

# Triggering and Modulation of Slow Slip: Implications for Mechanics and Hazard

Roland Bürgmann, UC Berkeley

With contributions, slides, data, and thoughts from Amanda Thomas, Bob Nadeau, David Shelly, Zhengkang Shen, Yongge Wan, John Wahr, Nick Beeler, Dave Lockner, Noel Bartlow, Herb Dragert, Gary Rogers, Zhigang Peng, David Hill, Aaron Wech, Ken Creager, John Vidale, Stephen Holtkamp, Mike Brudzinski, Tim Melbourne and TFS Institute participants.



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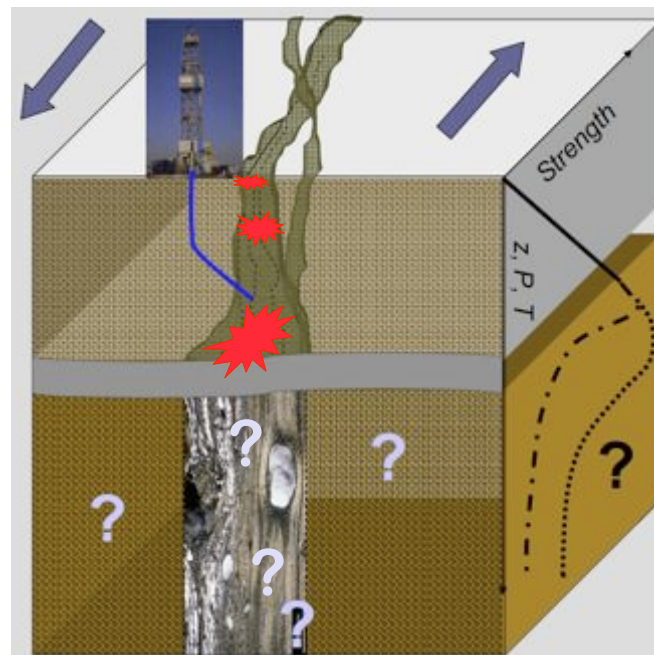
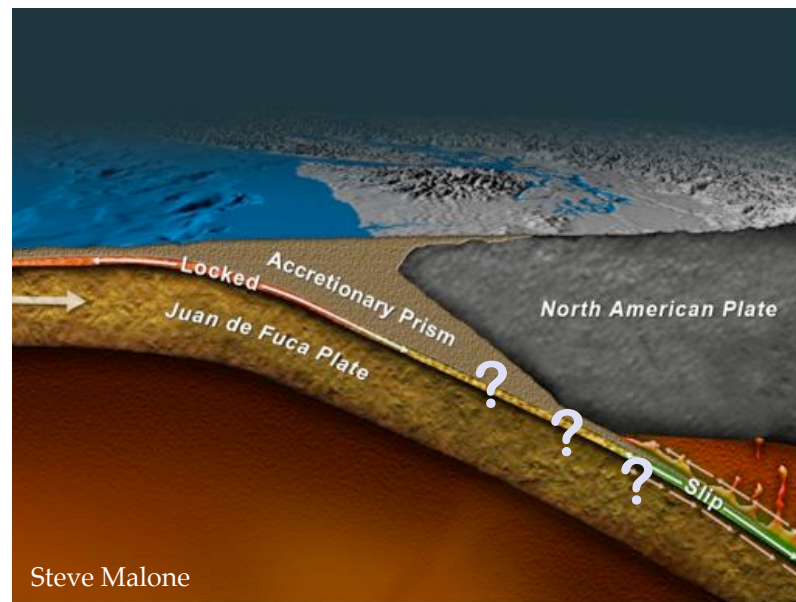
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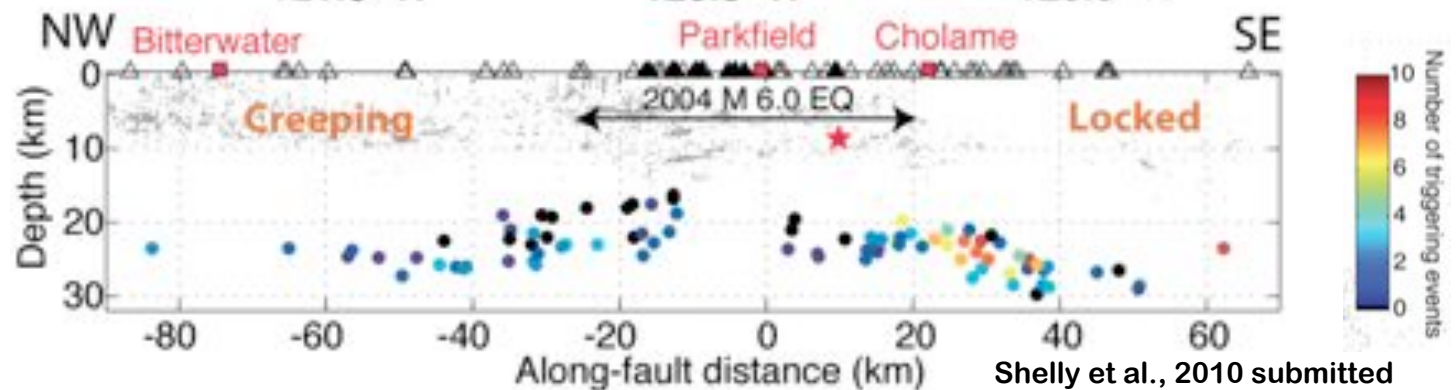
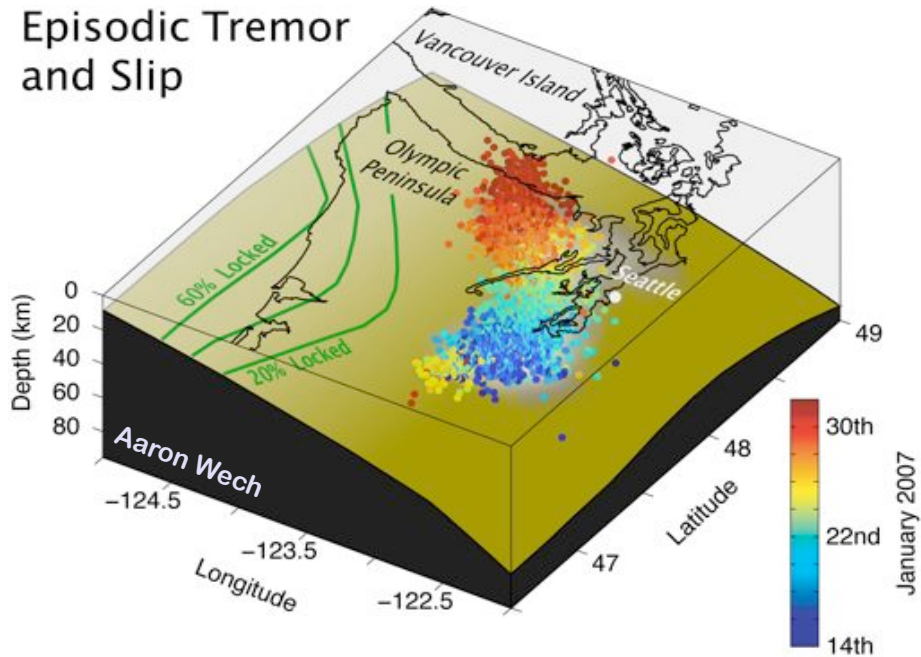
# Opportunities offered by Transient Fault Slip and Tremor

- What are conditions, mechanical properties and dynamics of lower crustal faulting?
- What is the geology, structure and environment around deep roots of major fault zones?
- What are implications for initiation of large earthquake ruptures?

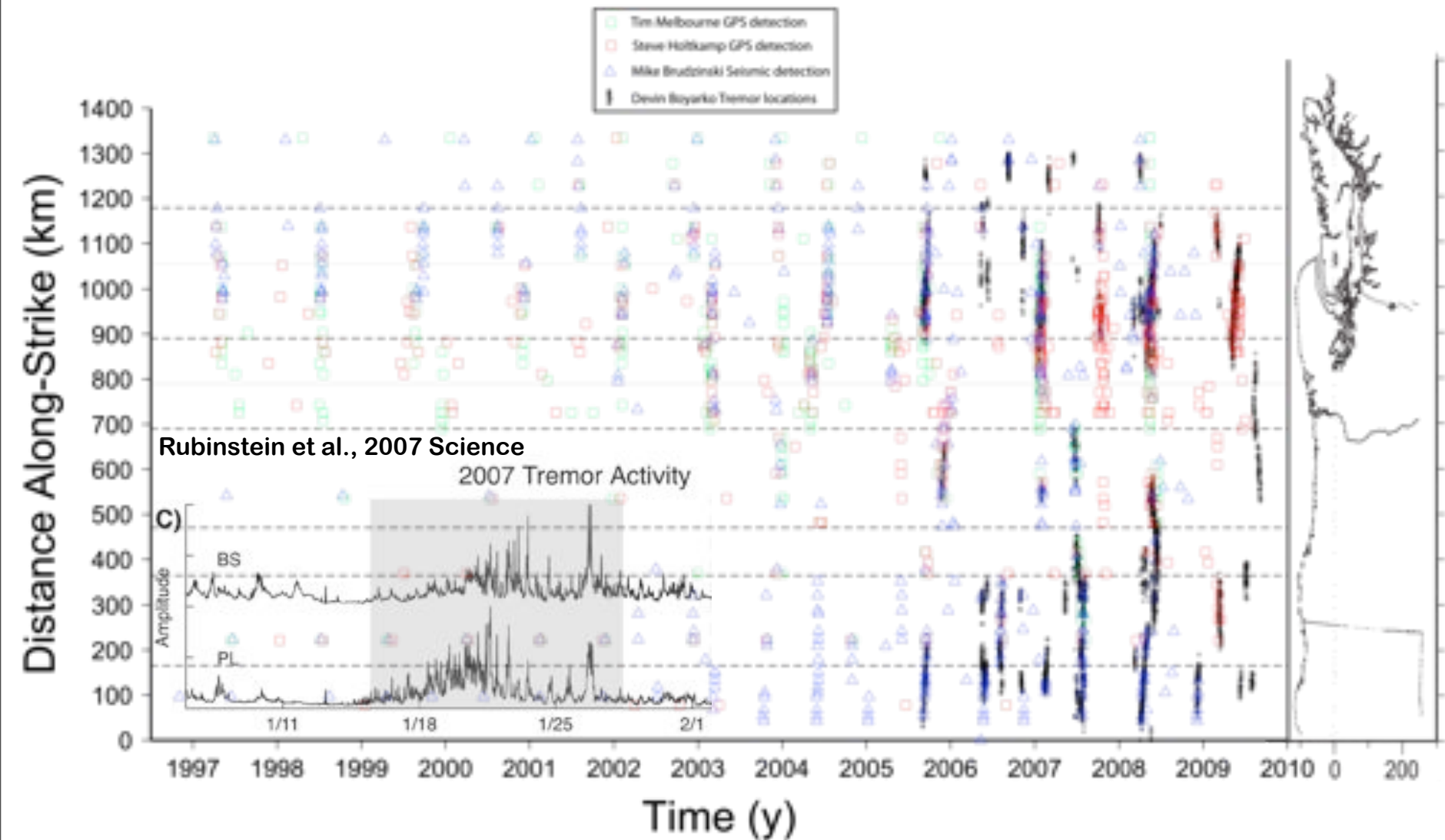


# Opportunities offered by Transient Fault Slip and Tremor

- Observations of slow slip and tremor illuminate structure, environment, mechanics, and rheology of deep shear near base of crust
- Tremor and slow slip are easily triggered: Response to various types, amplitudes and frequencies of external loads probes mechanical properties
- We can use observations from natural laboratory to inform rock mechanics experiments and constrain mechanical models

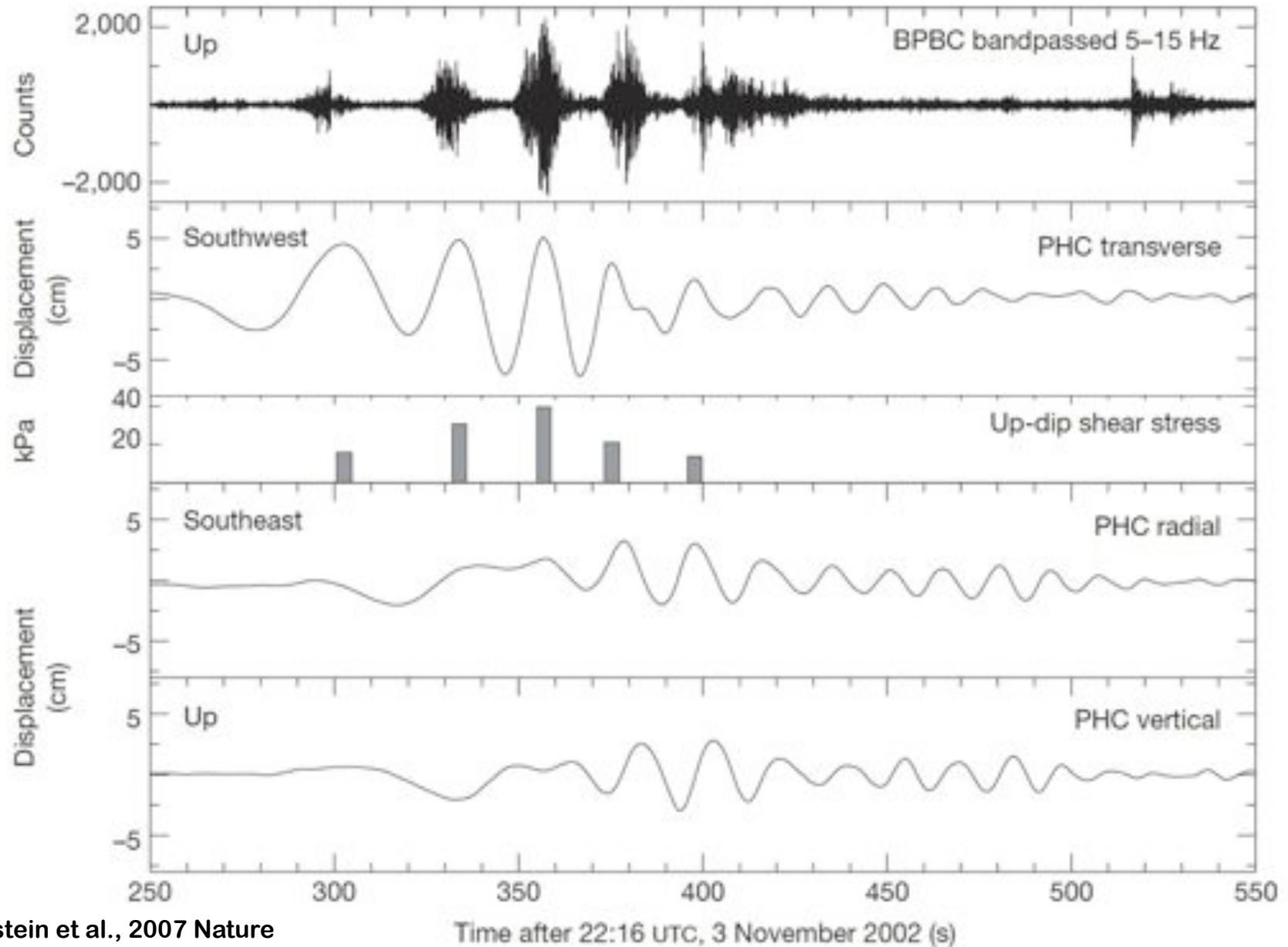


# Triggering and Modulation of ETS and Tremor at Cascadia





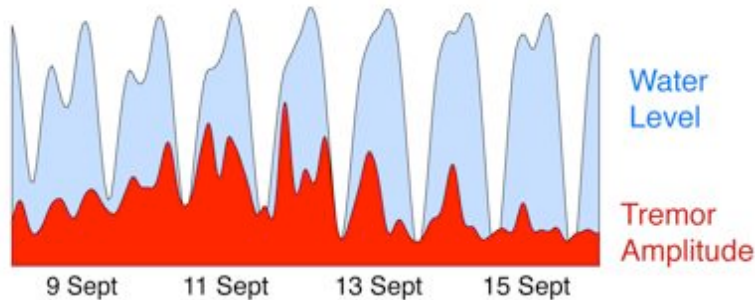
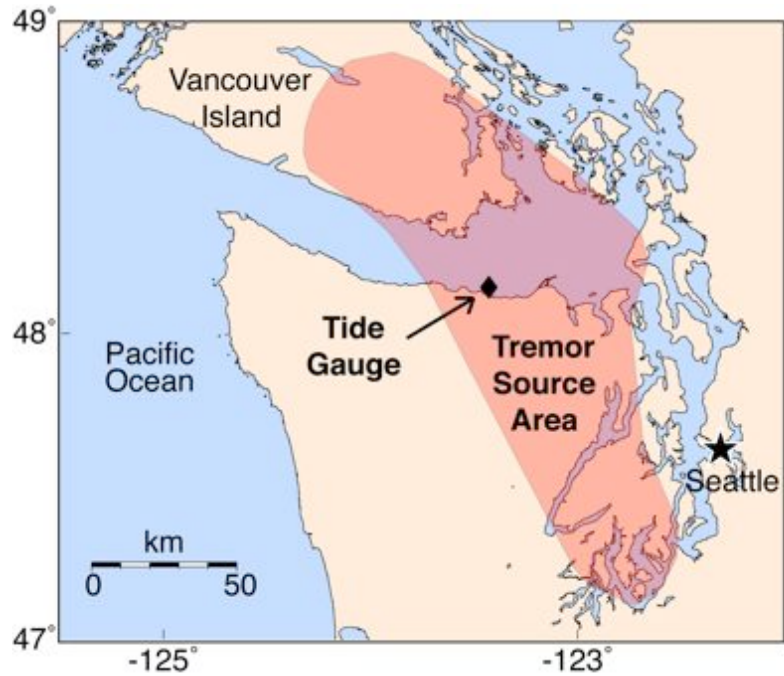
# Surface Wave Modulation of Tremor?



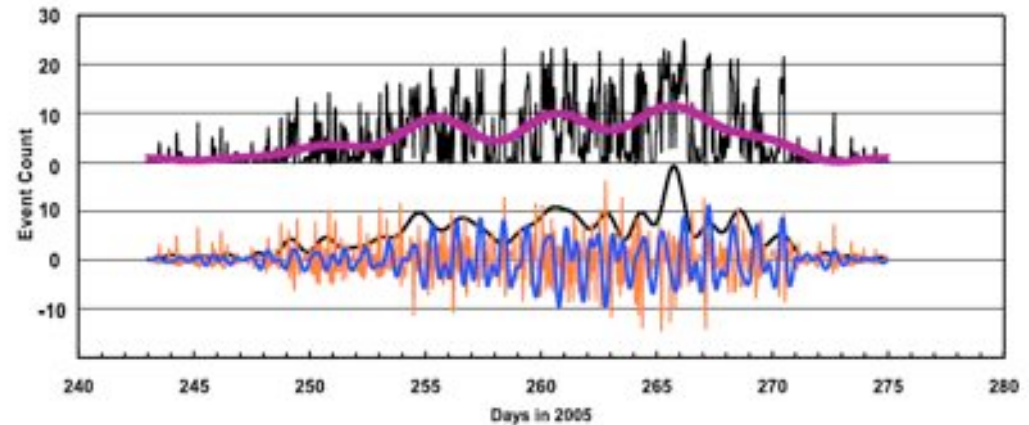
Rubinstein et al., 2007 Nature

Time after 22:16 UTC, 3 November 2002 (s)

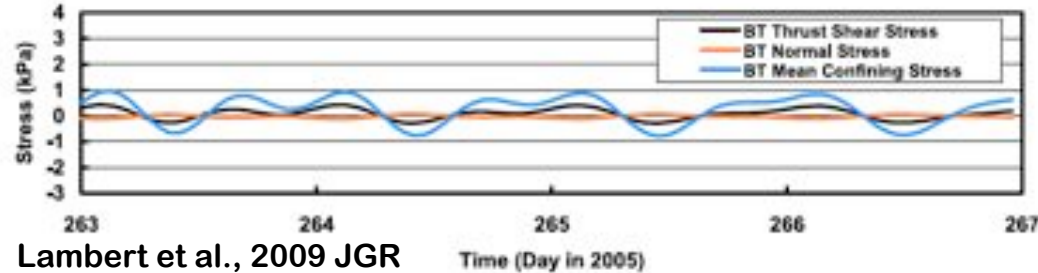
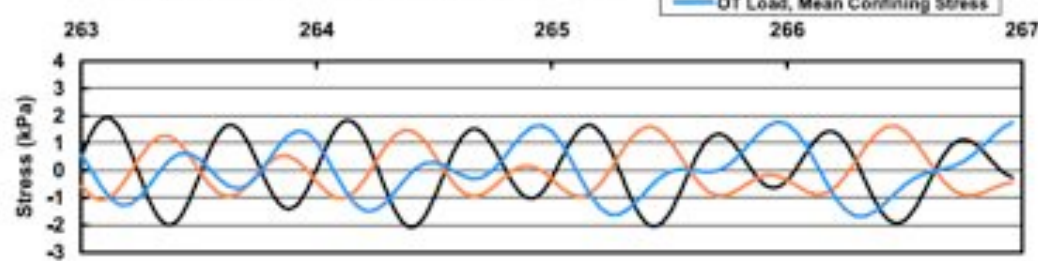
# Semidiurnal Modulation of Tremor?



Rubinstein et al., 2007 Science



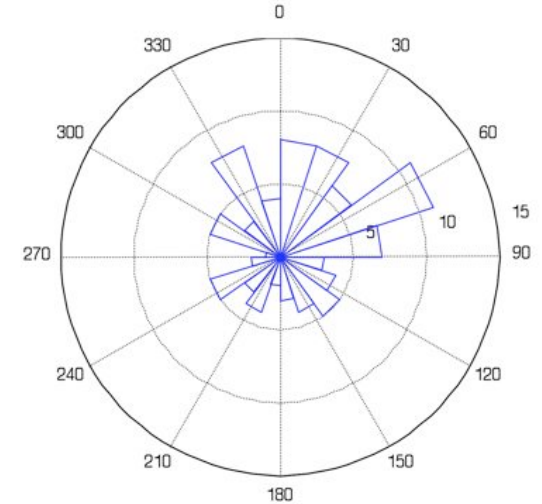
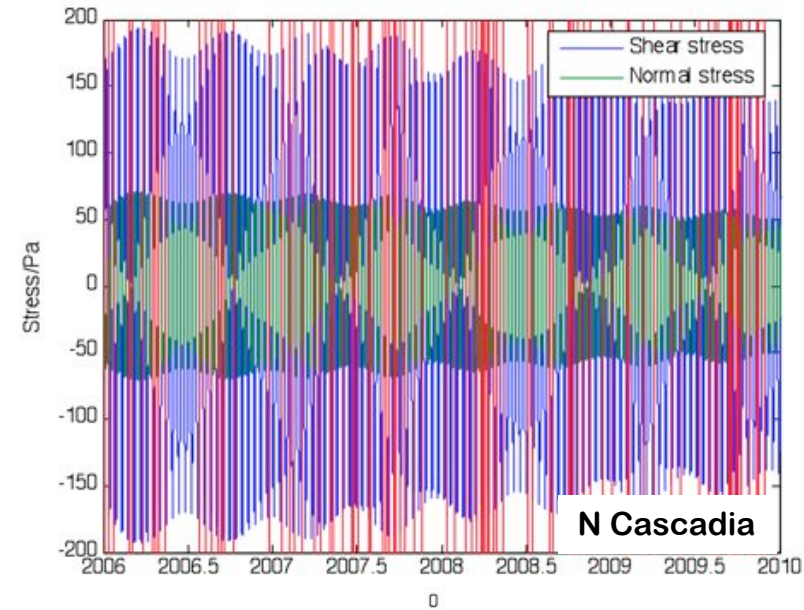
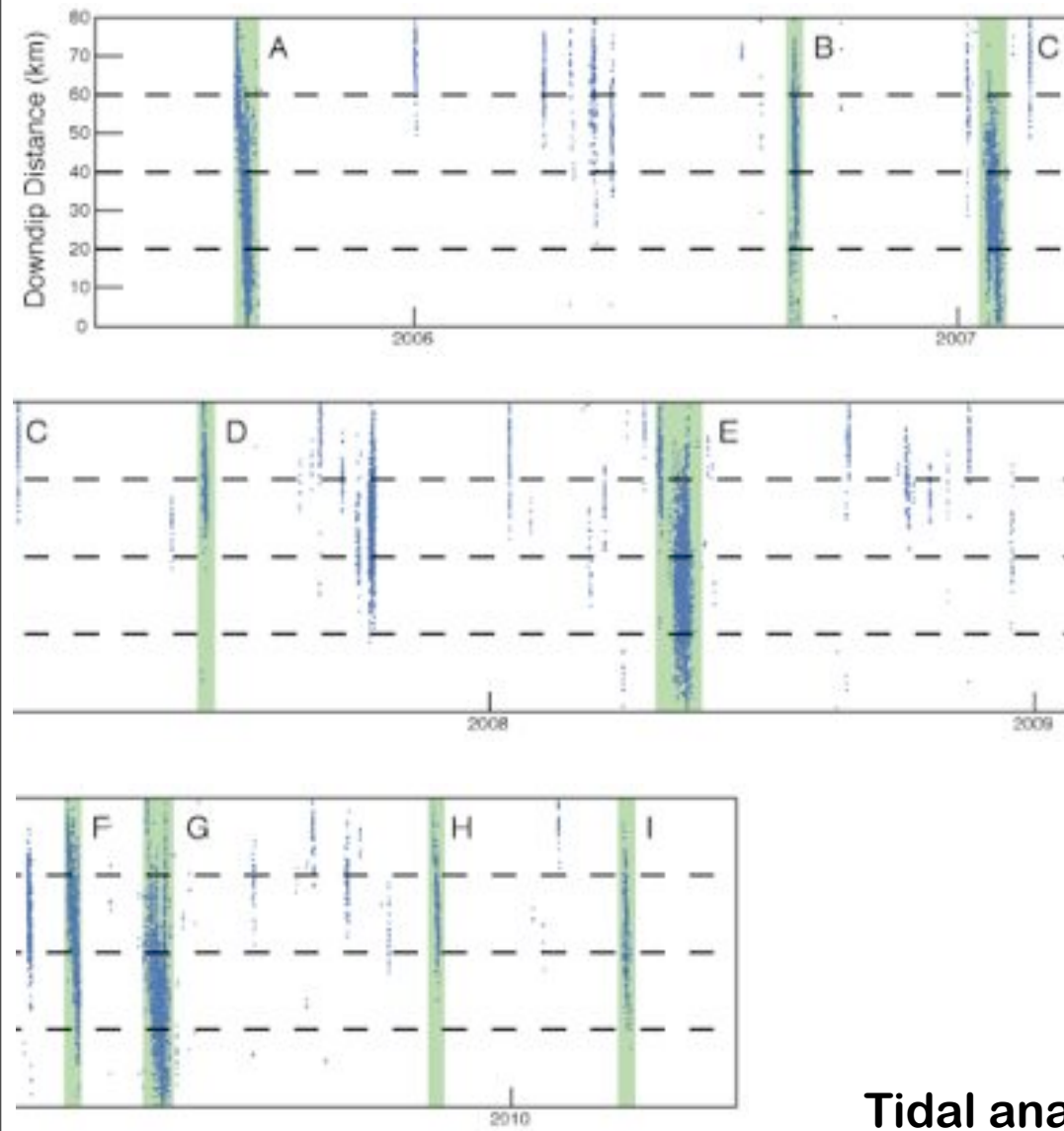
## THEORETICAL TIDAL STRESS VARIATIONS



Lambert et al., 2009 JGR

→ Peak tremor activity occurs at times of maximum tidal shear stress in the thrust direction

# Fortnightly Tide Modulation of ETS and inter-ETS?



Wech and Creager, 2010 SSA

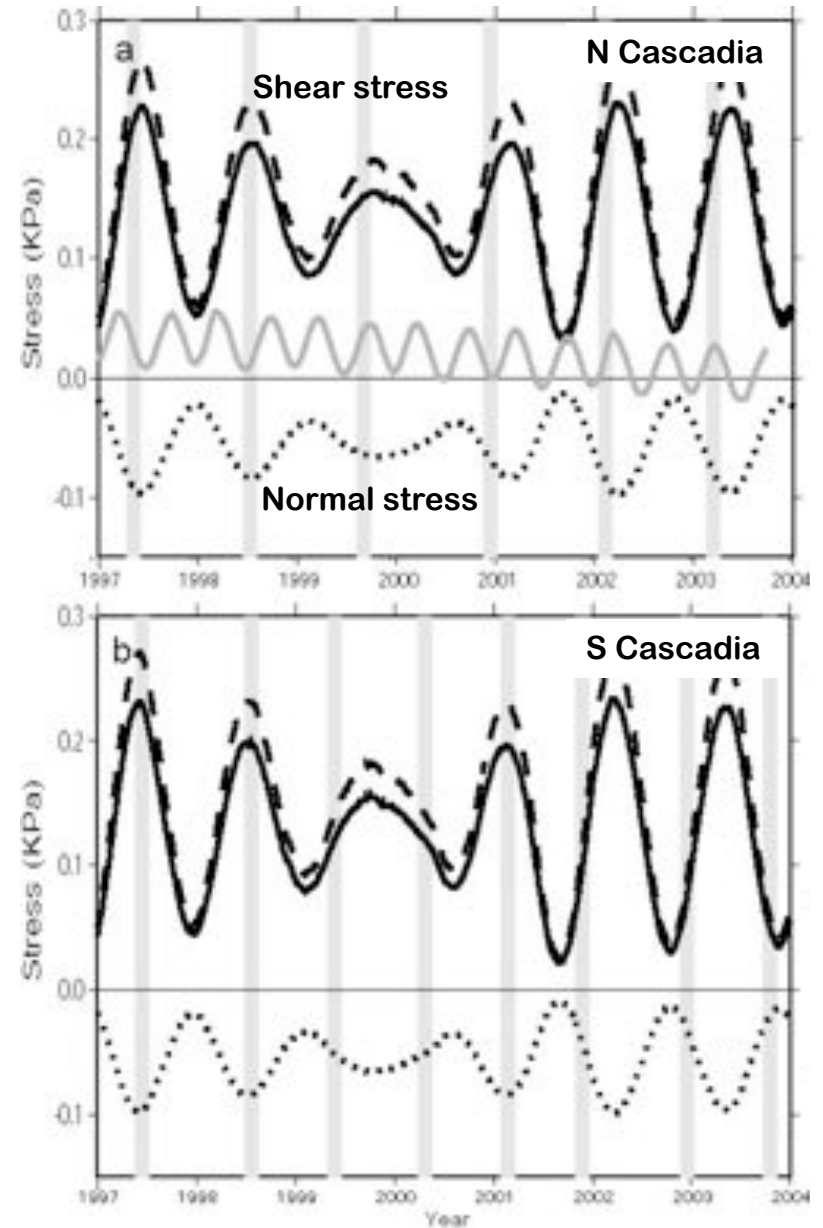
Tidal analysis using 2006-2010 tremor episode catalog for northern Washington by Wech and Creager (pers. comm.)



# 14-month Pole-Tide Modulation of ETS?

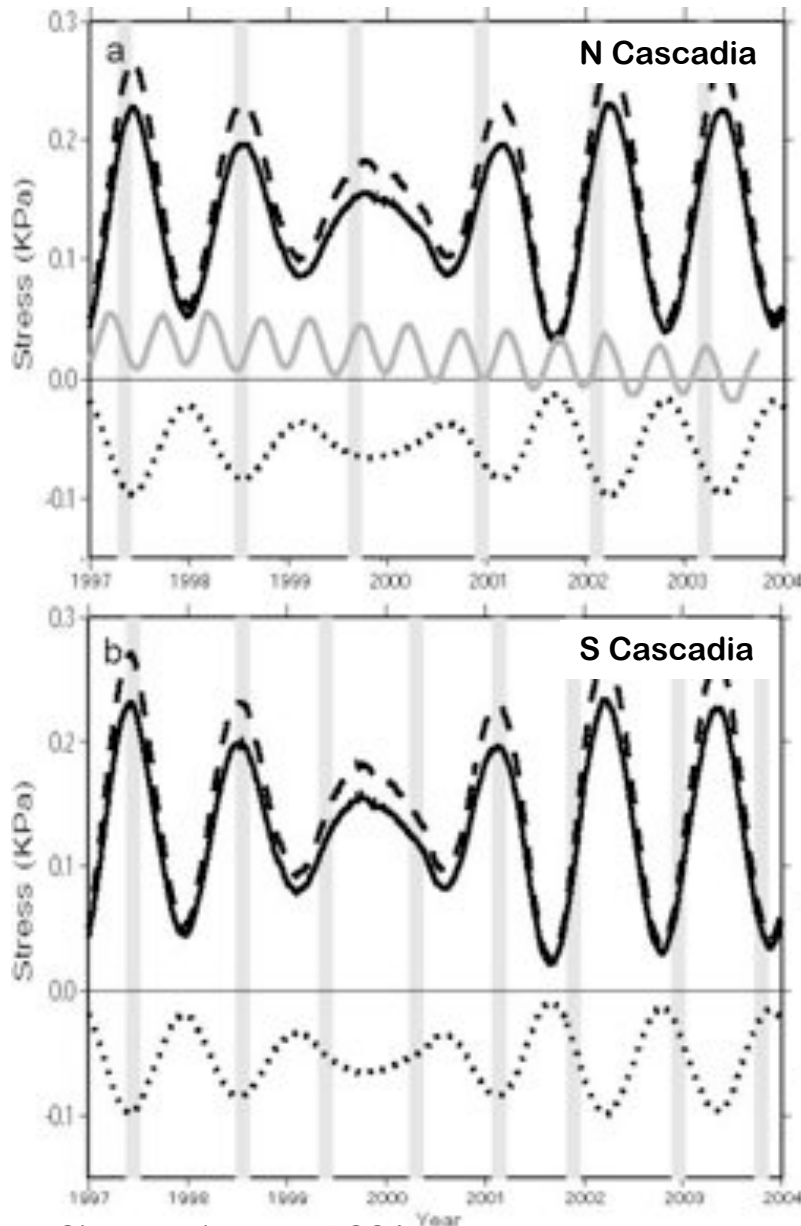


Brudzinski and Allen, 2007 Geology

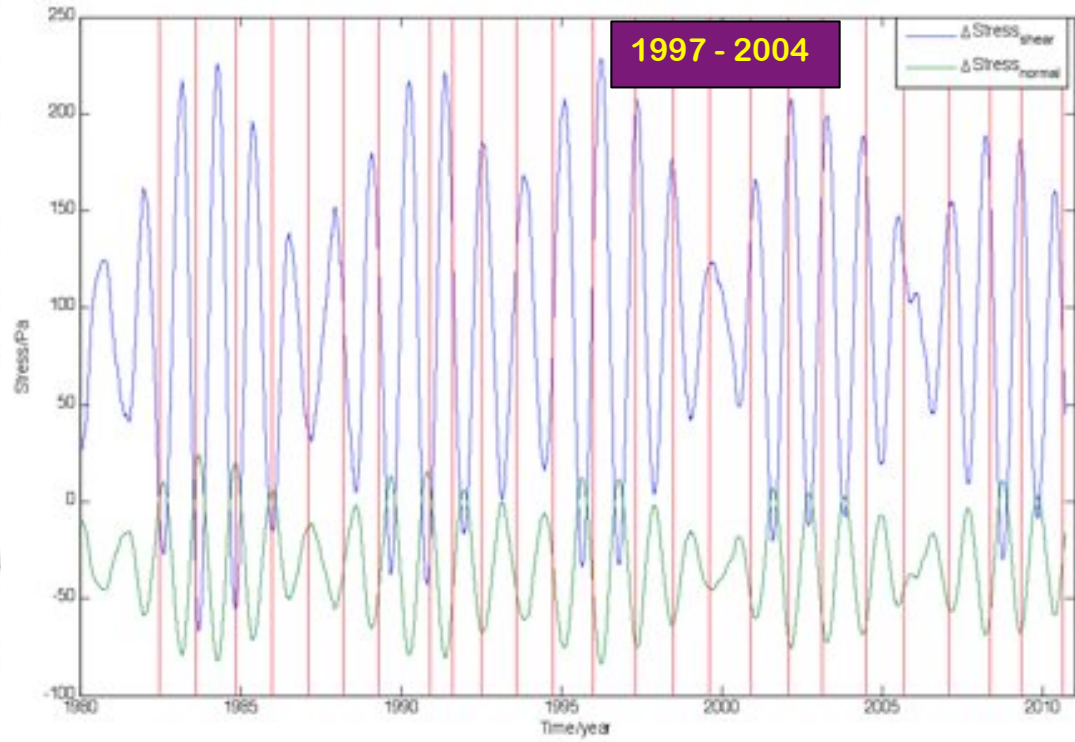


Shen et al., 2005 BSSA

# Inherent Periodicity vs. Modulation of ETS



Shen et al., 2005 BSSA

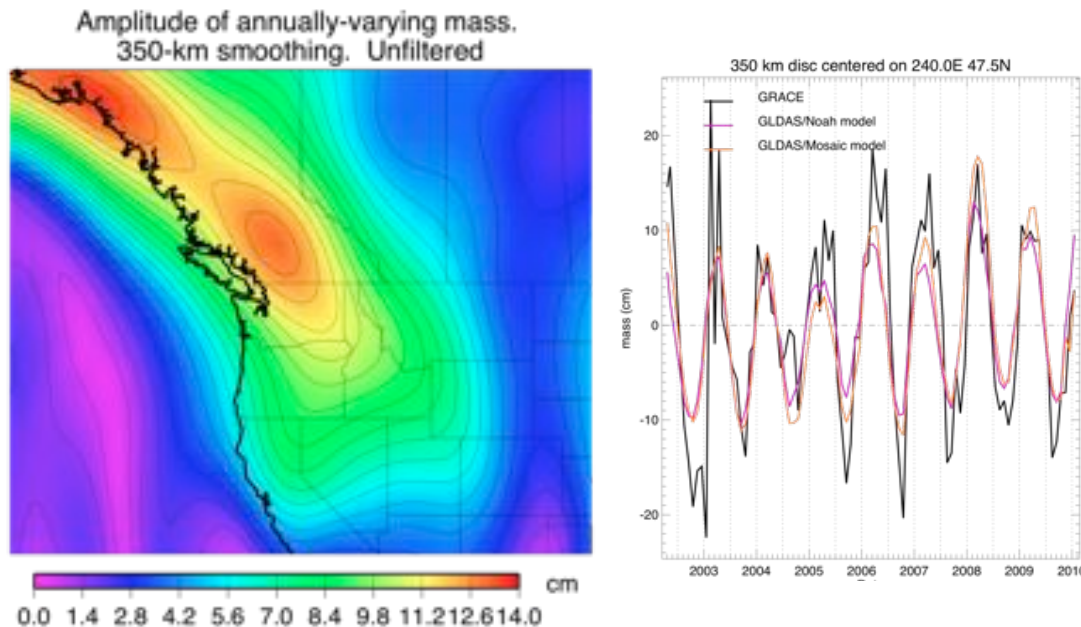


Updated pole-tide analysis using 1982 – 2010 ETS Catalog by Rogers and Dragert (pers. comm.)

→ While being episodic at very similar period, phase shifts to negative stress in 1980s.

# Long-period Triggering of ETS and Tremor at Cascadia

- There are other long-period forcings, in particular seasonal hydrological loads
- Correlated tremor episode along arc suggest external triggering



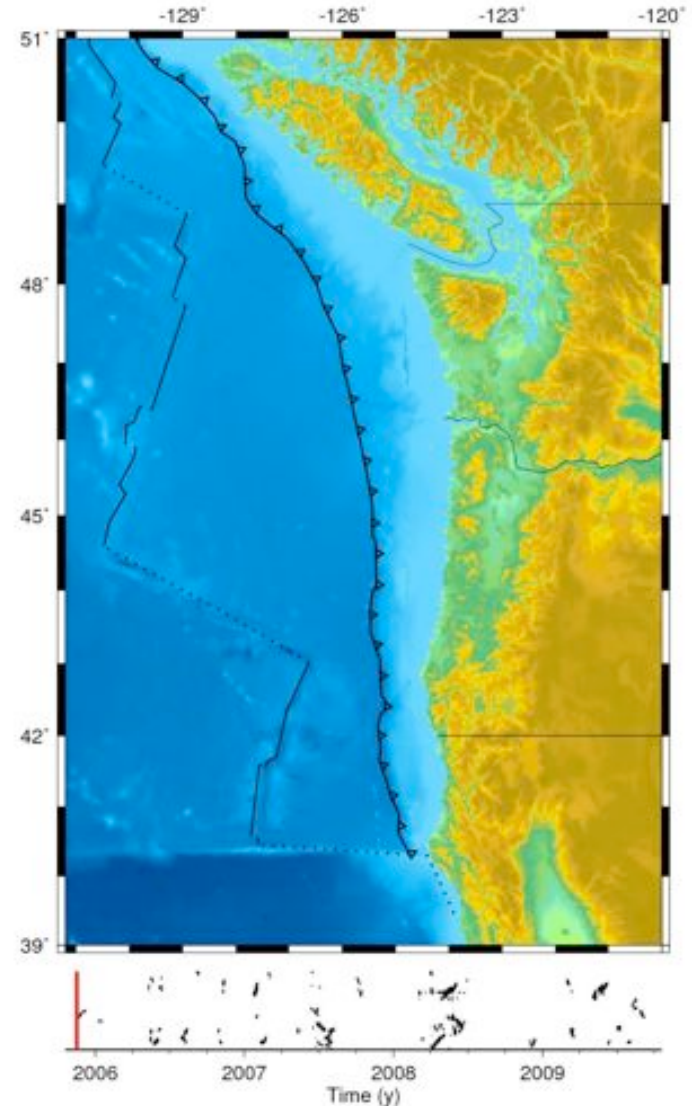
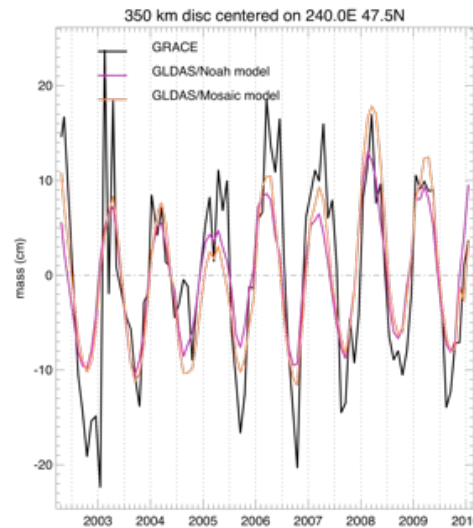
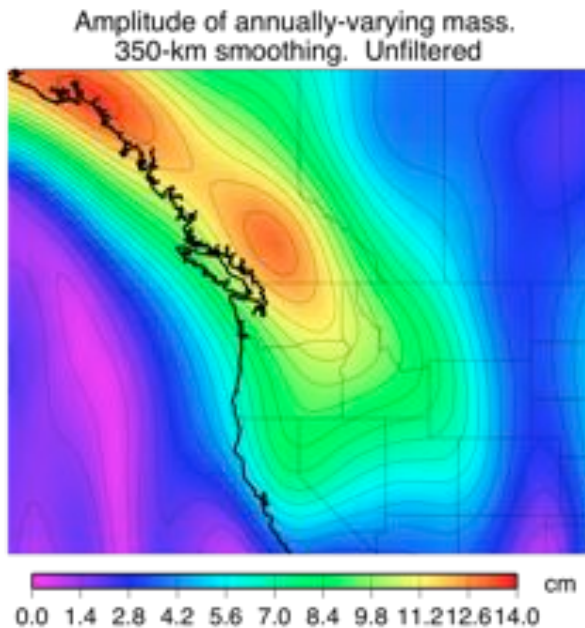
Seasonal surface load from GRACE data and hydrological models (John Wahr, unpublished)

Brudzinski, 2010



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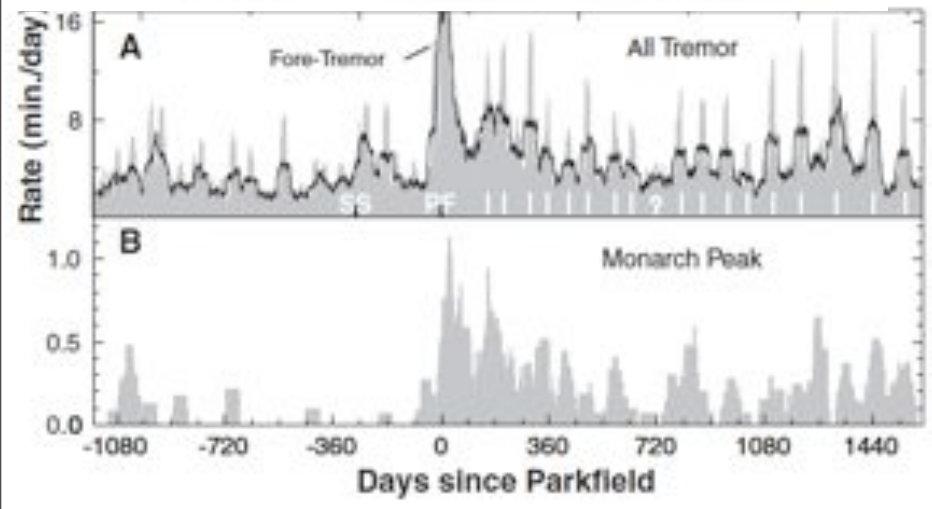
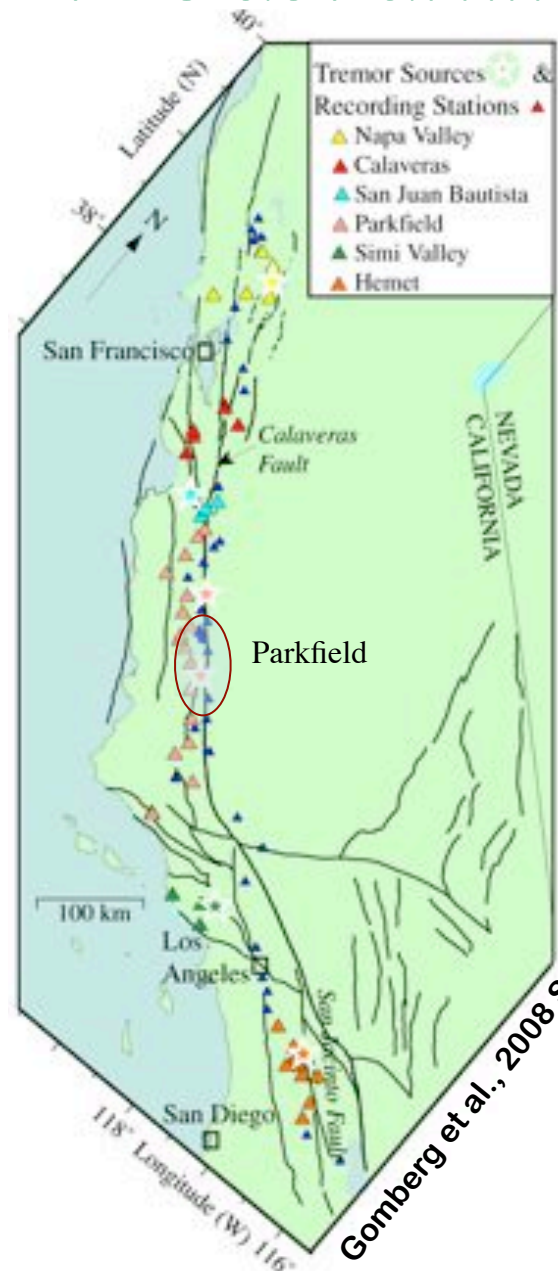
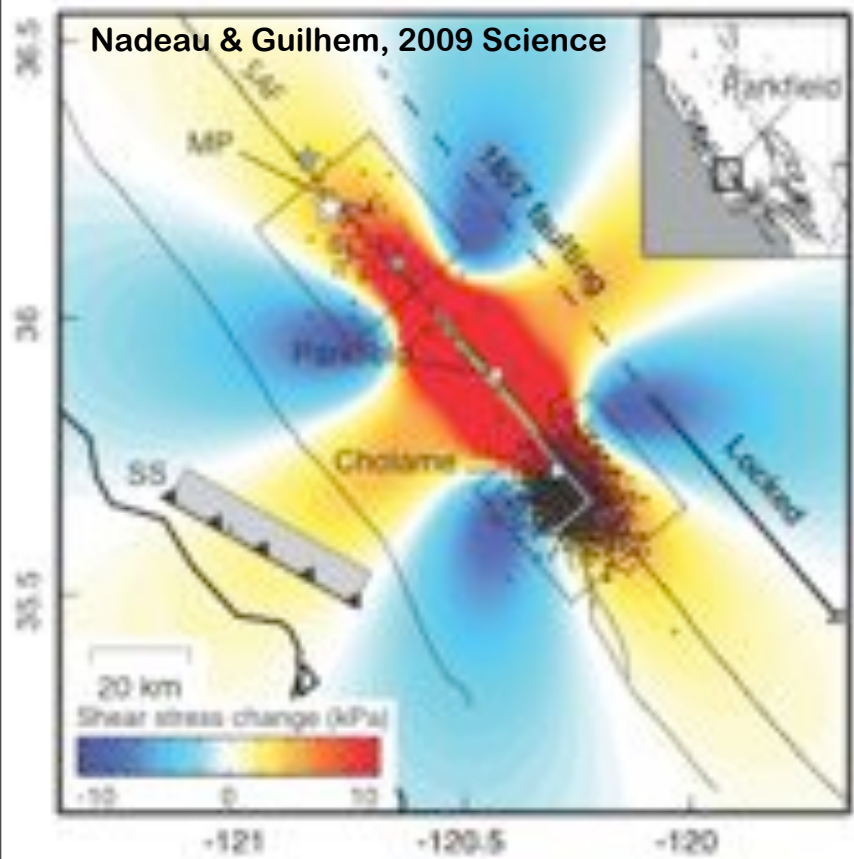
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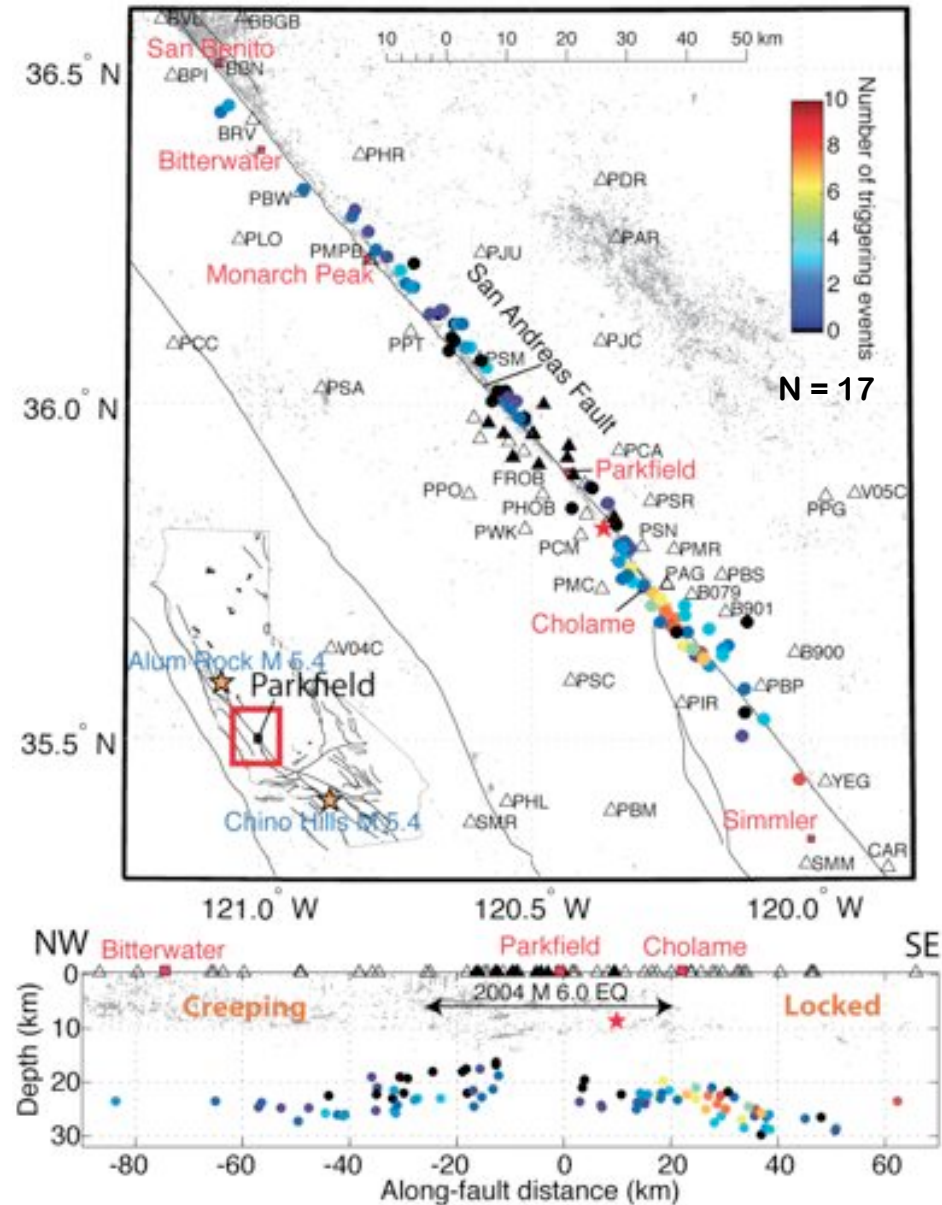
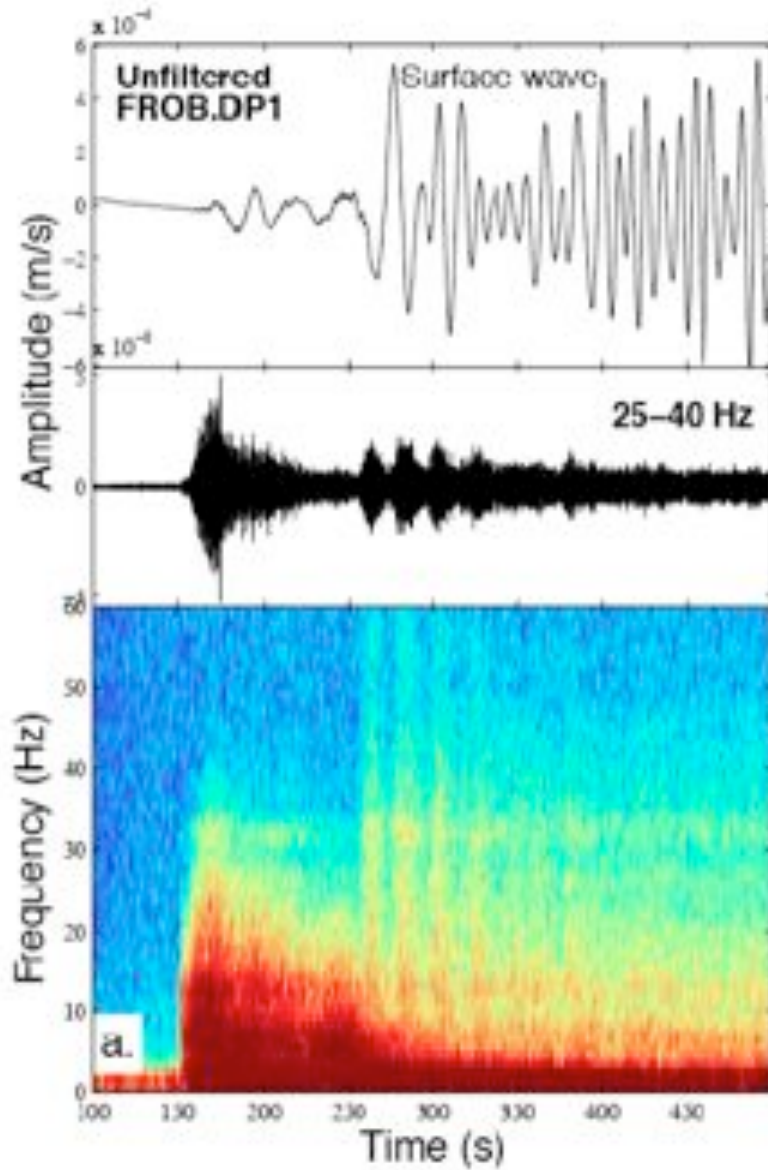
# Triggered Tremors and LFEs at Parkfield



Gomberg et al., 2008 Science



# Triggering by Regional and Global Earthquakes

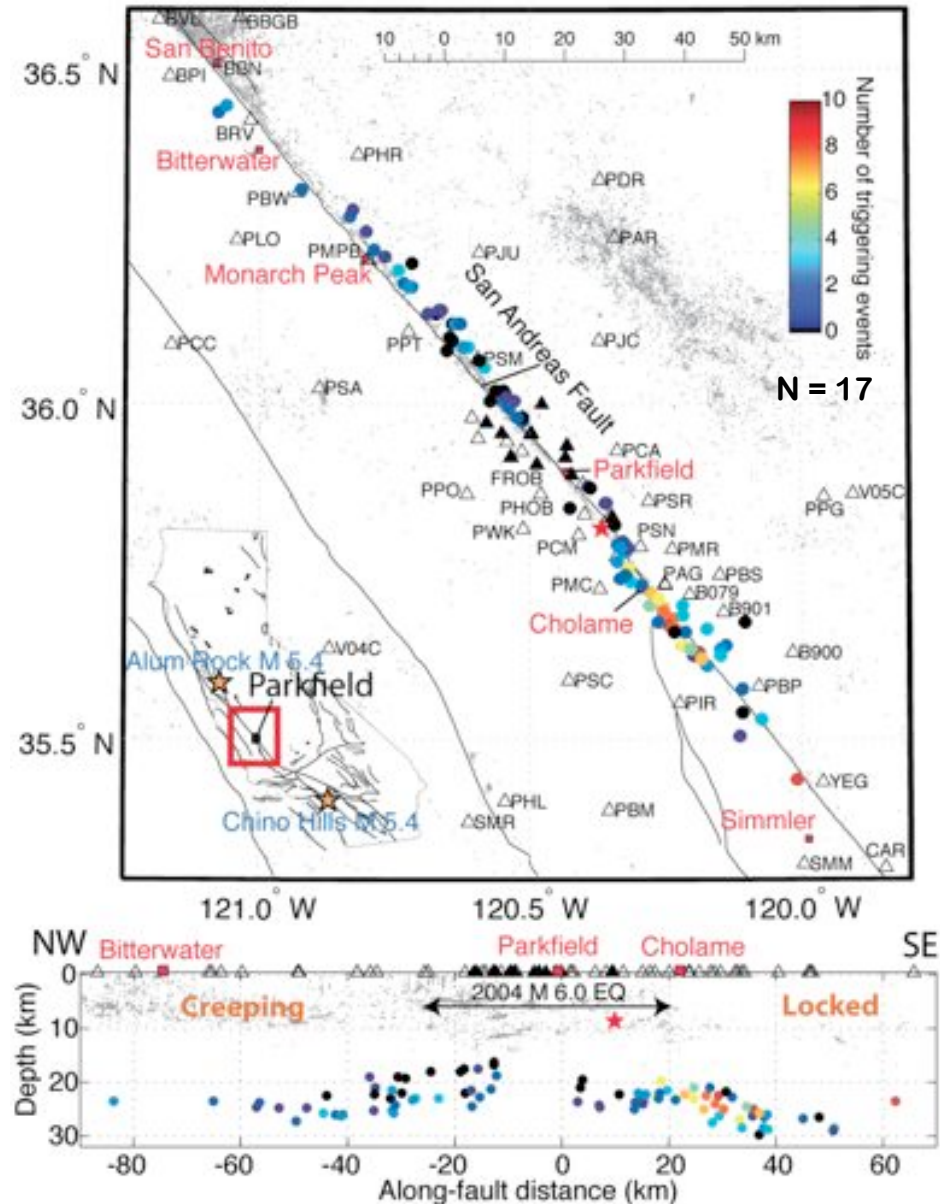
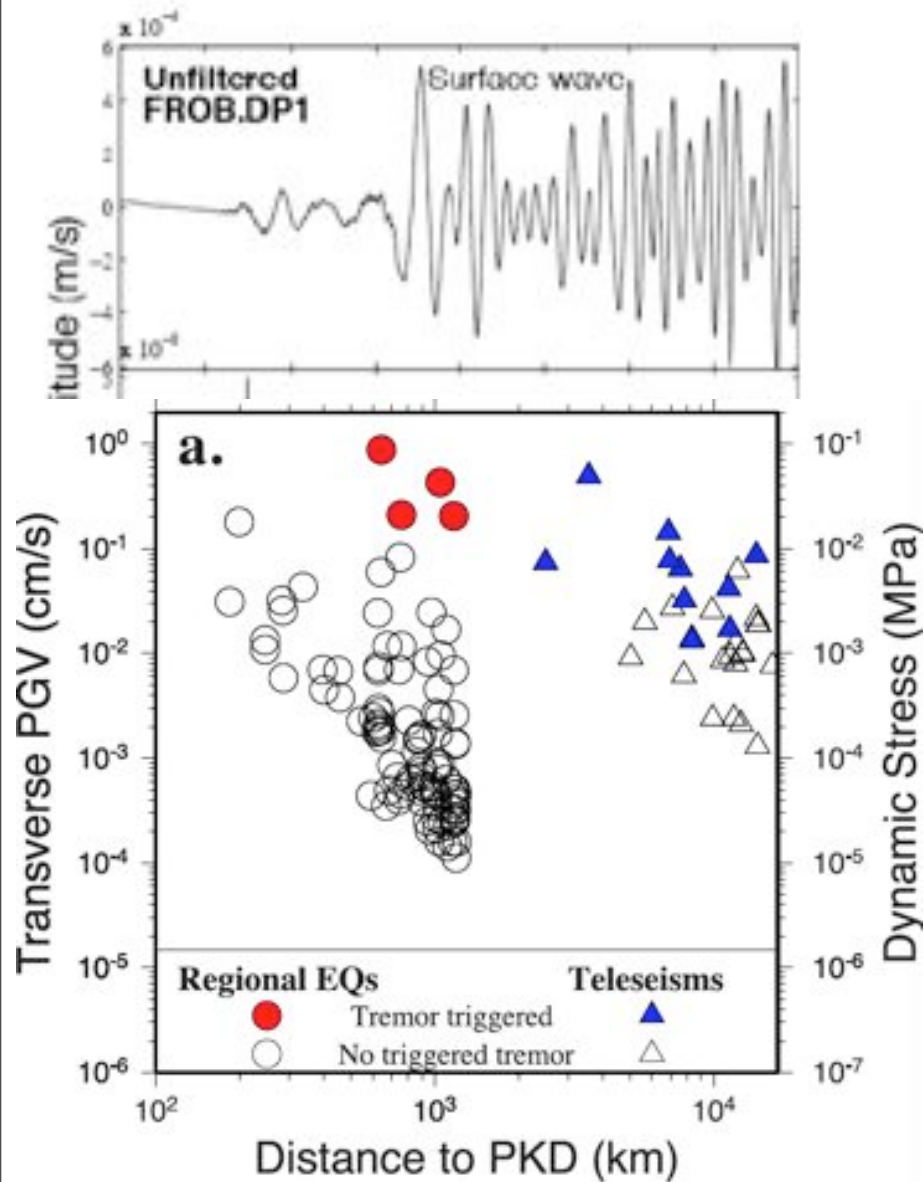


Guilhem et al., 2010

Shelly et al., 2010 submitted



# Triggering by Regional and Global Earthquakes

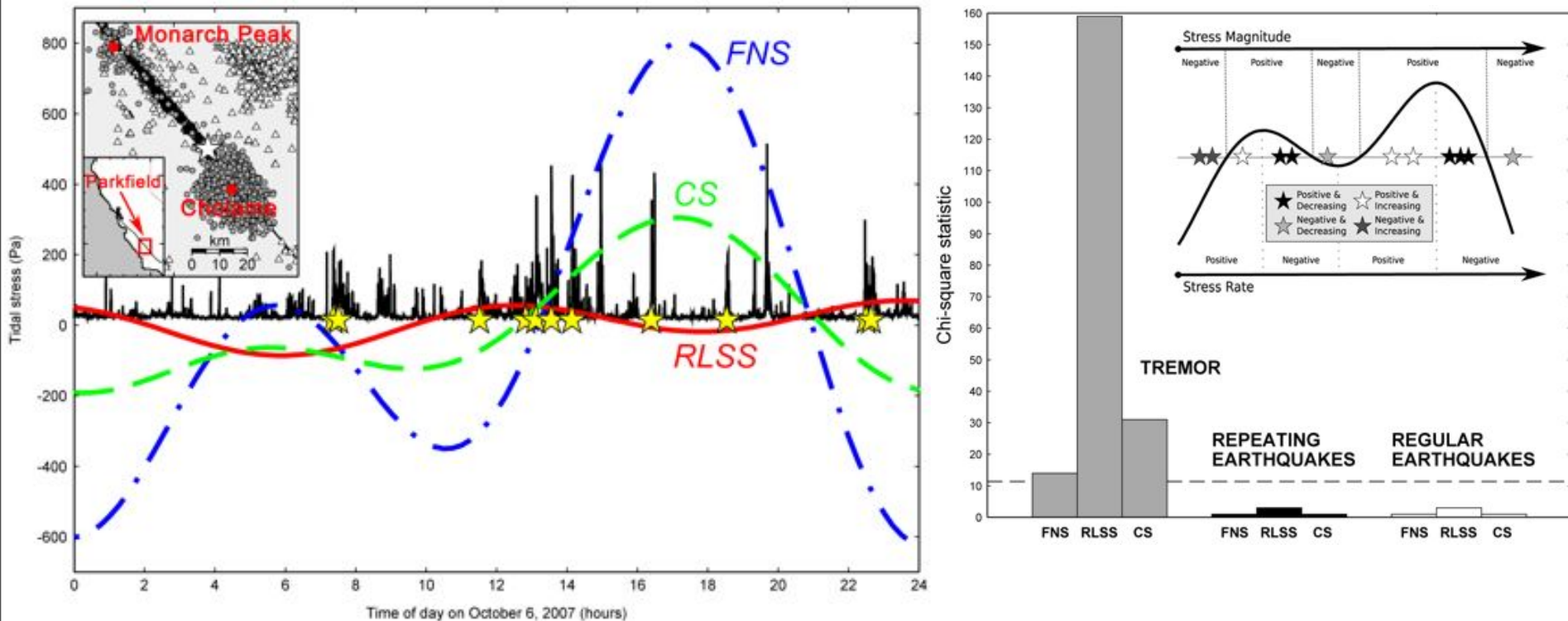


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Shelly et al., 2010 submitted

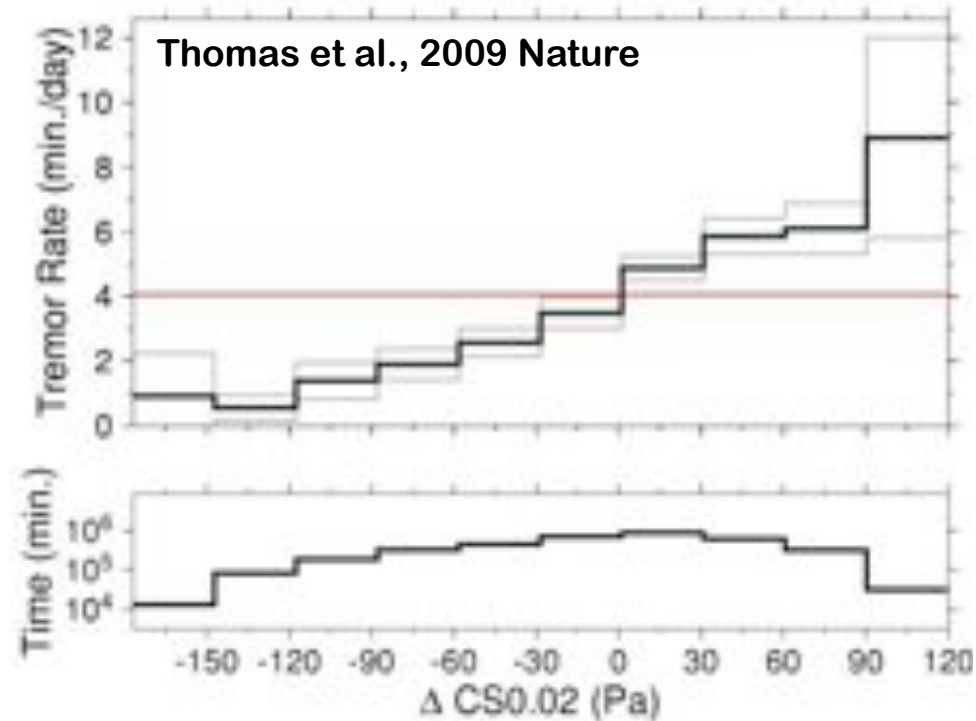
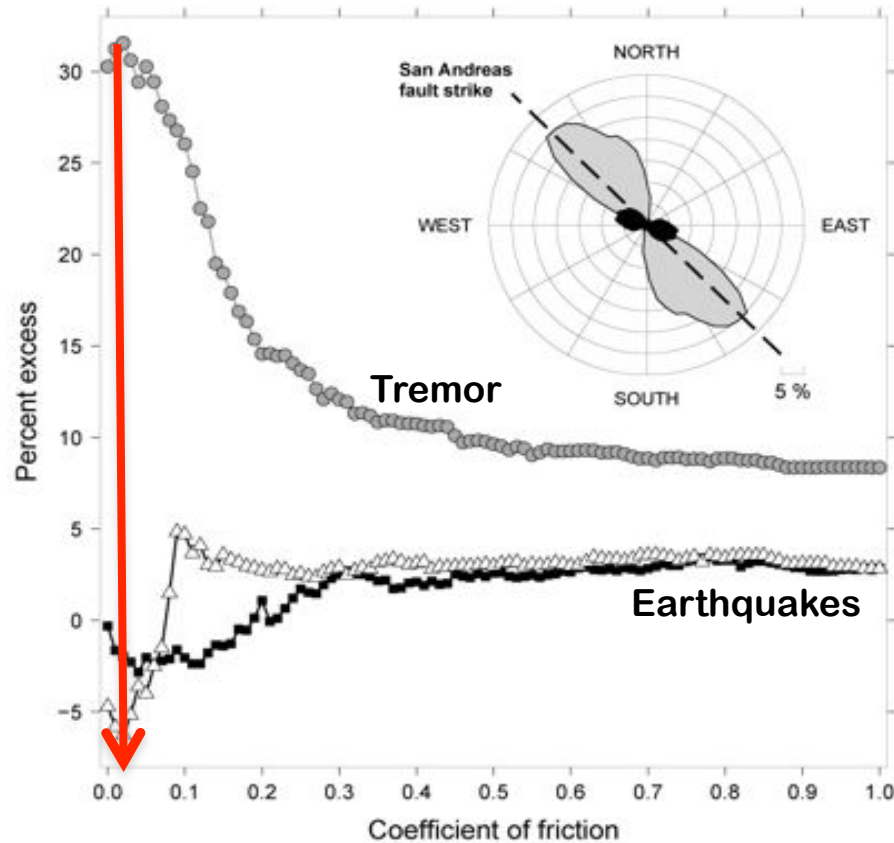
# Tremor-tide correlations and near-lithostatic pore pressure on the deep San Andreas fault

Amanda M. Thomas<sup>1</sup>, Robert M. Nadeau<sup>1</sup> & Roland Bürgmann<sup>1</sup>



- Tremors, but not earthquakes are easily triggered by tidal stress cycles
- Right-lateral shear stress ( $\leq 150$  Pa) parallel to SAF triggers tremor
- Almost no normal-stress triggering  $\rightarrow$  low friction  $\mu = 0.02$

# Friction and Effective Stress are Very Low

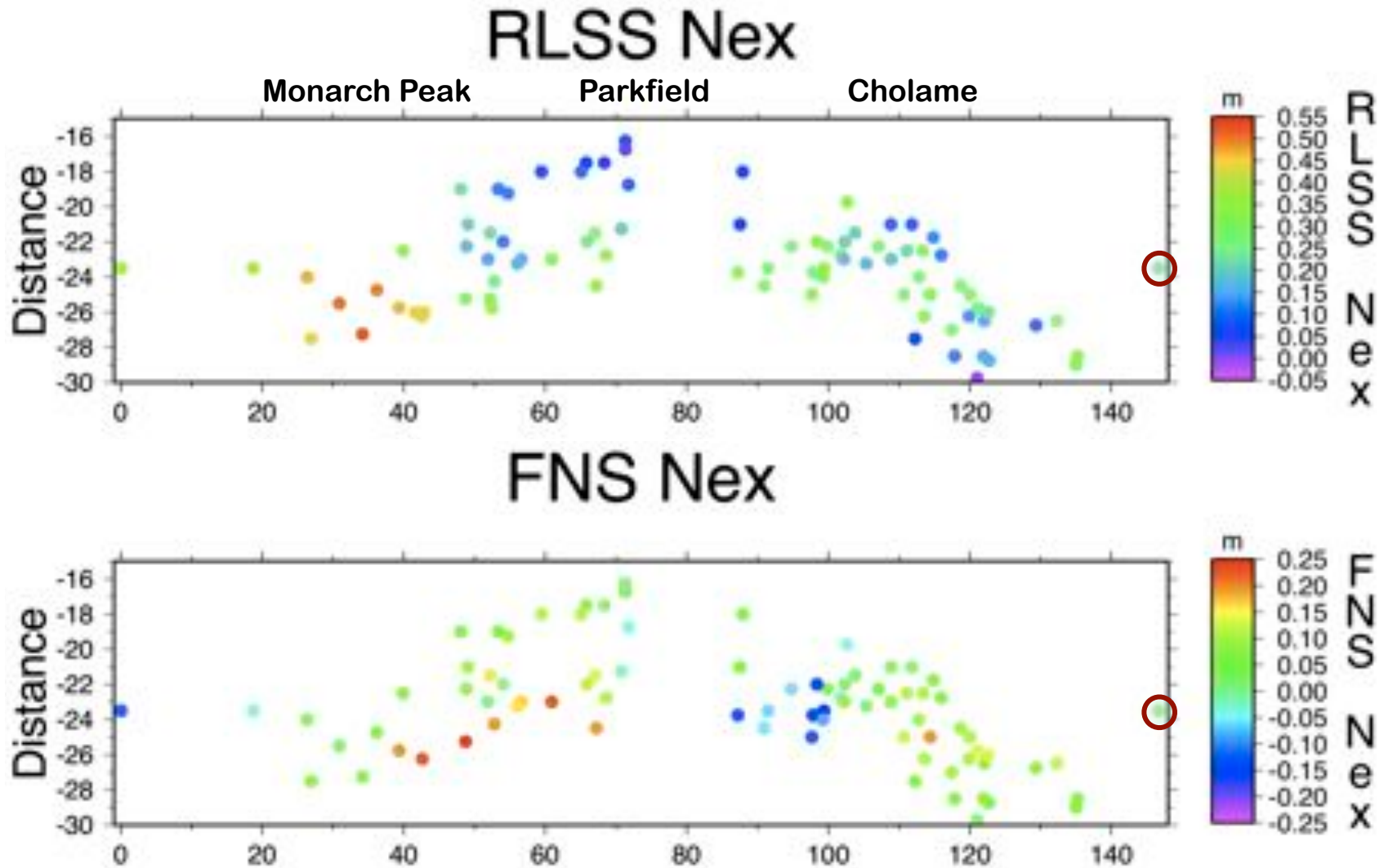


Overburden > 600 MPa  
(600,000,000 Pa)

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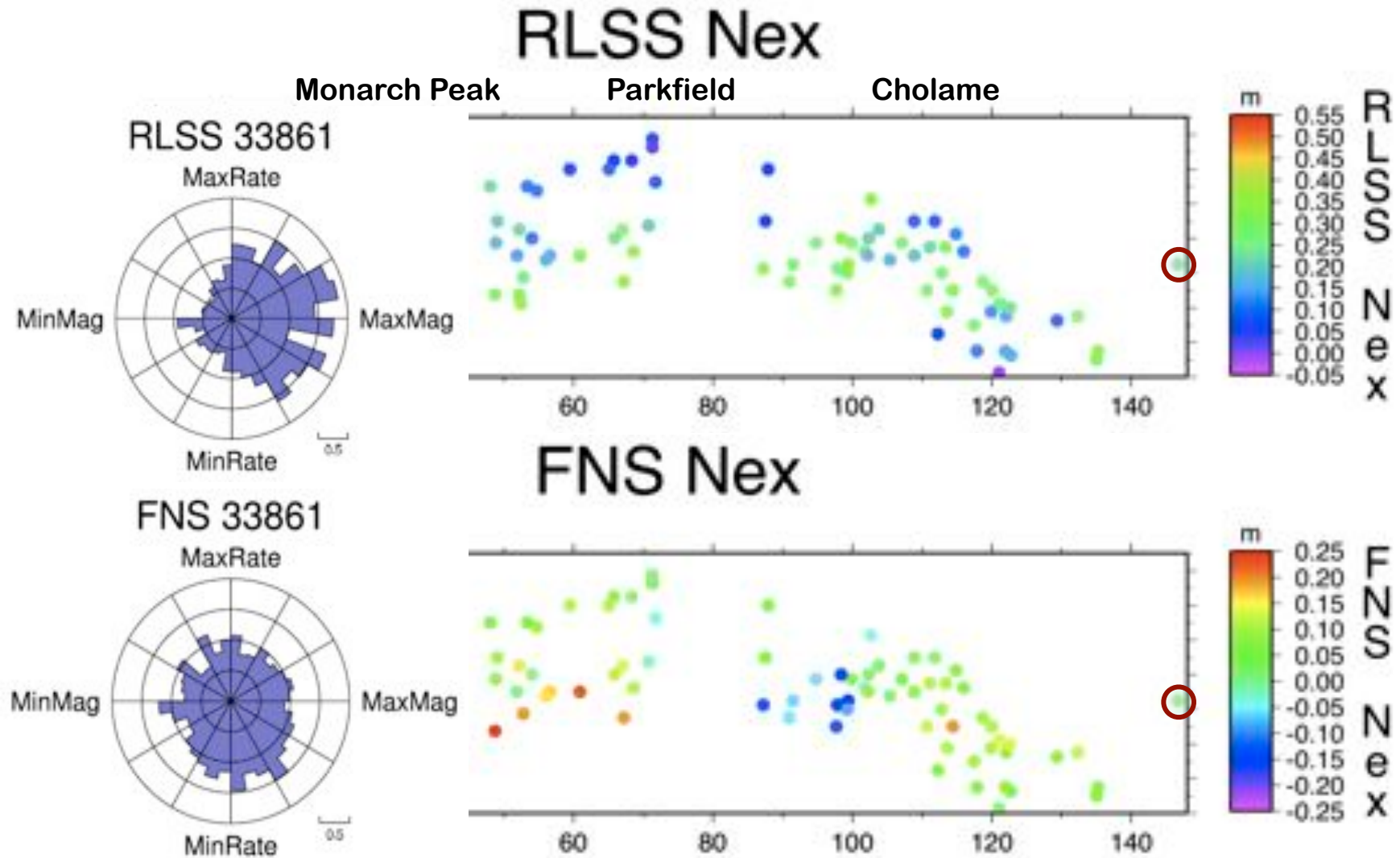
# Triggering is Spatially Heterogeneous



Thomas, Shelly & Bürgmann, 2010 SSA

- Variable tidal triggering of tremor with depth and along fault

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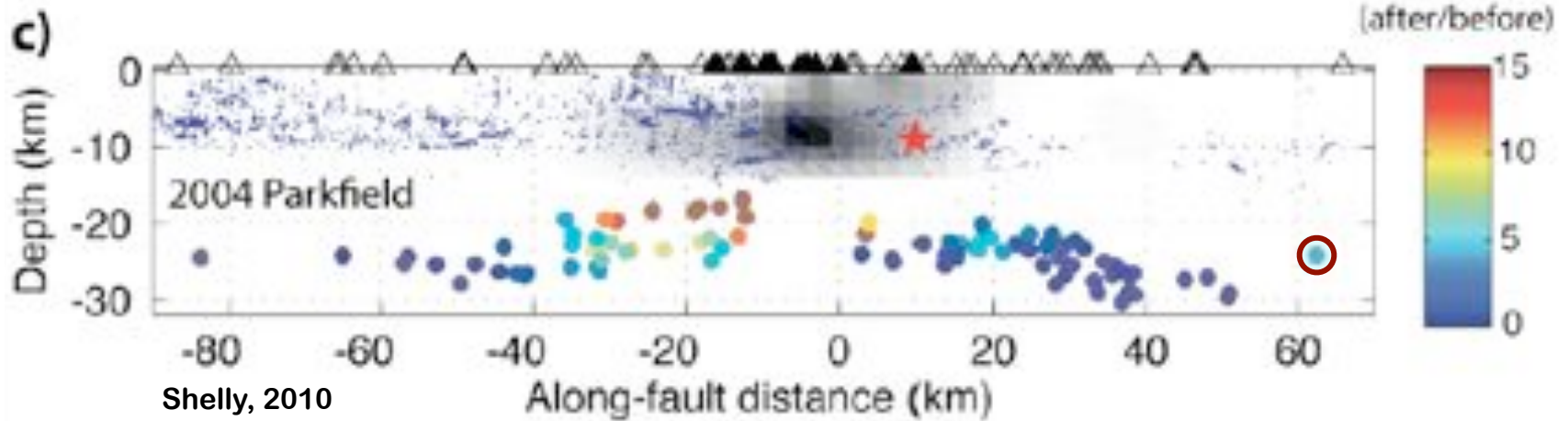
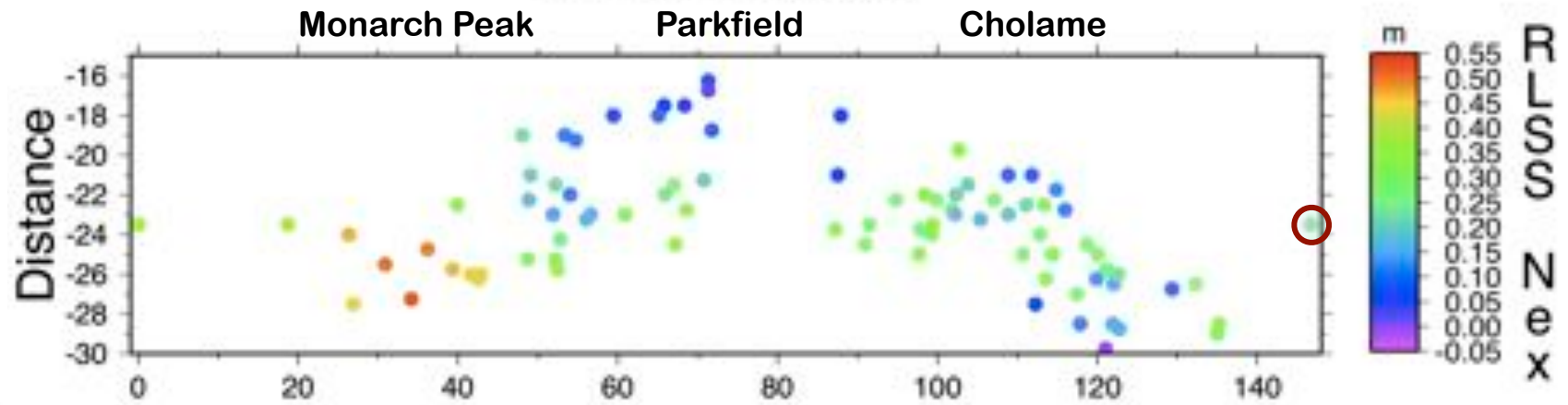


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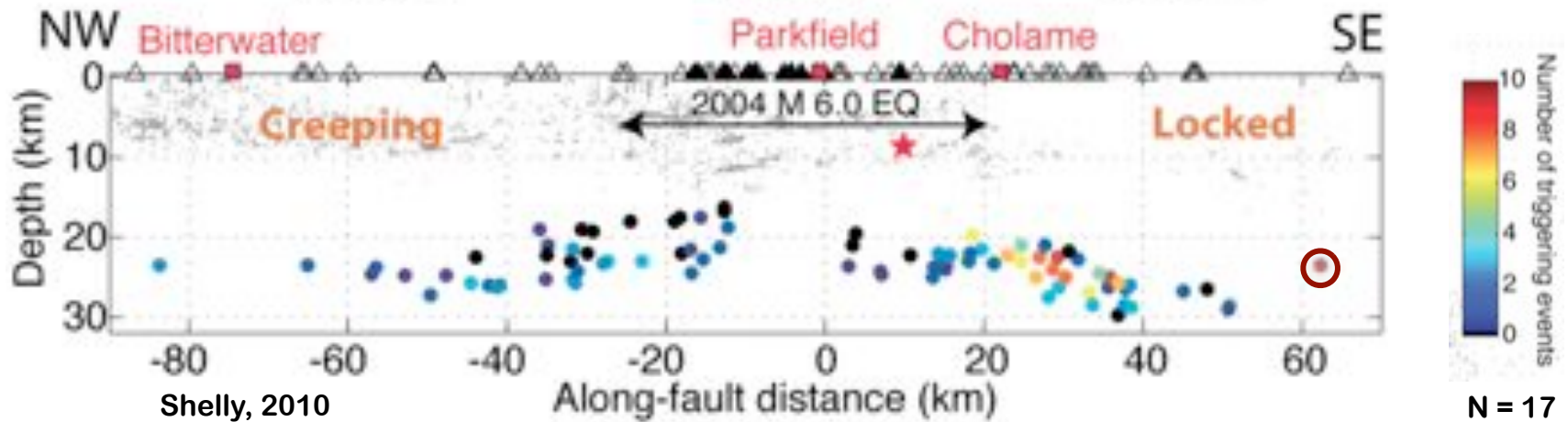
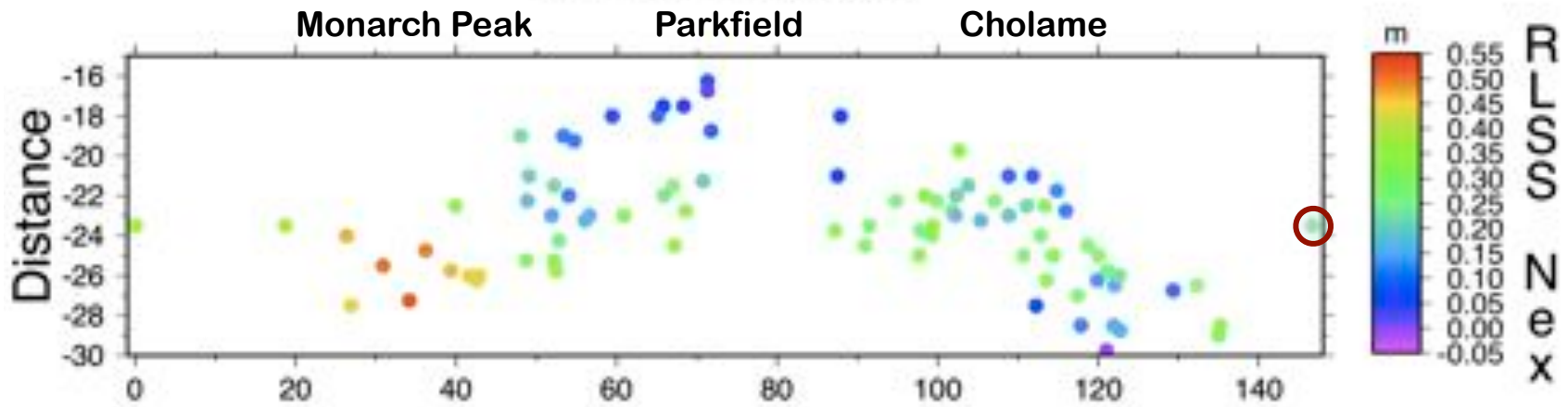
## RLSS Nex



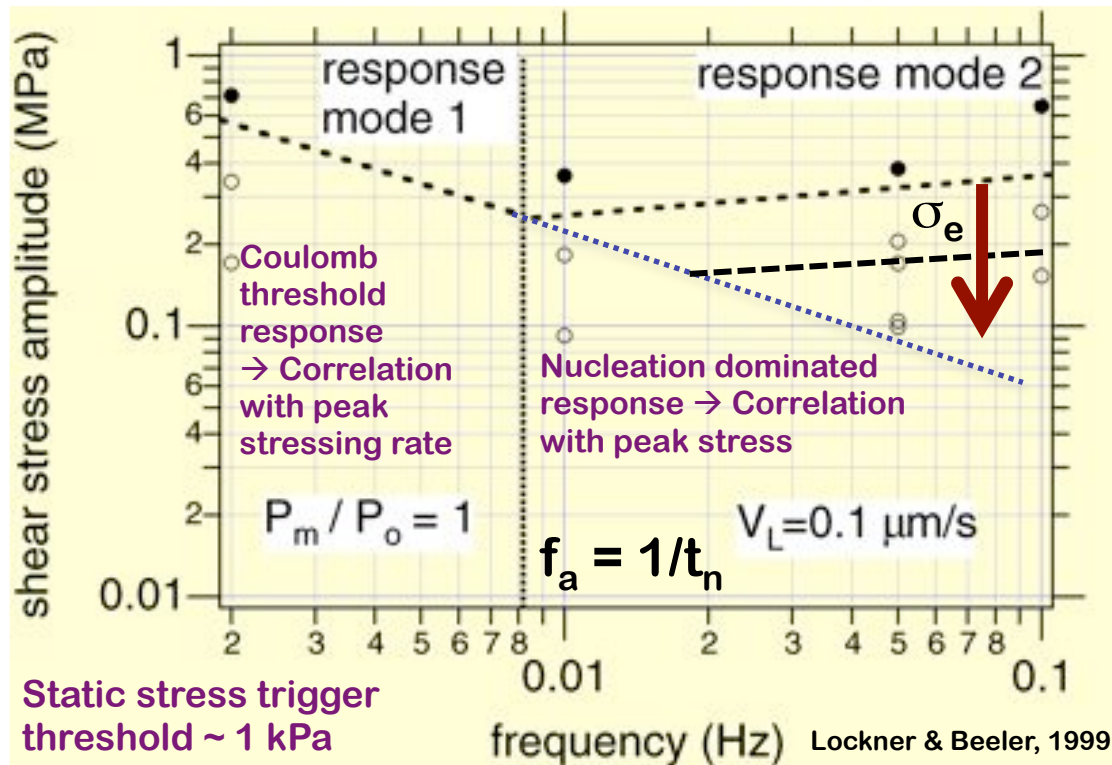


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## RLSS Nex



# Exploring Mechanical Behavior



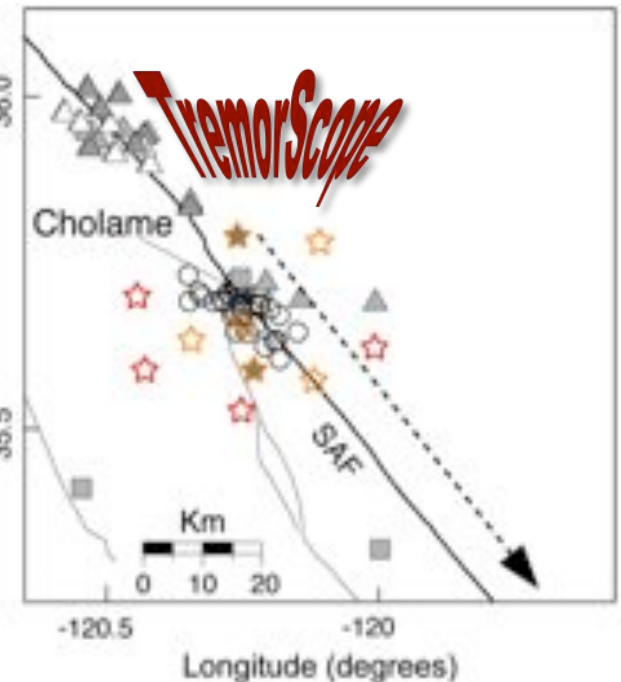
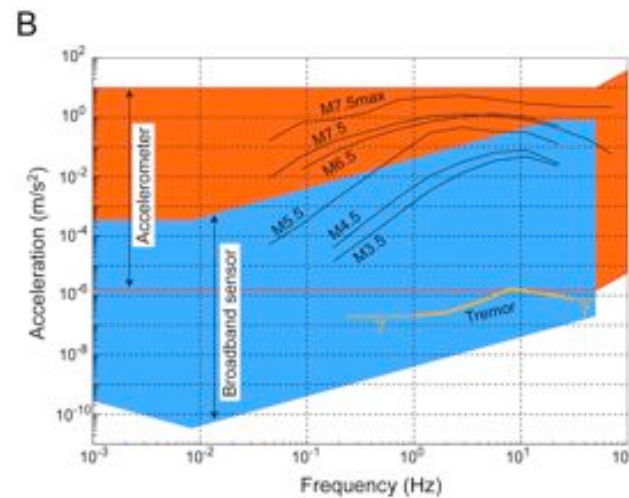
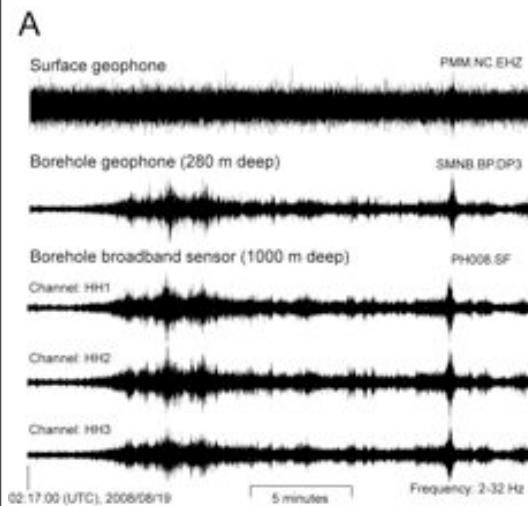
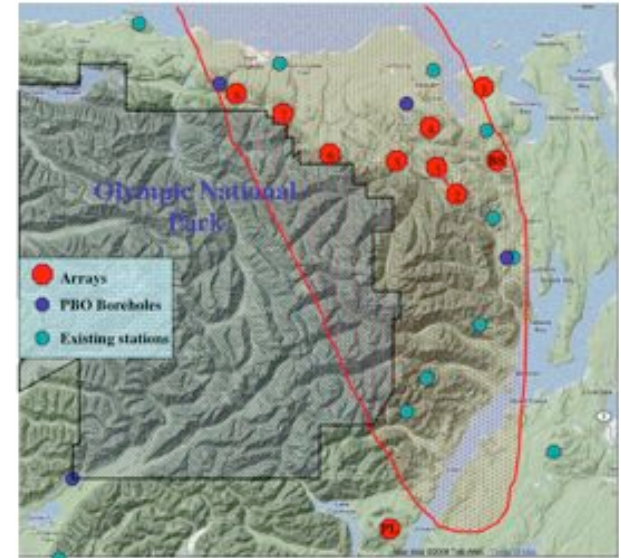
Triggering amplitude goes down with decreasing effective stress

$$f_a = \frac{\dot{\tau}}{2\pi a \sigma_e} \quad (\text{Dieterich, 1992})$$

- Observations of triggering by periodic forcings can be used to explore frictional properties of tremors
- Are LFE directly triggered or modulated by varying creep rate?

# Time to Build Tremor Observatories

- UW Array of Arrays
- Proposed TremorScope borehole/surface network
- We seek precise locations and detailed characterization of even the smallest tremor, LFE and VLF sources over long time period
- Tremor and earthquake data can be used to illuminate crustal structure and environment using receiver functions and seismic/ambient noise tomography





# Triggering and Modulation of Slow Slip: Implications for Mechanics and Hazard



- (1) We should optimize our observational tools for study of TFS and tremor**
- (2) Most important on the path ahead is to seek connections and build bridges between seismologic, geodetic and geologic observations and laboratory and modeling studies**

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