The Growing Wealth of Aseismic Deformation Data: What's a Modeler to Model?

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Topics

- Pre-earthquake deformation-rate changes
  - Some credible examples
- High-resolution crustal deformation observations
  - borehole strain
  - fluid pressure data
- Aseismic processes linking mainshocks to aftershocks
- Observations possibly related to dynamic triggering

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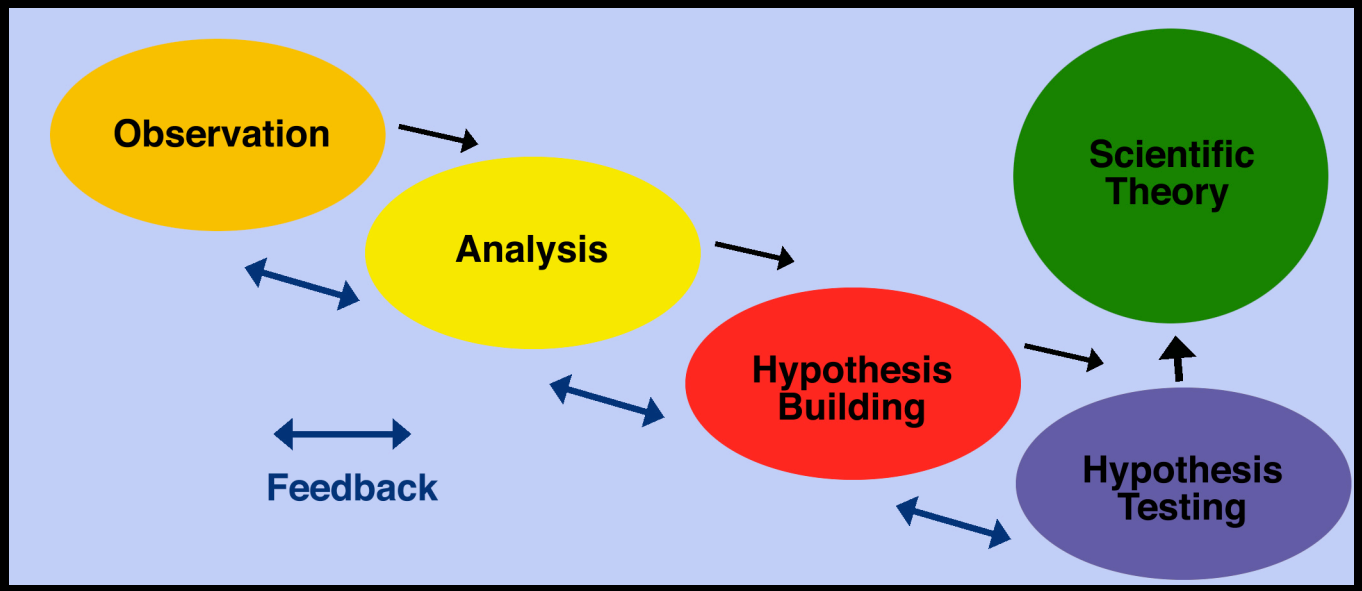
The Scientific Method

- The "hypothesis-testing" stage is a bottleneck for earthquake research because data are hard to obtain



- Modeling has a role in the hypothesis-building stage

http://www.indiana.edu/~geol116/

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Modeling needs to lead data collection

- Compared to acquiring high resolution deformation data in the near field of large earthquakes, modeling is fast and inexpensive
- So modeling should perhaps get ahead of reproducing observations
- Or modeling could look harder at observations that are significant but controversial, and could explore a wider range of hypotheses

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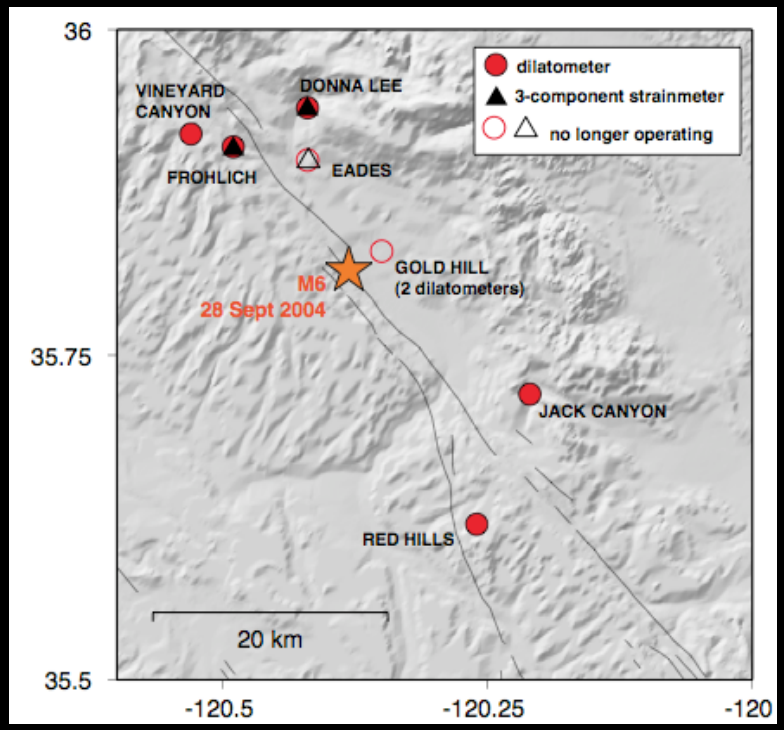
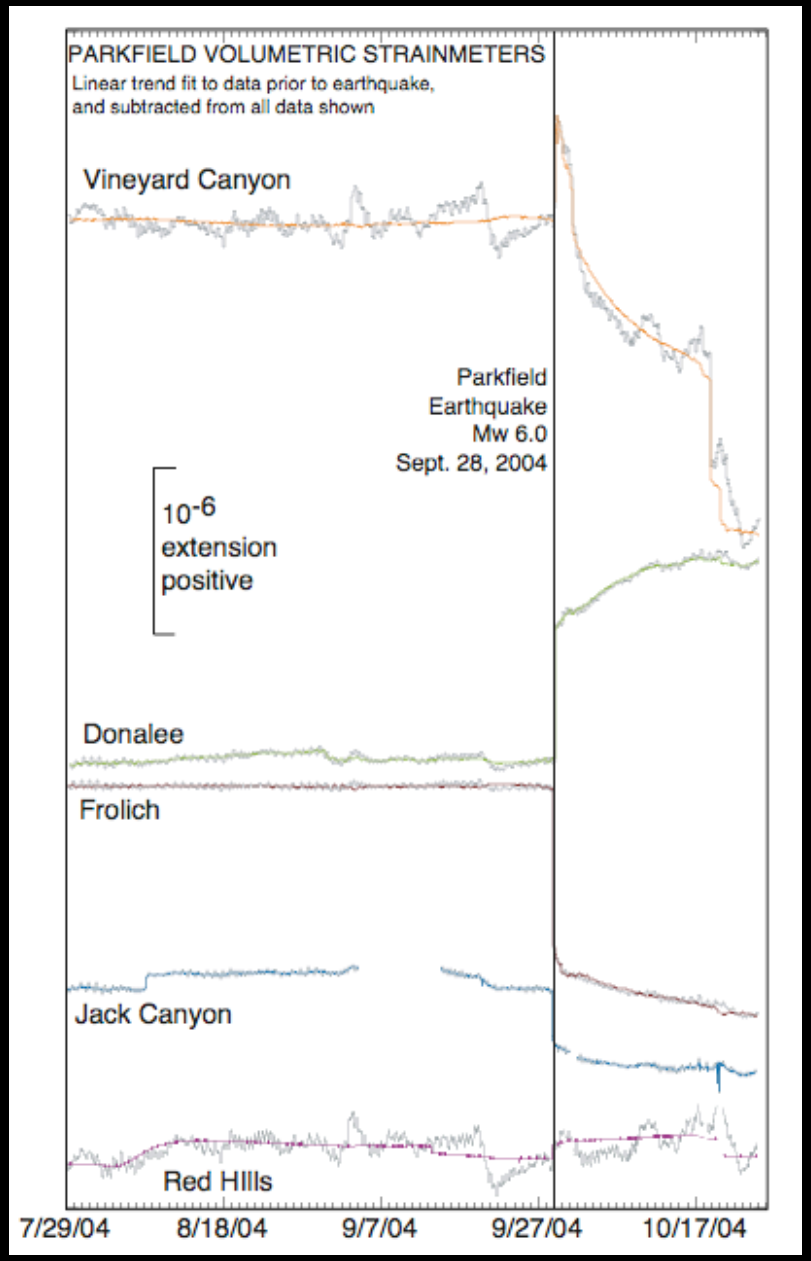
Earthquakes can happen without detectable pre-earthquake changes





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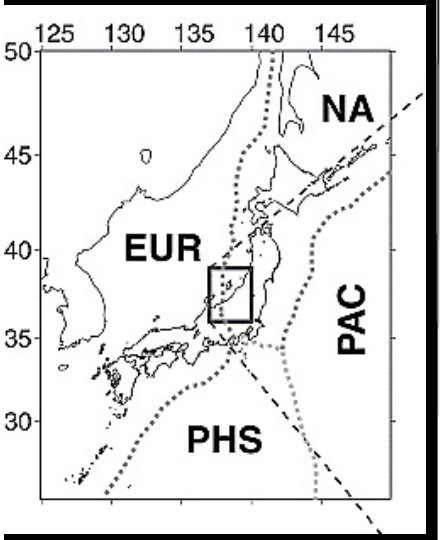
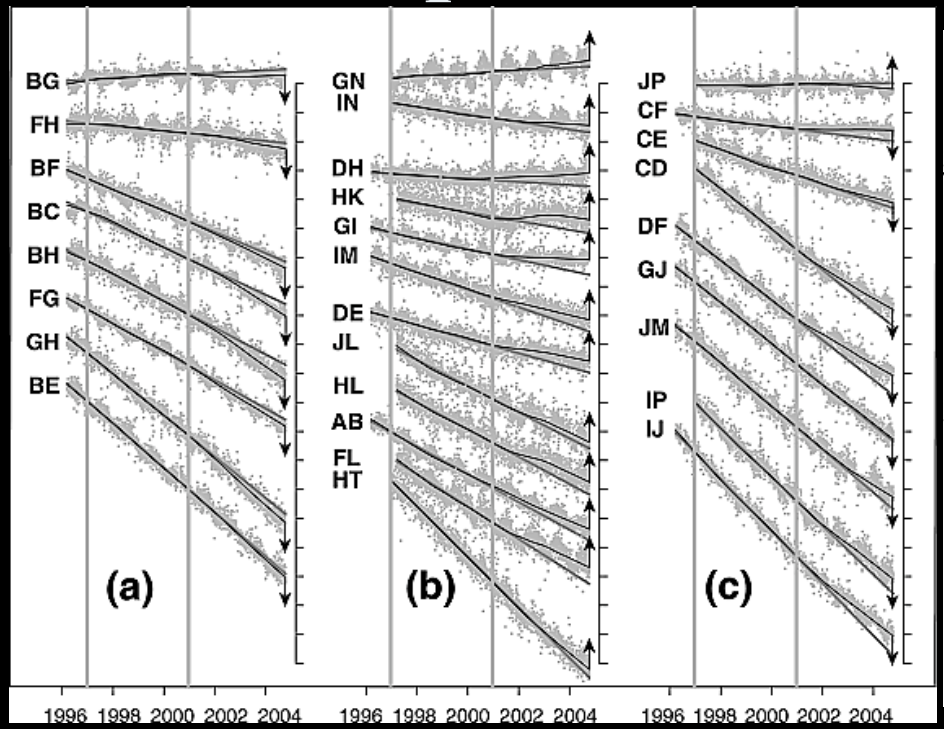
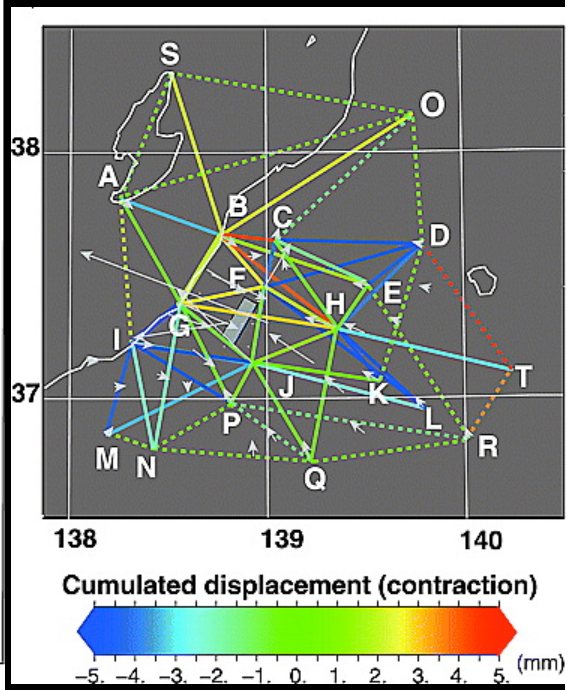
e.g.Parkfield M6 2004

Deformation-Rate Changes before the Mw 6.6 Chuetsu earthquake, 23 October 2004



Ogata, JGR 2007





- Intraplate thrust earthquake, depth 11 km
- GPS-detected rate changes about 3 years earlier
  - Moment of pre-slip approximately Mw 6.0 (1 div=1 cm)
  - deviations mostly in direction of coseismic displacement
  - not all consistent with pre-slip on the rupture plane

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Great Subduction Earthquakes with Evidence for Pre-Earthquake Aseismic Deformation-Rate Changes

- Chile 1960, M_w9.2
  - 20-30 m of slow interplate slip over a rupture zone 920+/-100 km long, starting 20 minutes prior to mainshock [Kanamori & Cipar (1974); Kanamori & Anderson (1975); Cifuentes & Silver (1989)]
  - 33-hour foreshock sequence north of the mainshock, propagating toward the mainshock hypocenter at 86 km day^{-1} (Cifuentes, 1989)
- Alaska 1964, M_w9.2
- Cascadia 1700, M9

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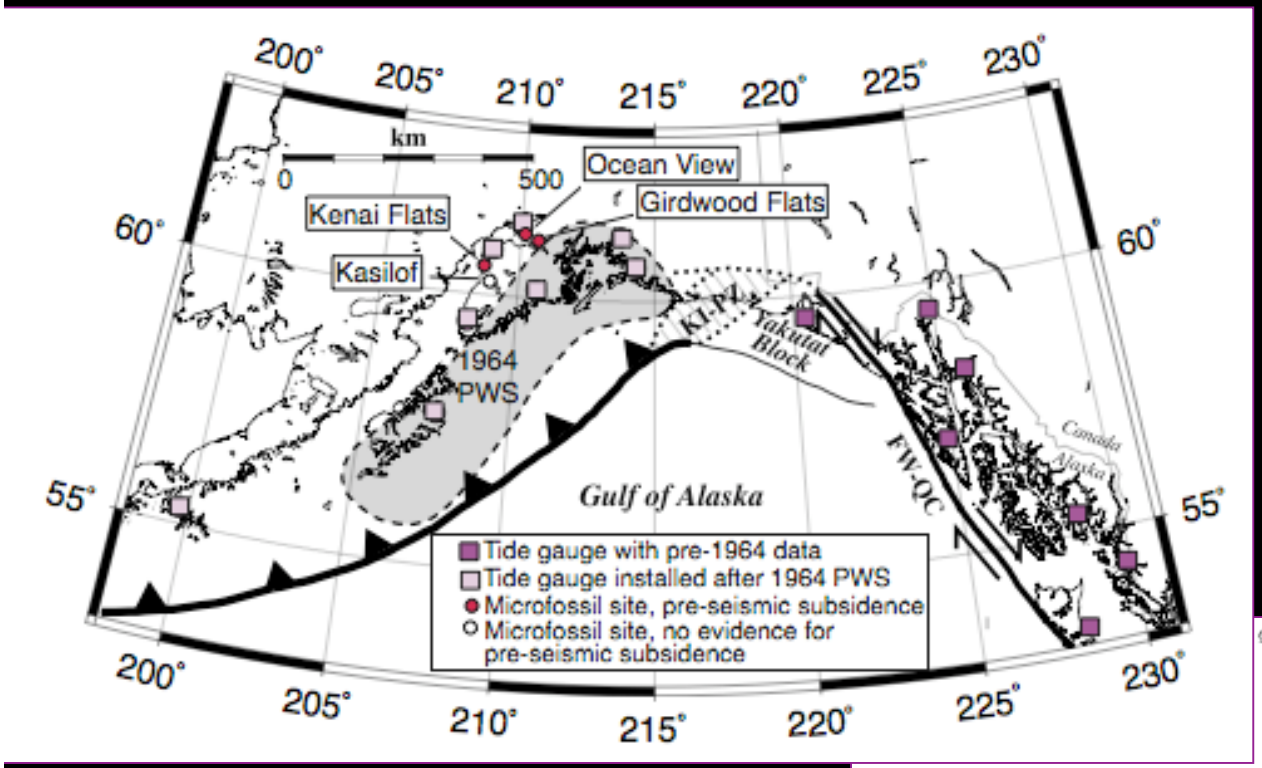
Microfossils => Sea level rise before1964 Alaska M9.2



- 0.12± 0.13 m sea level rise at 4 sites between 1952 and 1964

Hamilton et al. 2005

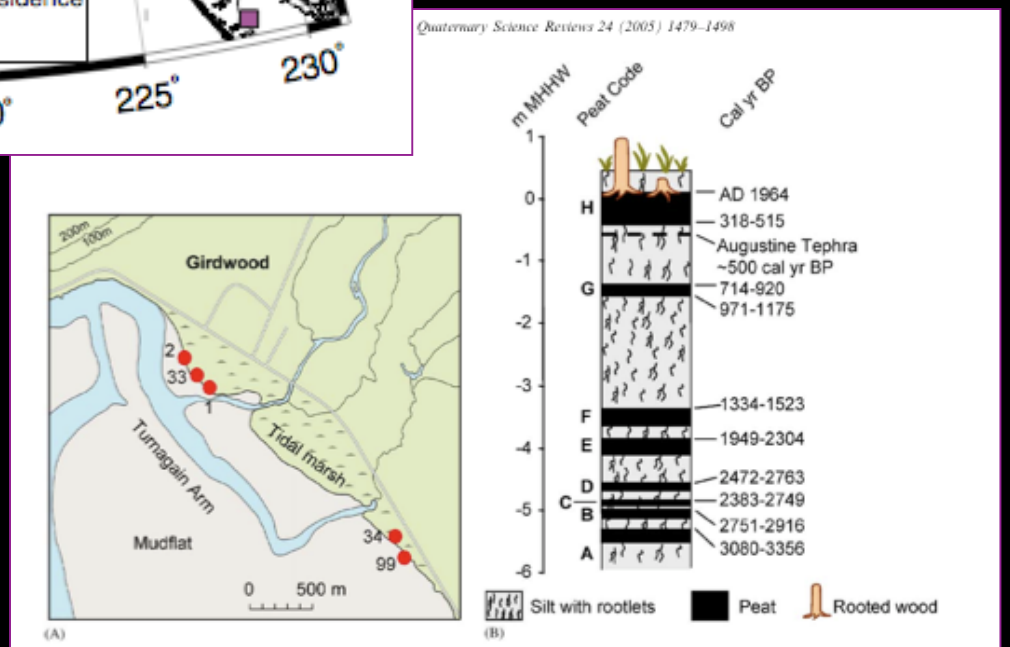


Fig. 8. Location of sampling sites (A) and composite section (B) showing buried peat layers beneath the marsh surface at Girdwood site GW-2. Peats G and H were also exposed and sampled at GW-1. GW-33 and 34 are sites reported by Zong et al. (2003) and GW-99 by Shennan et al. (1999).

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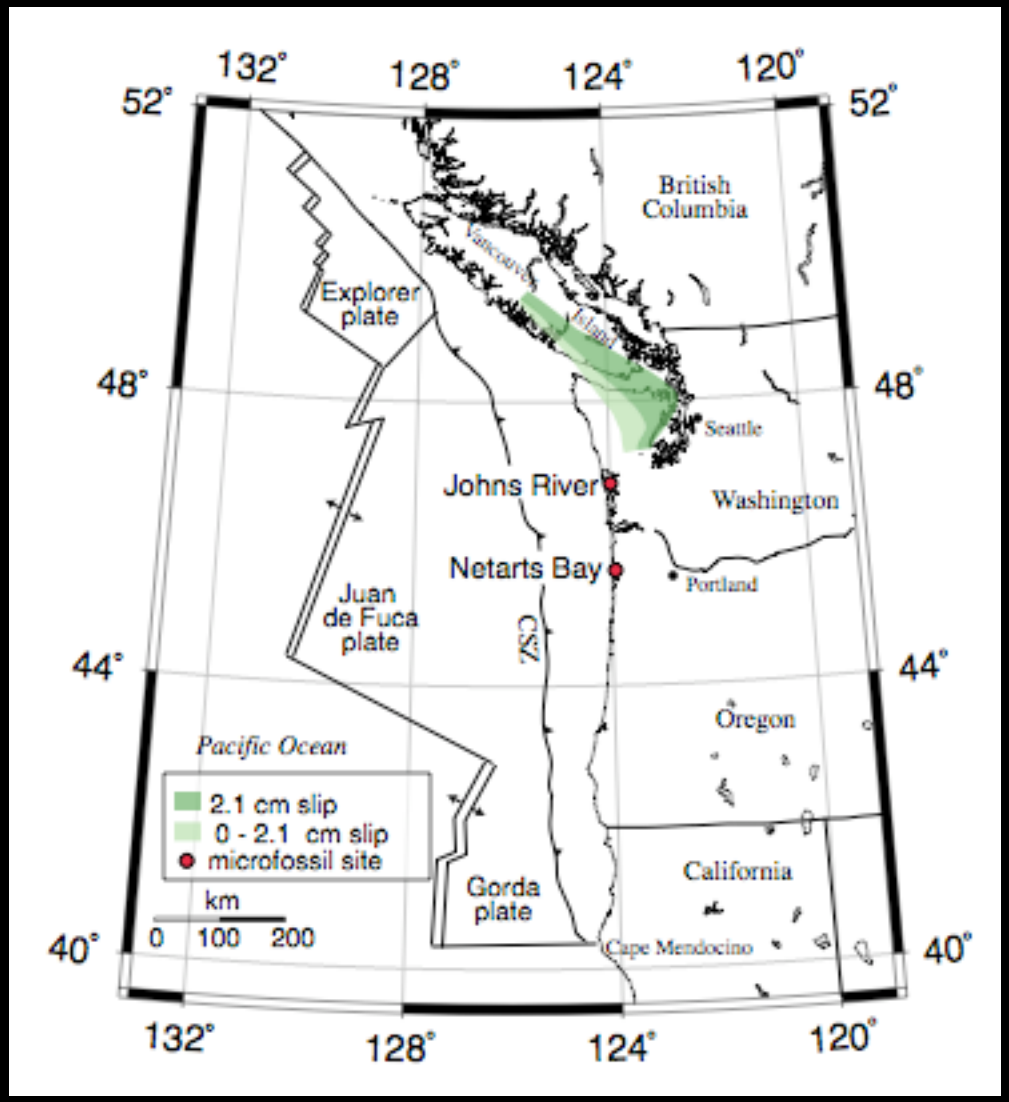
Cascadia Microfossil Studies



- Microfossils from sites at Netarts Bay show evidence for preseismic sea-level rise
- Time scale indeterminate

Shennan et al., 1996, 1998

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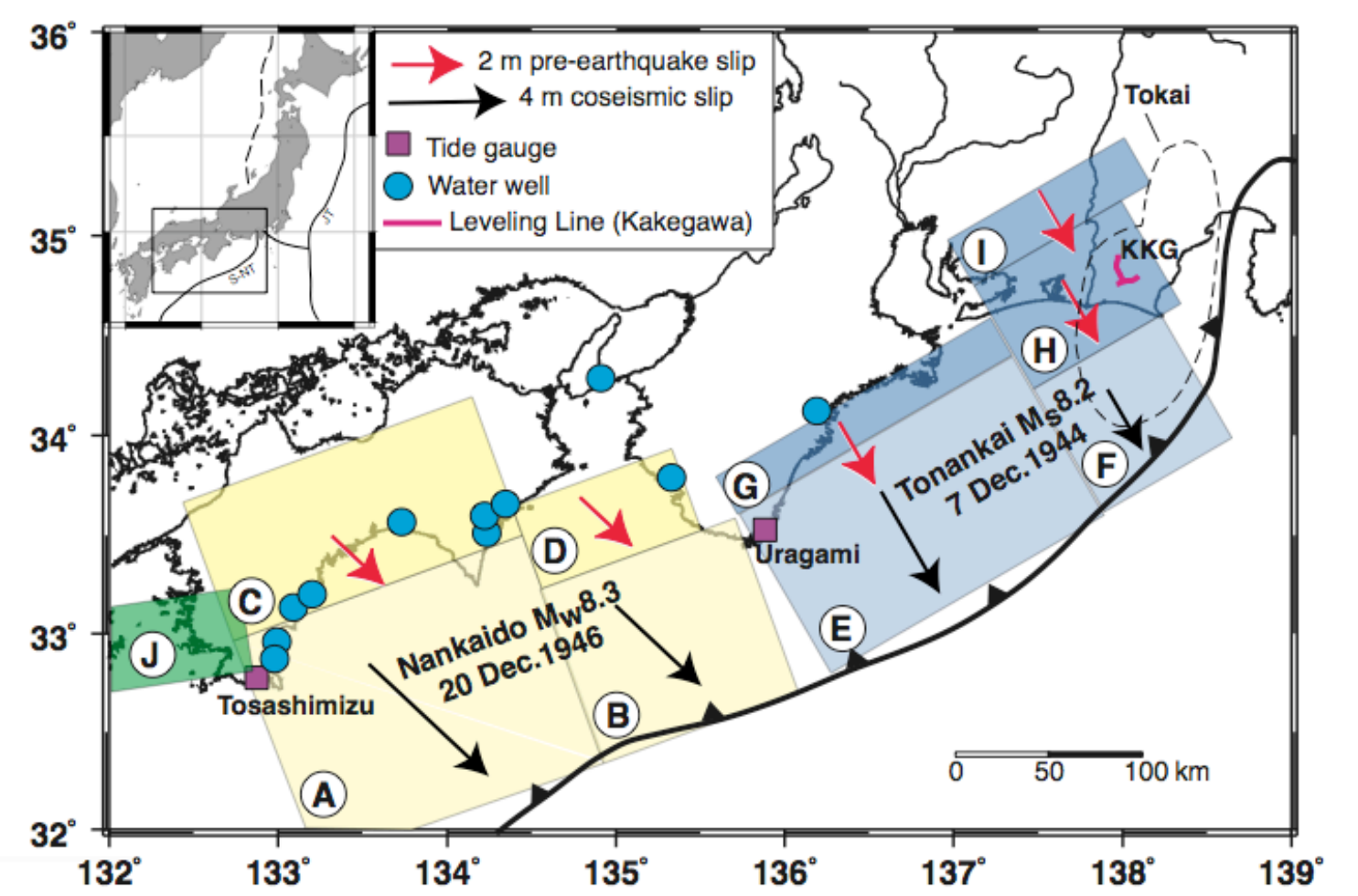
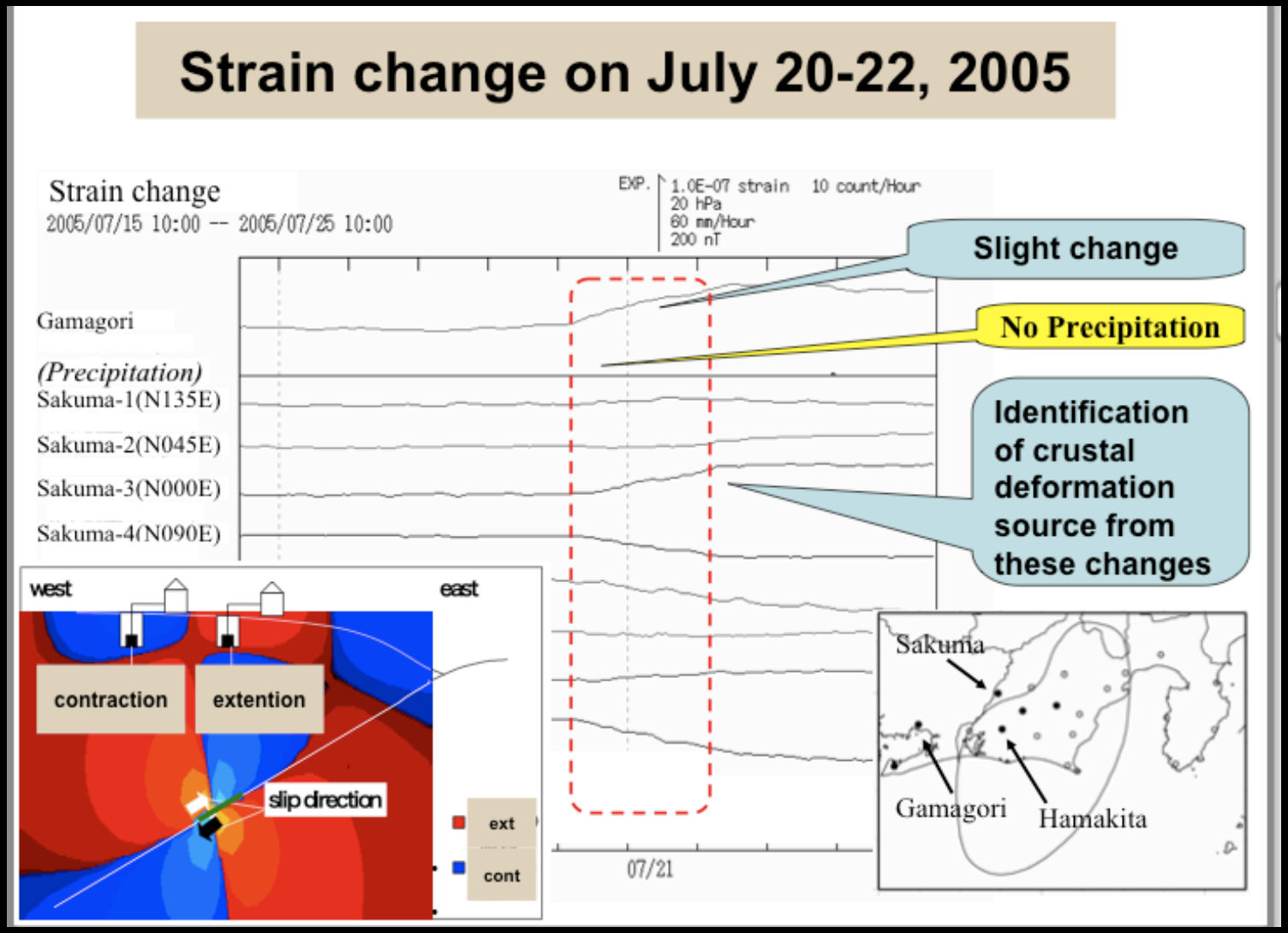
1944 Tonankai (Ms 8.2) & 1946 Nankaido (Mw 8.3)



(Inferred locations of preseismic slip from Linde & Sacks 2002)

Tokai Experiment Watches Slow Slip



M. Hoshiba, presentation at UJNR Workshop 2006

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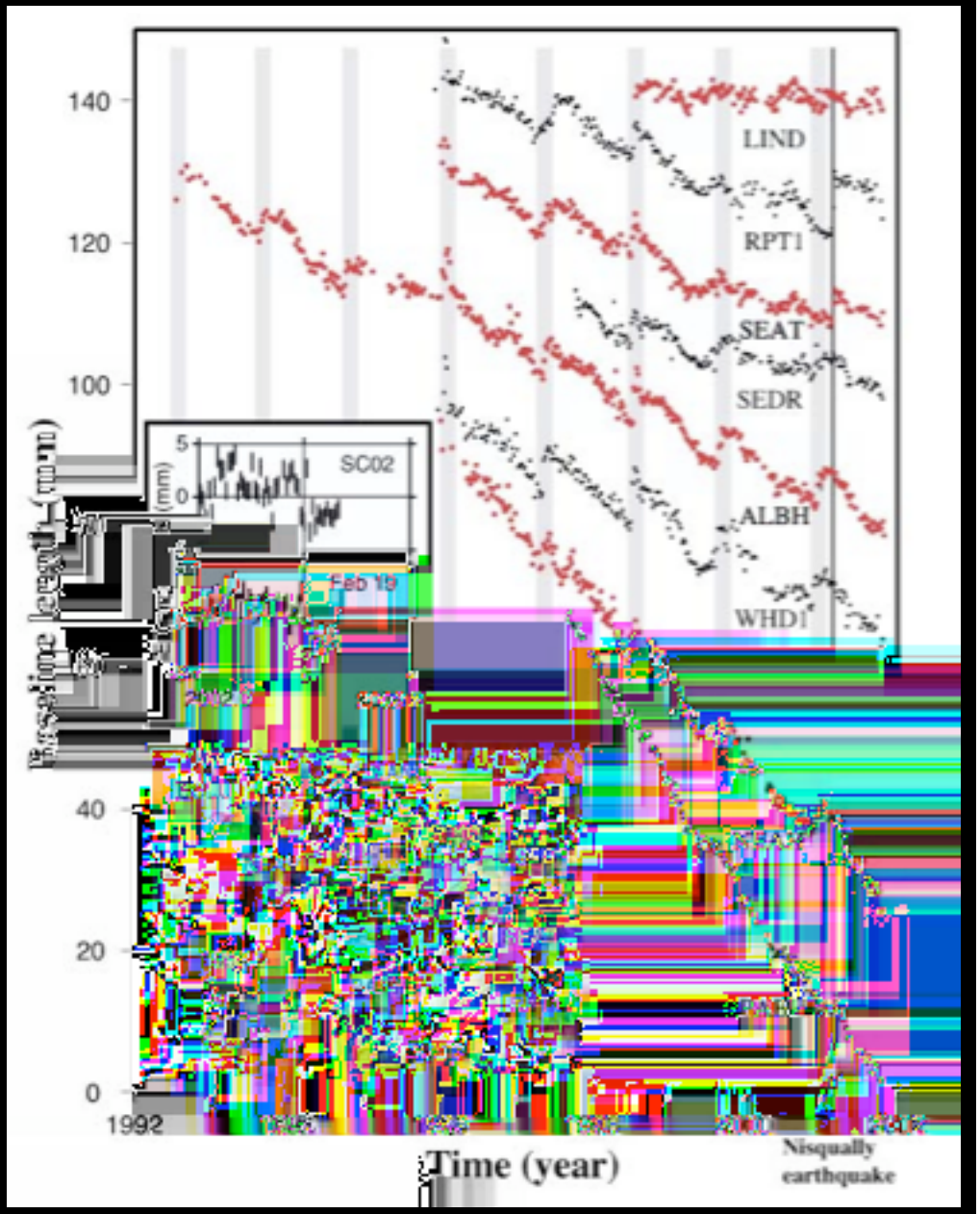
Cascadia Slow Slip Events

- Recur about every 14 months in northern Washington and Vancouver Island
- Generally accompanied by seismic tremor



Miller, Melbourne, Johnson and Sumner, 2002

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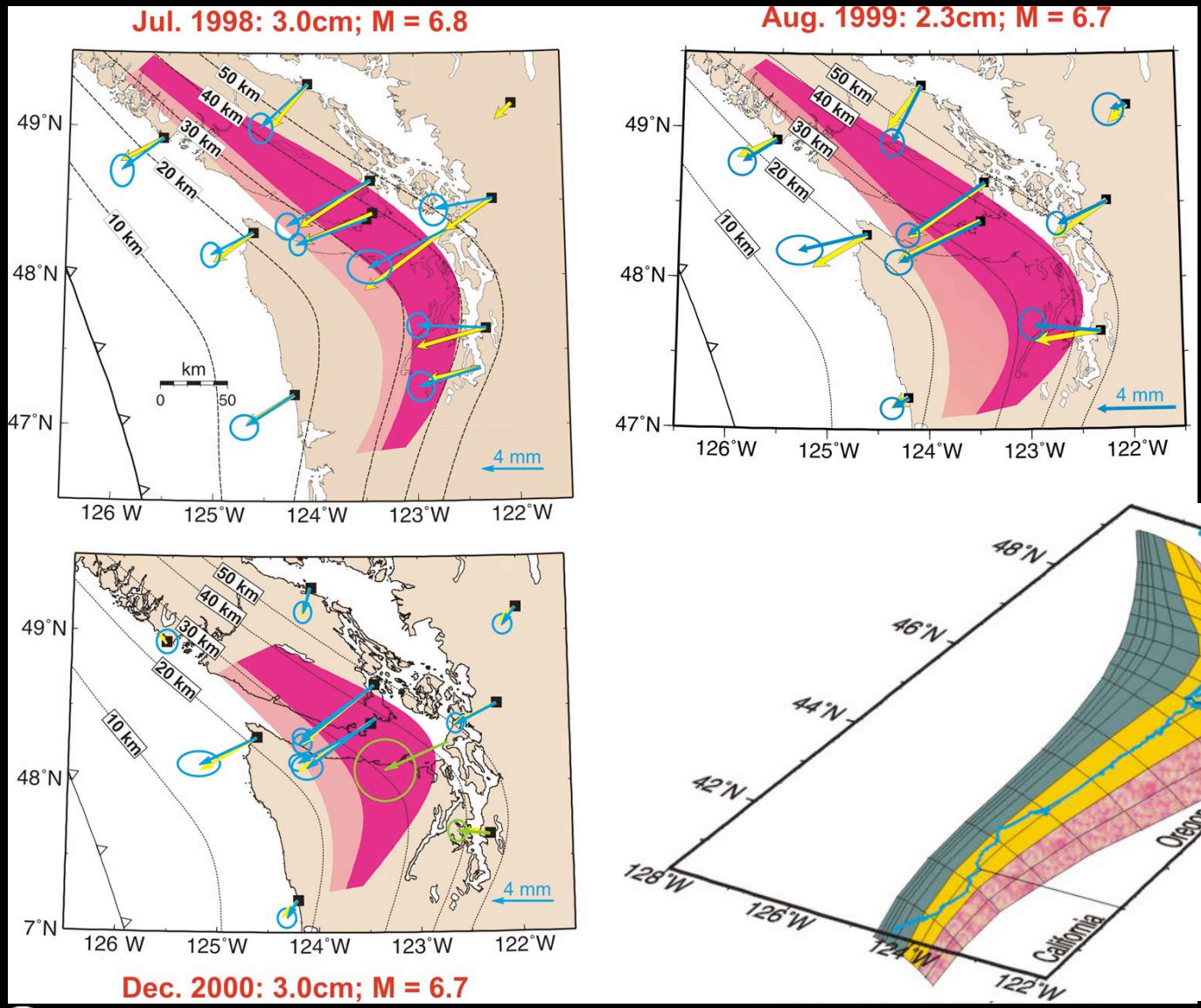
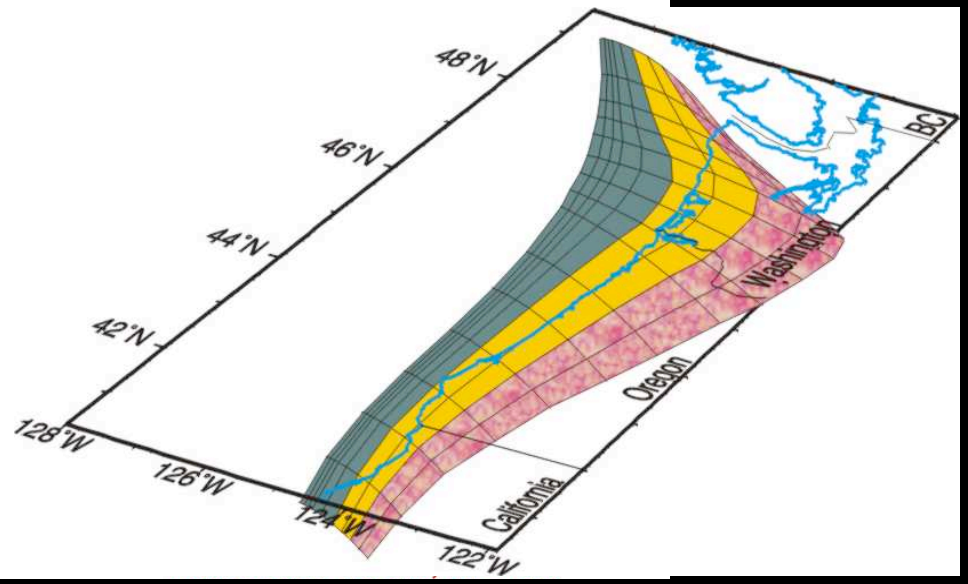
Elastic Dislocation Models for Slip Events
(constrained to the subduction interface)





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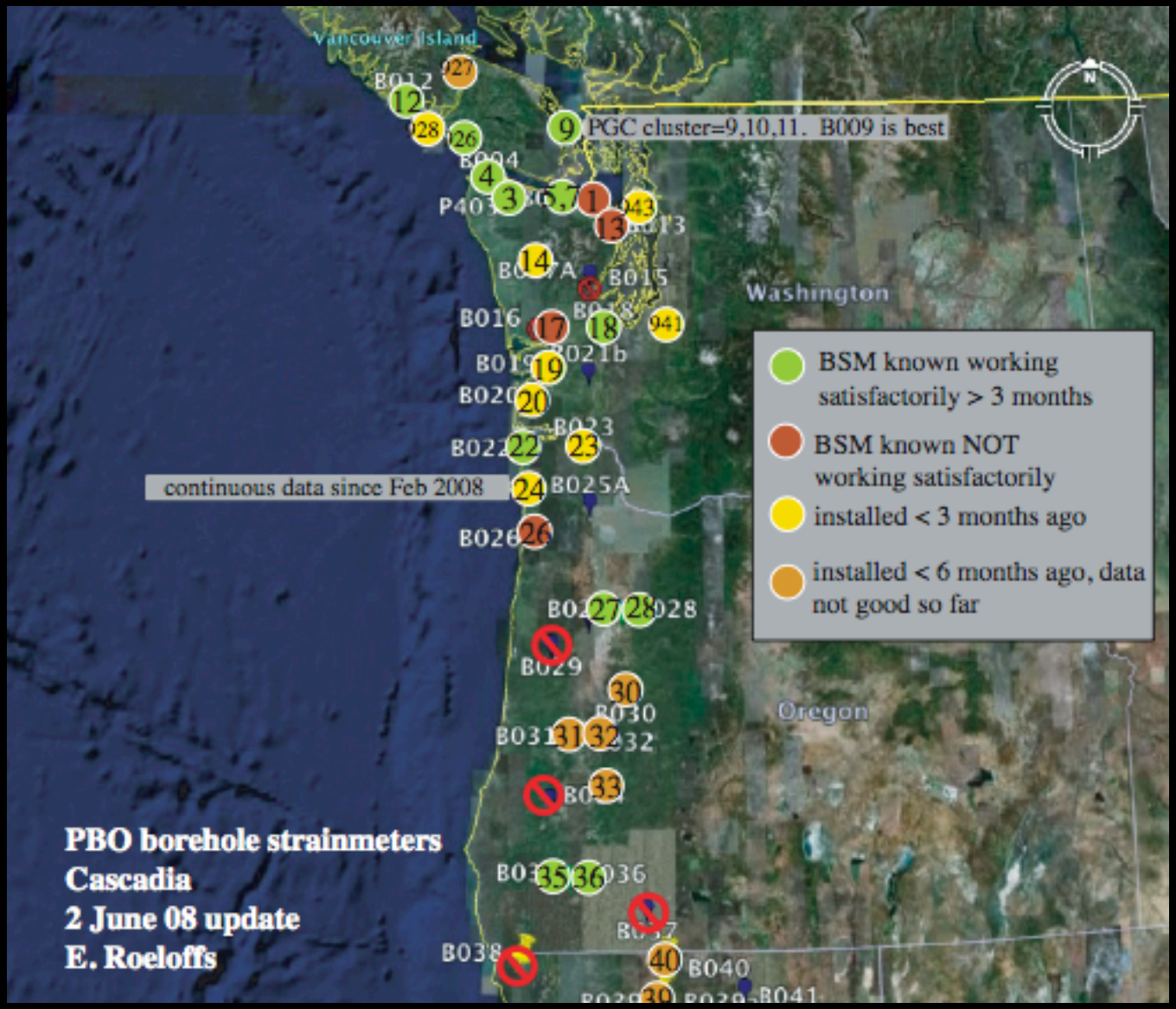
Dragert et al., presentation at ETS Workshop 2008

PBO Borehole Strain Network-Cascadia



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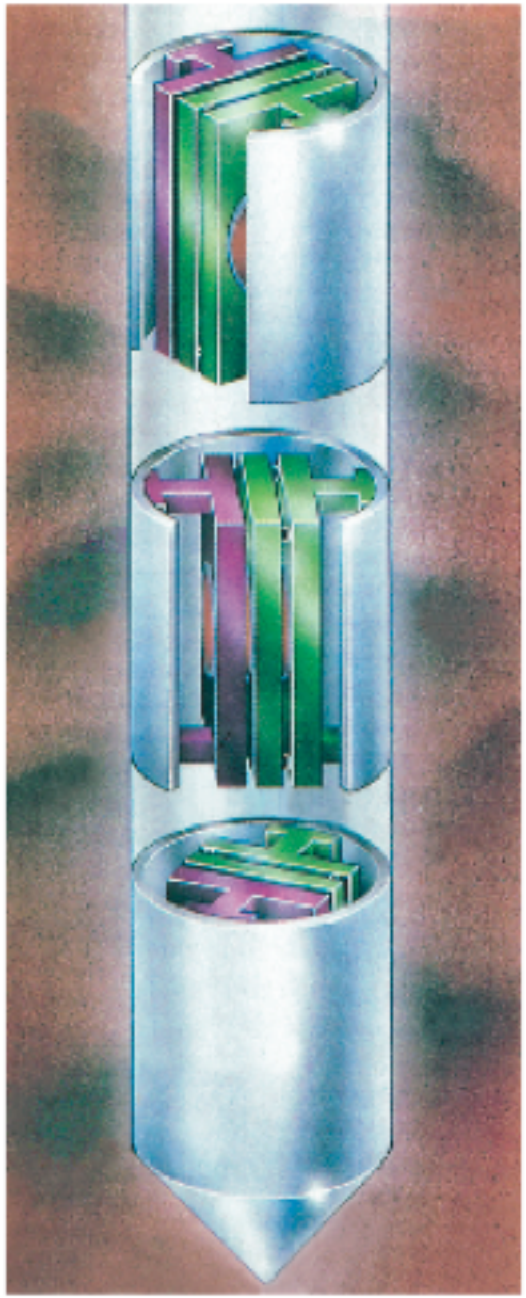
Strainmeter Diagram

- Designed by M.T. Gladwin
- Variable Capacitance Sensors
- Resolution better than 1 nanostrain
- Frequency Ranges:
  - "High Frequency" (20 sps)
  - "Tidal" (3 days to 1 hour)
  - "Intermediate Term" (3 months to 3 days)
  - "Long Term" (> 3 months)
    - Cannot measure absolute strain rates



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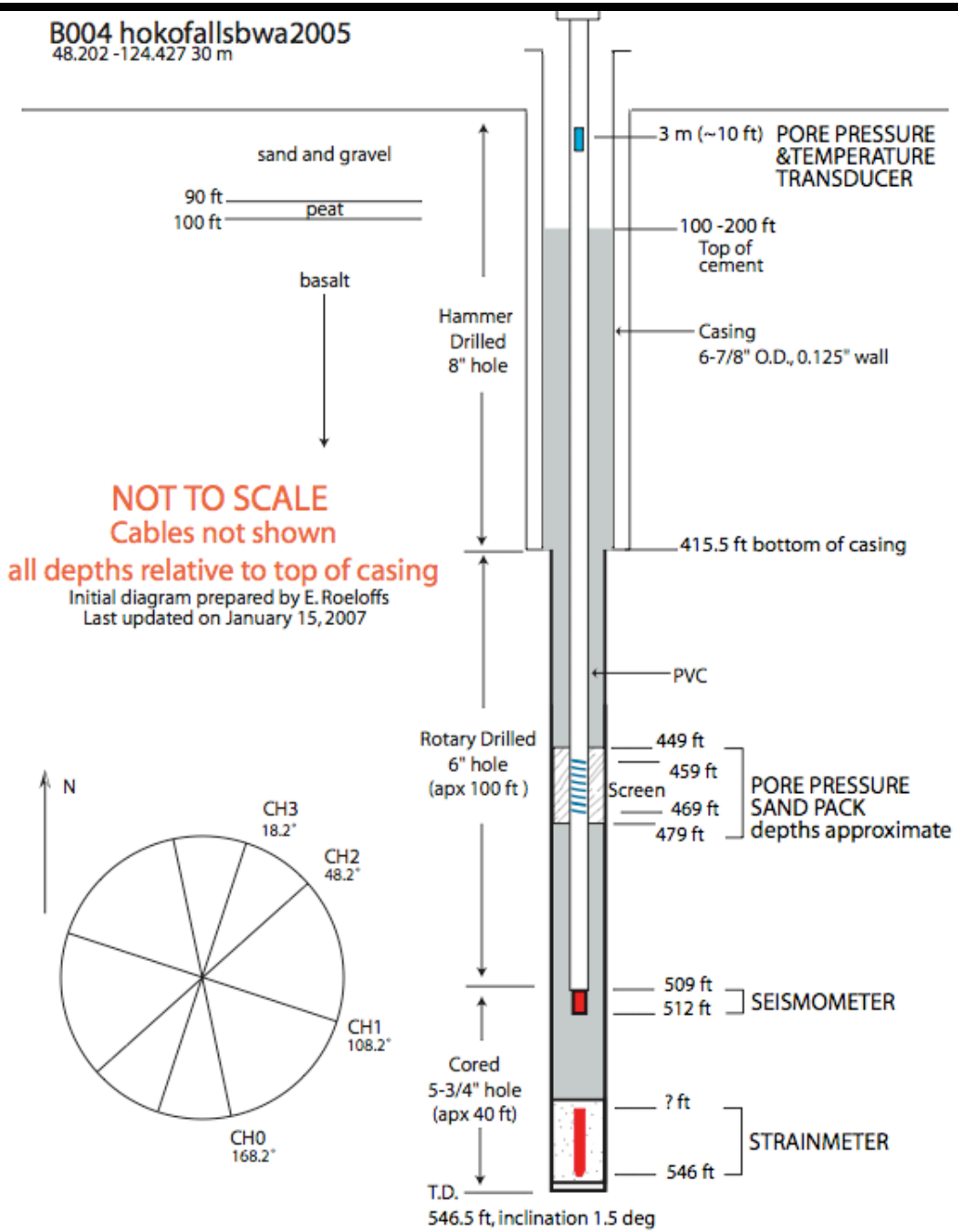

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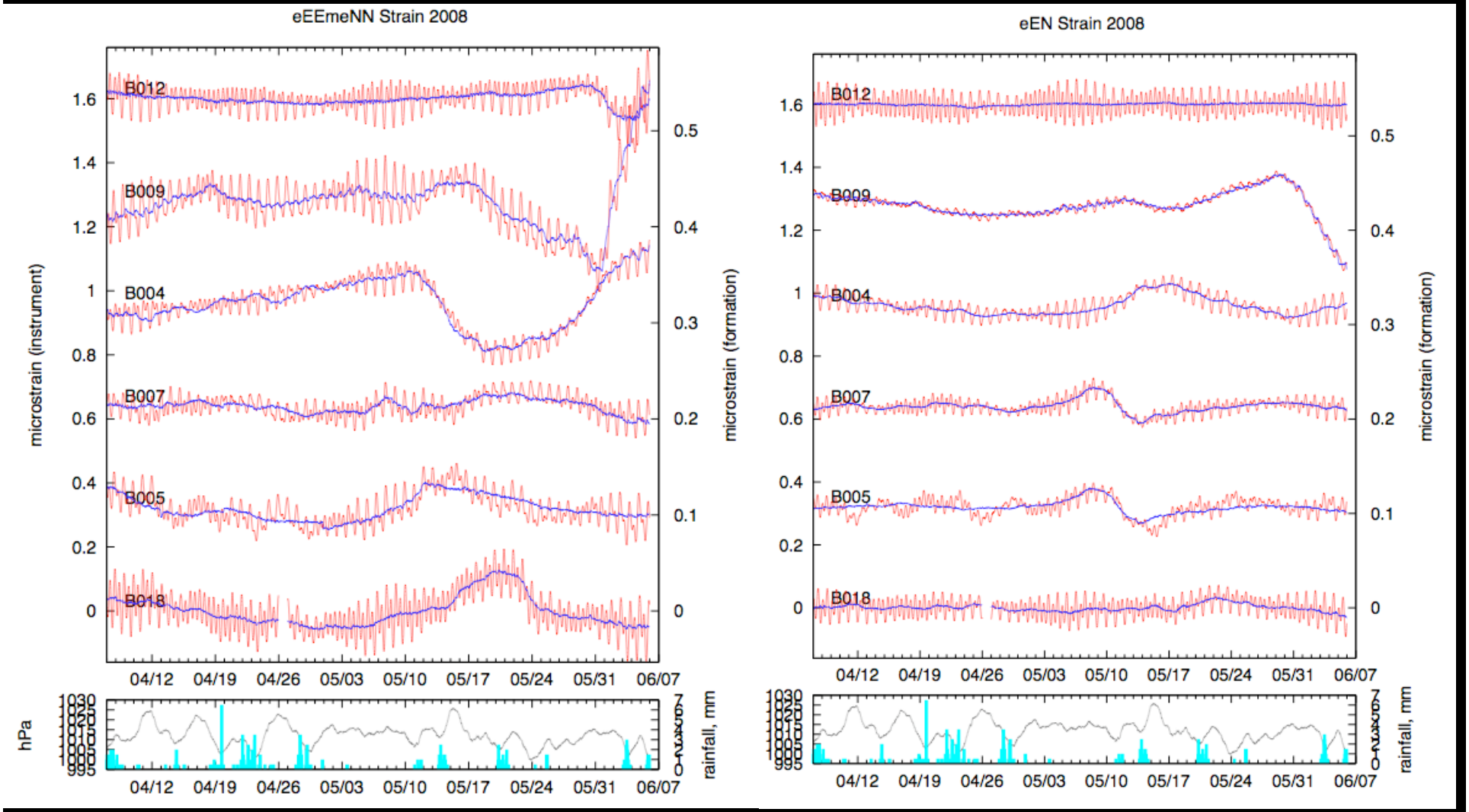
Cascadia Aseismic Slip Events



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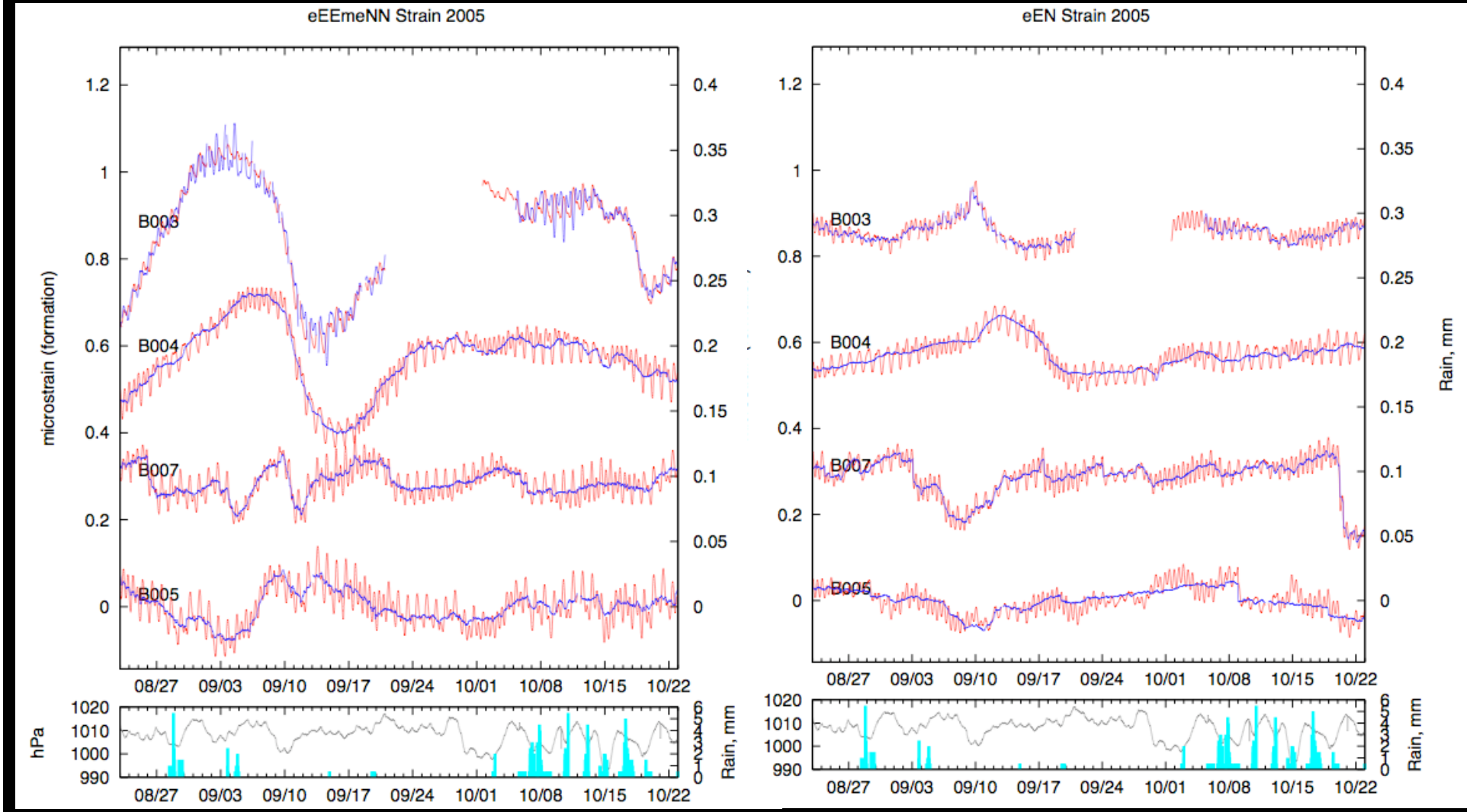
Cascadia Aseismic Slip in 2005



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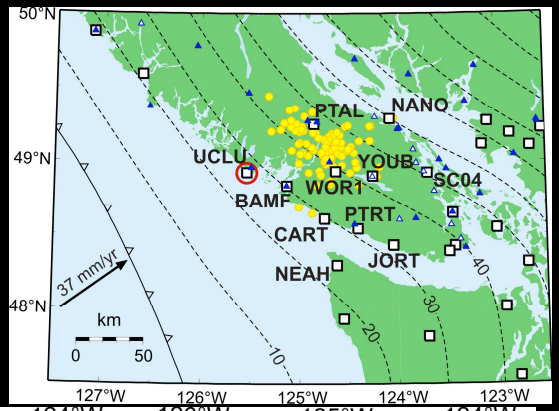
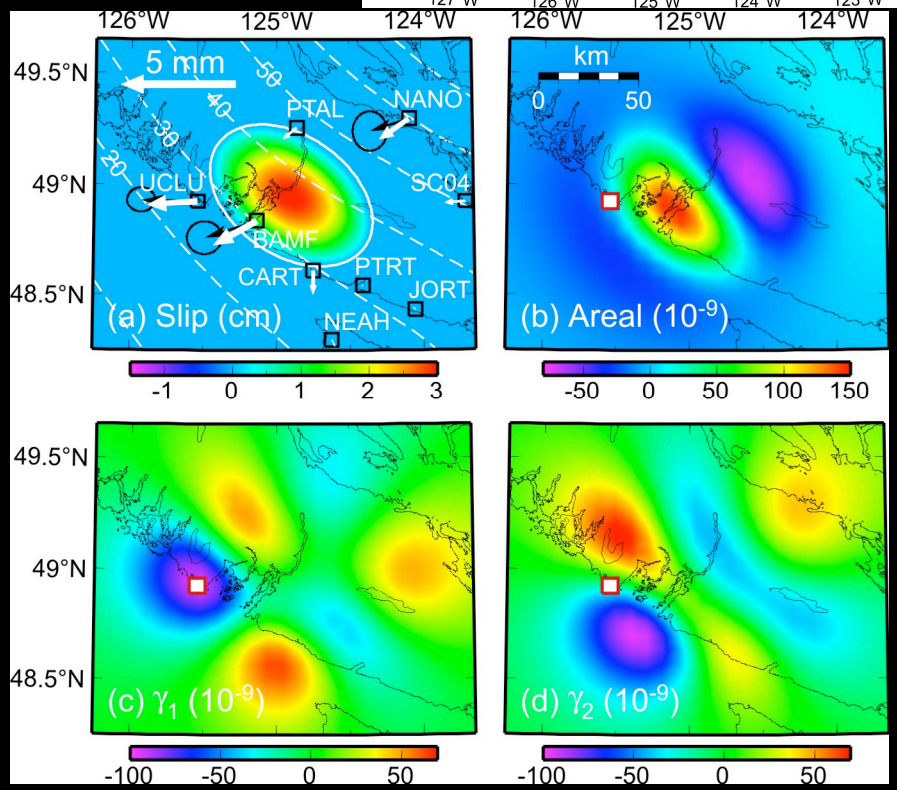
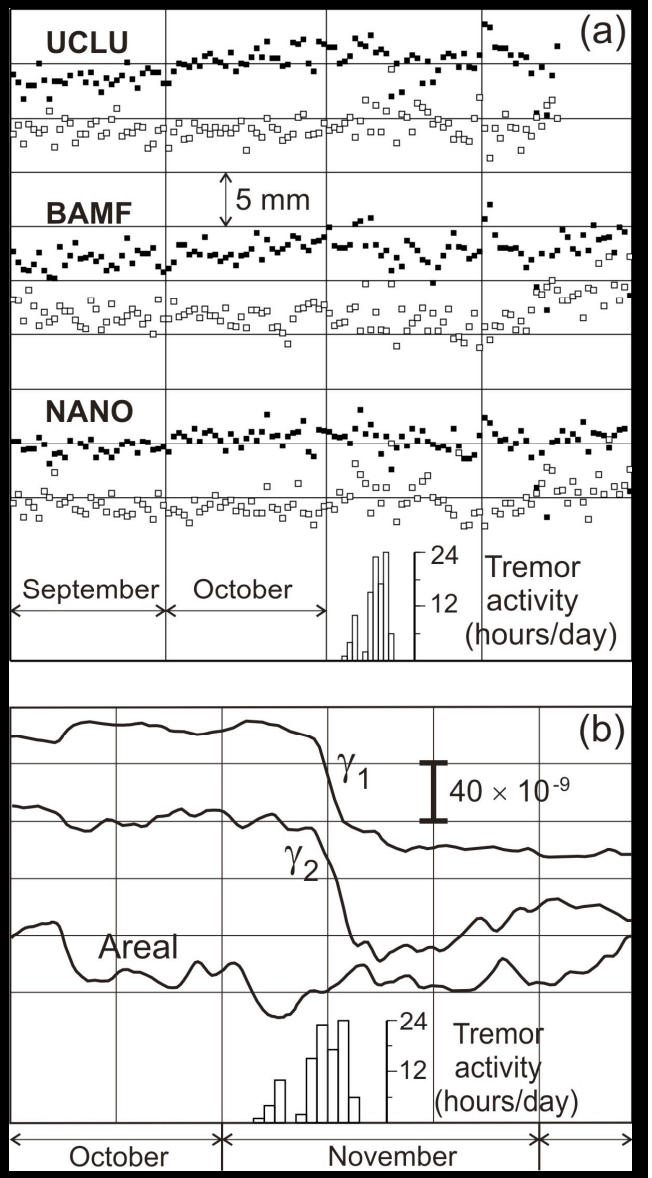
Nov. 2006: Slow Slip Event Vancouver Island







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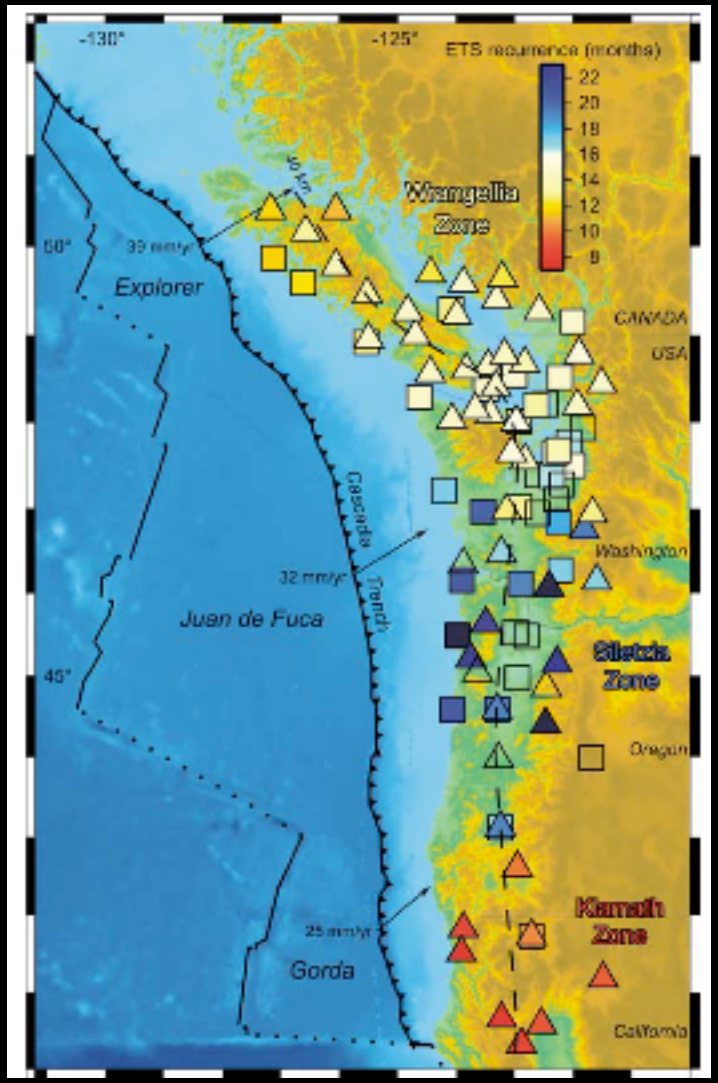
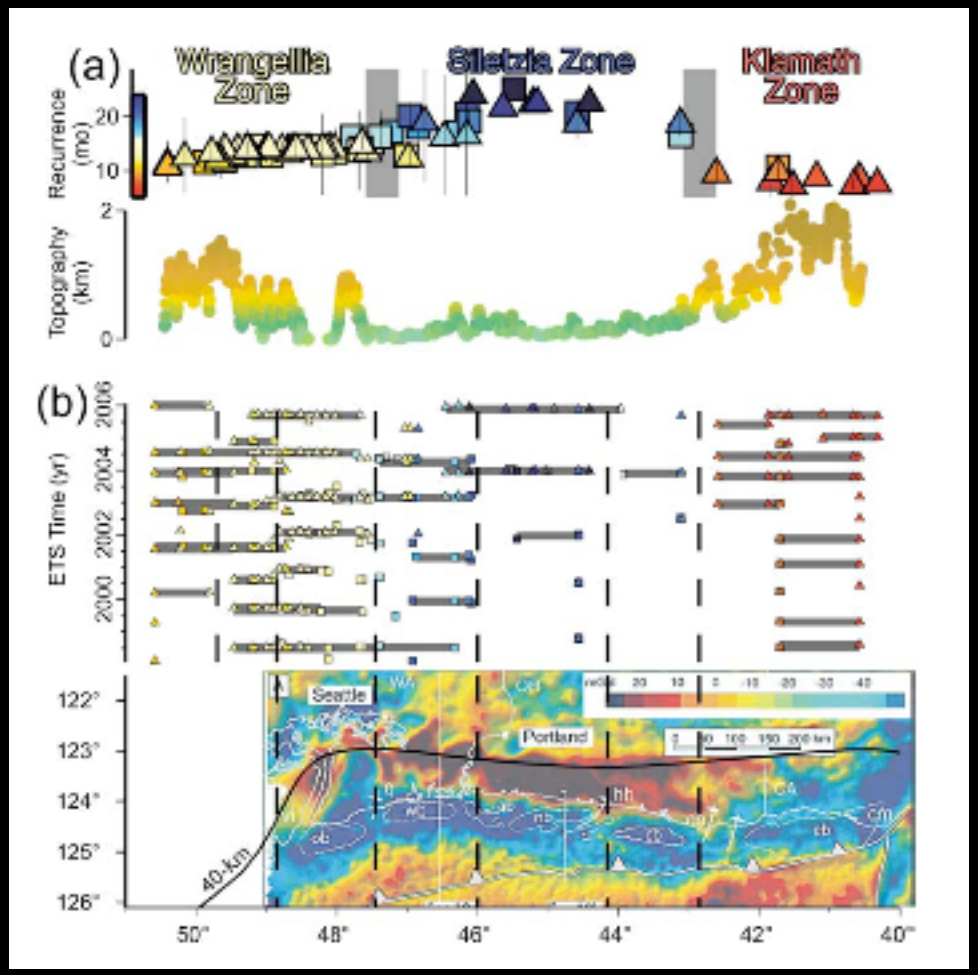
Wang et al, GRL, submitted

Transient Aseismic Slip Throughout Cascadia





Brudzinski & Allen, Geology 2007

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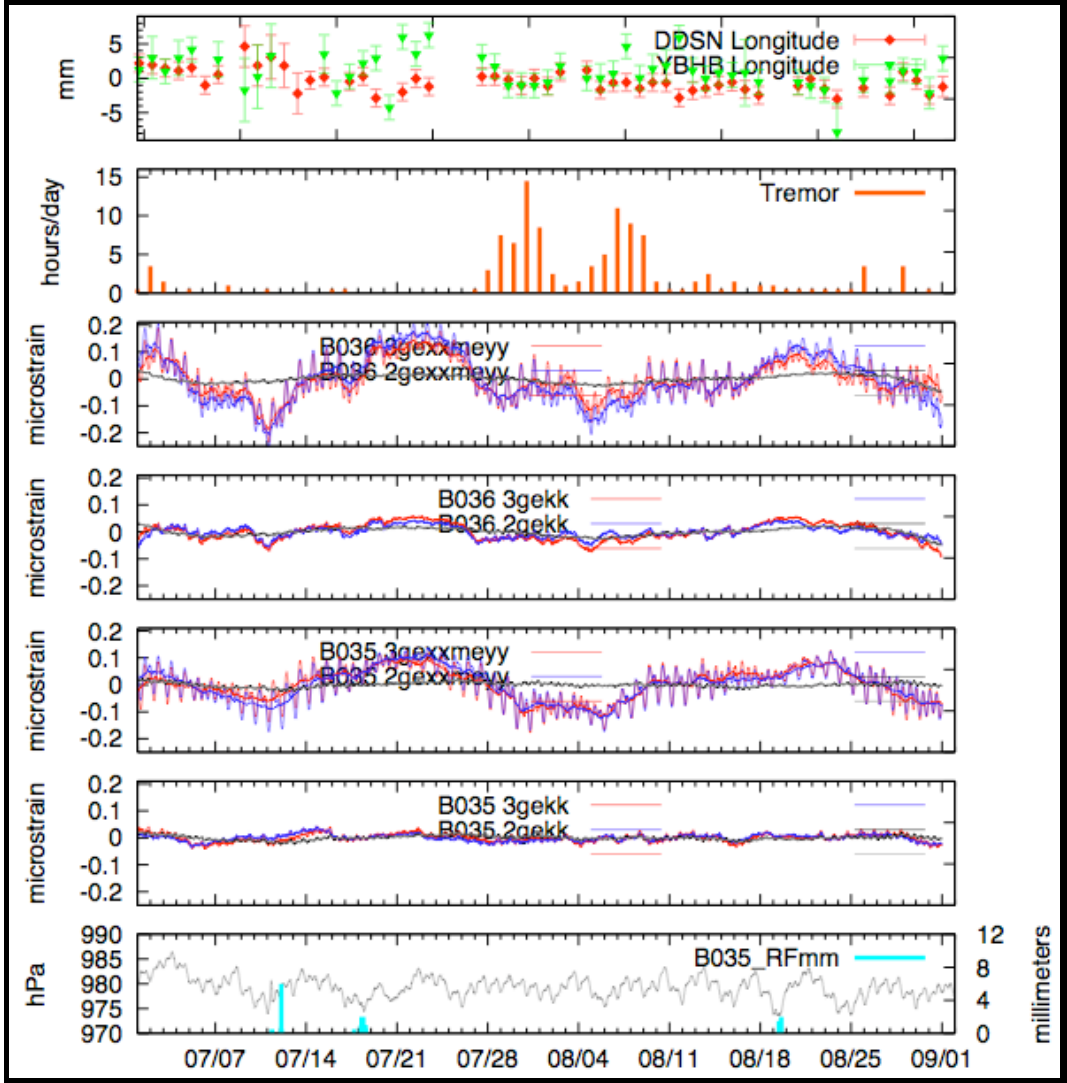
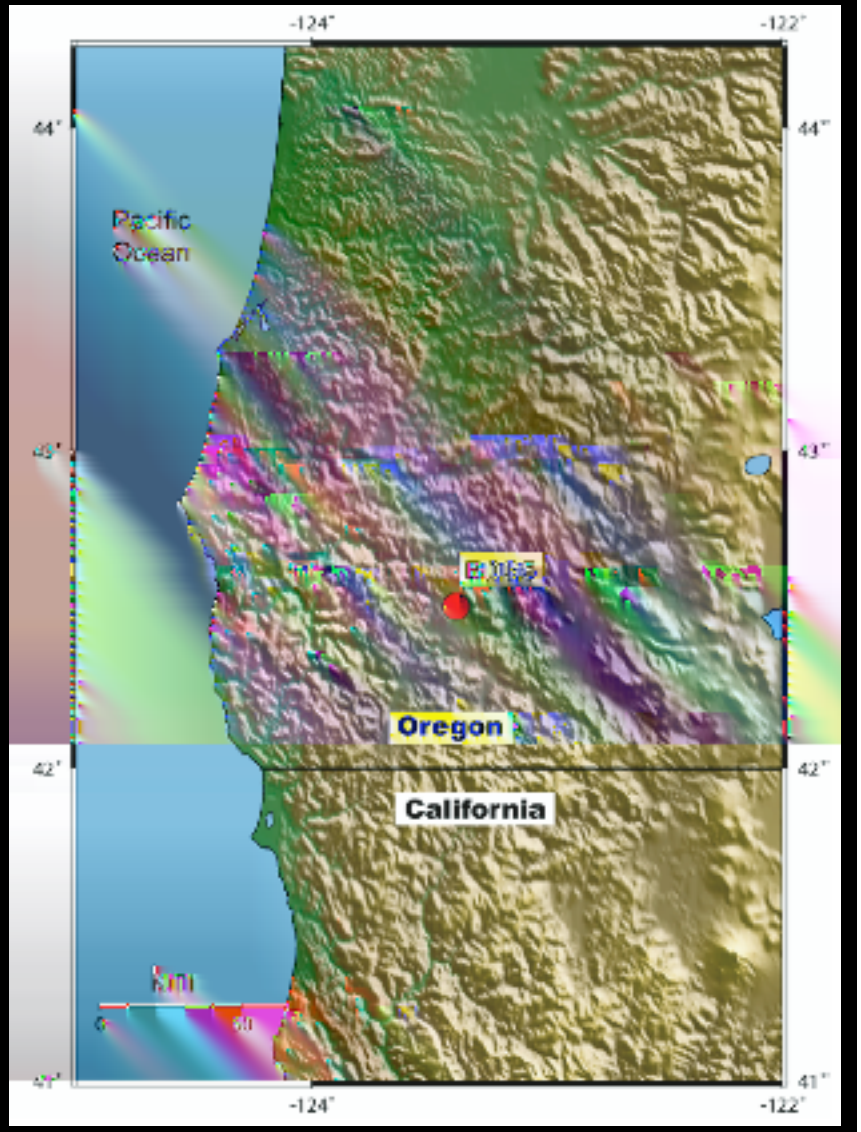
Grants Pass PBO Borehole Strain





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Slow Slip Events: Status of Models

- Models that reproduce transient aseismic slip for Cascadia
  - Liu and Rice: Rate-State Friction model
  - Segall: Dilatant Stabilization
- Questions not addressed by these models:
  - Relationship to megathrust earthquake initiation
  - Generation of tremor
  - Possible relationship with segmentation of the subduction zone

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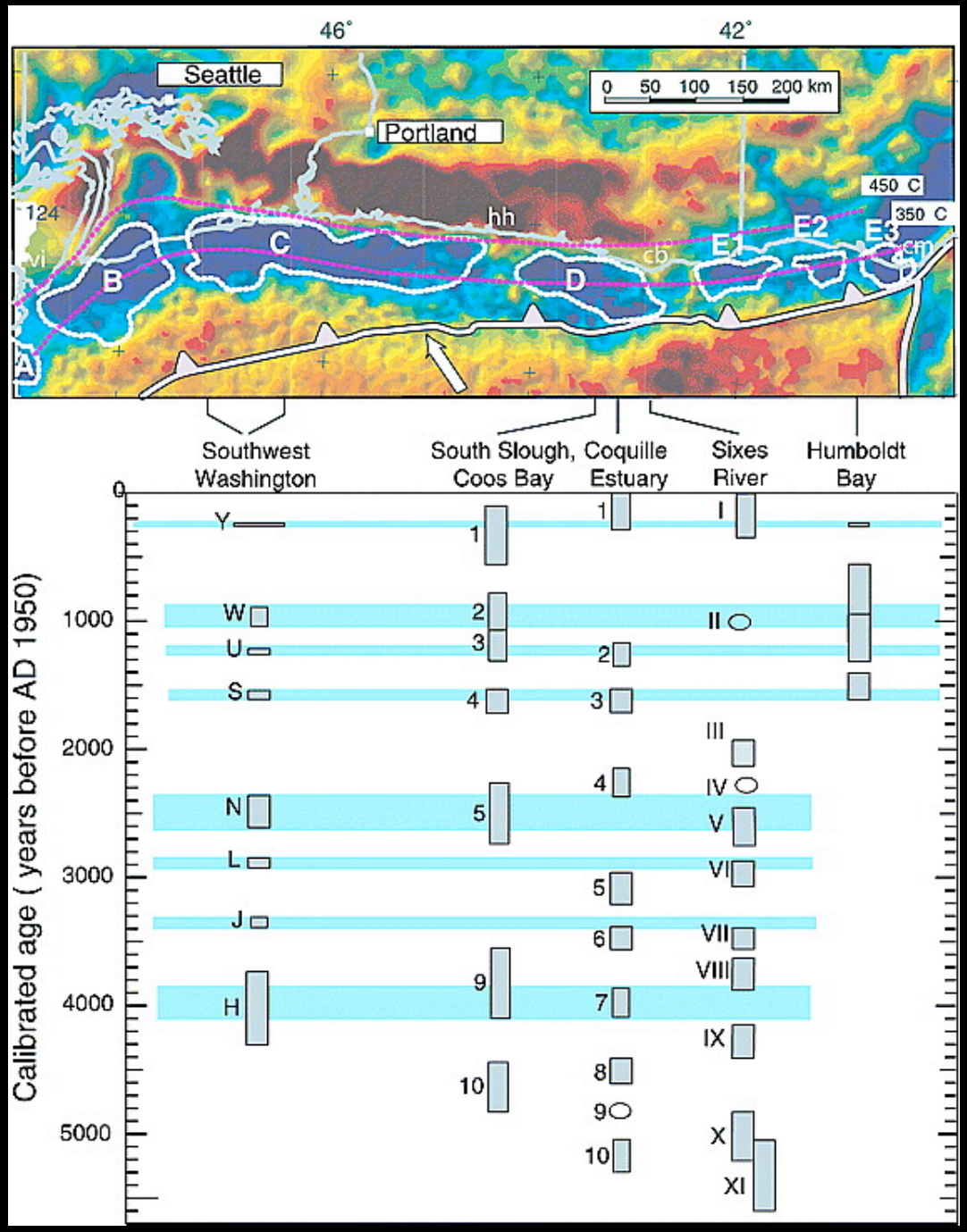
Cascadia Asperities from Basin-Centered Gravity Lows



Wells et al., 2003

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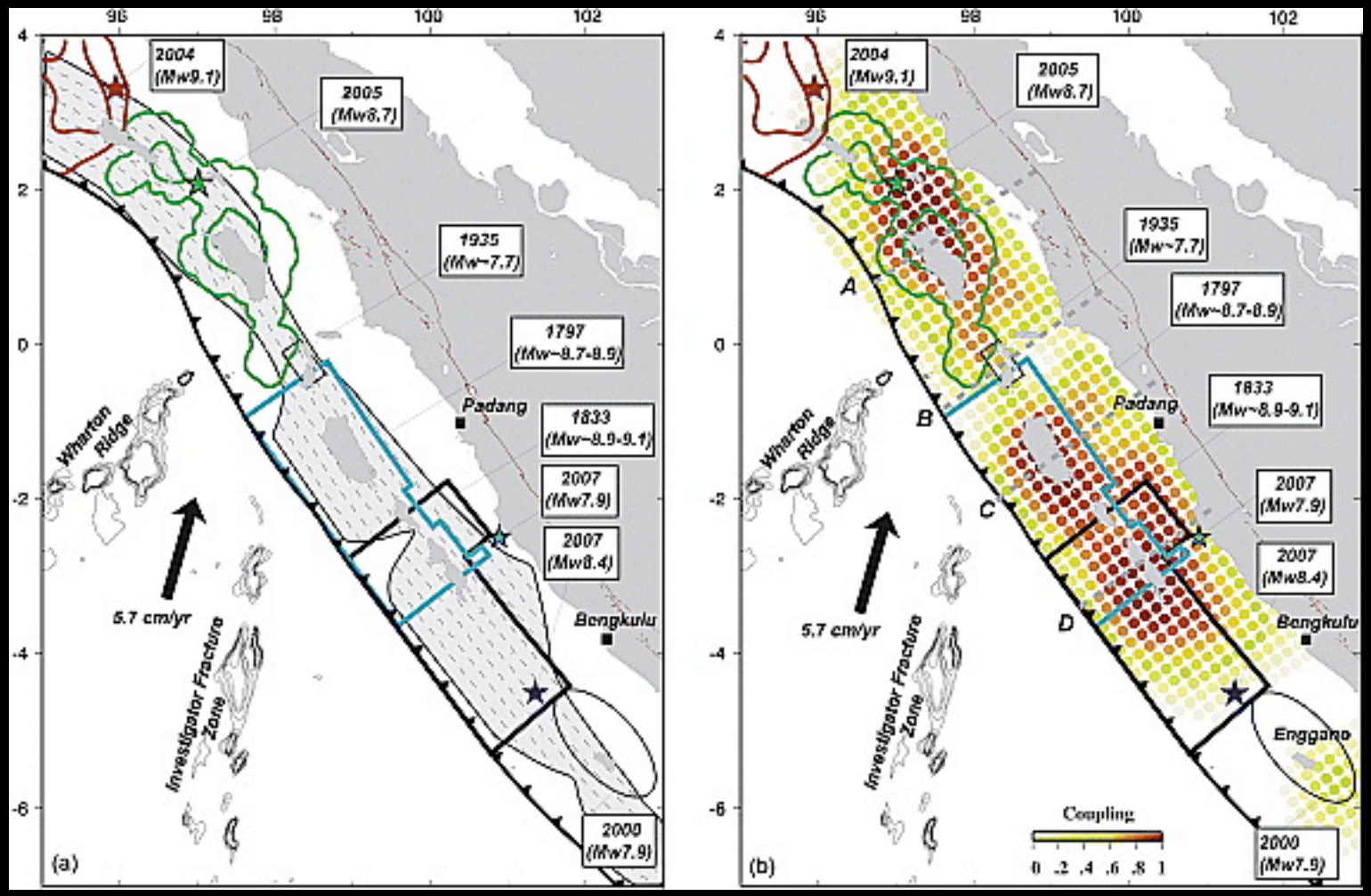
Sumatra: Asperities Underly Islands



Chlieh et al., 2008

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Could Major Subduction Sequences be Forecast?

- The *locations* of asperities are believed to be persistent features
- The asperity locations seem able to be identified from geophysical and/or geodetic data
  - Can modeling explain this?

- Could the *timing* of major subduction "aftershocks" be forecast?

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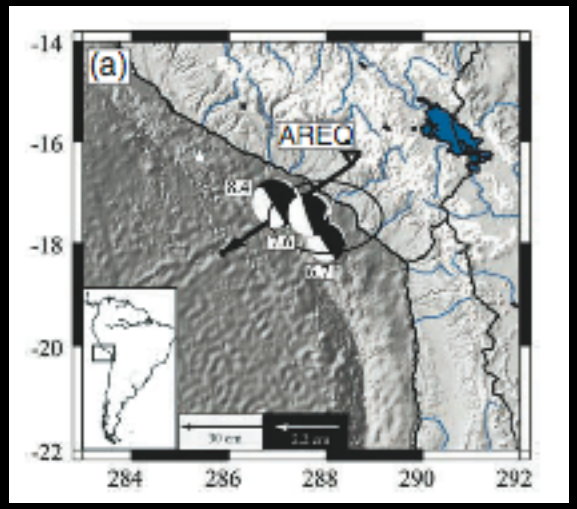
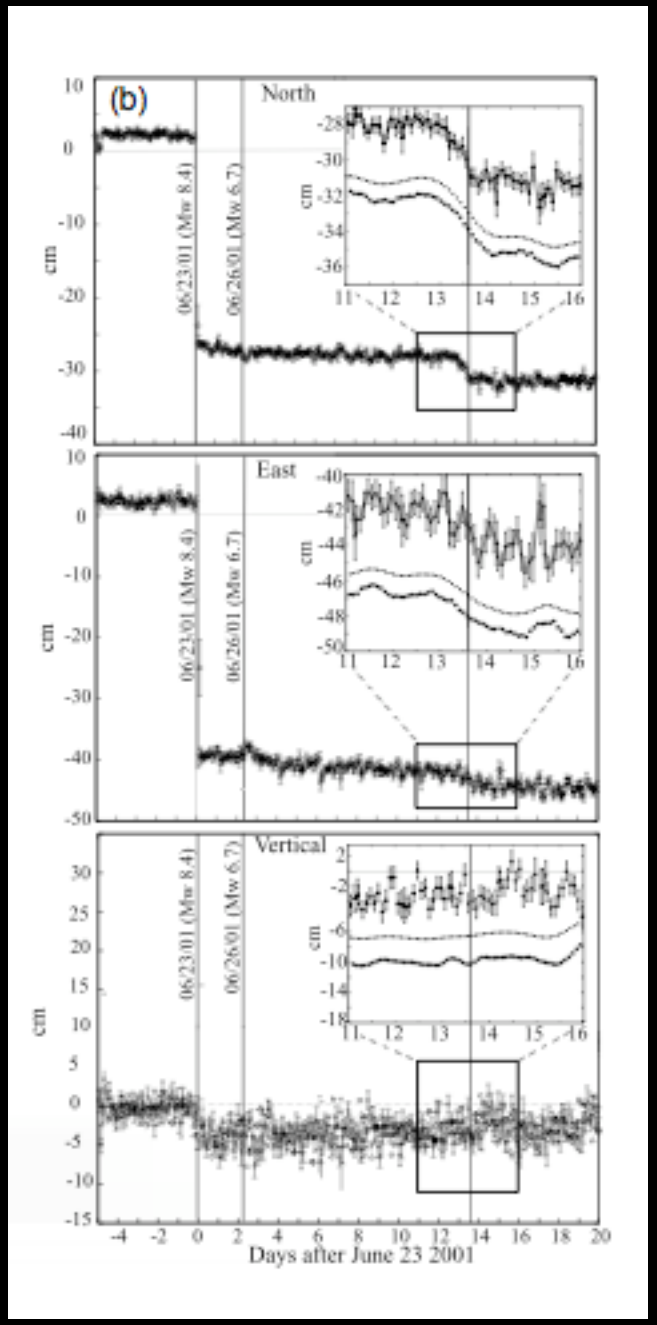
Transient Deformation Preceding M7.6 aftershock of M8.4 Peru Earthquake (23 June 2001)





Melbourne & Webb, 2002

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Need Models to Account for Observed Time Delays of Stress Transfer

- Delays of hours or days seem to require critical slip distances that are larger than laboratory observations
- However, observations show that strain and fluid pressure changes initiated by dynamic stresses can grow and persist over days

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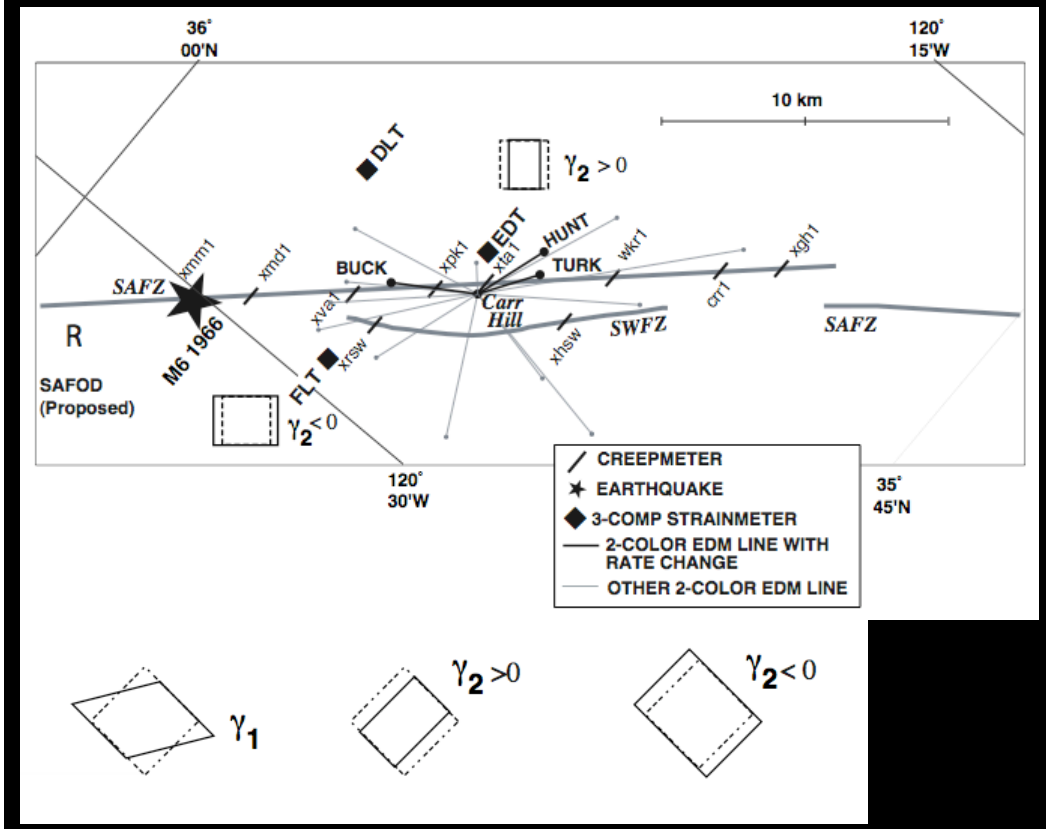
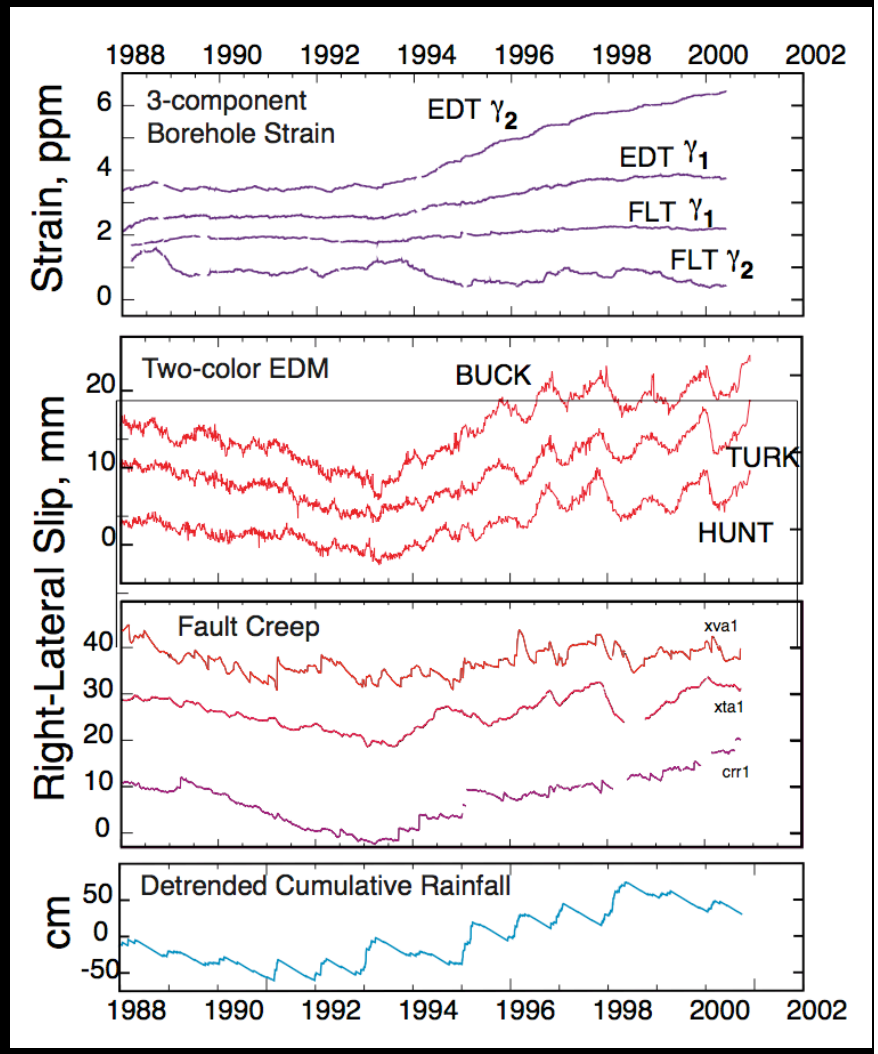
The "Parkfield Transient "





Recorded by strainmeters, 2-color geodimeter, creepmeters

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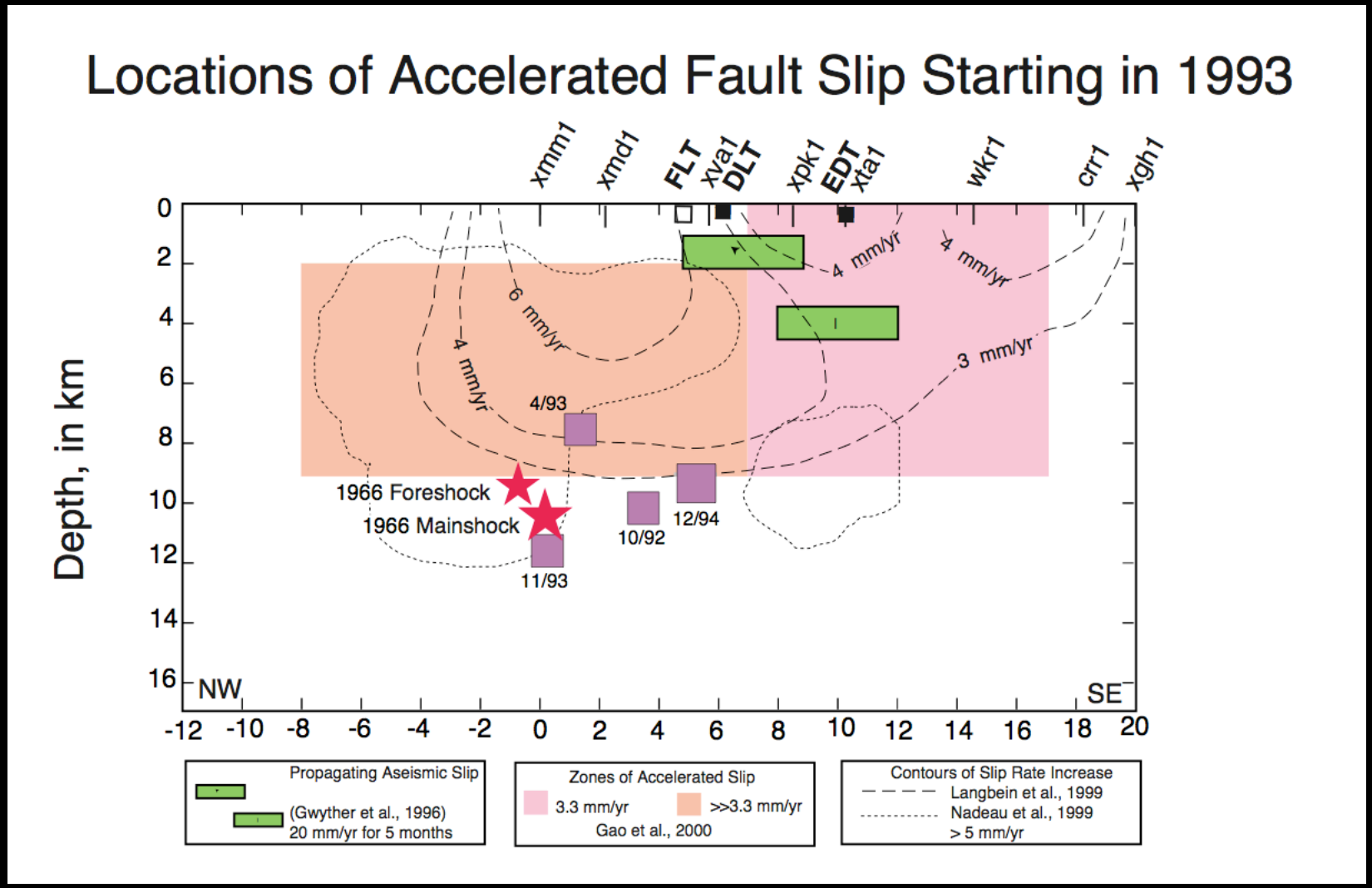

Rate increase also consisten with changes in intervals of repeating earthquakes

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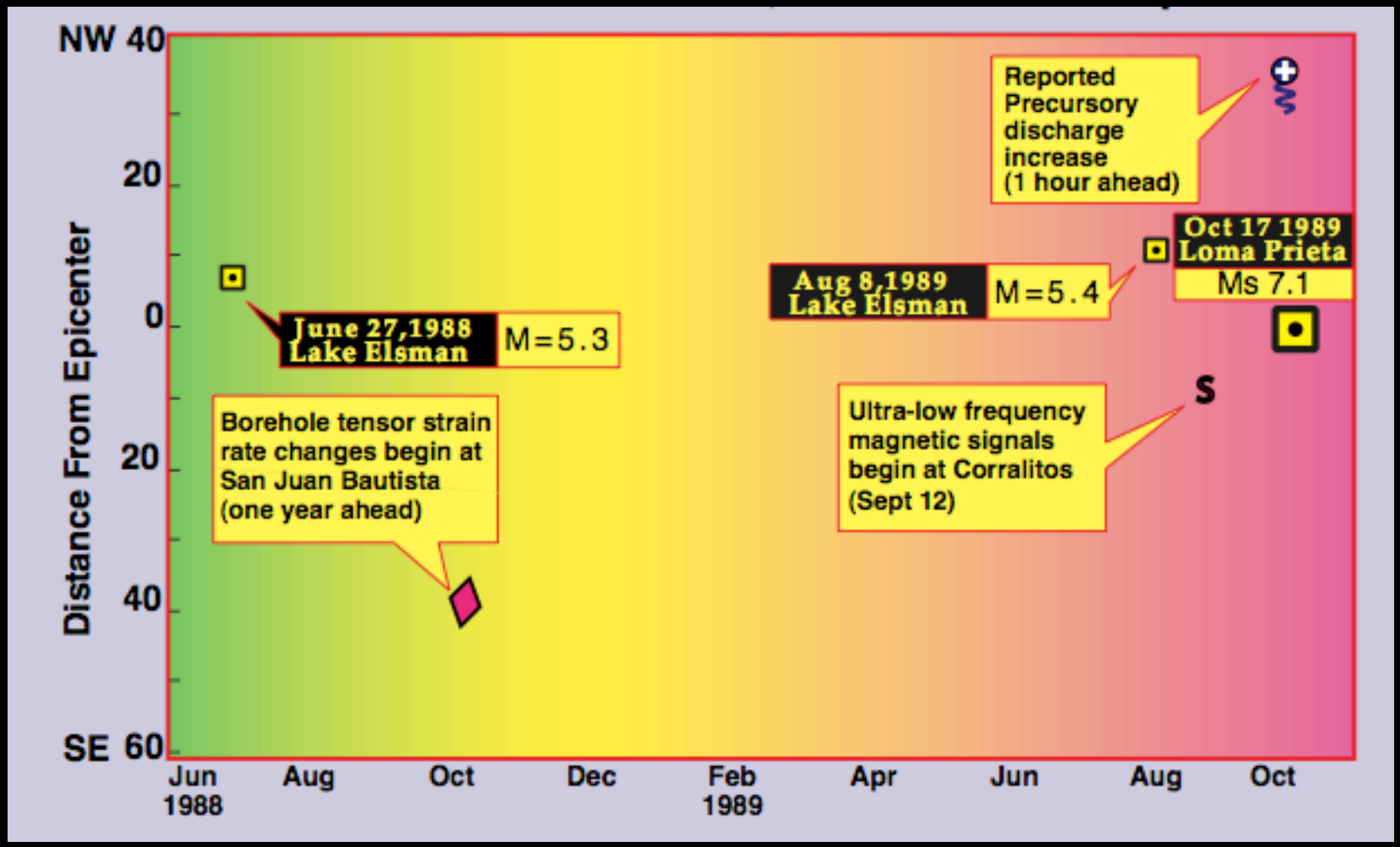
Reported Strain Change before the 1989 Loma Prieta Earthquake



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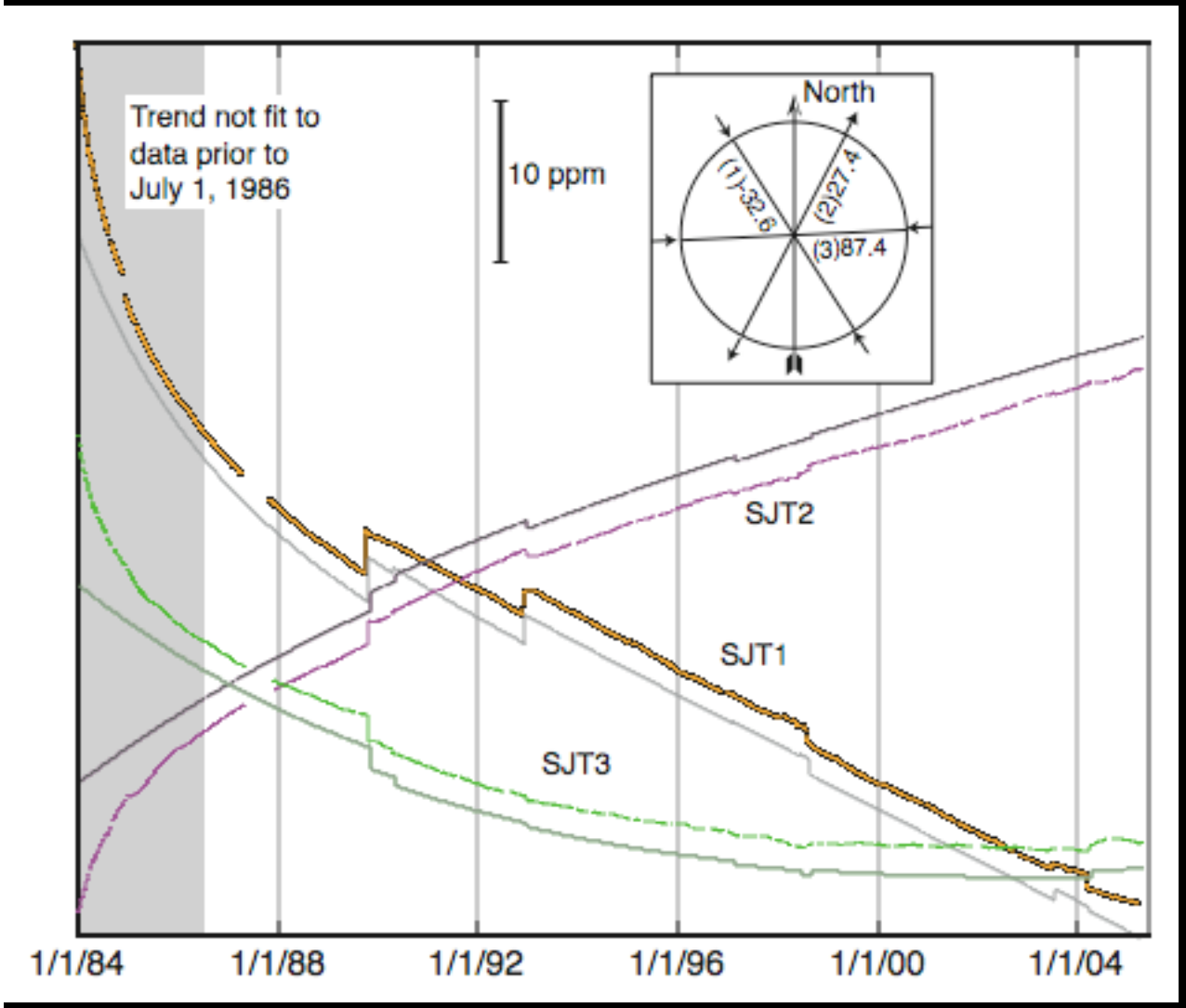
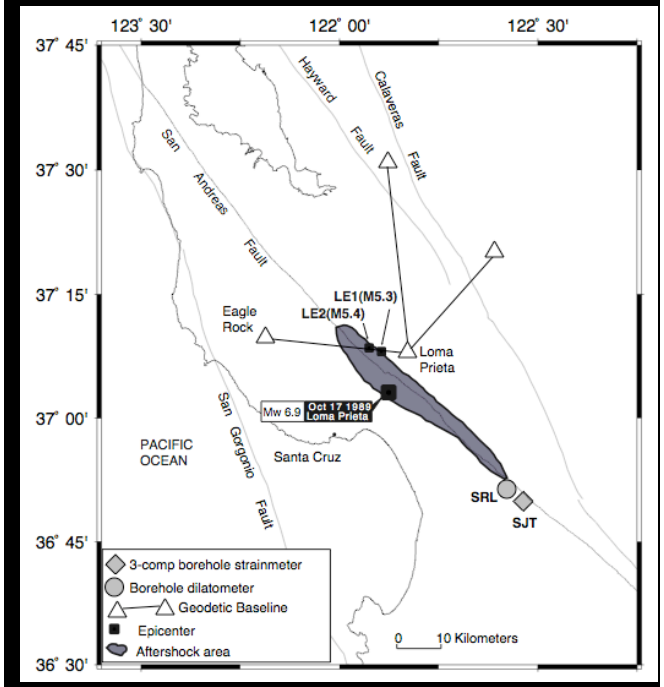
3-Component Borehole Strain Data





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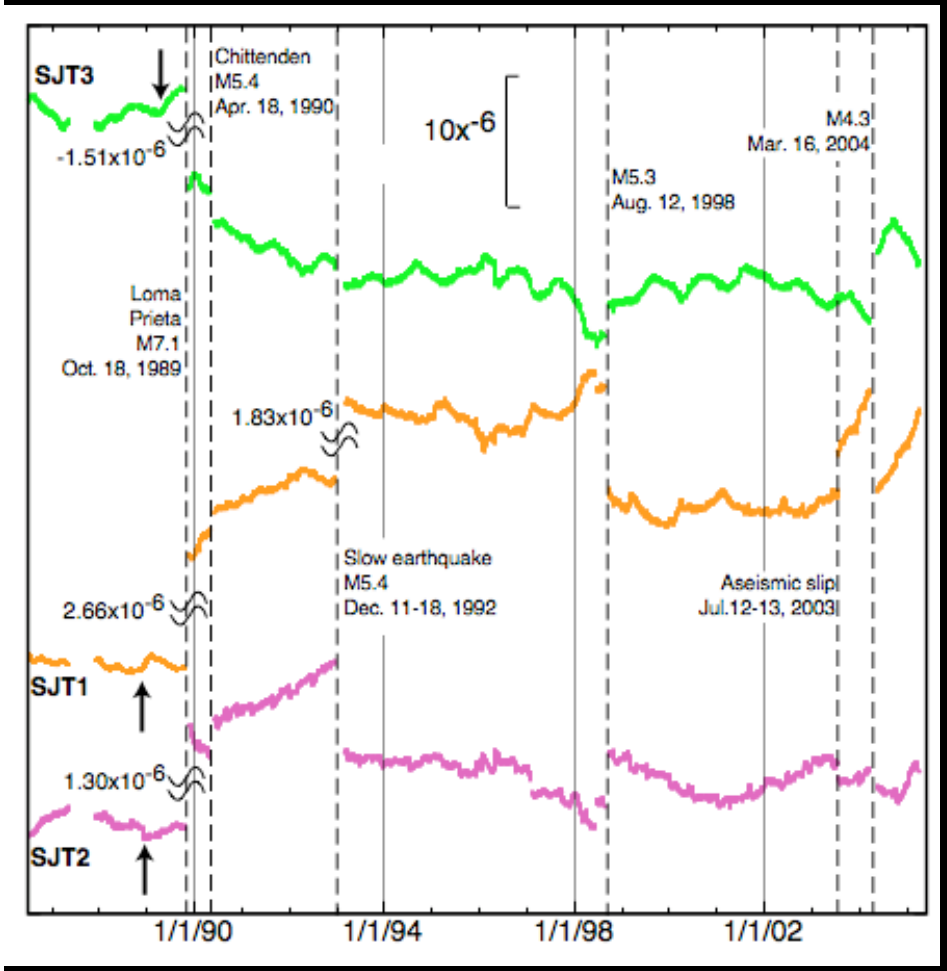
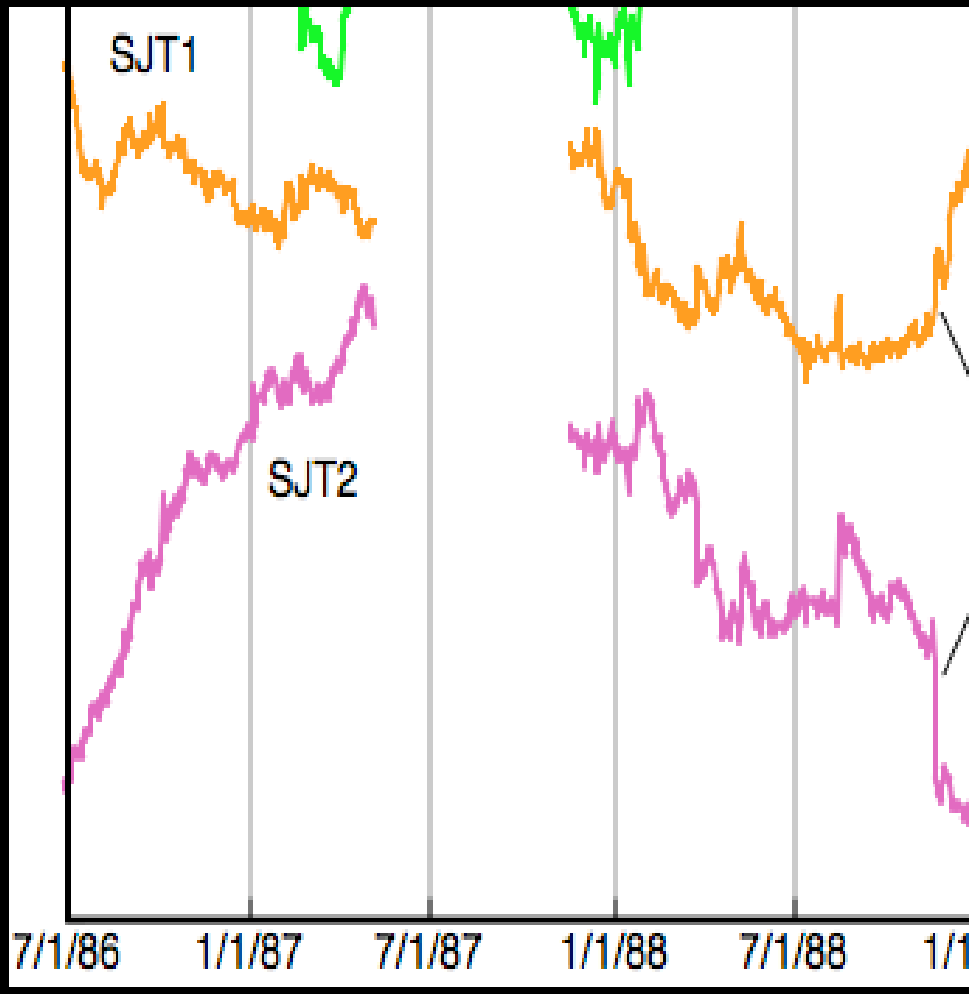
Detrended 3-Component Strain Data





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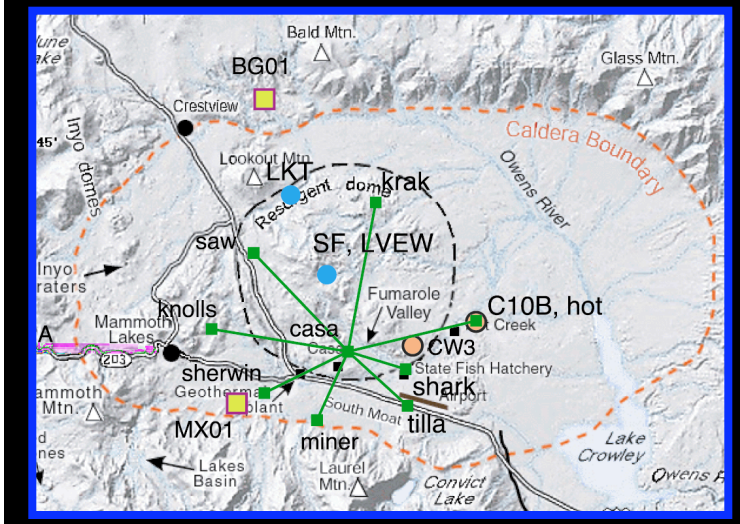
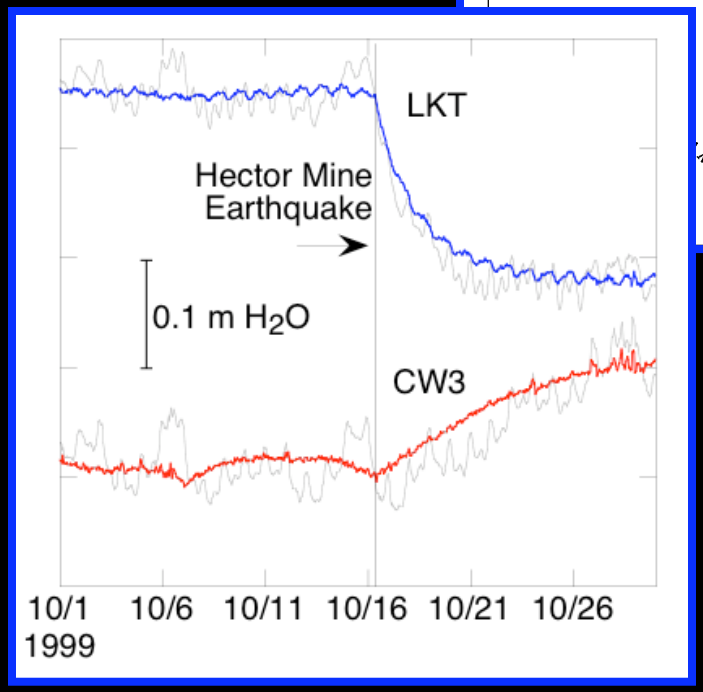
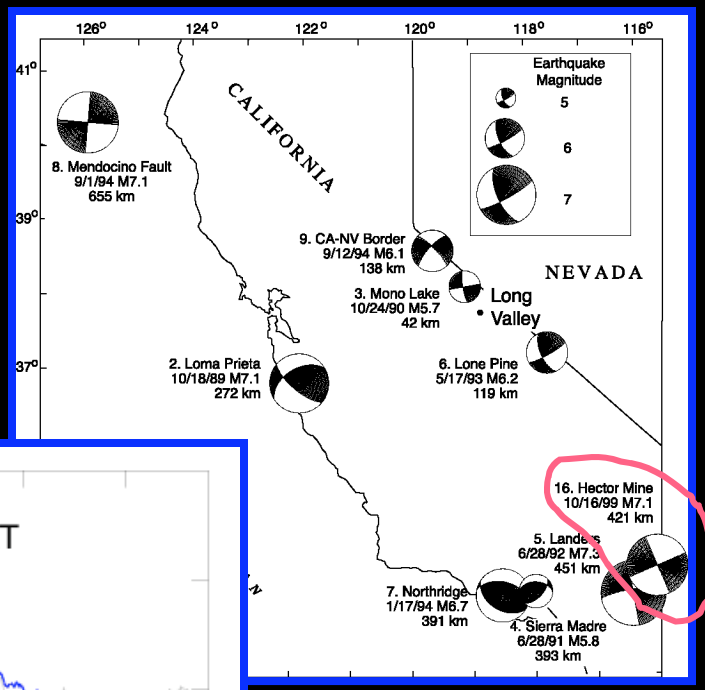
Strain and Fluid-Pressure Observations of Responses to Distant Earthquakes



- *Pressure drops in non-thermal wells on and around the resurgent dome*





- *Pressure rises in hot wells*

Hydrologic Data collected by USGS WRD

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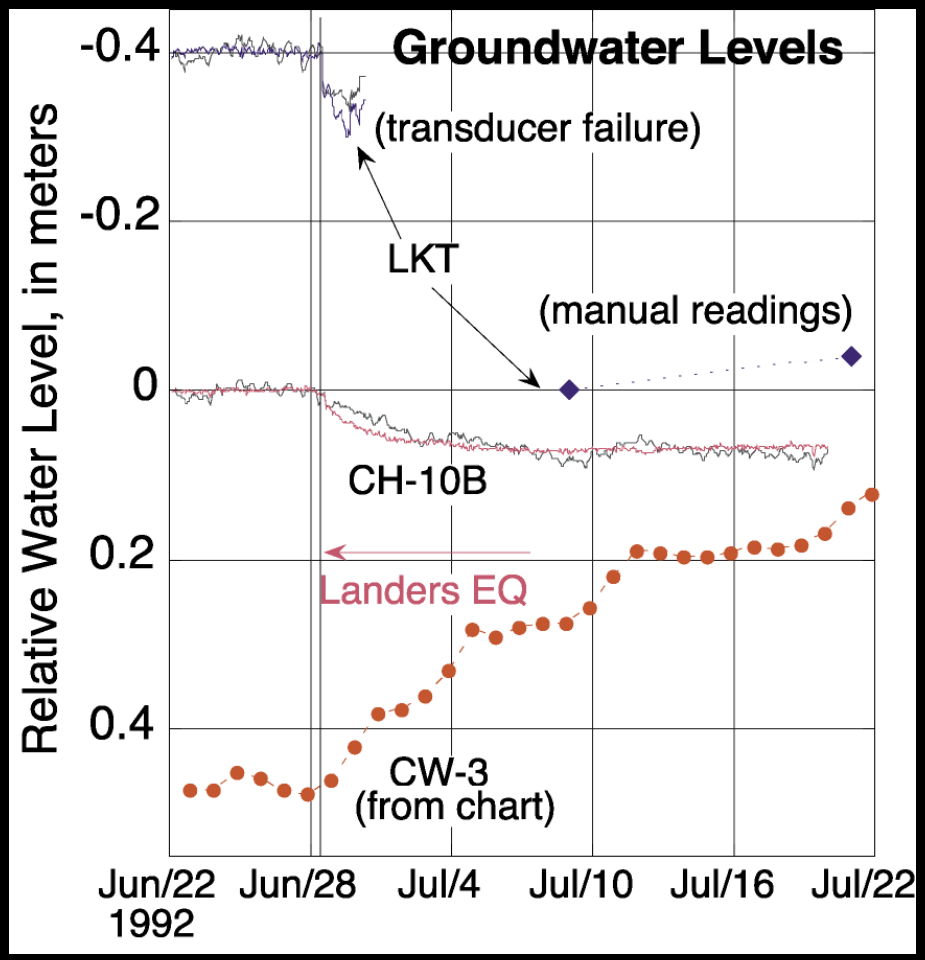
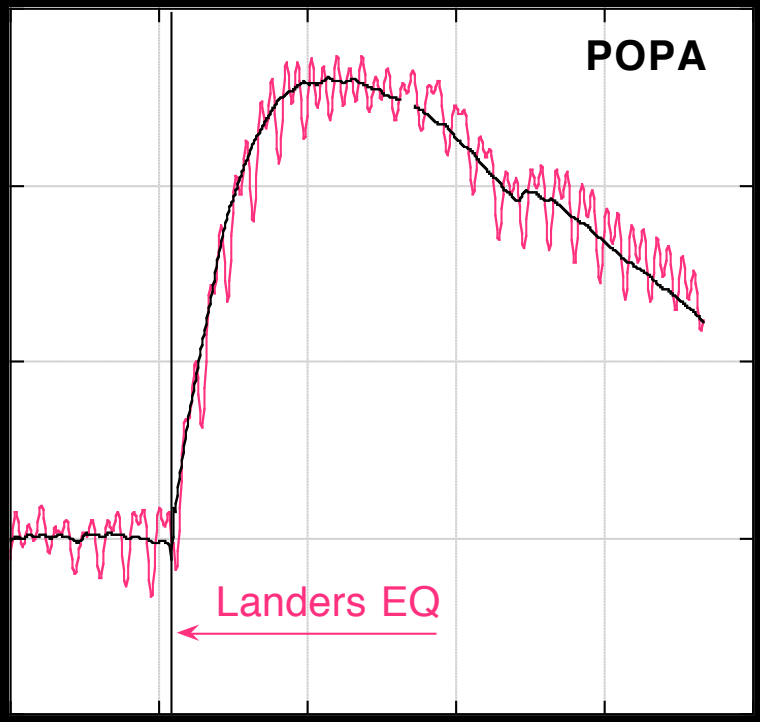
Landers Earthquake: M7.3, 451 km





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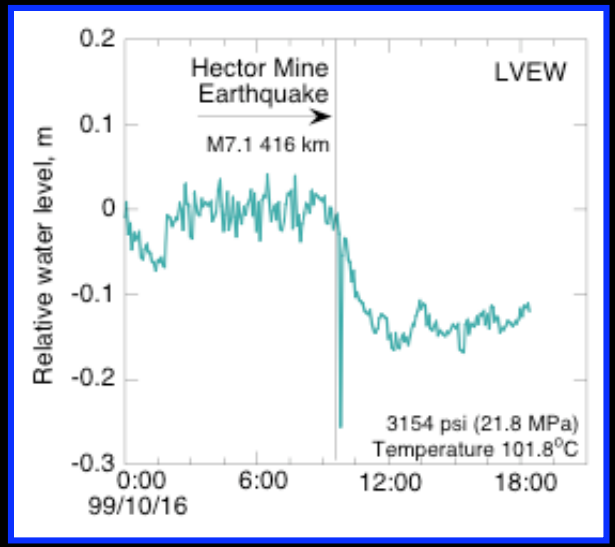
Earthquake-Induced Fluid-Pressure Changes are Not Limited to Shallow Depths

- *Serendipitous recording of fluid pressure drop in 3-km deep Long Valley Exploration Well caused by Hector Mine Earthquake*
- *Prototype Hi-T pressure sensor being tested by Sandia Labs*



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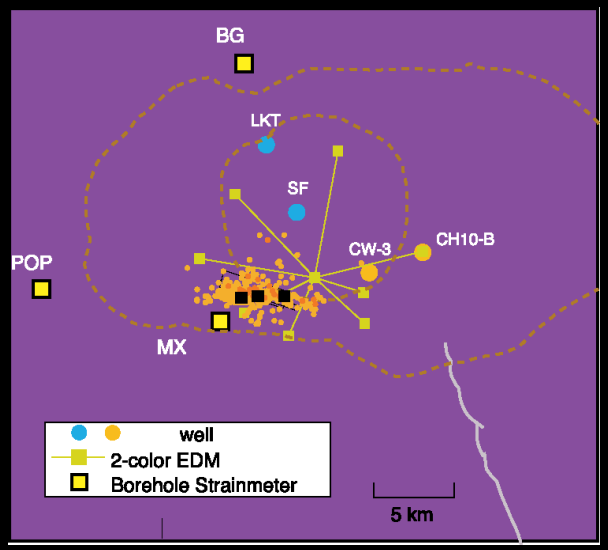
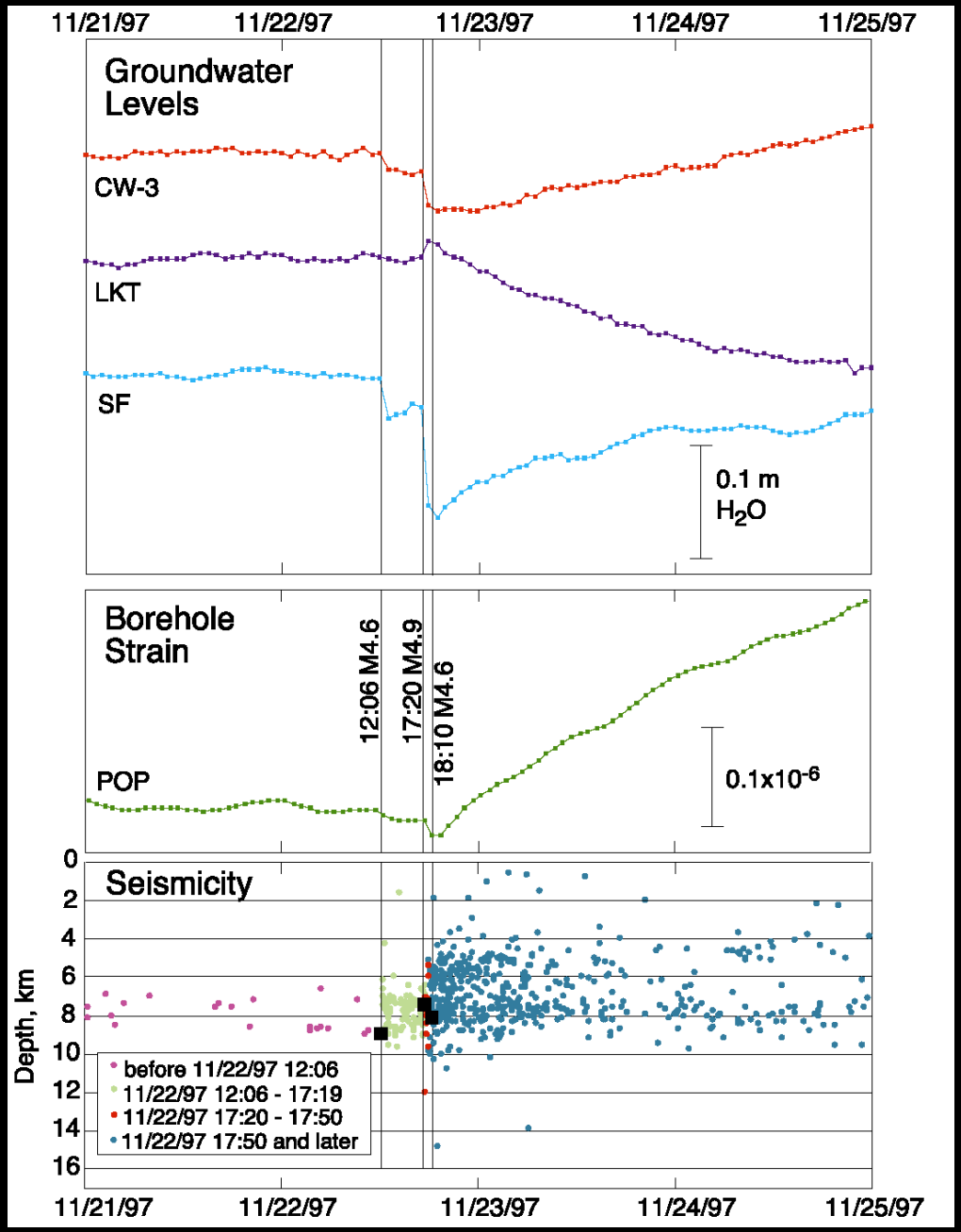
Nov. 22, 1997

- M4+ events with dilatational components and long duration P-waveforms (*Dreger et al.* [2000])
- Upward-propagating swarm including spasmodic bursts (*S. Prejean* [2002])
- Fluid pressure and strain changes just like Landers





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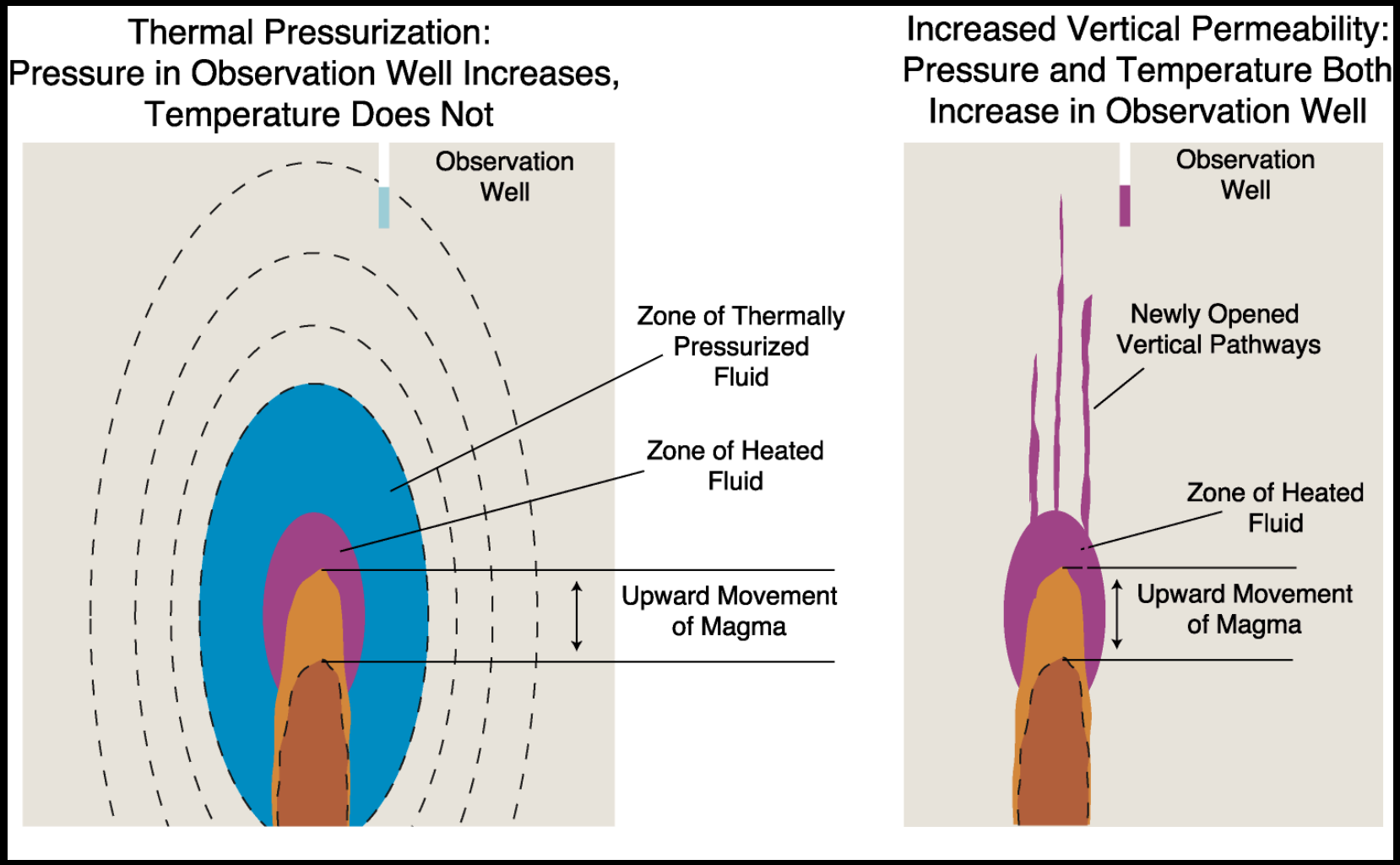
Pressure Increases in Thermal Wells: Non-Poroelastic Scenarios



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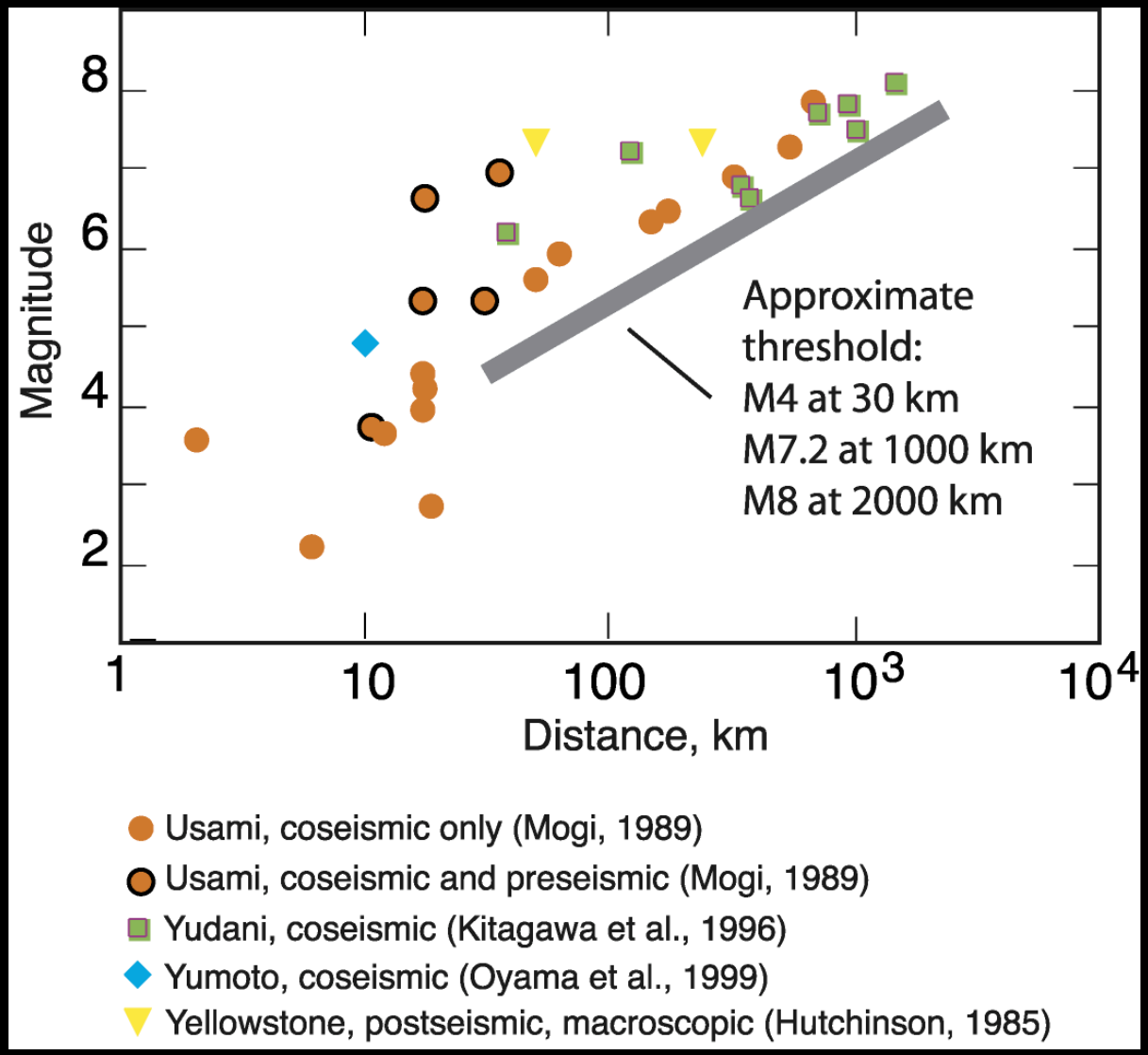
Seismic waves increase temperature at many hydrothermal locations



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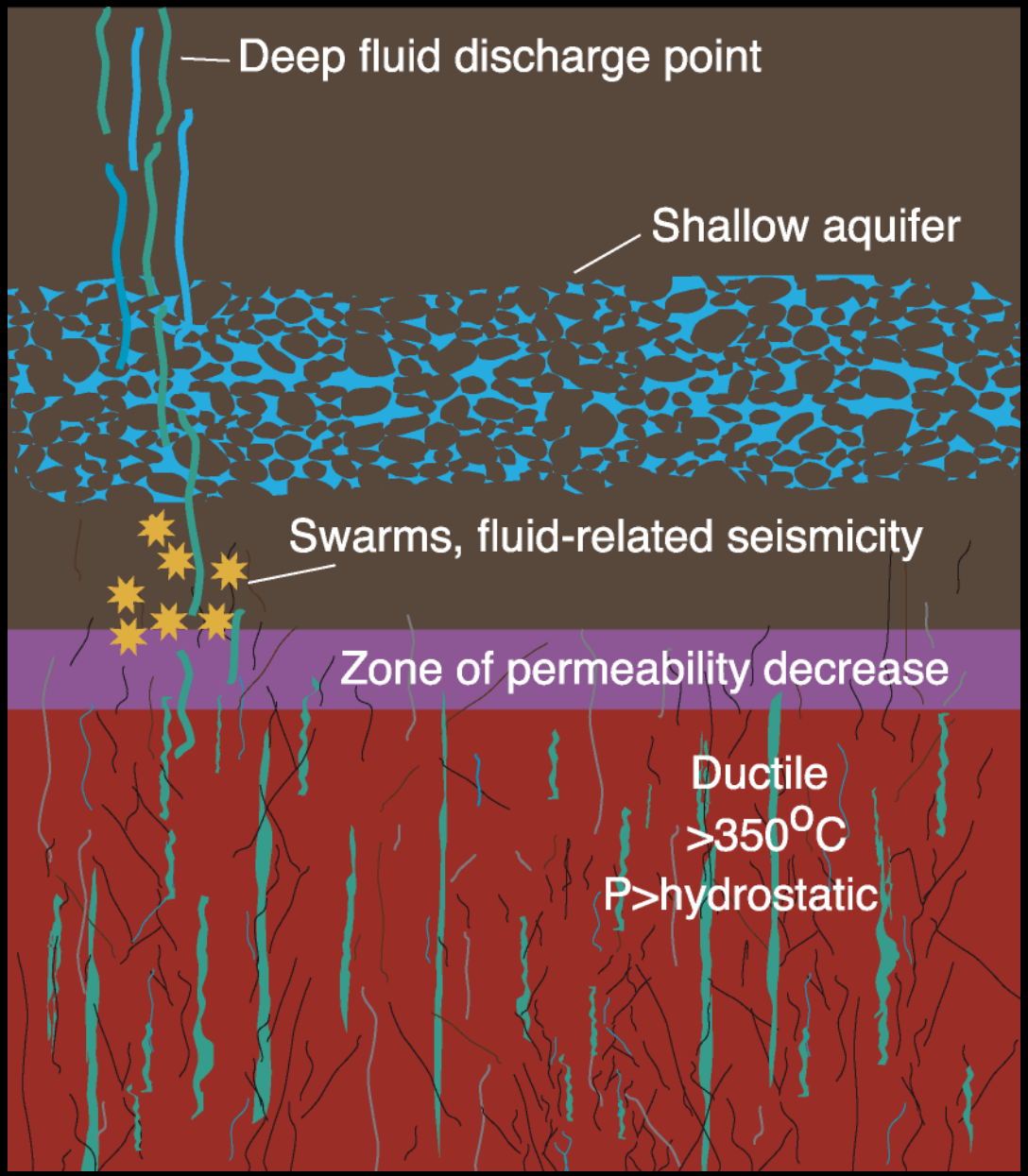
Time-Dependent Permeability (and Rheology)

- Mineral deposition and ductile creep reduce permeability
- Hydrofracturing and seismic activity restore permeability
- Fluid pressure and strain-rate changes affect rheology



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Summary: Modeling Targets

- Aseismic slip in subduction zones
  - Wide variety of time scales, moments
  - Possible association with pre-earthquake processes
  - Lots of new data from PBO, more networks to come
- Physical basis of asperities
- Linkages of mainshocks to aftershocks
  - What governs the time dependence?

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