Seasonal Loading Modulating Seismicity on California Faults

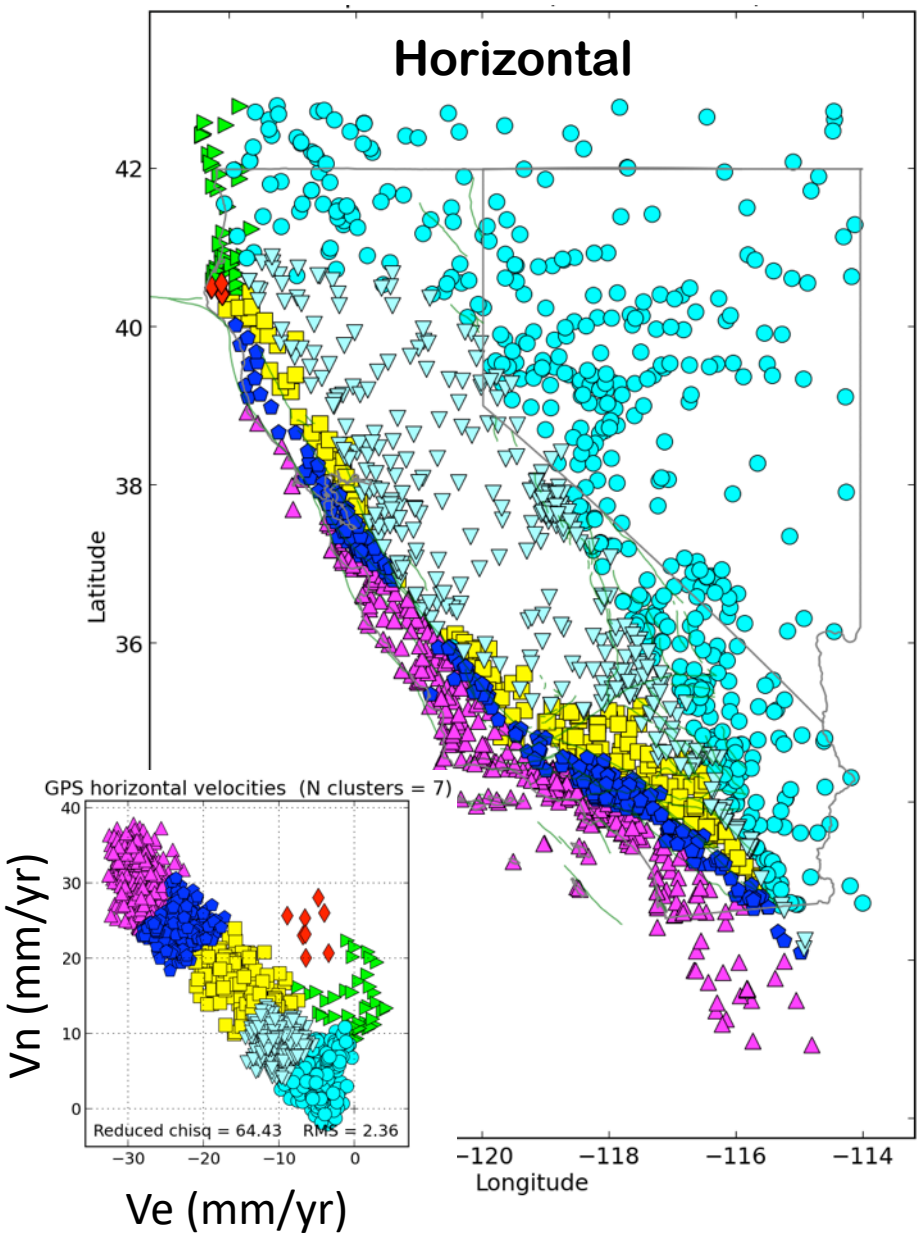
Christopher W Johnson

Yuning Fu (Bowling Green SU)

Roland Bürgmann (UC Berkeley)

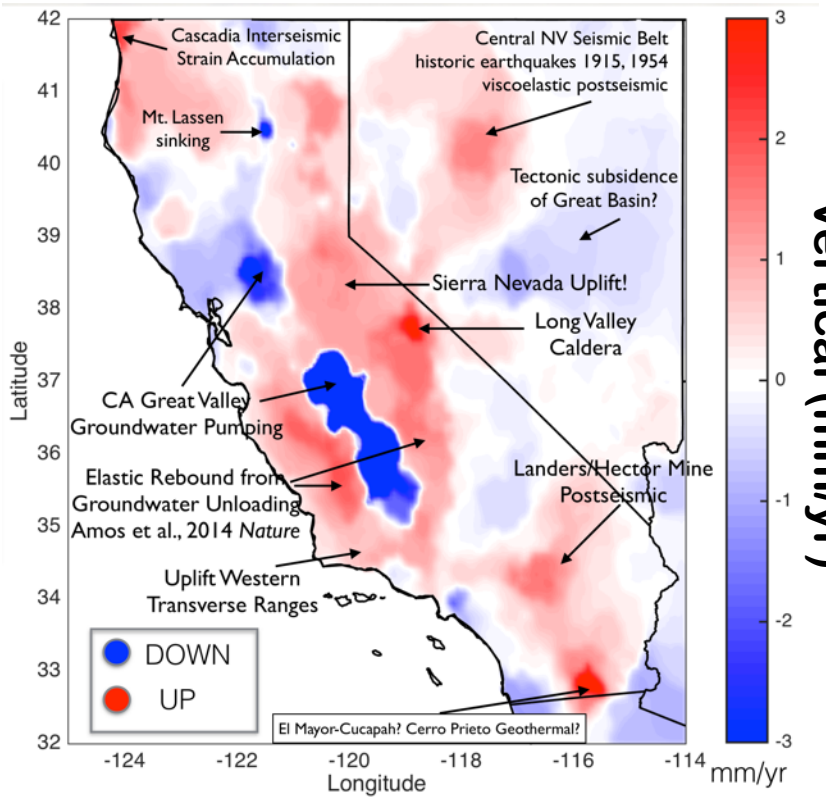
cGPS PBO Station P314 http://www.earthscope.org

California Deformation and Uplift



Major Features Delineated

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

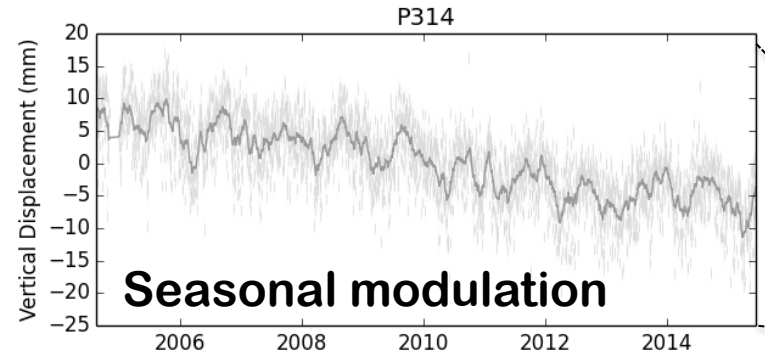


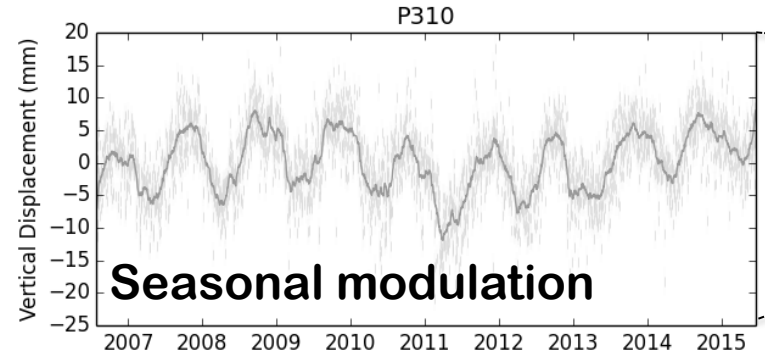
Simpson & Thatcher, USGS

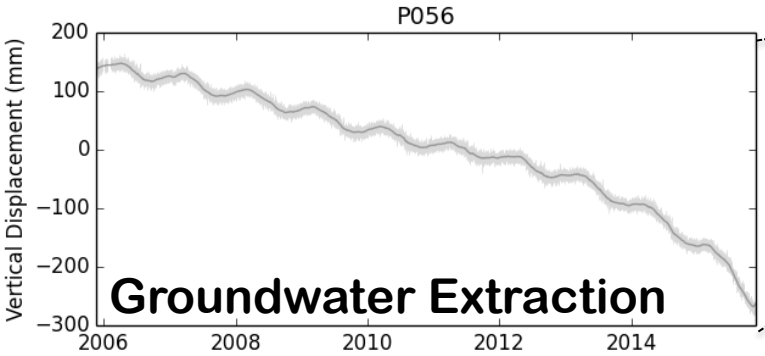
Bill Hammond, UNR, pers. comm. MIDAS vel. solution

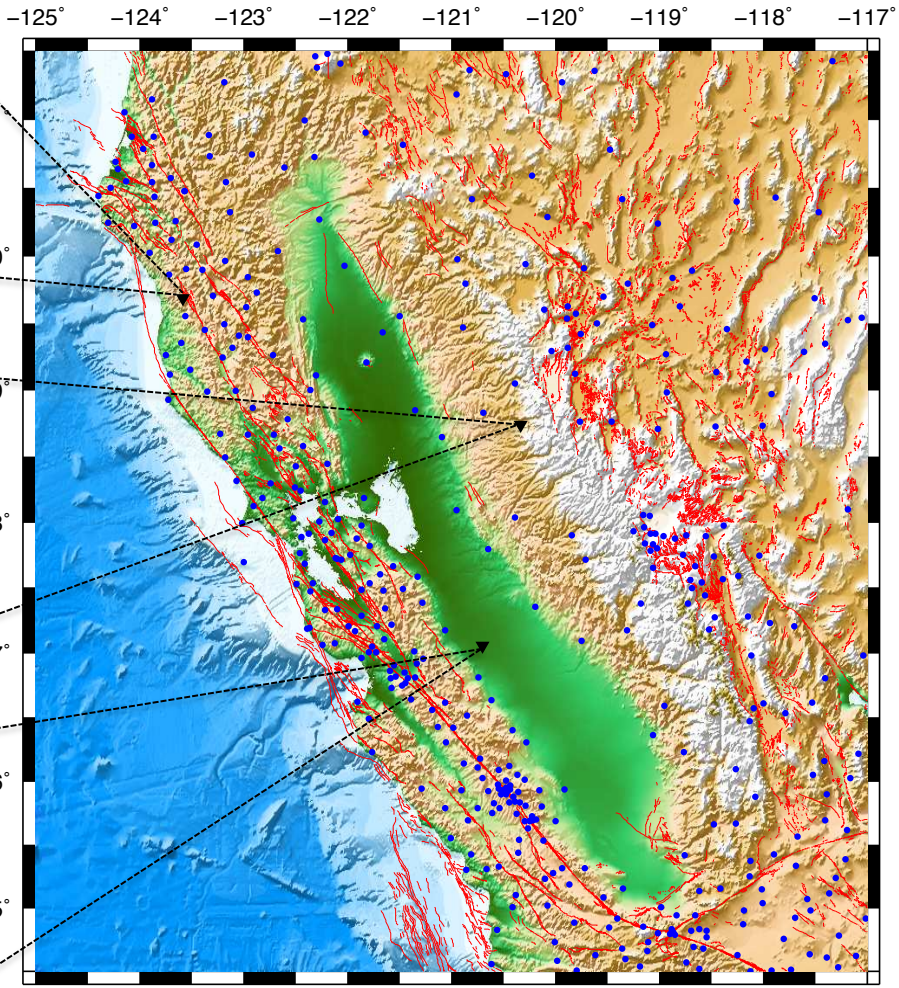
Seasonal Deformation

Vertical GPS Time Series







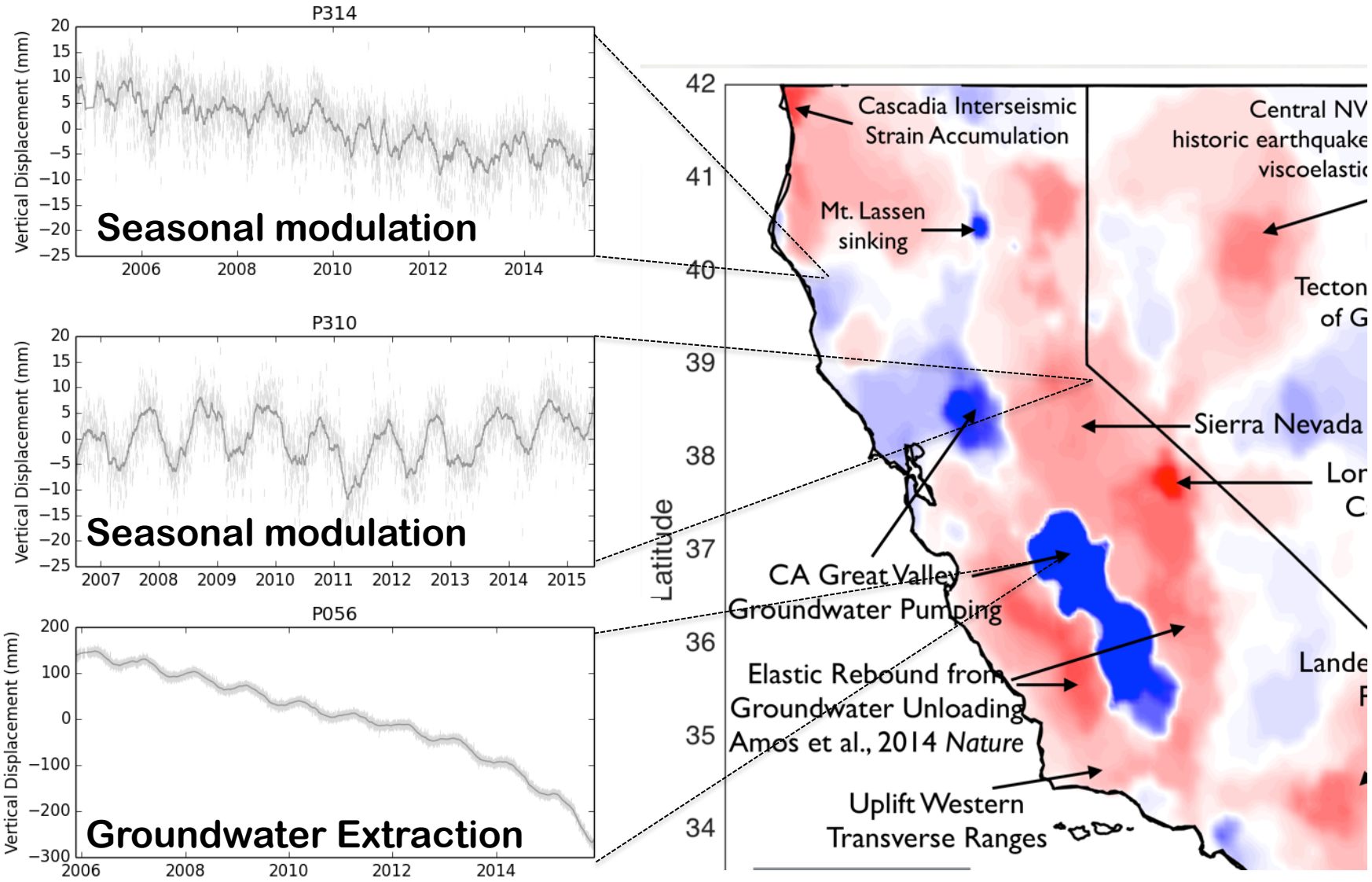


661 GPS Stations

USGS mapped faults

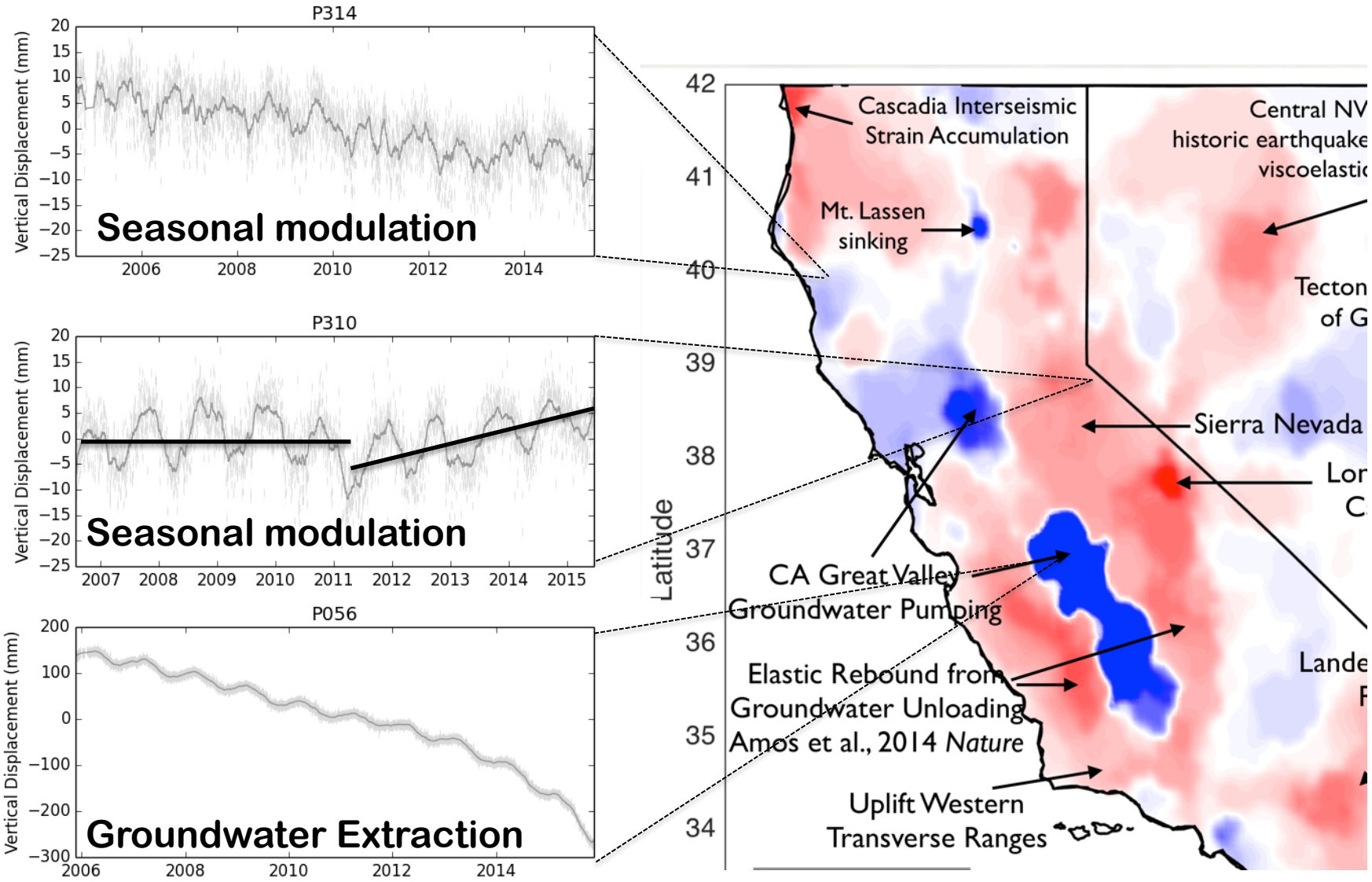
Seasonal Deformation

Vertical GPS Time Series



Seasonal Deformation

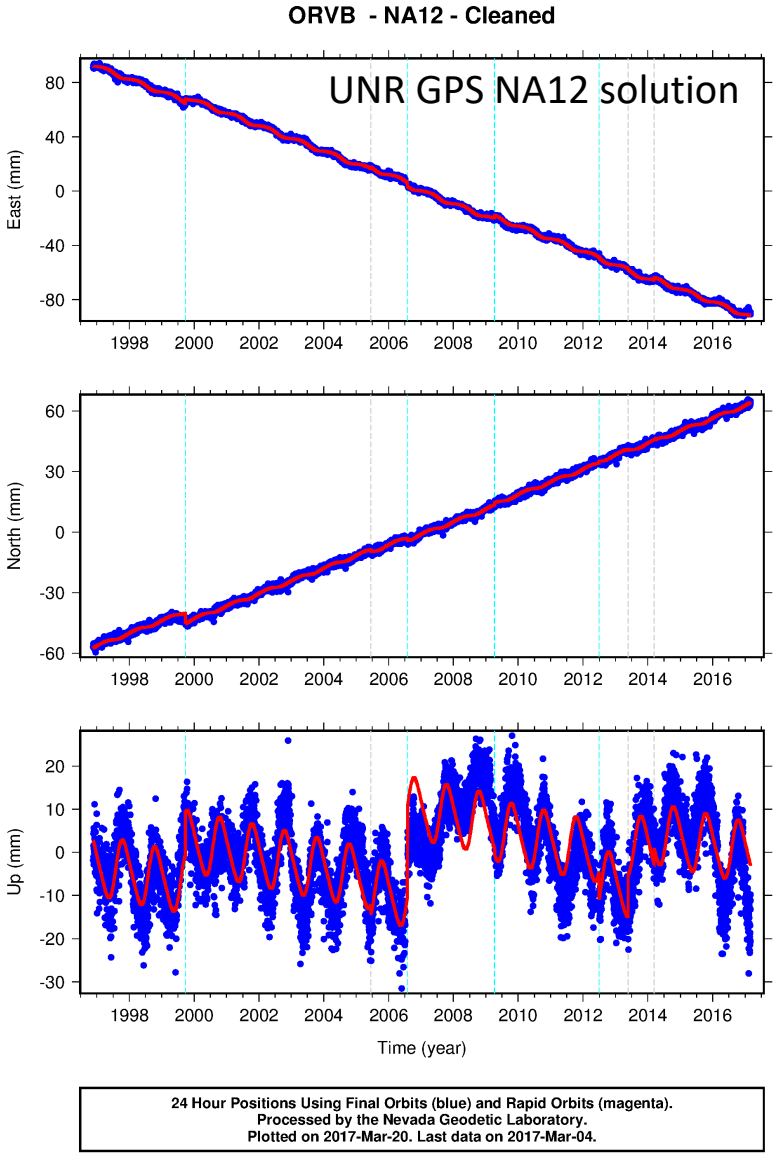
Vertical GPS Time Series



Climatic Changes Observed in Loading

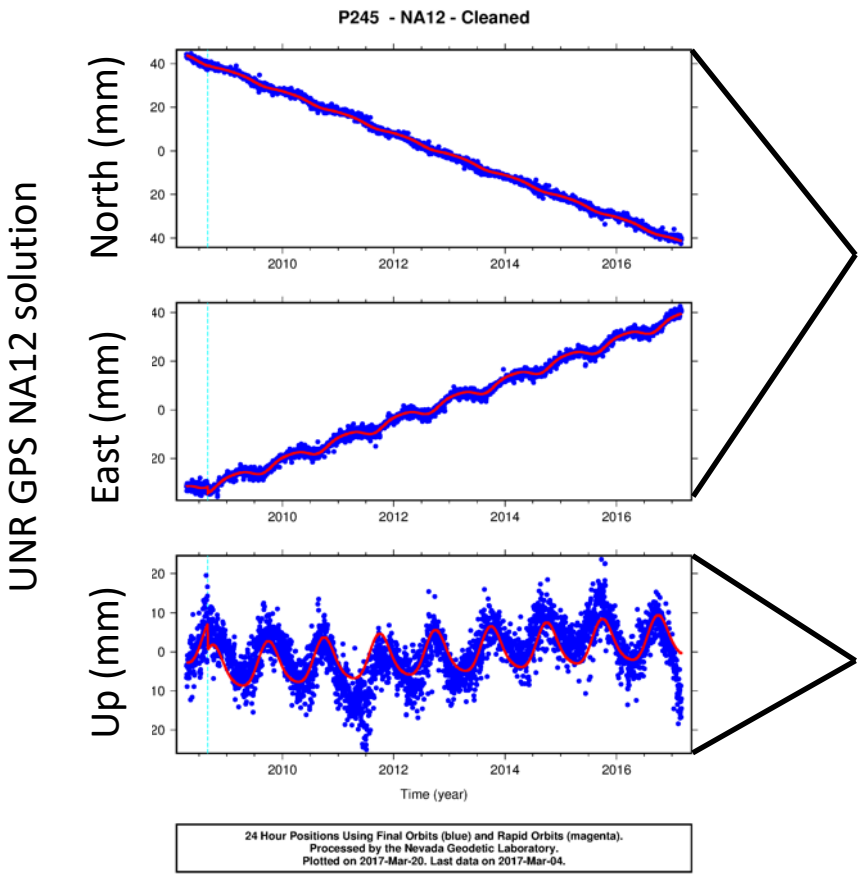
Lake Oroville, 19 August 2014
Drought Crisis

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



http://geodesy.unr.edu

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

What do we want to learn?

Is Seasonal Hydrological Loading Modulating Seismicity?

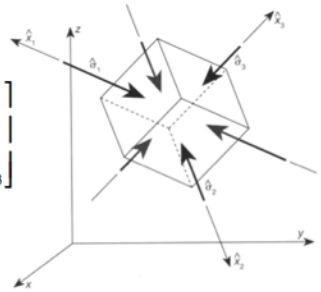
Are faults responding to stress perturbations with annual periods?

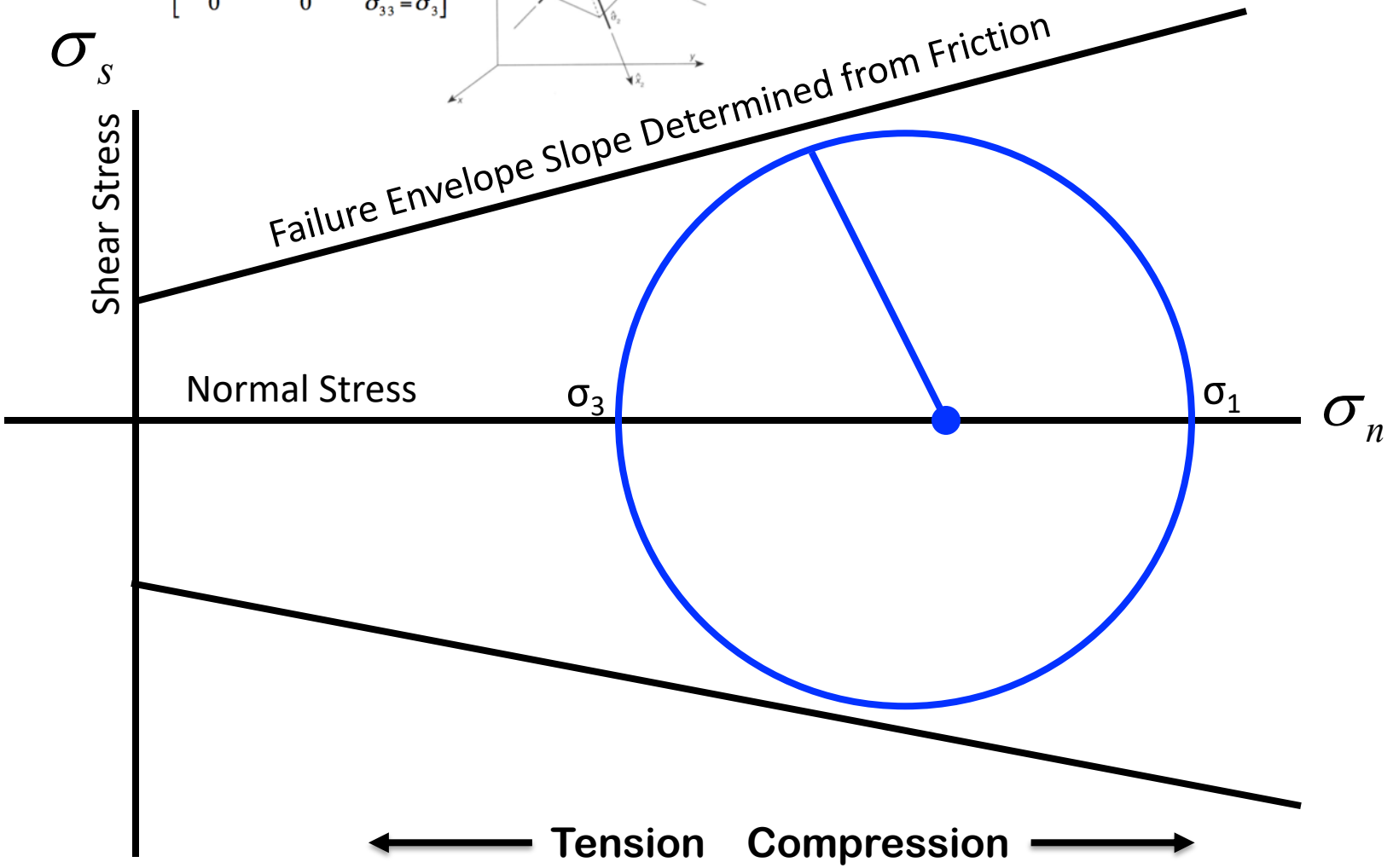
Is the crust critically stressed?

What is the failure mechanism for earthquake nucleation?

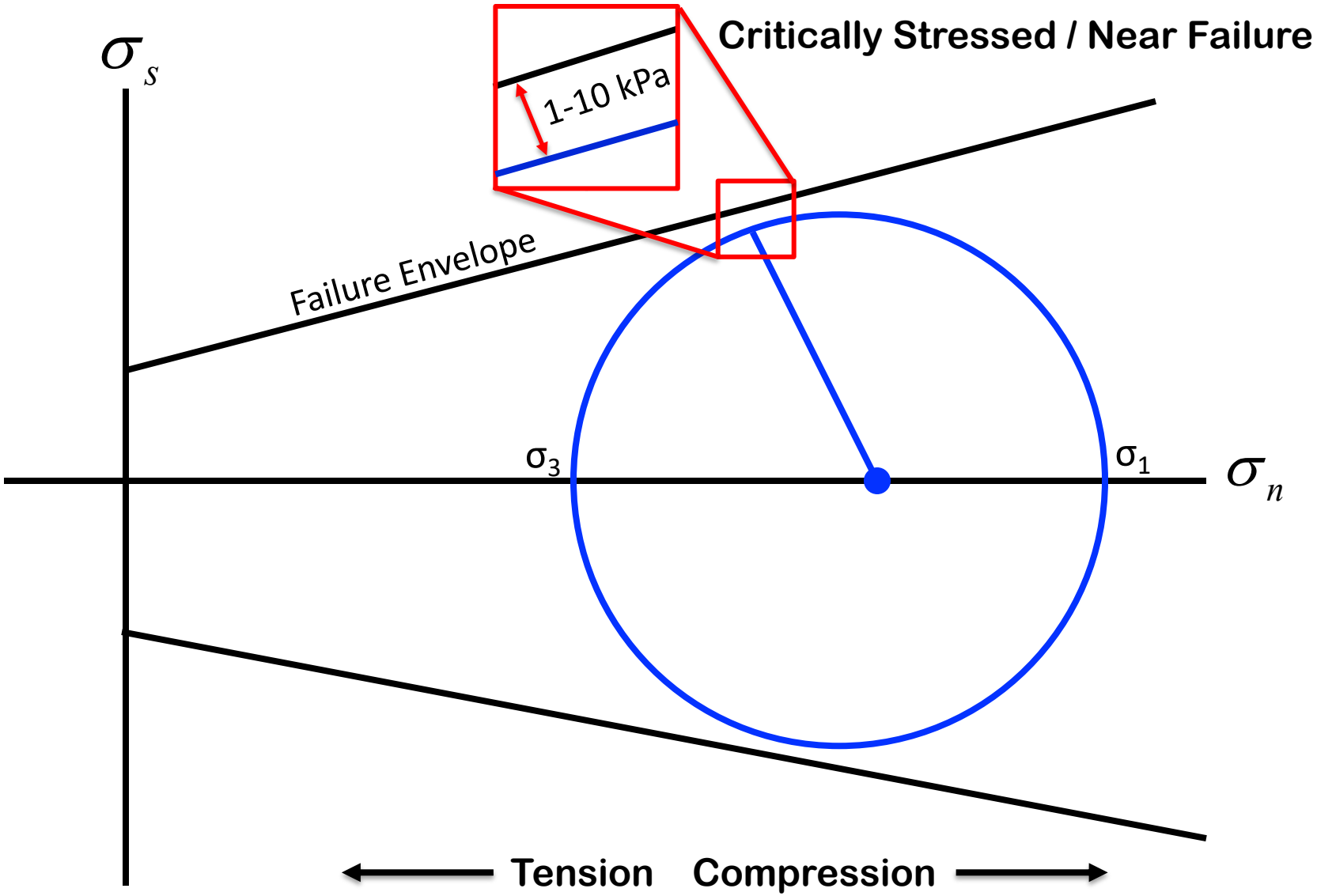
Coulomb Failure and Mohr Circles

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





Coulomb Failure and Mohr Circles

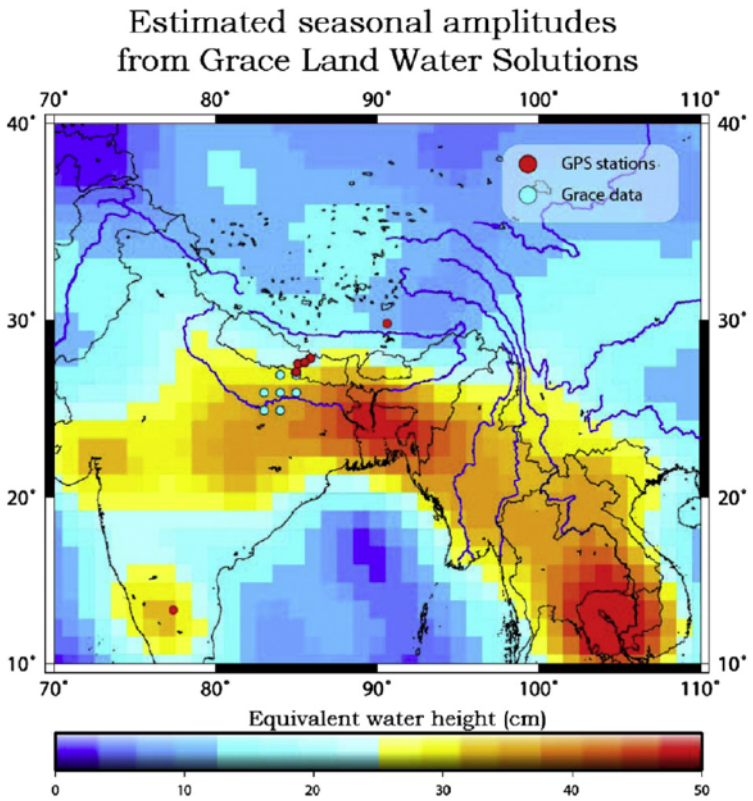


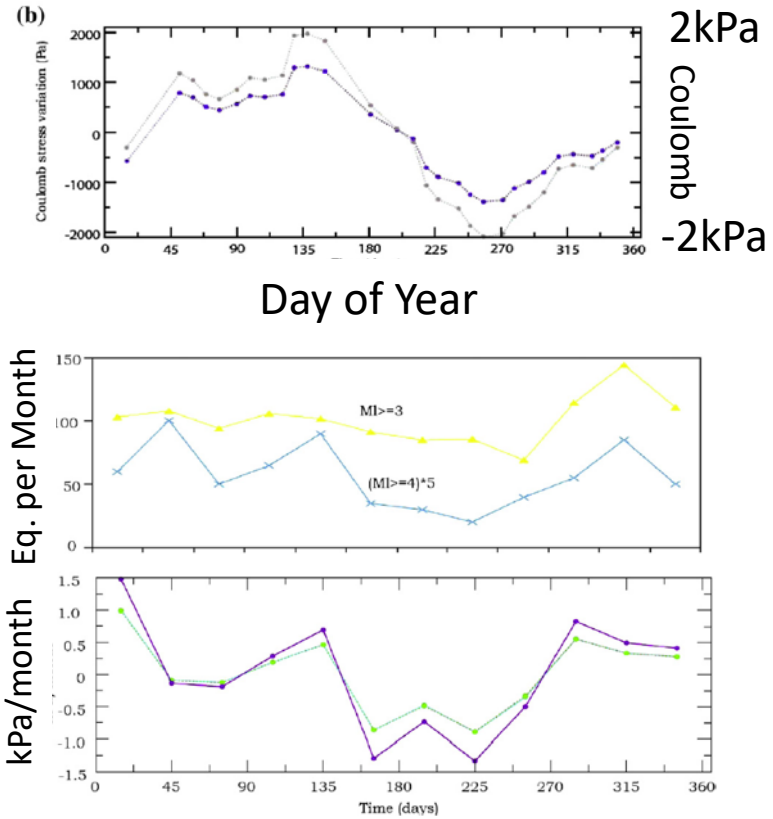
Seasonal Loading Modulating Seismicity on California Faults

i. Motivation – Annual Loading Cycles
   i. Nepal 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

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

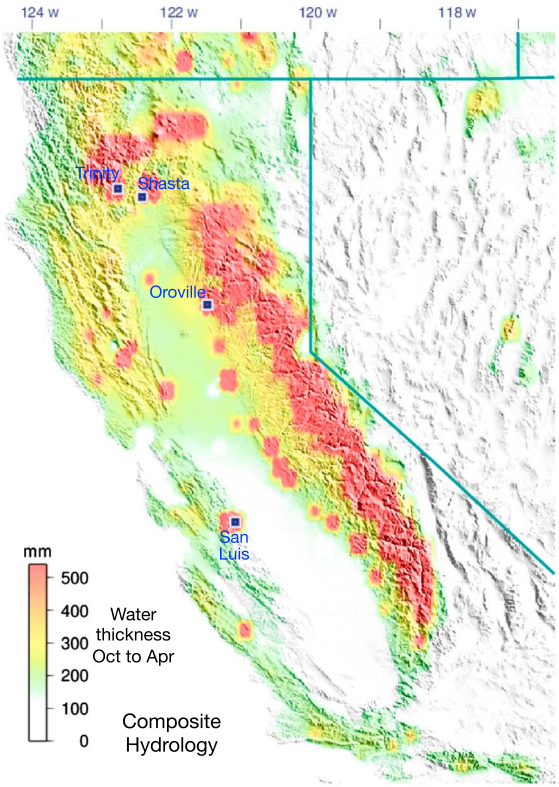




Bettinelli et al., 2008

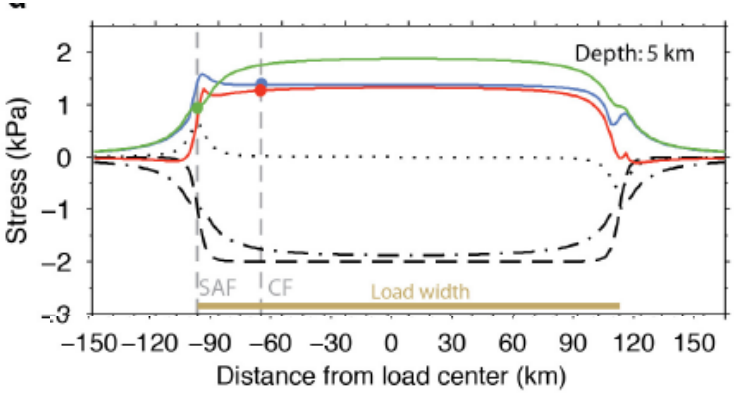
Water/Snow Loading Examples

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



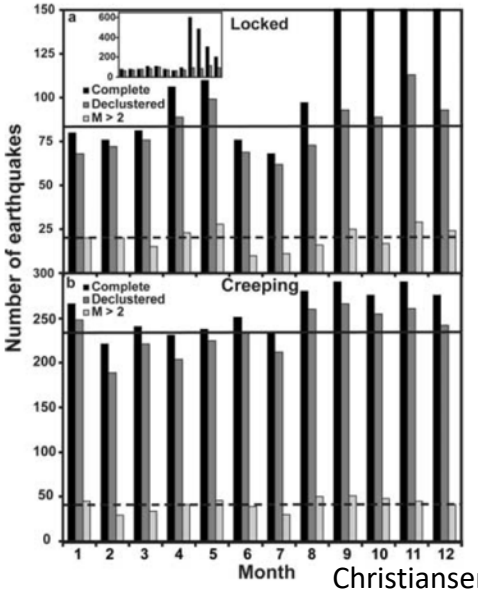
Argus et al., GRL, 2014

Line Load Stress Estimate



Amos et al., Nature, 2014

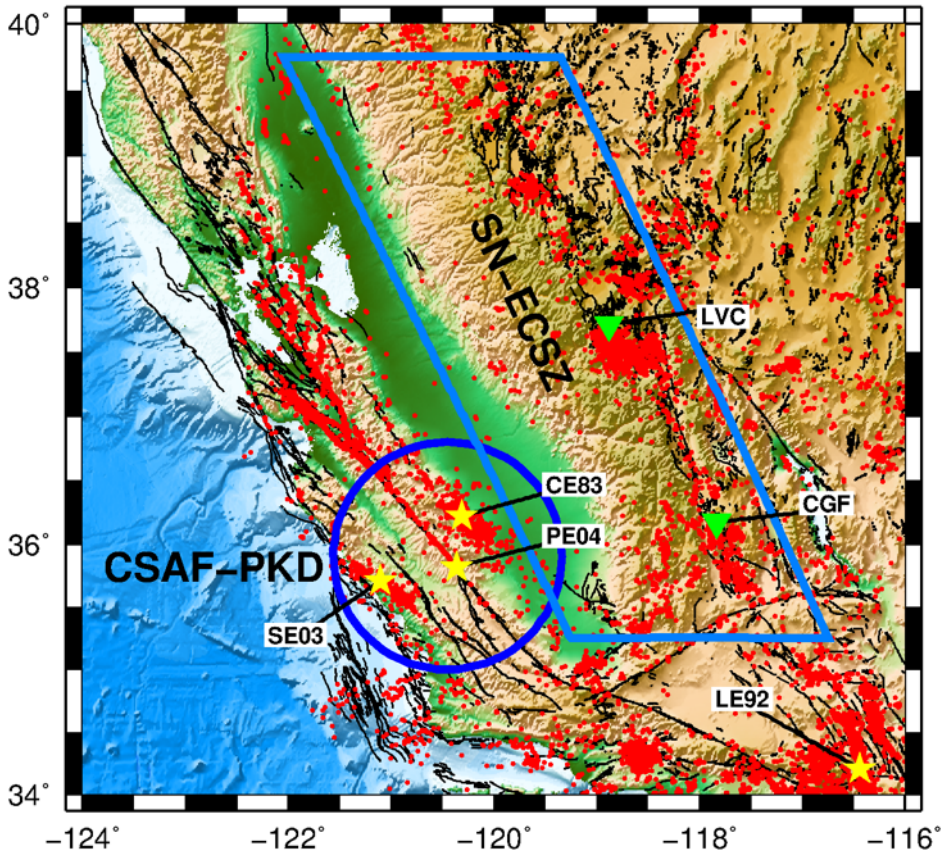
Central SAF Seismicity Stack



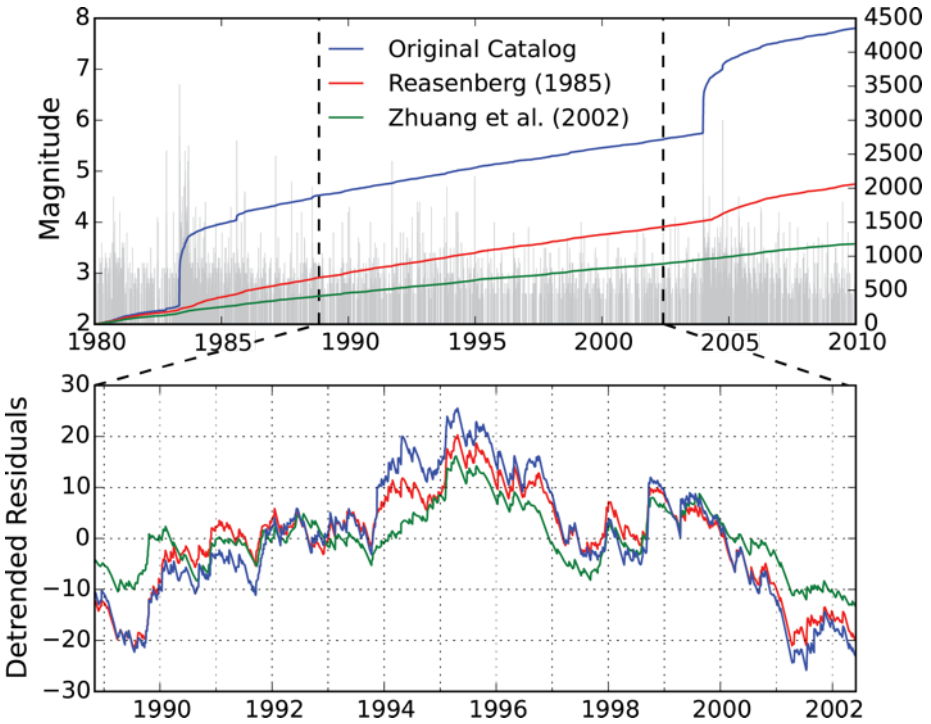
Christiansen et al., GRL, 2007

Periodicity in Seismicity Records

Evidence for Stress Modulation



Central Coast Ranges Seismicity
M≥2.5 Declustered and Detrended



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

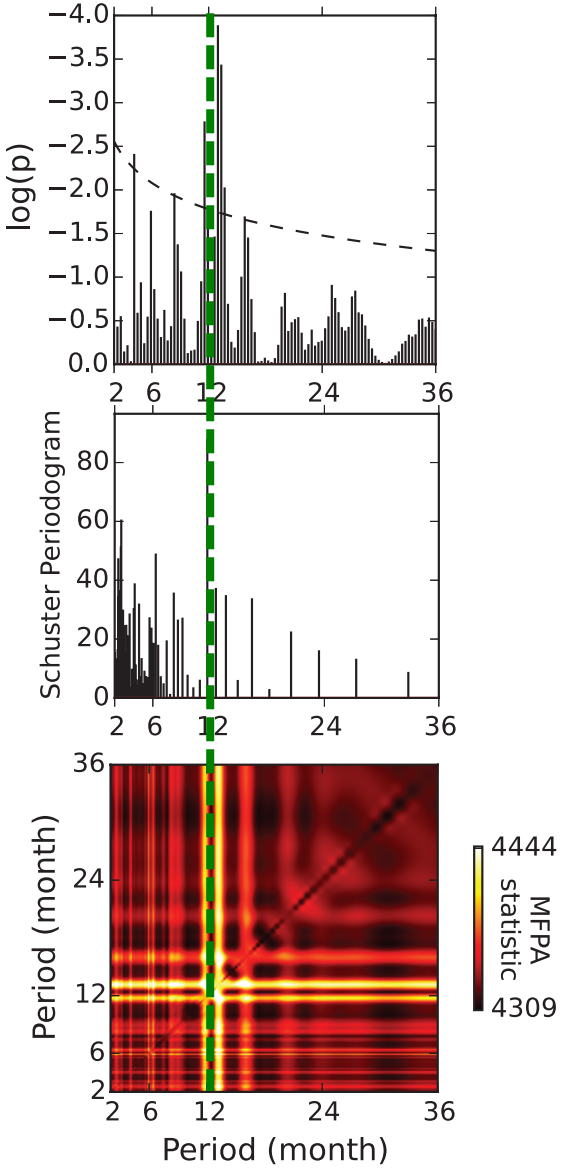
Annual Periodicity

Three Independent Tests

Schuster Spectrum

Schuster Periodogram

Multifrequential Periodogram Analysis



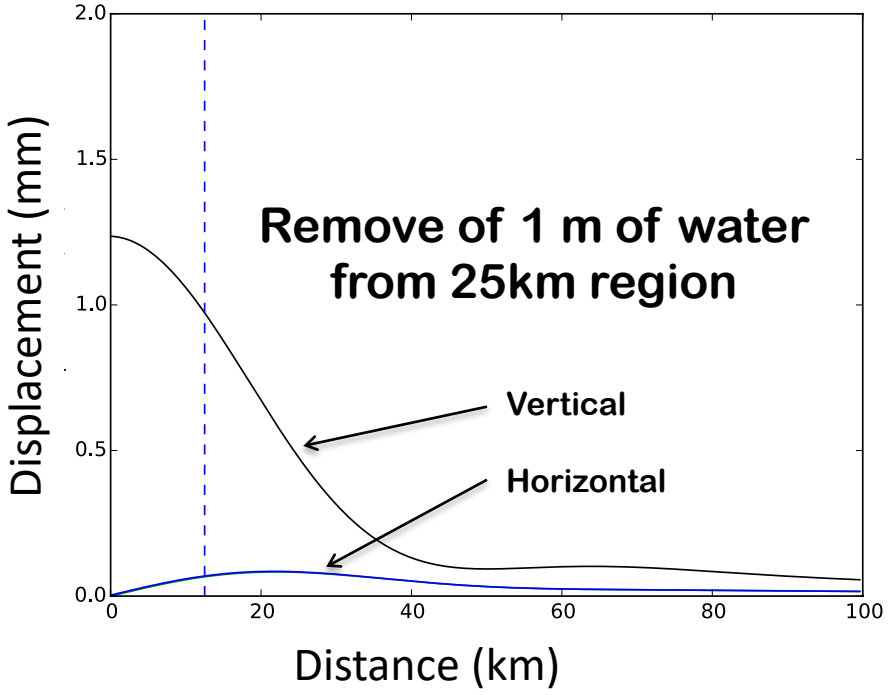
Dutilleul, Johnson, Bürgmann, et al., JGR, 2015

Seasonal loading modulating seismicity on California faults

i. Motivation – Annual Loading Cycles
   i. Nepal 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?

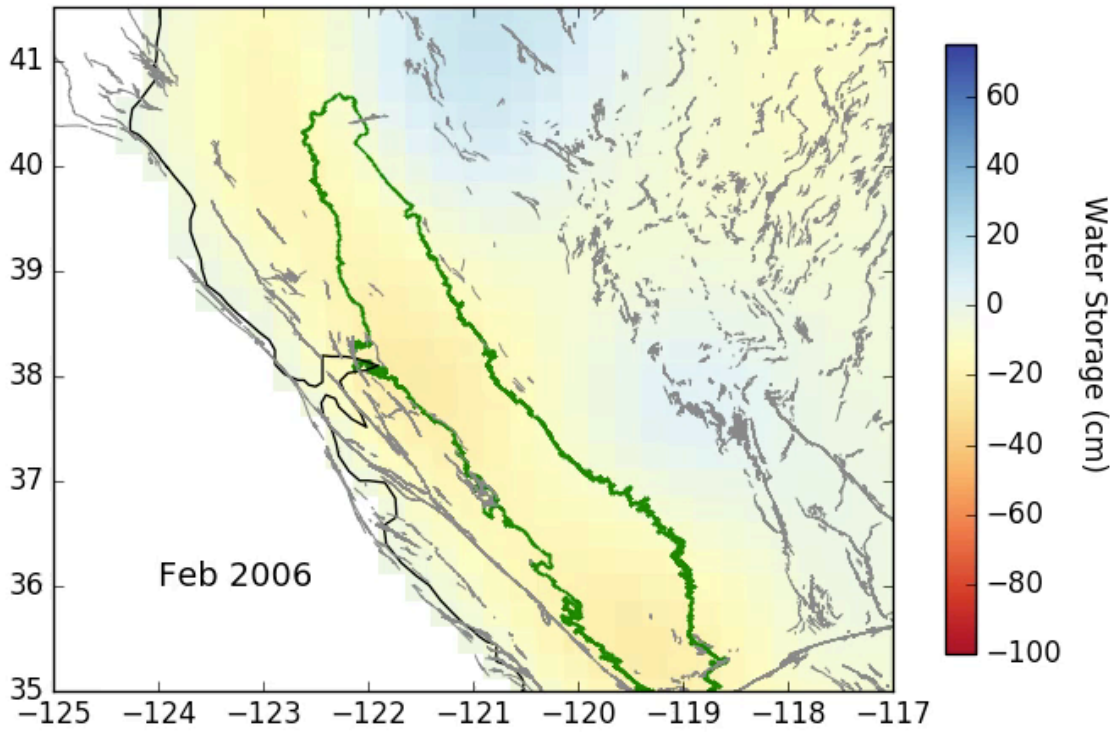
Elastic Load Model

- 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

Water Storage



Effective Water Storage from vertical GPS displacement (Argus et al., 2014)

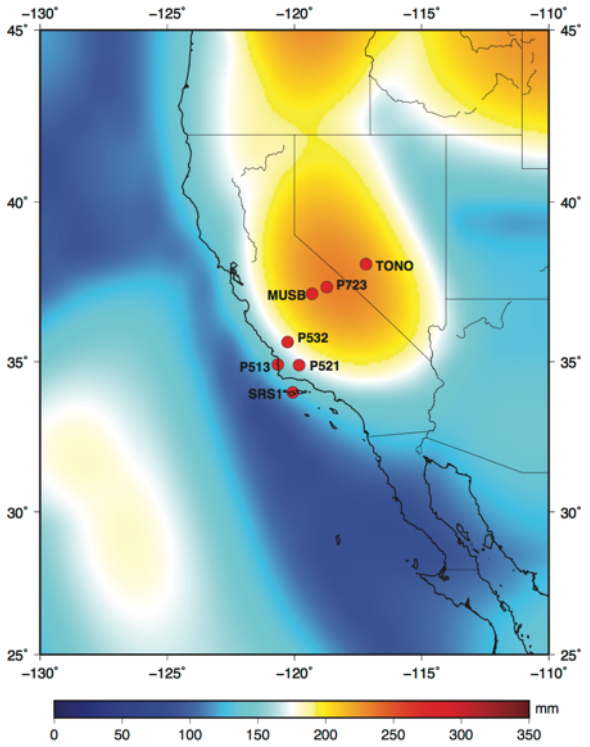
0.25˚ x 0.25˚ resolution

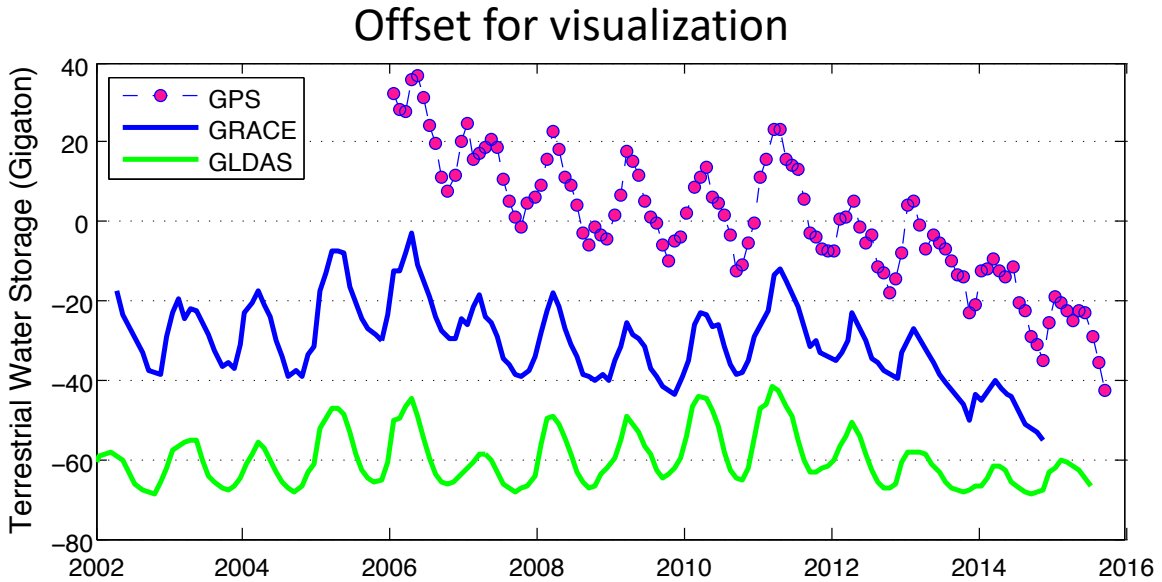
Johnson, Fu, Bürgmann, in review

GRACE / GLDAS Comparison

Gravity Measurements to Infer Water Storage

Composite models





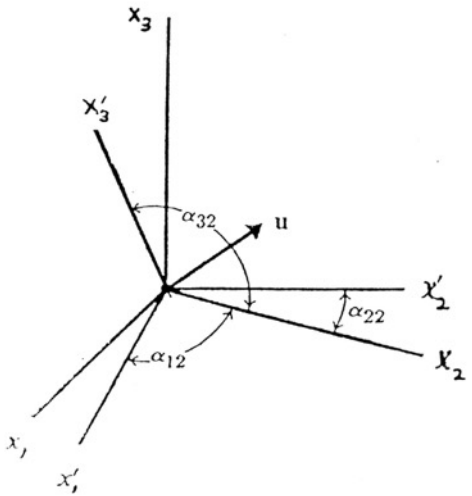
Seasonal loading modulating seismicity on California faults

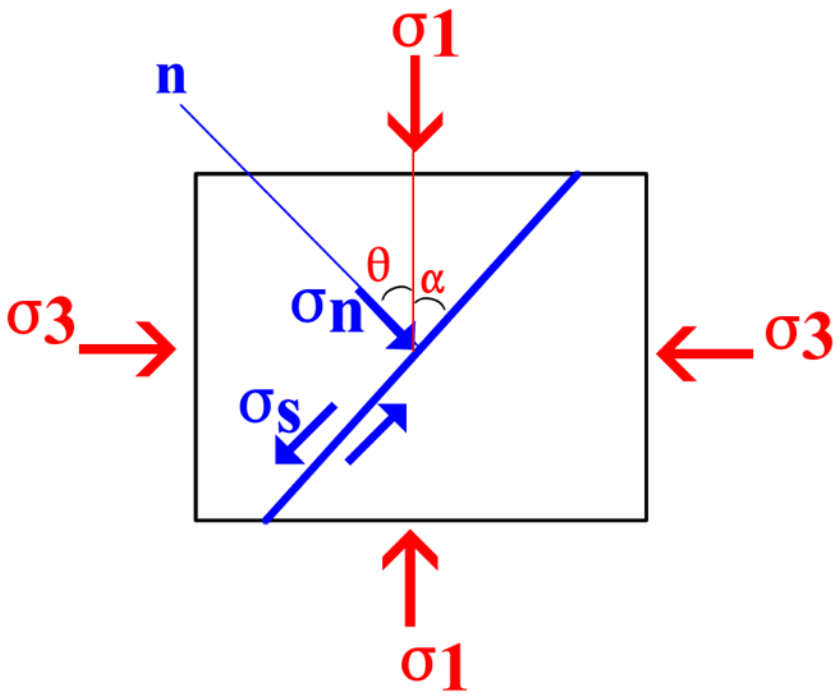
i. Motivation – Annual Loading Cycles
   i. Nepal and California
ii. Seasonal Loading and Deformation
   i. Modeling Efforts
   ii. Stress calculations
iii. Stress and Seismicity Analysis
   i. Is Seasonal Hydrological Loading Modulating Seismicity?
   ii. Are Other Loading Sources Contributing?

Deformation Modeling

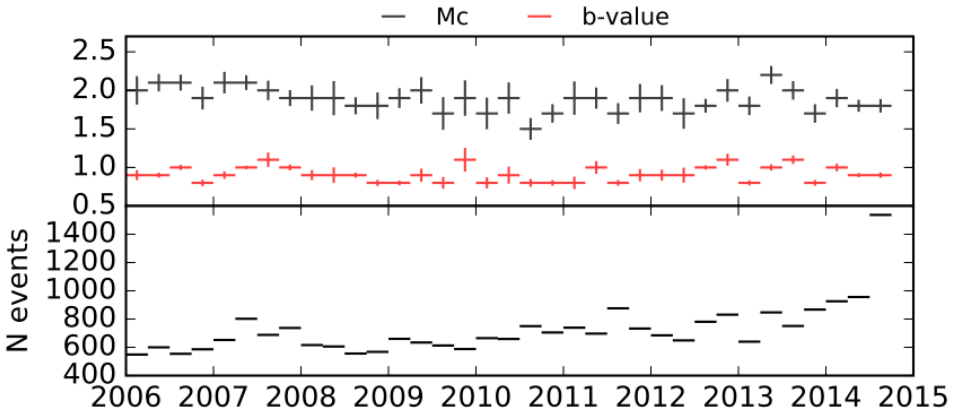
- **Assume Linear Elastic**
- **Calculate Stress at 8 km Depth**
- **Rotate to Failure Plane**
- **Shear (σ_S) and Normal (σ_N)**
- **ΔCoulomb = $\Delta\sigma_S + \mu\,\Delta\sigma_N$**

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





NCSS Focal Mechanisms



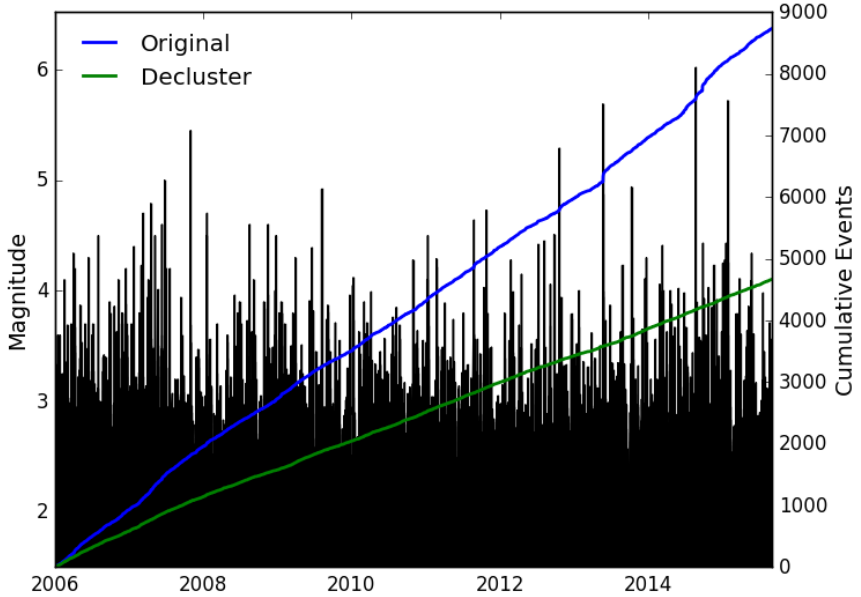
ETAS Declustering

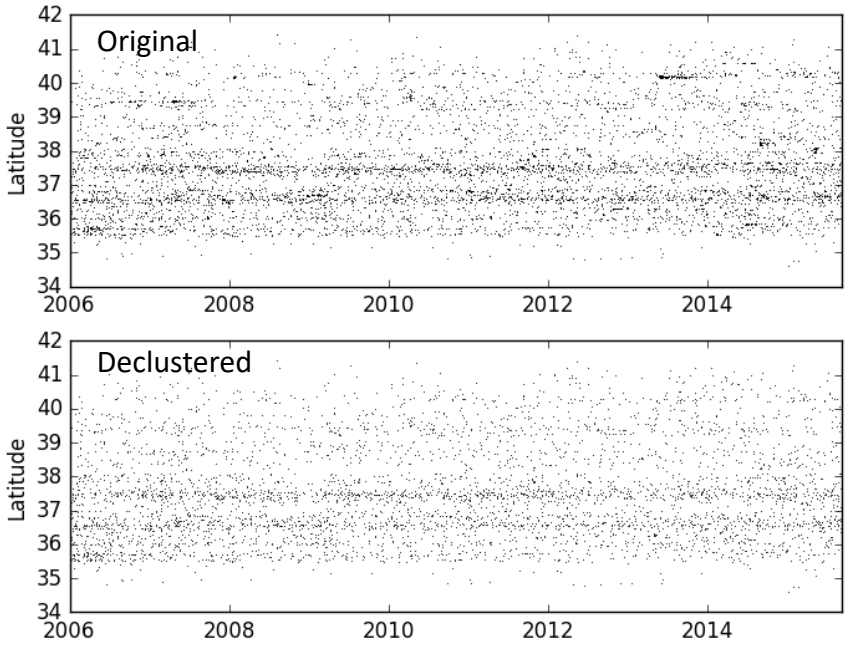
2006-2014

Exclude geothermal & volcanic

Mc ~ 2.0 (w/ 0.25 yr window)

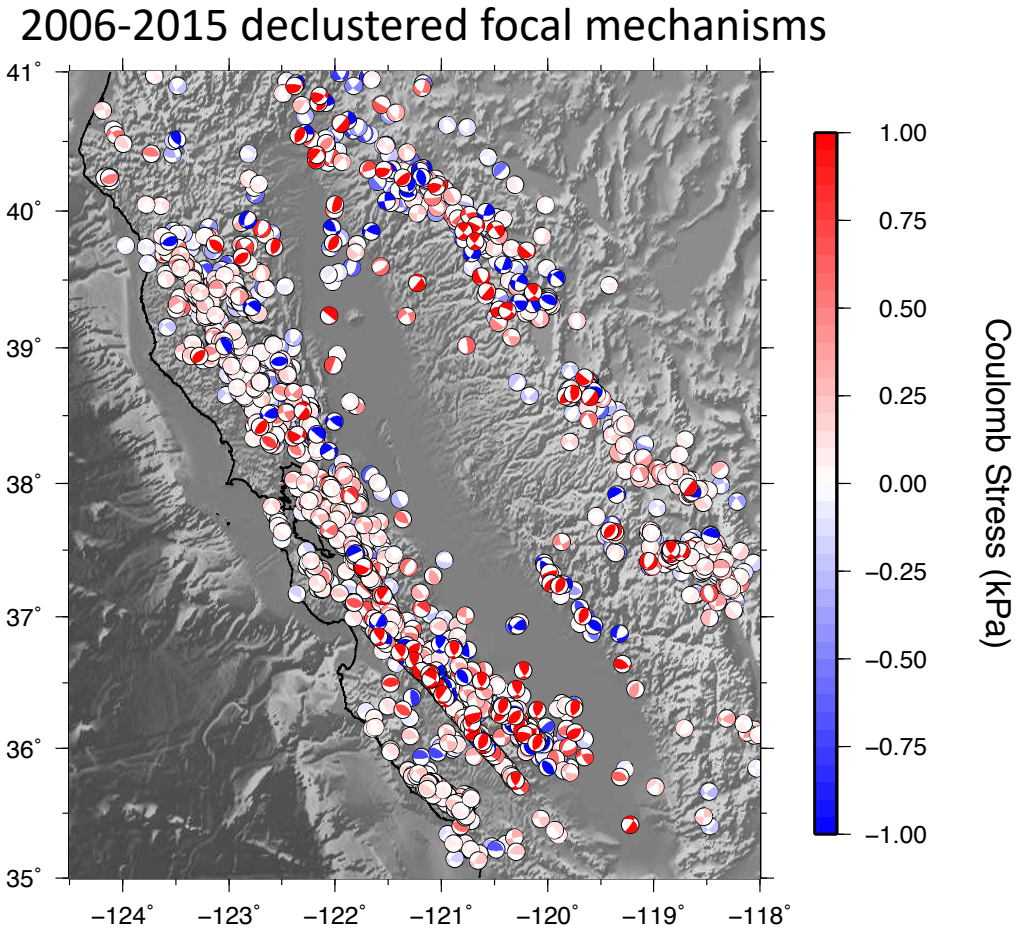
ETAS 2D (Zhuang et al., 2002)





Is Seasonal Hydrological Loading Modulating Seismicity?

Look at the stress change on the focal plane



Johnson, Fu, Bürgmann, in review

Percent excess M≥2.0 seismicity

Excess Seismicity N_{ex} Plot

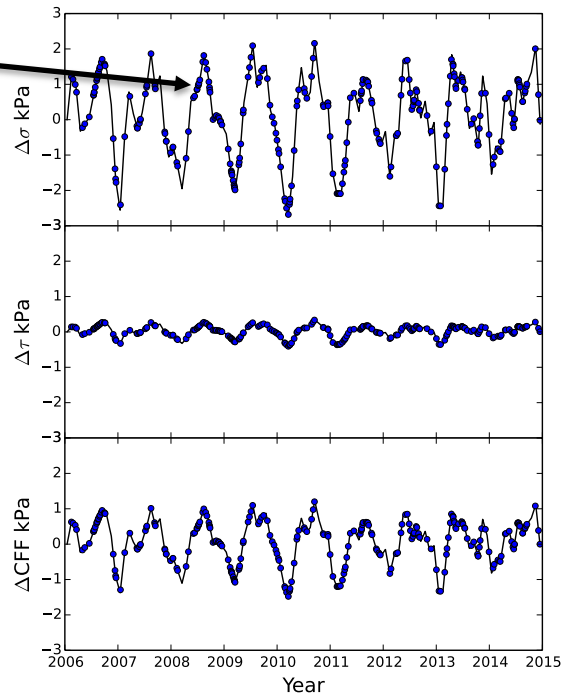
$N_{ex} = (N_{Act} - N_{Exp}) / N_{Exp} * 100$

N_{Act} = stress at event time

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

Actual event time for the location

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



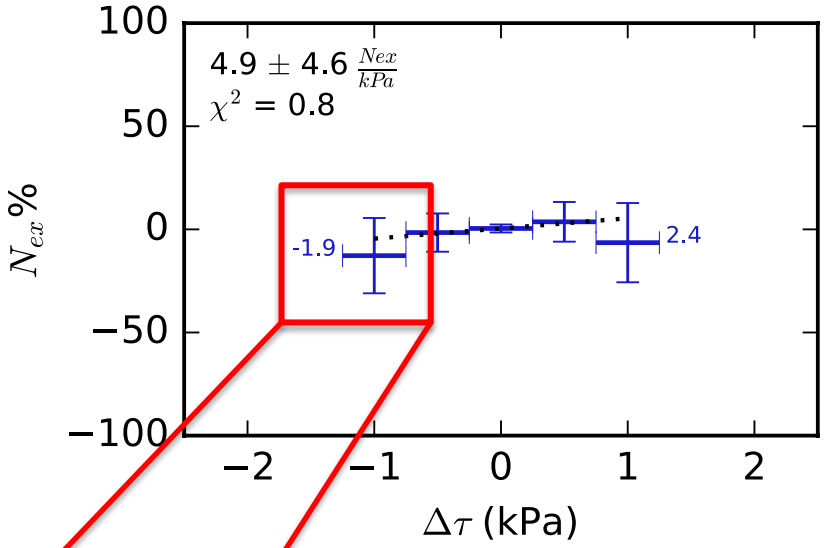
Percent excess M≥2.0 seismicity

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



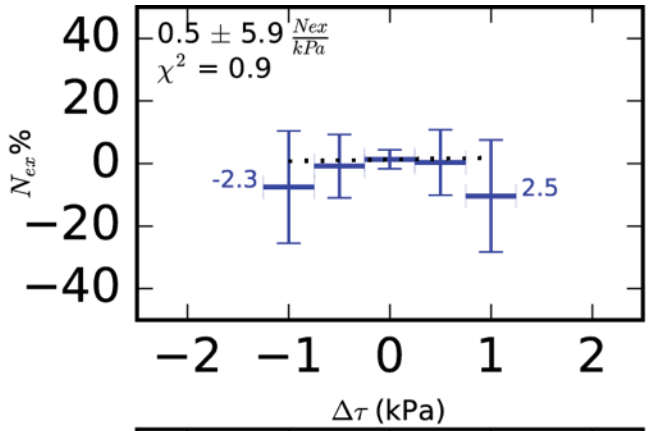
For all times with ~-1 kPa shear stress decrease ~16% less events

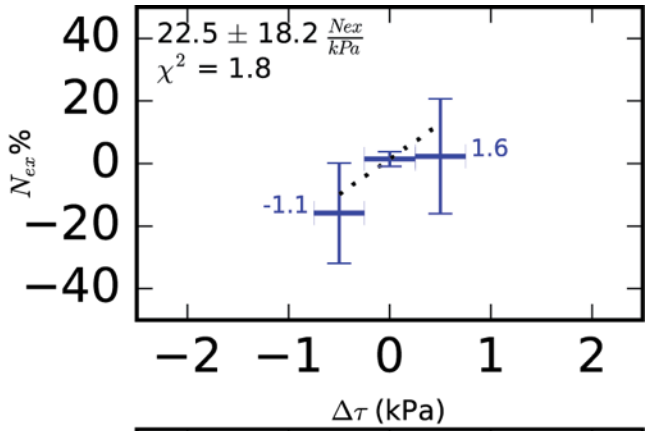
-1.9 kPa is minimum shear stress in the population

Percent excess M≥2.0 seismicity Stress Amplitude

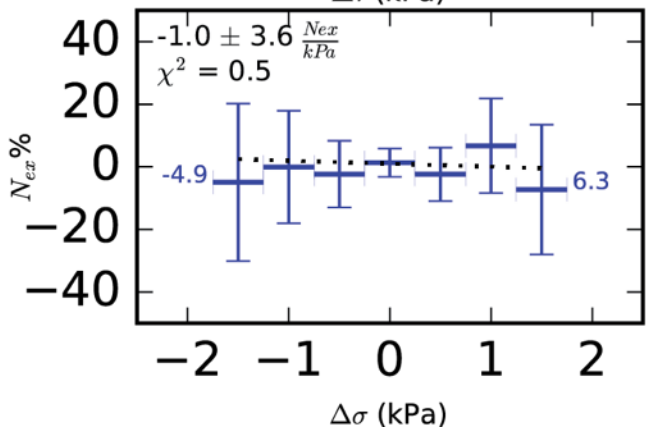
Reverse/Normal/Oblique

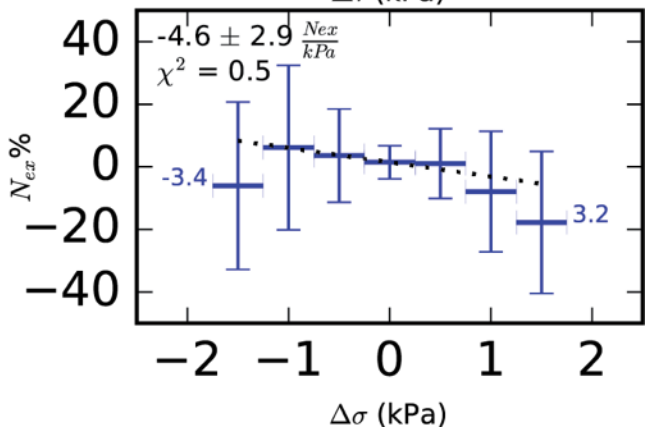
Strike-slip





Shear

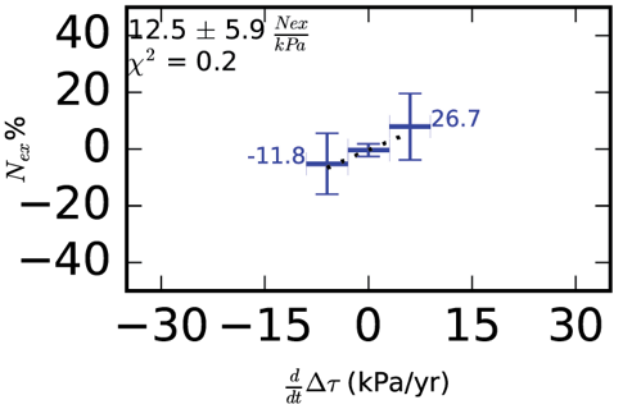


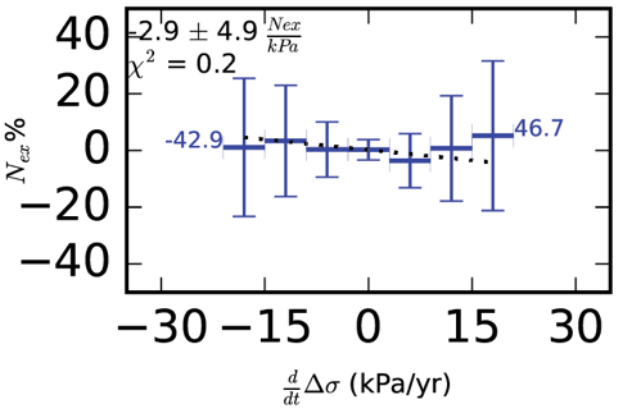


Normal

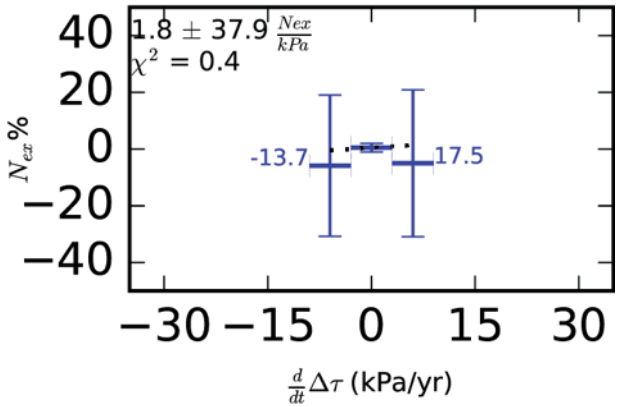
Percent excess M≥2.0 seismicity Stressing Rate

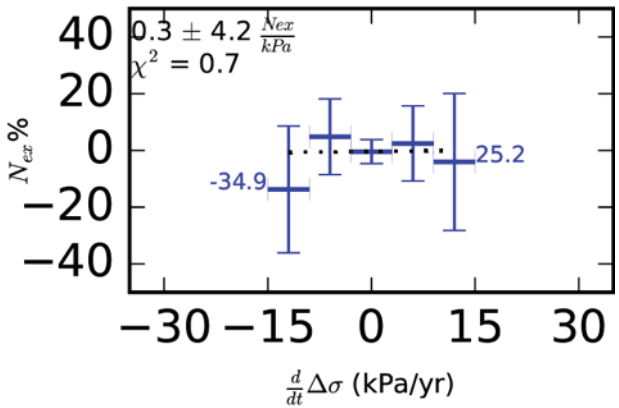
Reverse/Normal/Oblique





Strike-slip





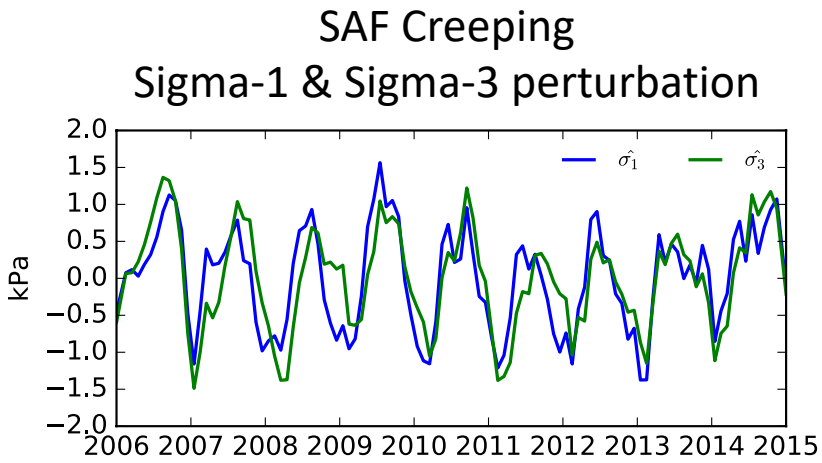
Shear

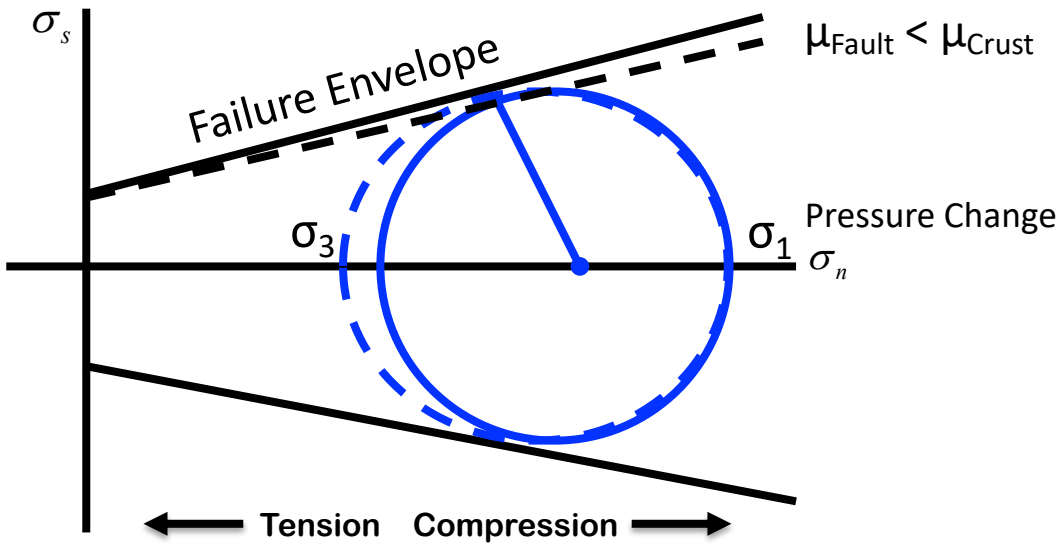
Normal

Failure Mechanism

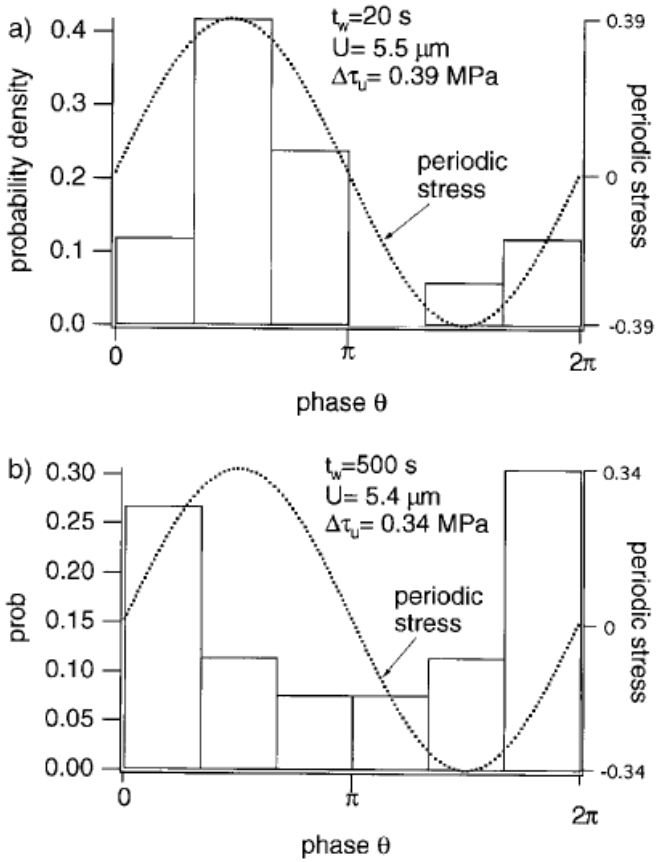
- Critically Stressed
- Increase σ_1 or Decrease in σ_3
  - Oblique / Dip-slip – Optimally Oriented

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





Lab and Model Comparison



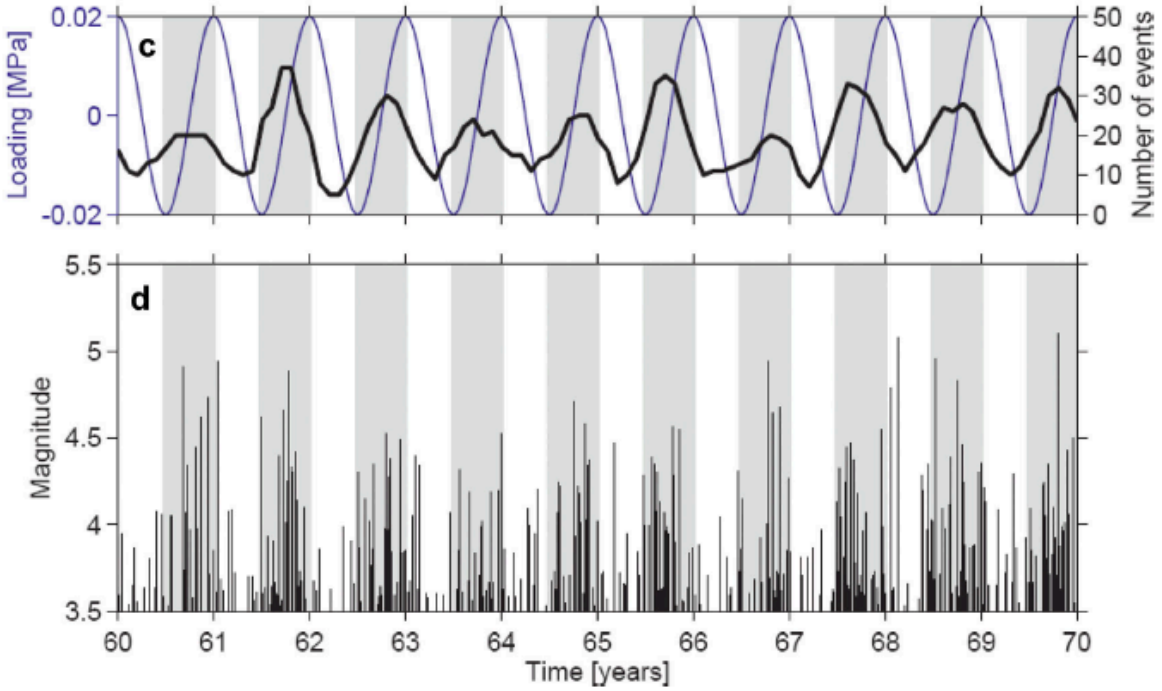
Short period loading
Stress Amplitude

Long period loading
Stress Rate

Beeler and Lockner, 2003

Lab and Model Comparison

Snapshot of model simulation with periodic loading superimposed on background stress



Ben-Zion, 2012

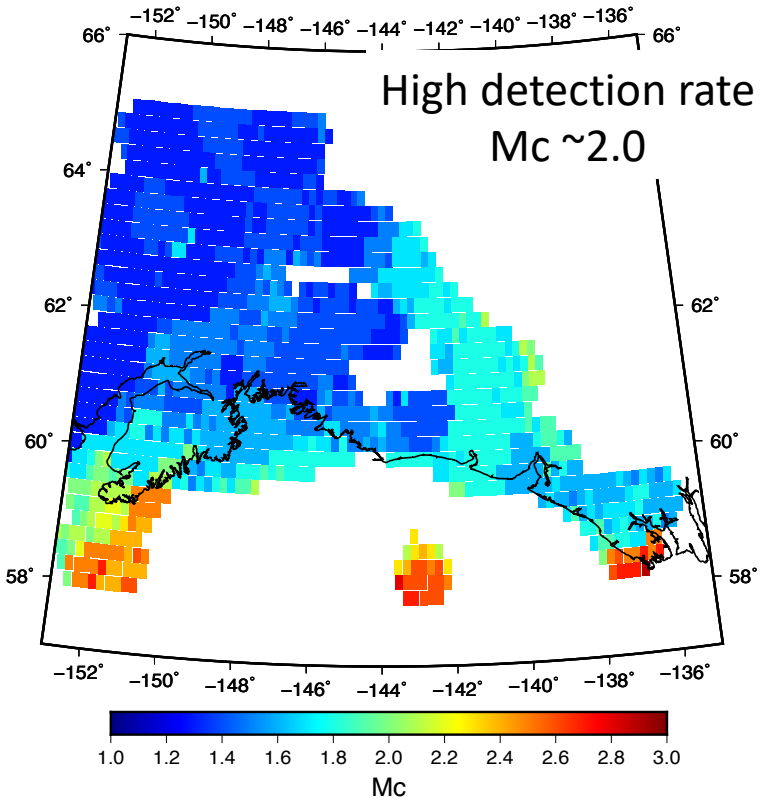
Is Seasonal Hydrological Loading Modulating Seismicity?

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

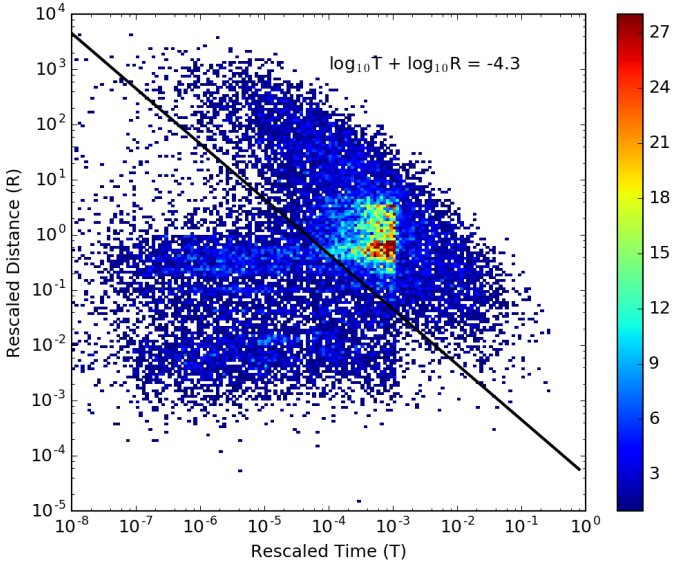
Is the crust critically stressed?
Excess seismicity from a 1-5 kPa

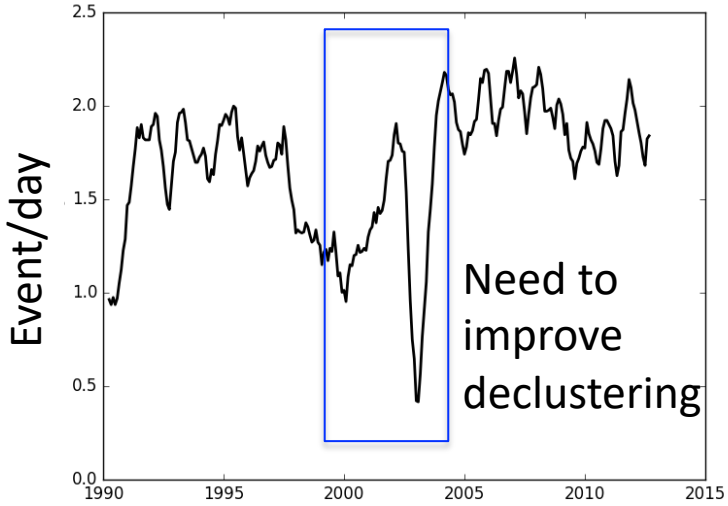
What is the failure mechanism for earthquake nucleation?
Positive correlation with peak stress amplitude suggests an instantaneous threshold failure stress. Positive correlation with peak stressing rate suggests agrees with lab and model results

Alaska Seismicity



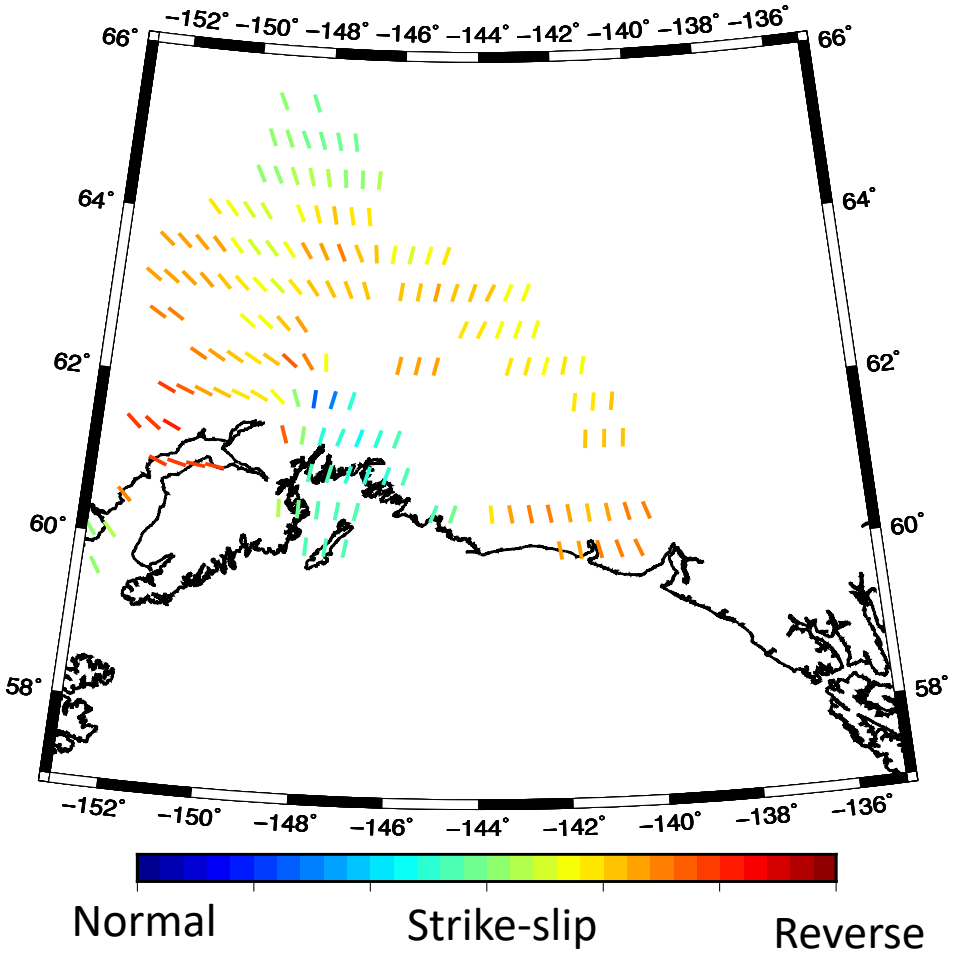
Nearest Neighbor Clusters





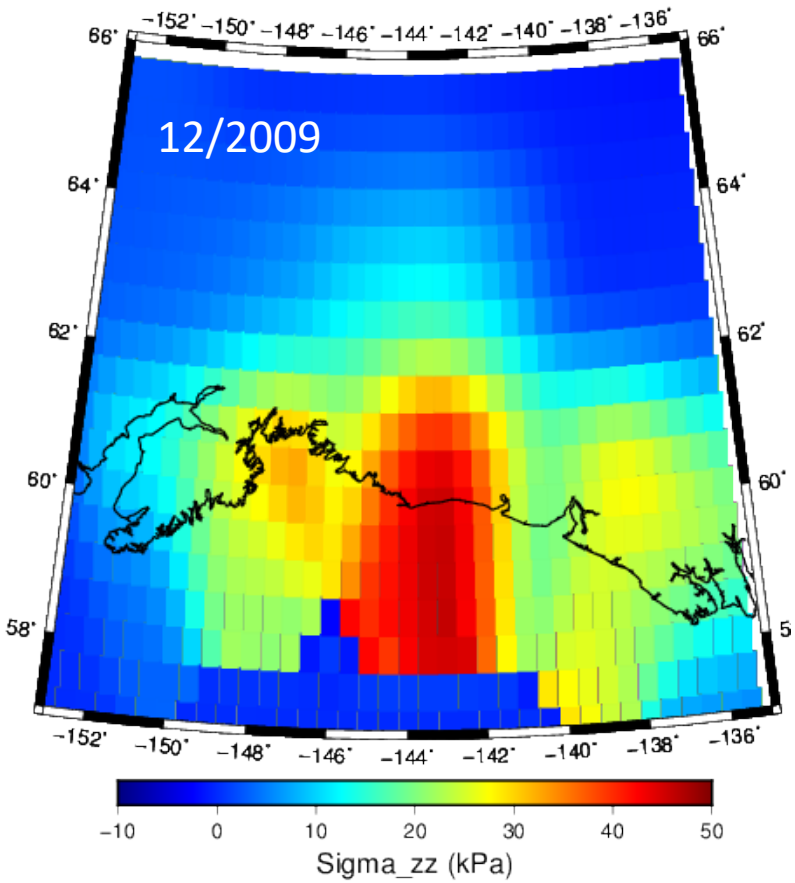
Alaska Seismicity

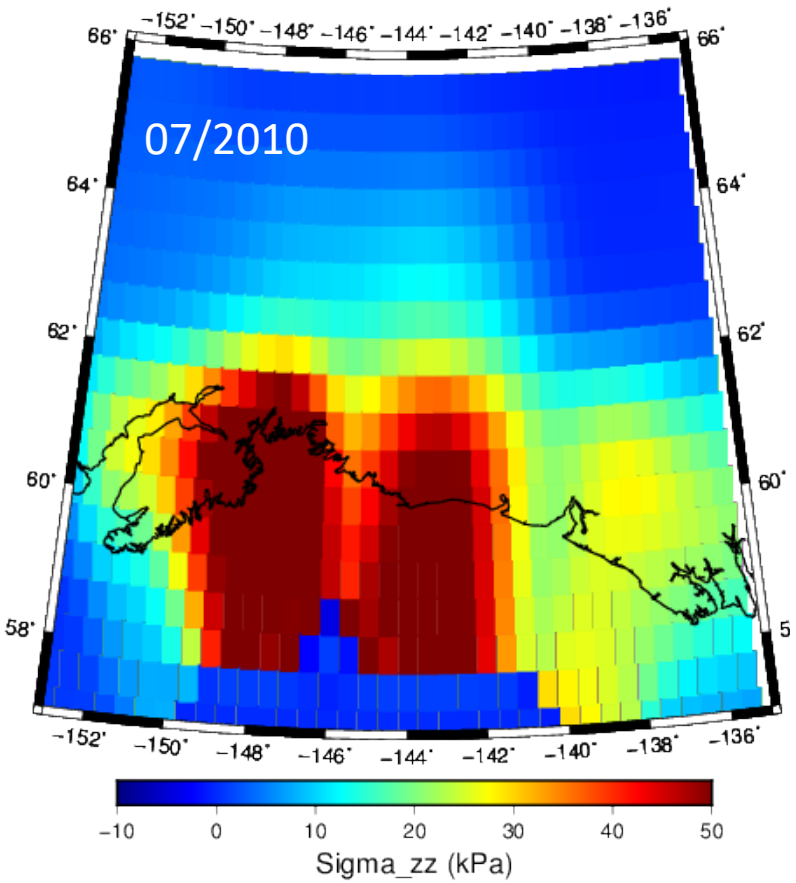
Background Stress Orientation
Crustal Events <30km



Alaska Loading

Deformation at 10 km
Vertical Load





Thank You