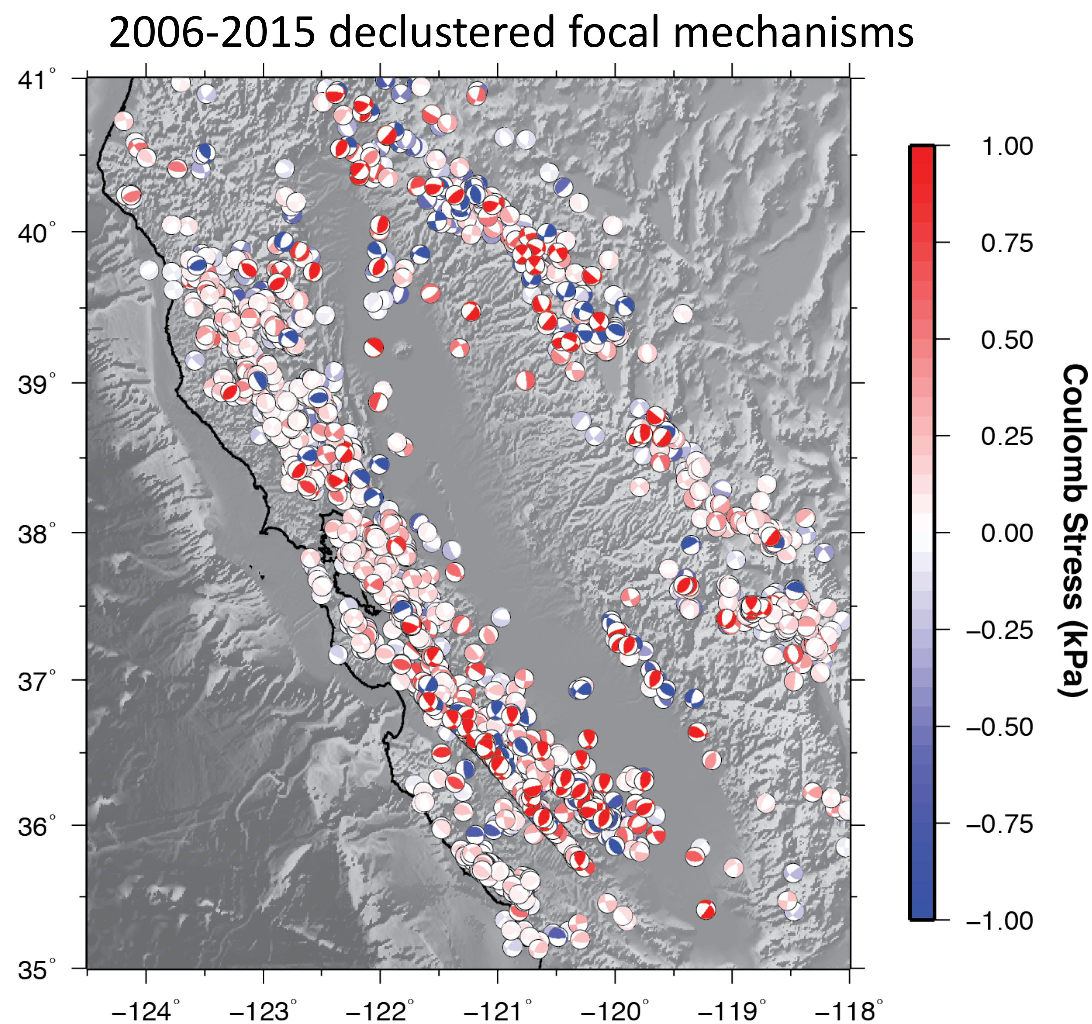




Johnson, Fu, and Bürgmann, Science 2017

Is Seasonal Hydrological Loading Modulating Seismicity?

The seasonal stress change on the focal plane



Johnson, Fu, and Bürgmann, Science 2017

Percent excess M≥2.0 seismicity

Excess Seismicity N_{ex} Plot

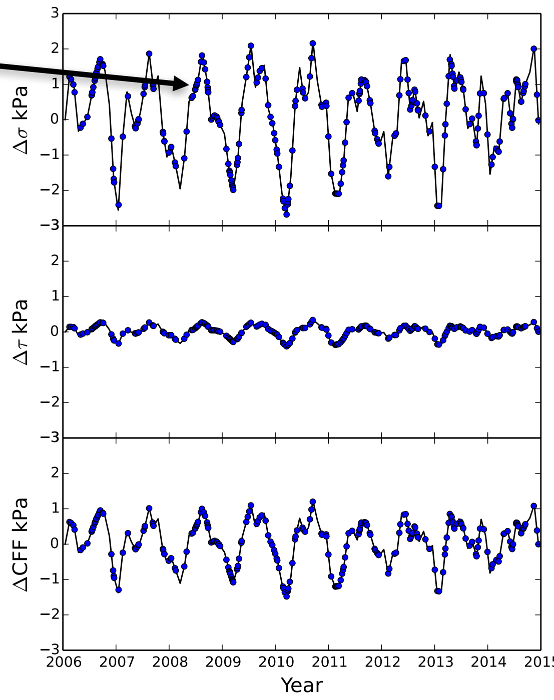
$N_{ex} = (N_{Act} - N_{Exp}) / N_{Exp} * 100$

N_{Act} = stress at event time

N_{Exp} = Uniform distribution of 250 random events times for stress cycle

E.g. blue dots are uniform distribution on stress curve

Actual event time for the location



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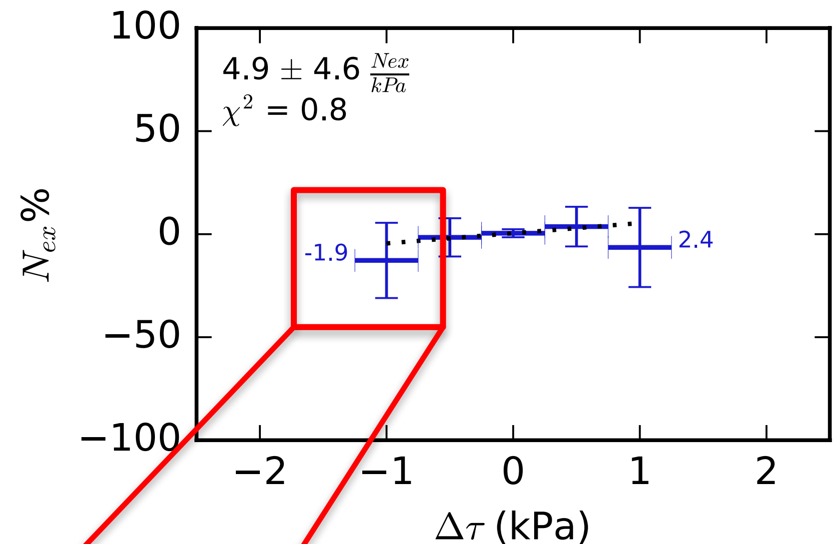
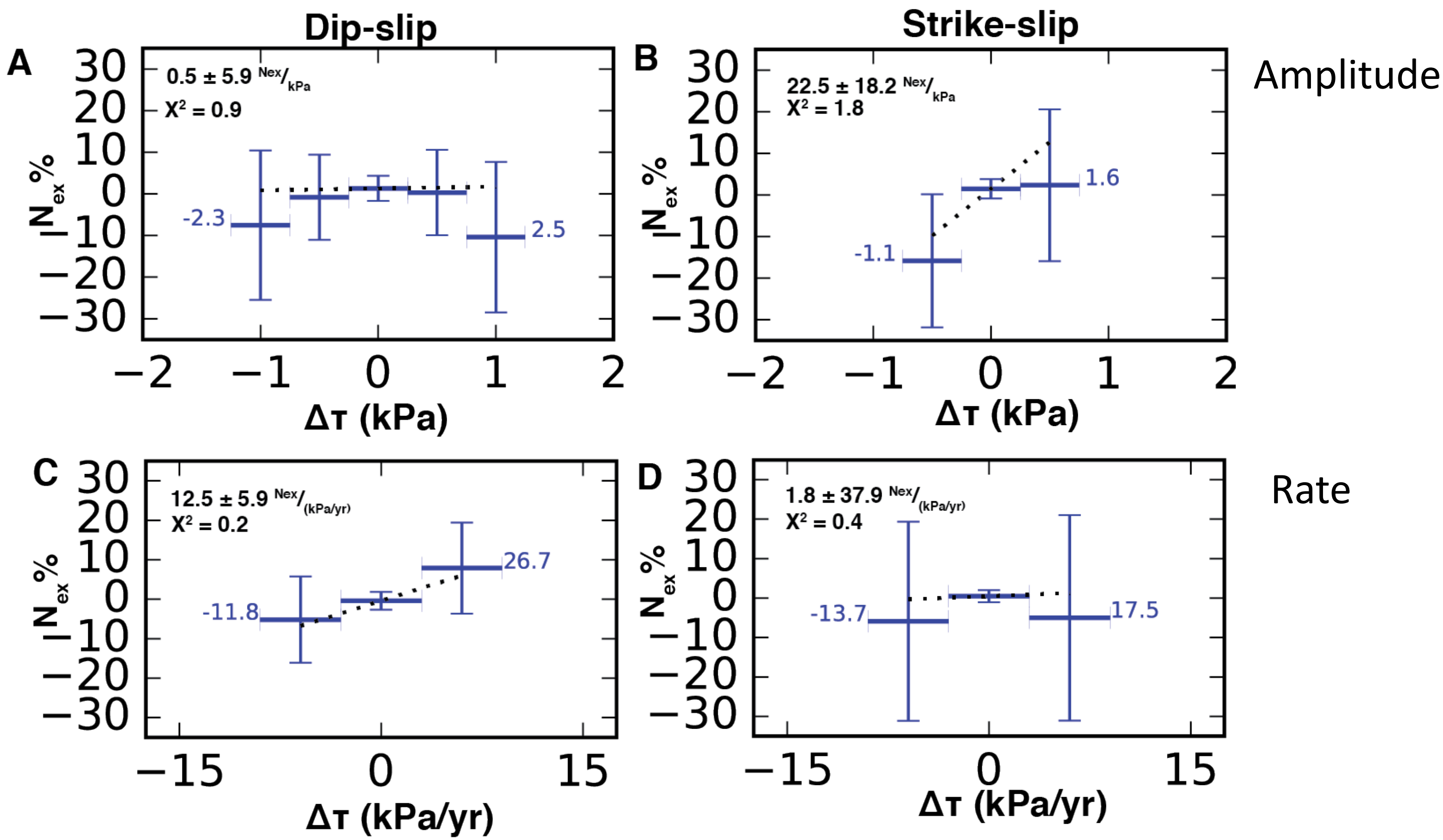


For all times with ~-1 kPa shear stress decrease ~16% less events

-1.9 kPa is minimum shear stress in the population

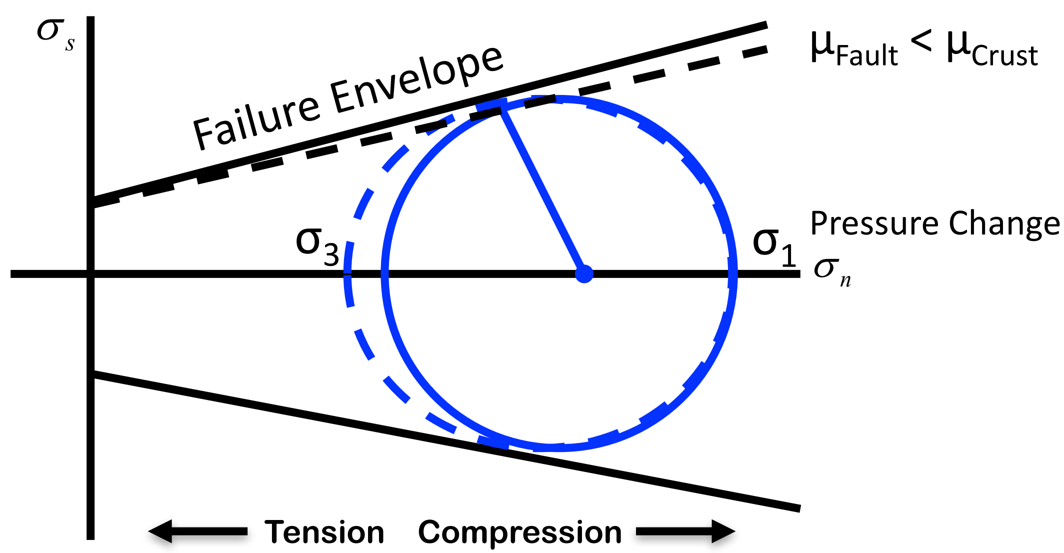
Percent excess M≥2.0 seismicity Shear Stress Amplitude and Rate



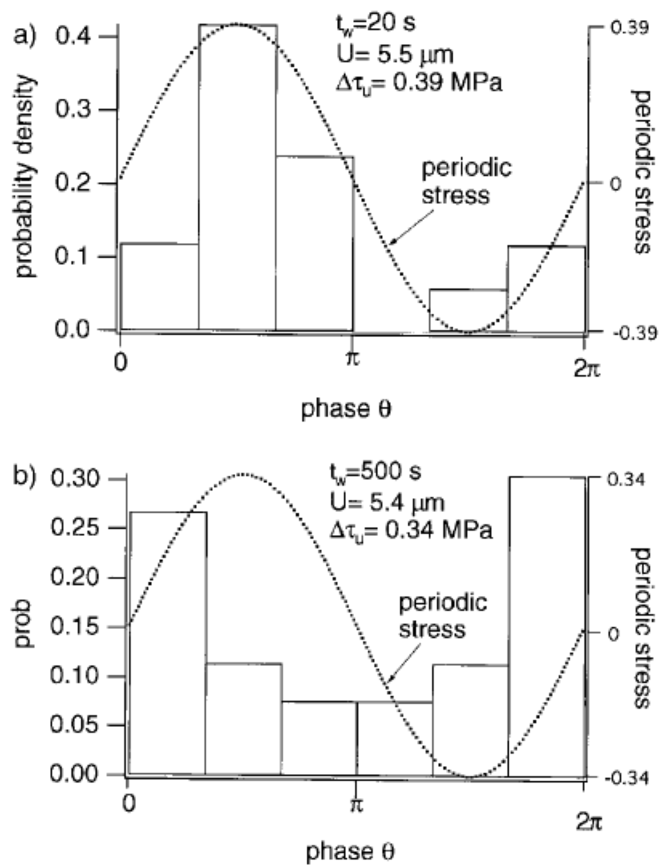
Failure Mechanism

- Critically Stressed
- Increase σ_1 or Decrease in σ_3
  - Oblique / Dip-slip – Optimally Oriented

- Low strength, weak fault
  - Strike – slip small shear stress change
  - Shallow SAF μ=0.15 (Lockner et al., 2011)



Lab and Model Comparison

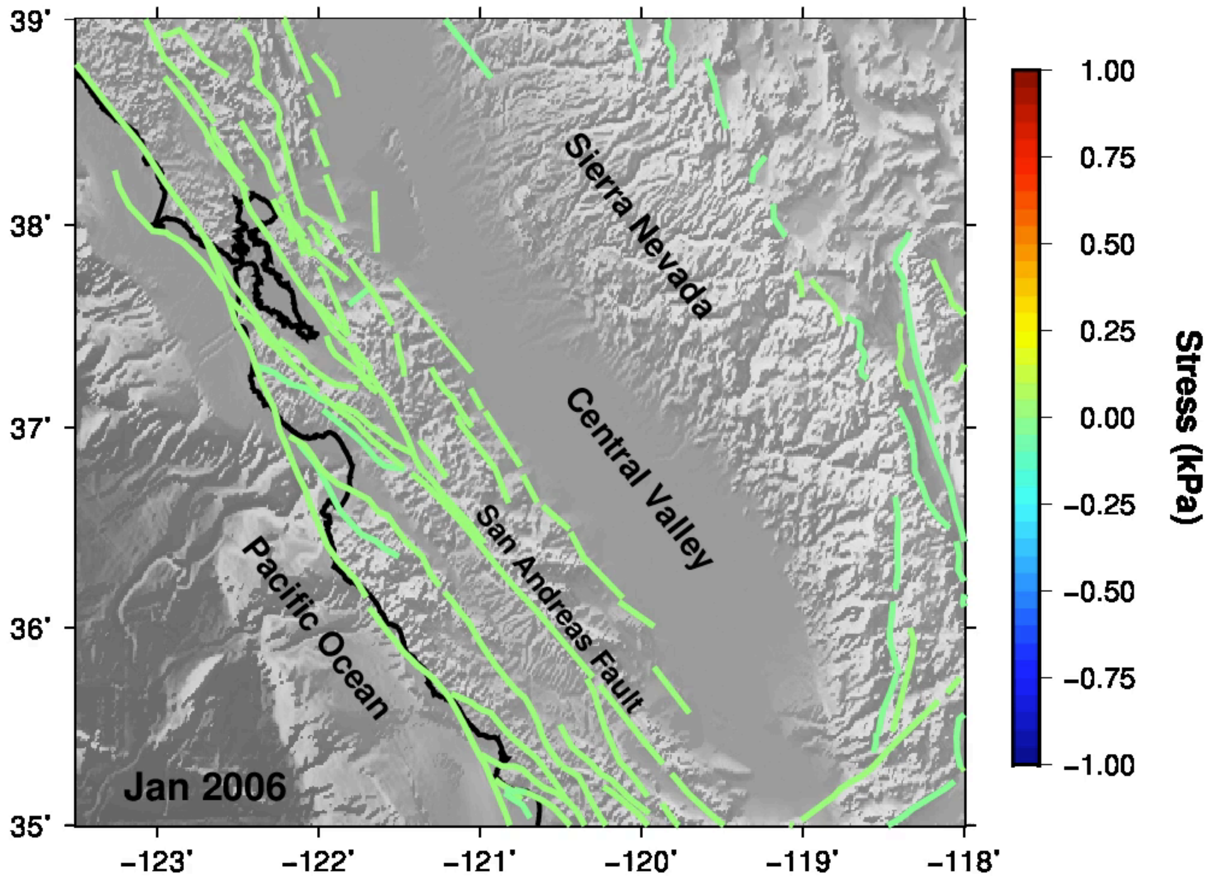


Short period loading
Stress Amplitude

Long period loading
Stress Rate

Beeler and Lockner, 2003

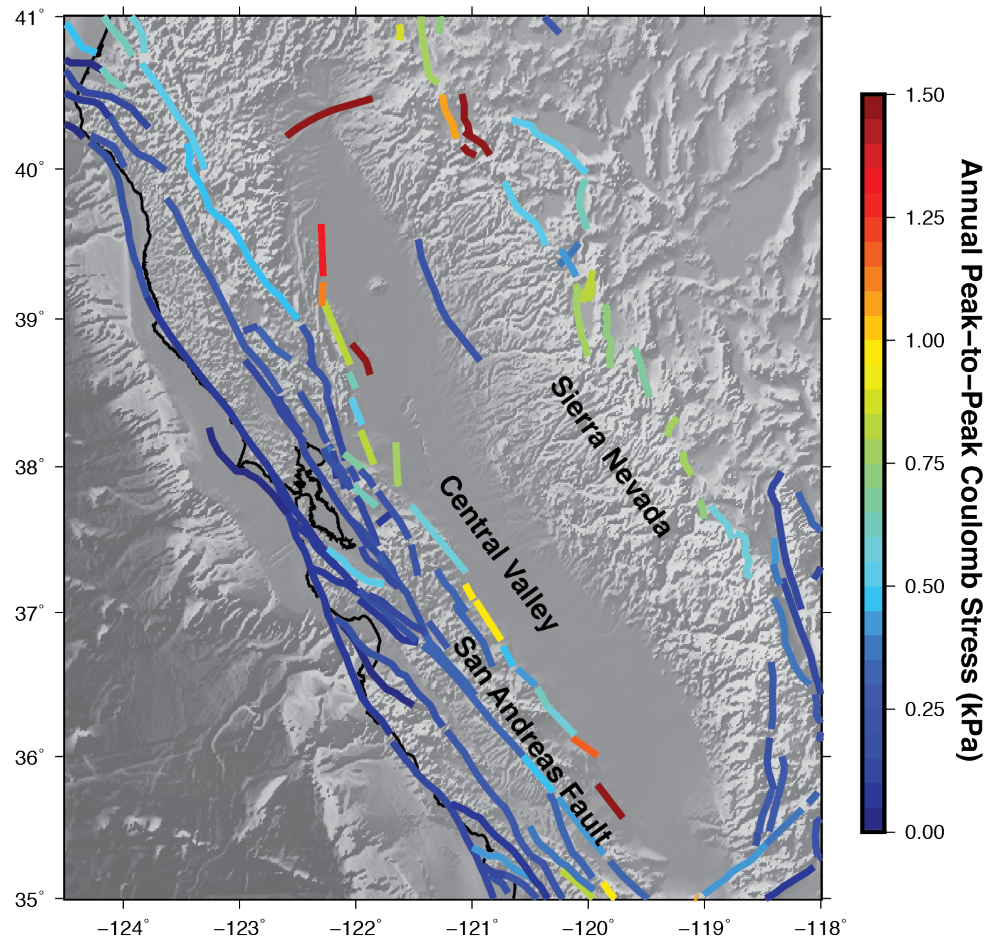
Water Loading Seasonal Stresses on the UCERF3 Community Fault Model



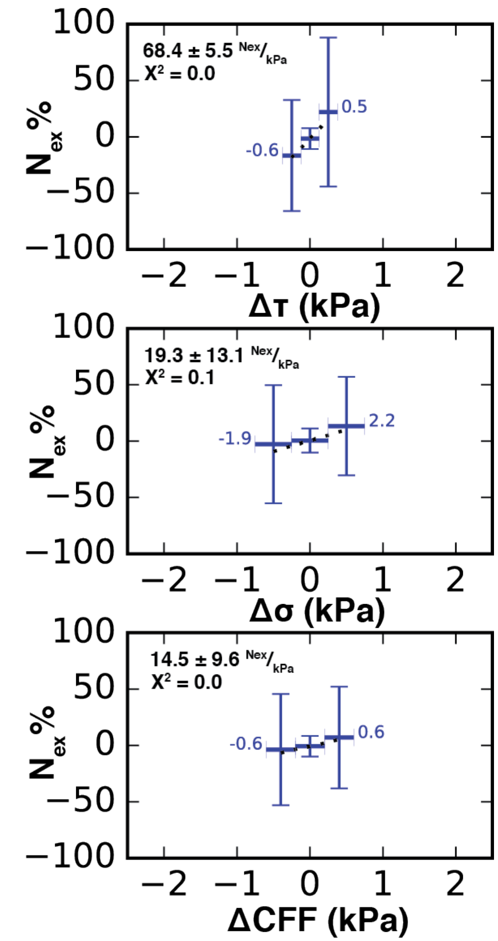
Positive Stress Favors Slip on the Fault

UCERF3 fault model: Field (BSSA, 2014)

Average Monthly Stress Seismicity (1781-2012) M≥5.5

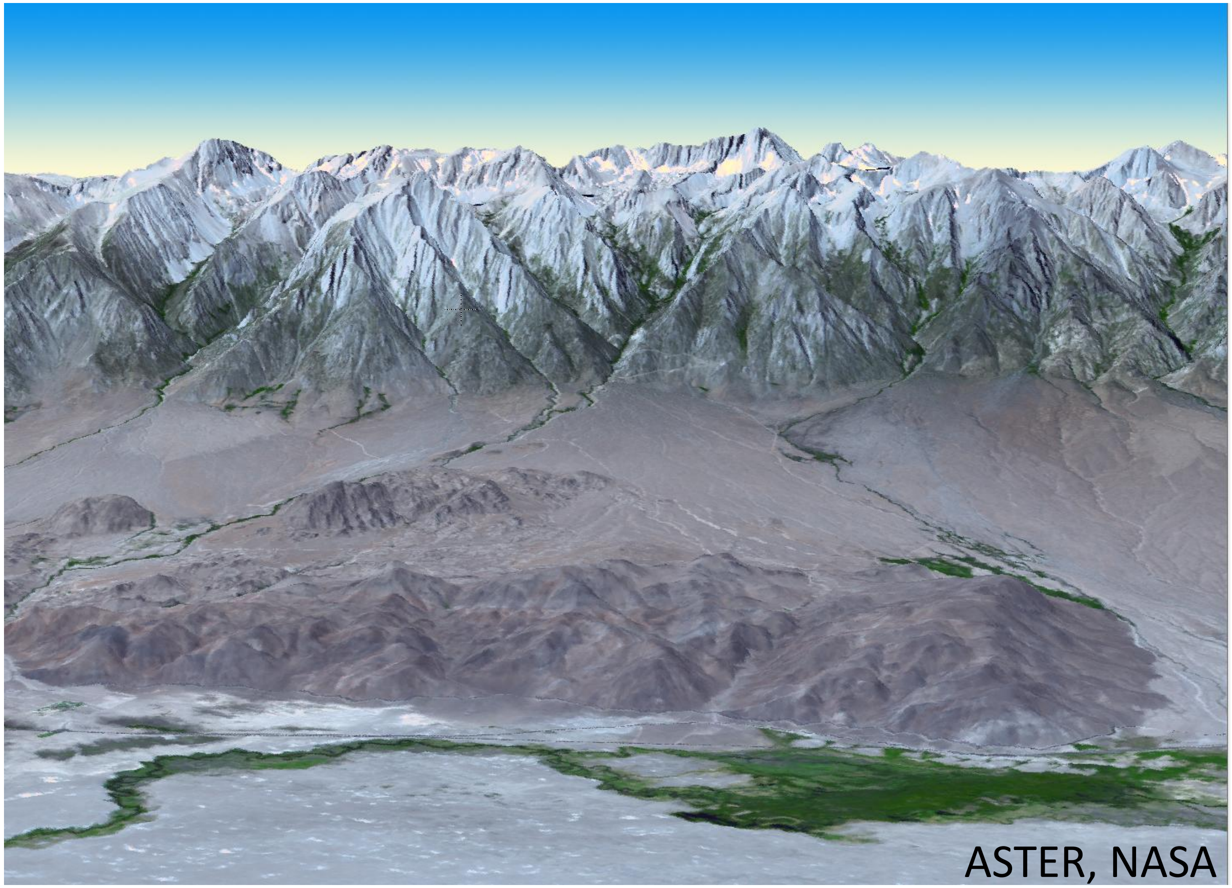


UCERF3 Model Geometry



Are Other Loading Sources Contributing?

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



ASTER, NASA

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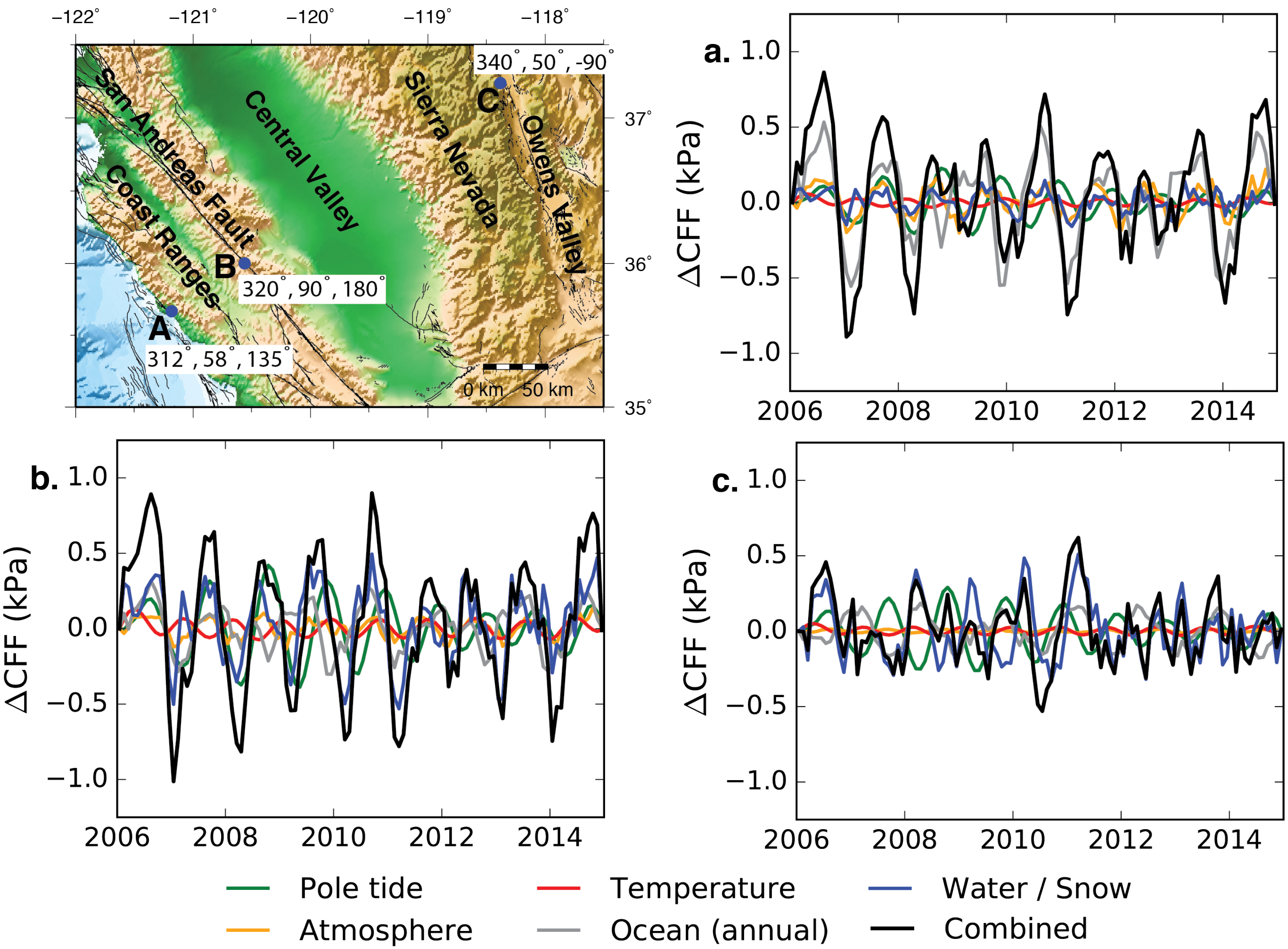
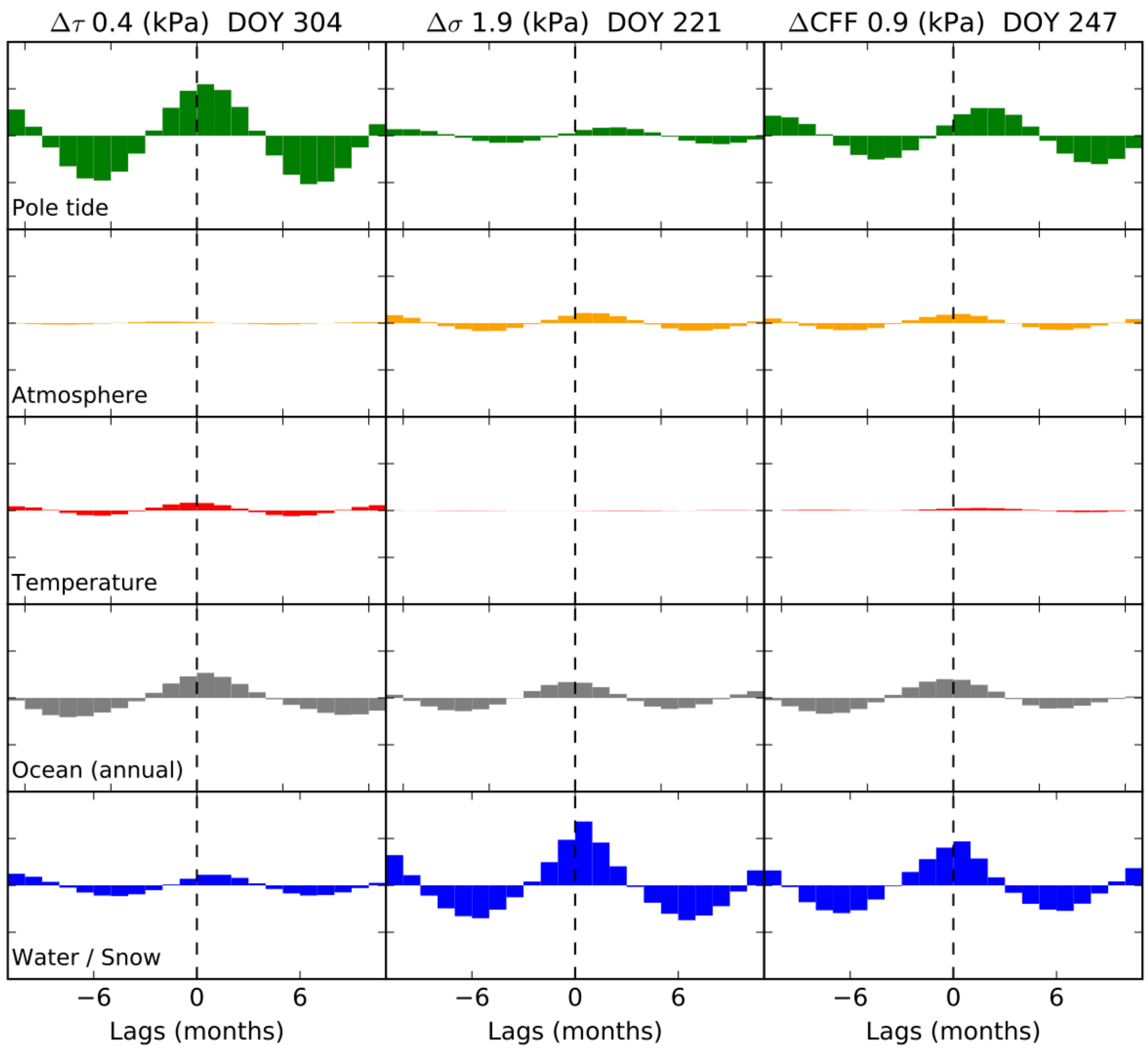


Johnson, Fu, Bürgmann, in prep

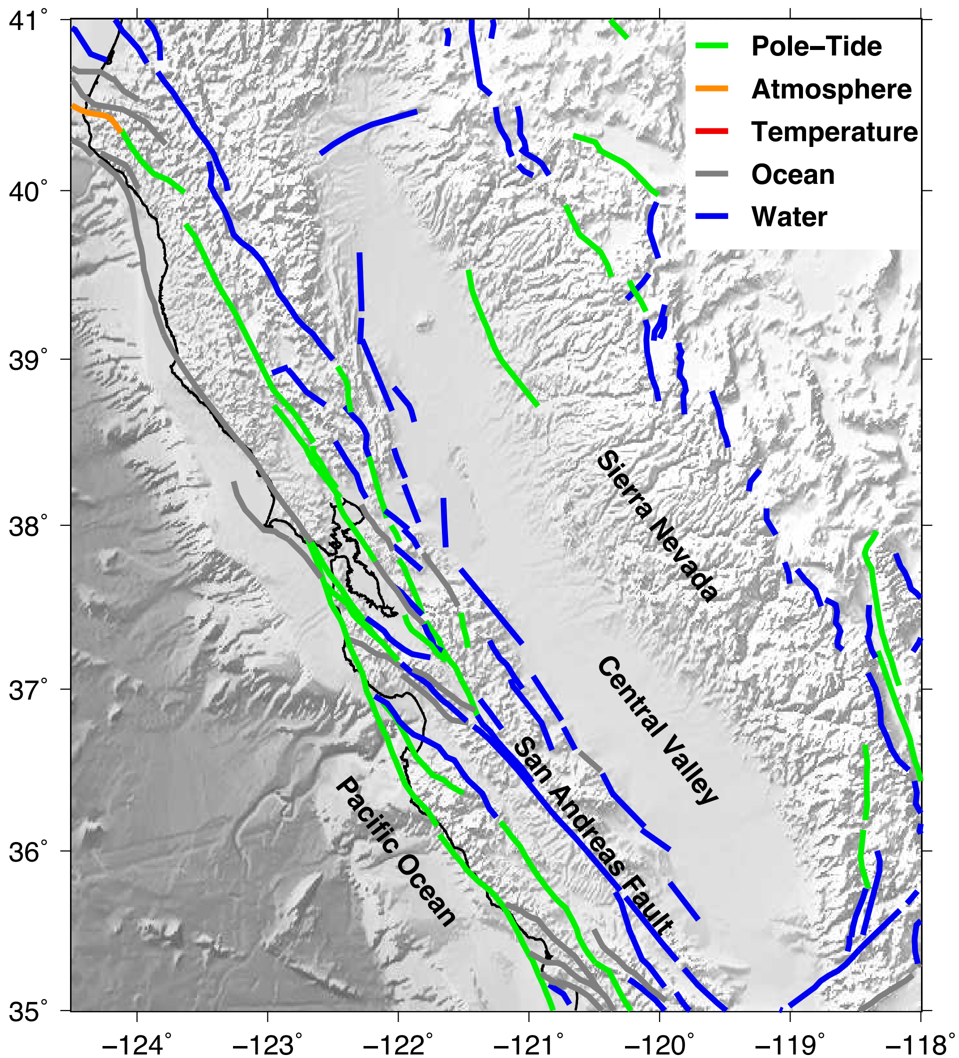
Loading Contribution on SAF

Amplitude and Time Lag w.r.t. Total Loading



Johnson, Fu, Bürgmann, in prep

What Load Contributes the Most?



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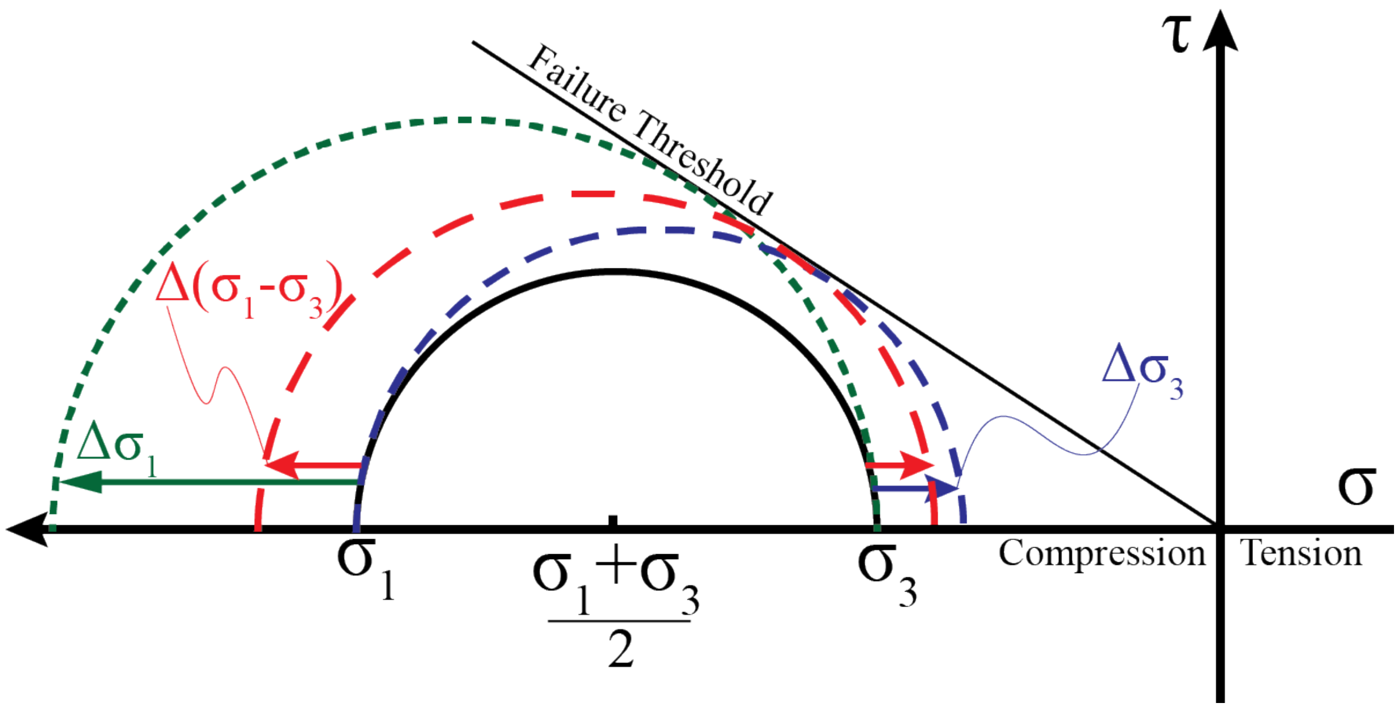
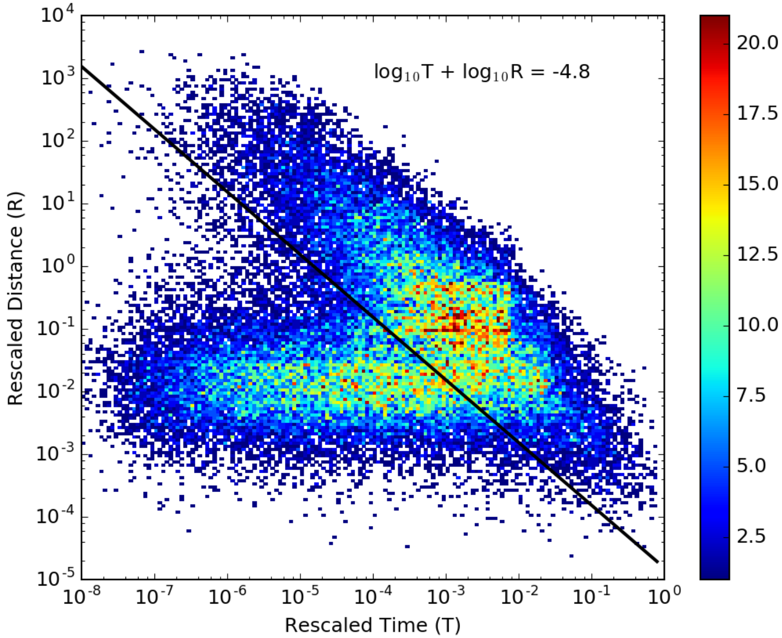
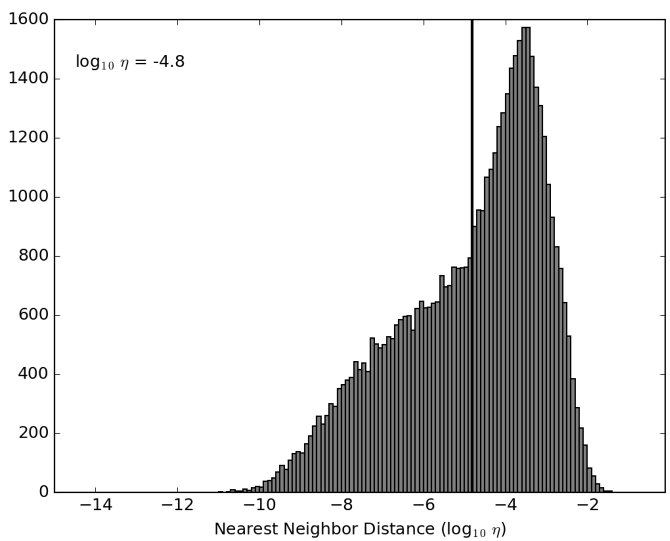


NCSS Focal Mechanisms





- **M≥1.5 1984-2015 (69,296)**
- **Remove Geysers & LVC 50,716)**
- **Nearest Neighbor Distance (η)**

$$\eta_{ij} = T_{ij}R_{ij}$$
$$T_{ij} = t_{ij}10^{-qbm_i}$$
$$R_{ij} = \left(r_{ij}\right)^{d_f}10^{-(1-q)bm_i}$$

- **Scale the interevent time and hypocentral distance with magnitude**
- **Remove events log η < -4.8**
- **Retain 28,121**

Background Stress Orientation

Invert using high quality focal mechanisms

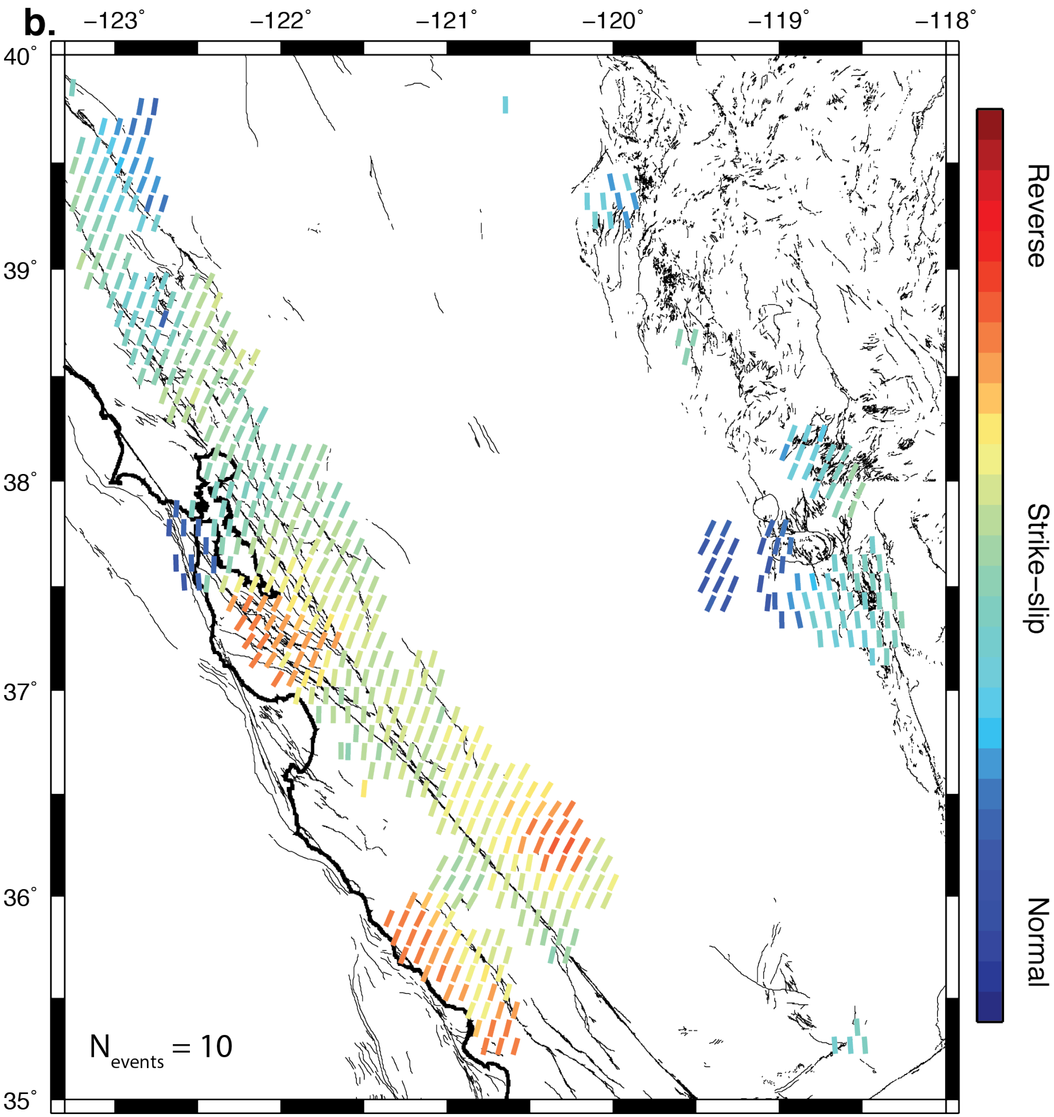
No amplitude information

S_{Hmax} Azimuth shown

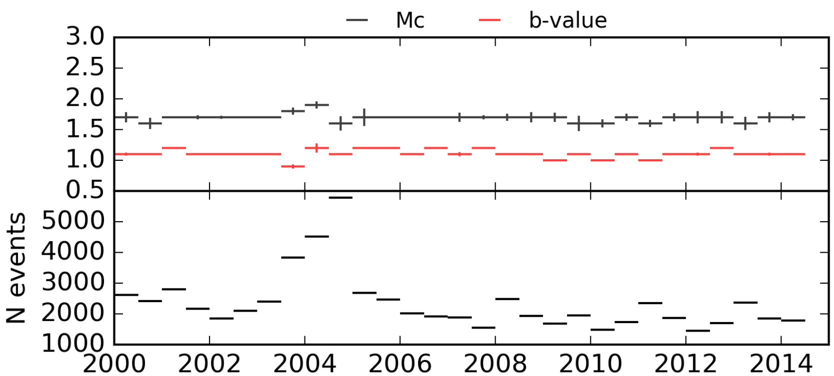
Colored by Tensor Shape Describes the Rupture Style

Project Seasonal Stress into Principal Orientations

Test for Excess Seismicity

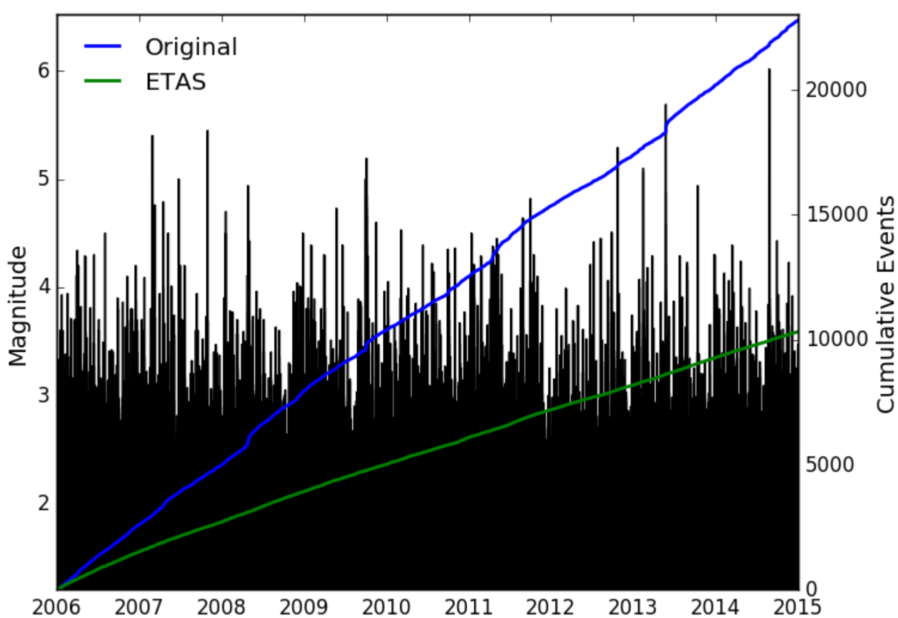


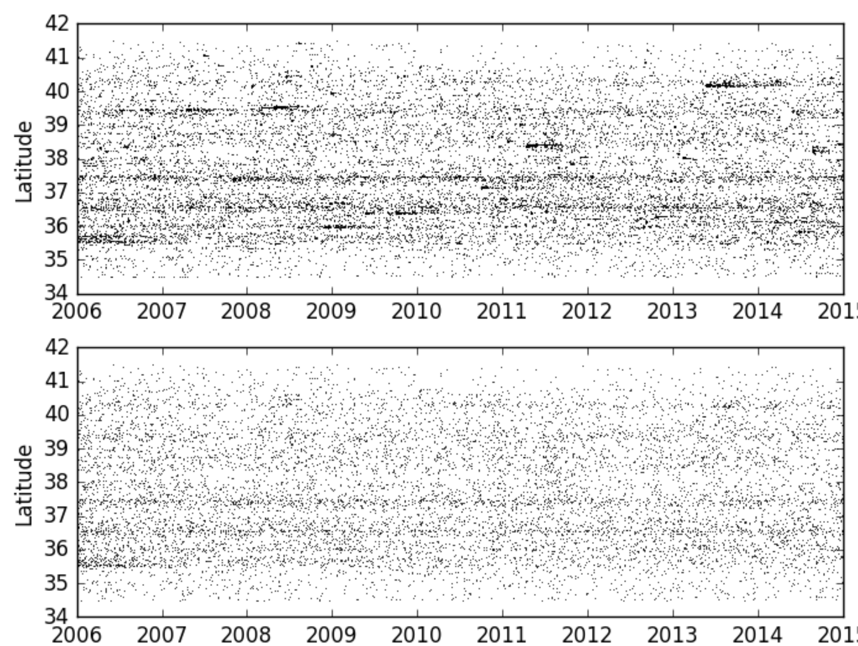
ANSS Catalog M≥1.7



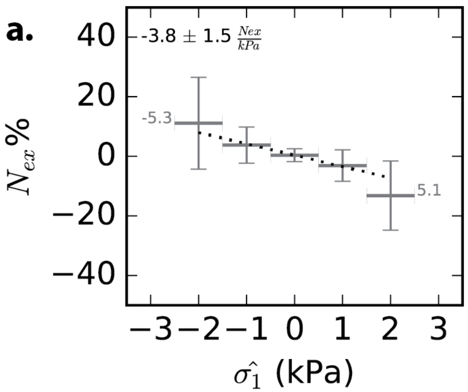
ETAS Declustering

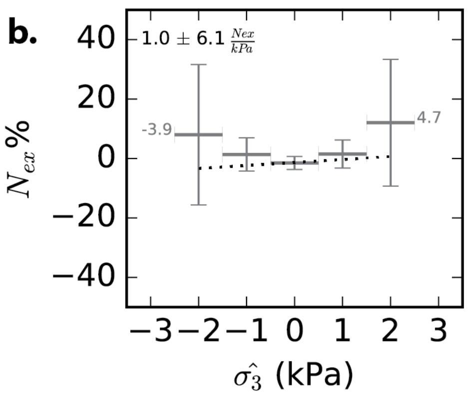
2006-2014
Exclude geothermal & volcanic
N = ~24,000
Mc ~ 1.7 (w/ 0.25 yr window)
ETAS 2D (Zhuang et al., 2002)

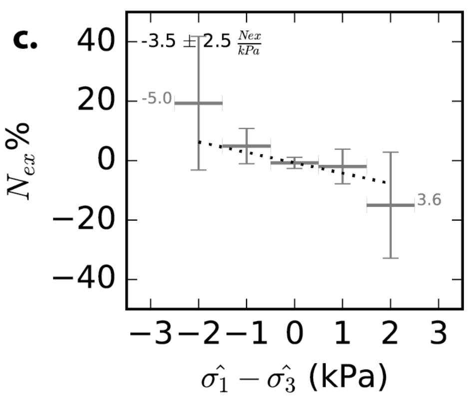


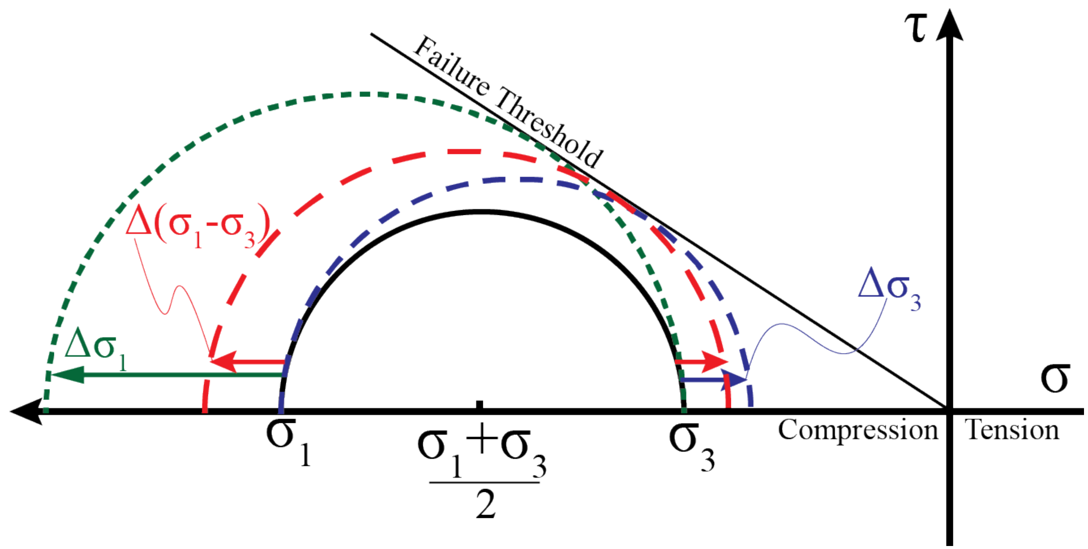


Excess Seismicity









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 and Pole-tides are largest.

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

Thank You
Questions?