Strain Signals Associated with the January 2007 Cascadia Episodic Tremor and Slip Event as Recorded on PBO Borehole Strainmeters

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Abstract

The Plate Boundary Observatory (PBO) was designed to study the strain fields resulting from the tectonic deformation at active plate boundaries, including The Episodic Tremor and Slip (ETS) events in the Cascadia subduction zone. As yet, it is not known whether the same source causes both the seismically-measured tremor and the geodetically-measured slow slip. In September 2005, the first ETS related strain event was recorded on two of the borehole strainmeters located on the Olympic Peninsula. During the next anticipated ETS event in January 2007, thirteen PBO borehole strainmeters were operational. Preliminary analyses of the 1 Hz data on station B018 (near Delphi, WA) show a strain event beginning around January 16, 2007. The event first manifests as a shear event, and then as E-W extension. The strain changes are roughly concurrent with the onset of strong tremor in the southern to central Puget Sound, and with geodetic changes recorded on the regional GPS network and long-base tiltmeter at Shelton, WA. Preliminary analyses of station B004 on the Northern Olympic Peninsula show a strain event that begins around January 26, 2007, later than at B018. The event first shows up as E-W compression and then as shear. The timing of the event at B004 is consistent with the migration of the tremor epicenters. The availability of 20 Hz strainmeter data will allow for better evaluation of the timing of the slow slip event than is possible from the GPS data and may reveal strain associated with the tremor.

Study Location:

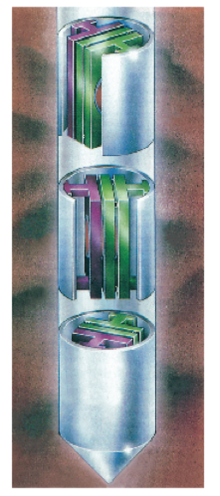
Map showing the locations of PBO borehole strainmeters in Canada, Washington, and Oregon. Red triangles show locations of currently installed and operating stations. Blue squares are planned stations. Stations B004 and B018 are labelled because they are used in the analyses at right.
Map modified from Unavco/PBO website.

Goal:

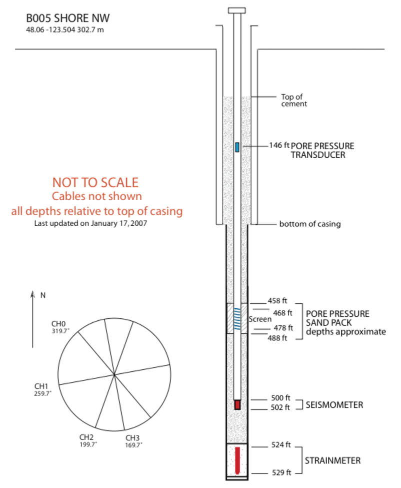
Our goal is to incorporate the strainmeter data into geodetic models of slow slip events. To do this we need to calibrate the instruments from instrument strain to formation strain. Finally we compare the strainmeter data to simple slip models.

Gladwin Tensor Strainmeter

Strainmeter measures horizontal extension on variable capacitance sensors from which the full horizontal strain tensor can be determined. Three of the gauges are oriented at 120 degrees intervals and the fourth gauge is perpendicular to one of the other three gauges. Resolution of the sensors is 1 nanostrain, the sampling rate is 20Hz and the depth of installation is between 500 and 800 feet.



Drawing: GTSM Technologies



From UNAVCO/PBO Website

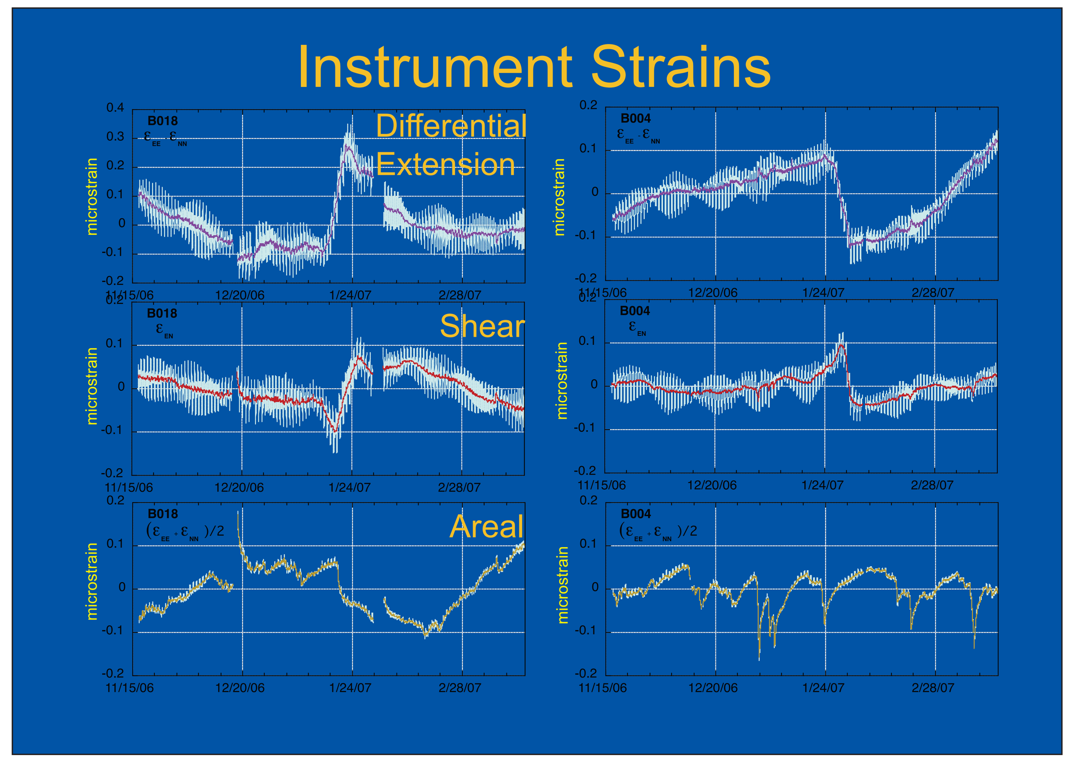
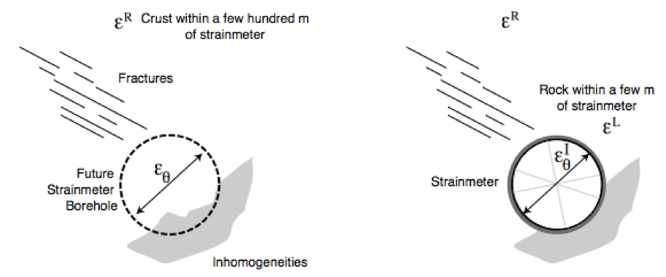


Figure showing the strain signals when the 3 evenly spaced gauges are combined into geographic coordinates: differential extension, shear and areal strain components. The timeseries have been linearized and the long-term trends have been removed. Blue time series is before the atmospheric pressure and tides have been removed.

Relating Instrument Strains to Local Strains



At angle θ relative to x, y:

Linear strain in rock: $\varepsilon_\theta = \frac{\varepsilon_{xx}+\varepsilon_{yy}}{2} + \frac{\varepsilon_{xx}-\varepsilon_{yy}}{2}\cos 2\theta + \varepsilon_{xy}\sin 2\theta$

Strain of strainmeter gauge (isotropic model): $\varepsilon_\theta^i = C\left[\frac{\varepsilon_{xx}+\varepsilon_{yy}}{2}\right] + D\left[\frac{\varepsilon_{xx}-\varepsilon_{yy}}{2}\right]\cos 2\theta + D\varepsilon_{xy}\sin 2\theta$

Shear coupling D > Areal coupling C

We want to measure elongation along an azimuth in the rock formation. If the strainmeter weren't there we would measure the linear strain equation. But when a strainmeter is present in the ground, we get a similar equation with the factors C and D (areal and shear coupling coefficients). The coefficients reflect the coupling of the instrument and grout to the formation. D is typically larger than C, meaning the instrument is more sensitive to shear strain than areal strain. The relationship between regional strain and strain within meters of the instrument has yet not been determined. C, D are normally estimated from earth tide-induced strains. Tidal models are not accurate in this region therefore we sought another way to estimate C and D using teleseismic earthquake phases.

Displacement broadband seismogram at OPC compared with B005 strainmeter data for Nov 15, 2006 Kuril 8.3 Earthquake Rayleigh and Love Waves

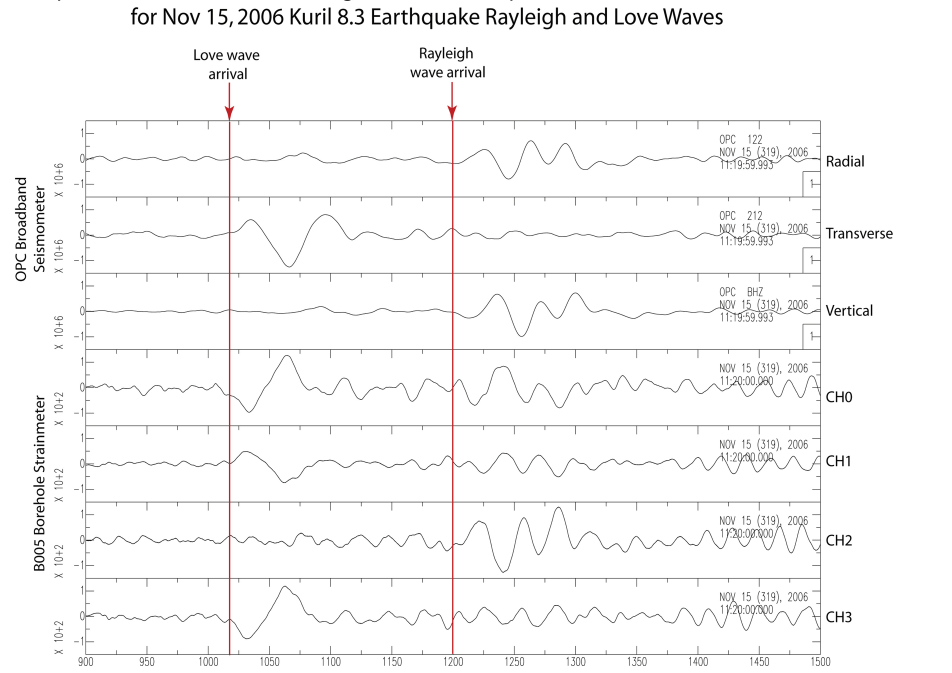
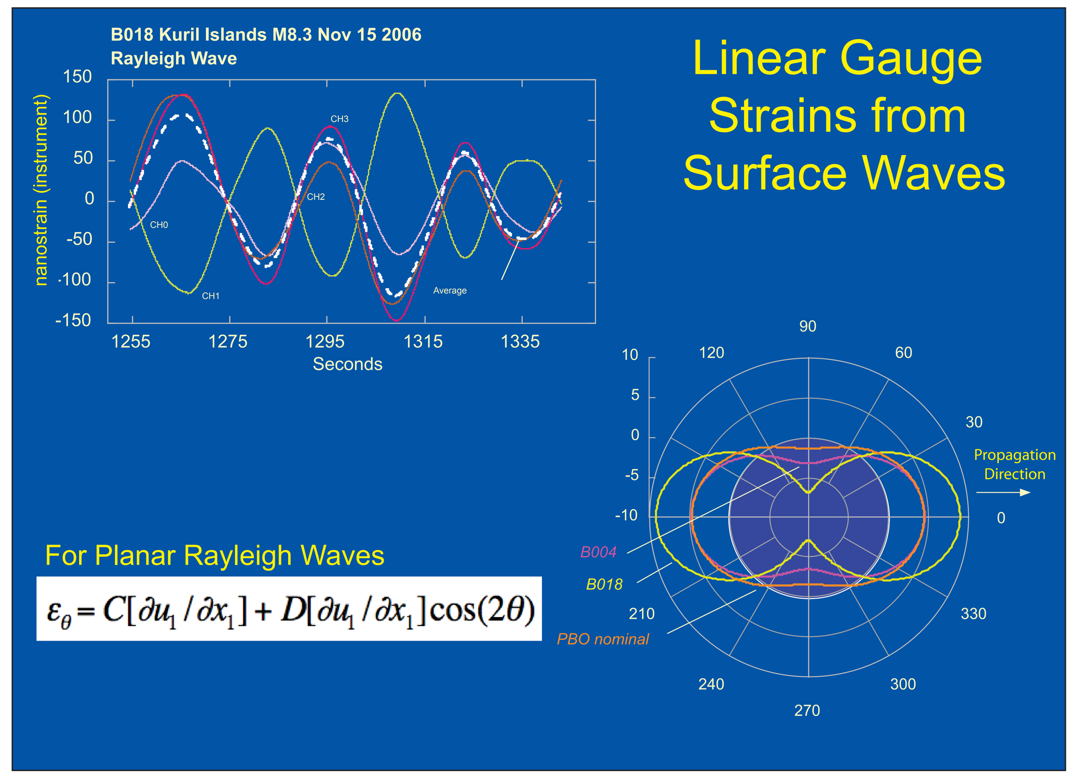
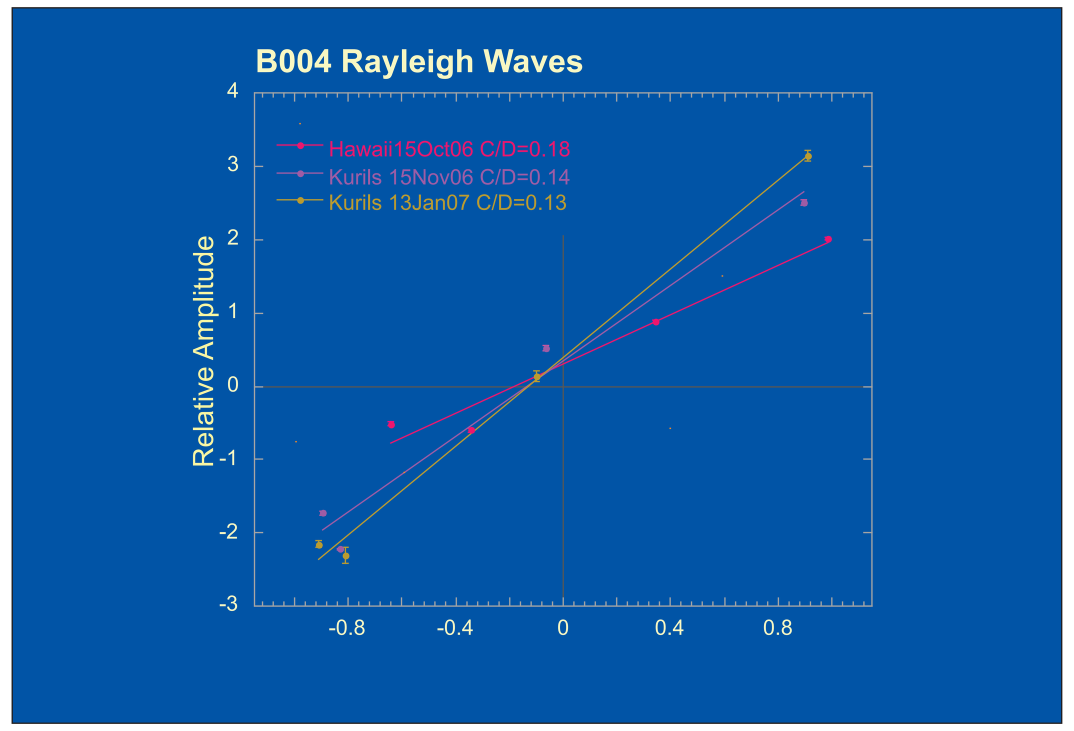


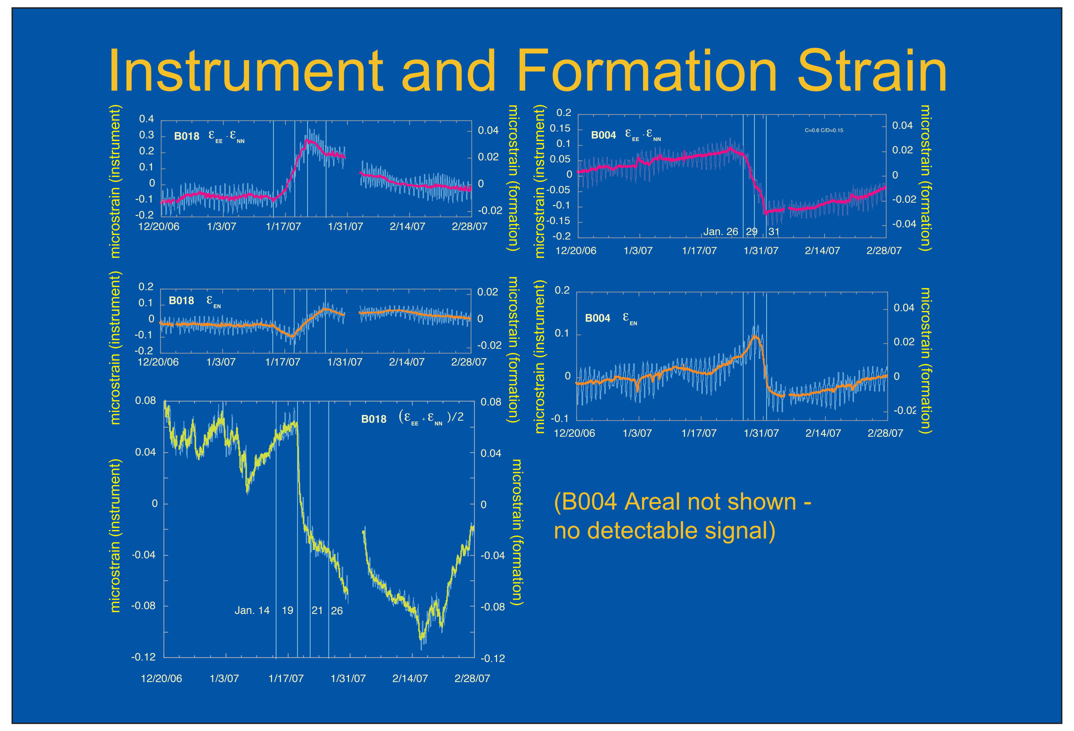
Figure showing a teleseismic earthquake on a broadband seismometer and a nearby borehole strainmeter. The seismogram has been rotated into radial and transverse components and converted to a displacement seismogram. The Love and Rayleigh wave arrivals are marked.



For planar Rayleigh waves we can expect the strain to vary as cosine(2*theta). Theta is the angle between the wave propagation direction and the gauge orientation. Figure above shows the expected strain equation; strainmeter data for the Rayleigh wave of an earthquake at station B018 for the different gauges; and the theoretical distribution of strain amplitude given the nominal calibration used by PBO, and the values determined at B004 and B018 based on Love and Rayleigh wave phases from 3 teleseismic events. Figure below shows the relative gauge amplitudes are plotted with respect to cosine(2*theta). As expected the values are linear and the slope of that line describes the ratio C/D.



Using the calculated values of C and D, and gauge weights determined from the consistency equation, we can transform the instrument strain to formation strain. Figure below shows the instrument strain values on the left vertical axes and the formation strain values on the right axes for both B004 and B018. Timeseries includes the January 2007 slow slip event.



Strainmeter Results from January Cascadia Slow Slip Event

Strainmeters are good at recording the detailed time history of the slip event.

Because the data is detrended, the net strain change is difficult to determine.

The strain changes on these two strainmeters do not overlap in time, but occurs on B018 before B004 indicating the slip event migrated to the north.

The areal signal on both instruments is weak.

Both stations have a reversal in the shear strain, but not in the differential extension. The reversal suggests that the source moved past the station.

The sense of strain is different on the two instruments indicating they have a different spatial relationship to what is slipping.

Seismic Results from January 2007

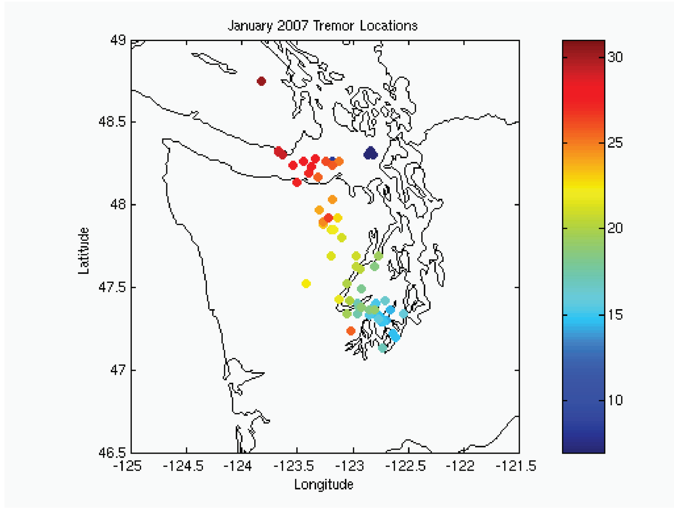


Figure showing network locations by Aaron Wech and Ken Creager. Tremor generally migrates from south to north during the tremor and slow slip event. From PNSN website.

GPS Results from January 2007

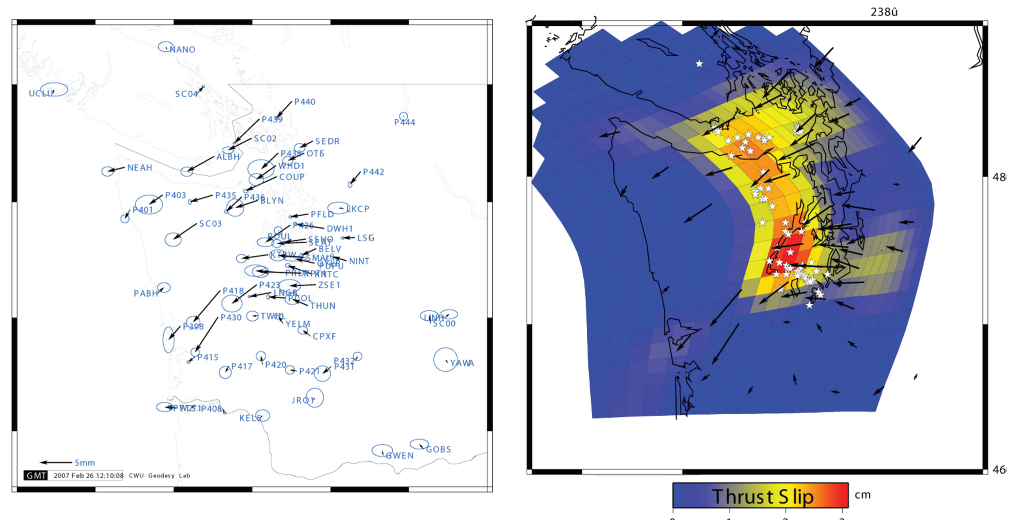
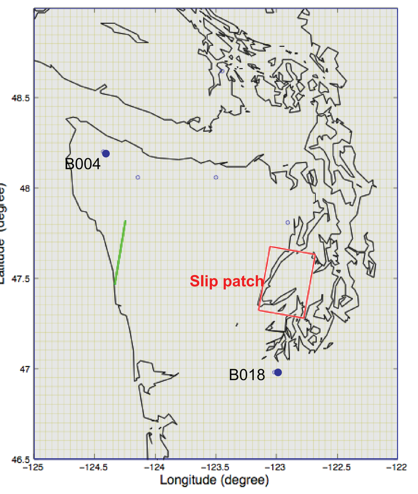


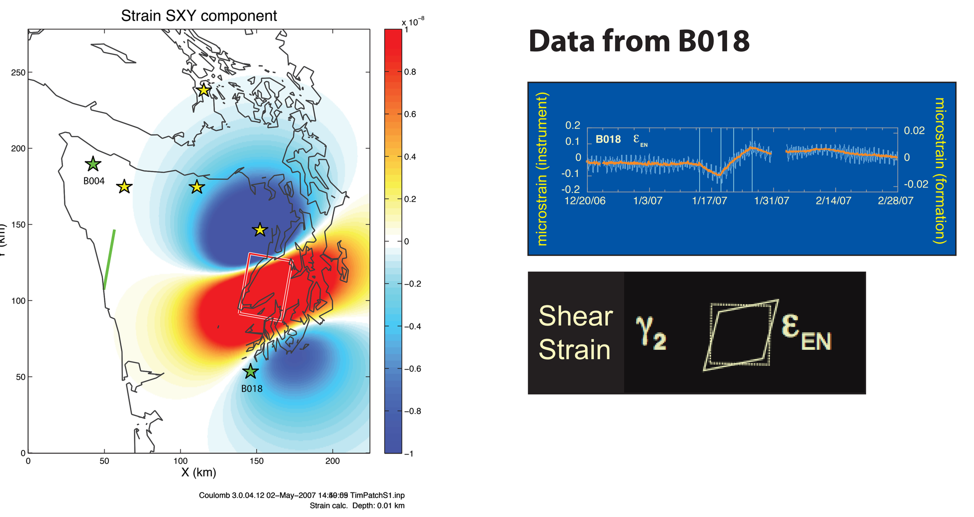
Figure on left shows the net GPS-determined displacements and the figure on the right shows a geodetic model of the slip patch based on the data in the figure on the left.. From PANGA website. GPS data show a northward slip progression as well.

Comparing Strain Data to Simple Slip Models

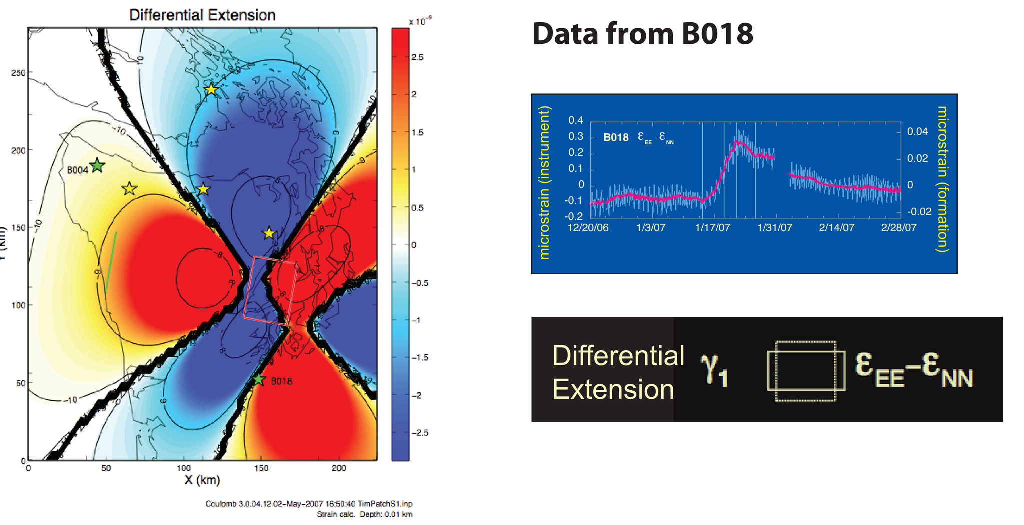


We used Coulomb 3.0 (Toda, Stein, Lin, Sevilgen) to model a slip patch centered at 47.5N 122.9W with a slab depth of 40km, slab dip of 20 degrees and a total slip of 1cm. We modeled oblique slip in the opposite direction to North America- Juan de Fuca convergence direction (~55deg).

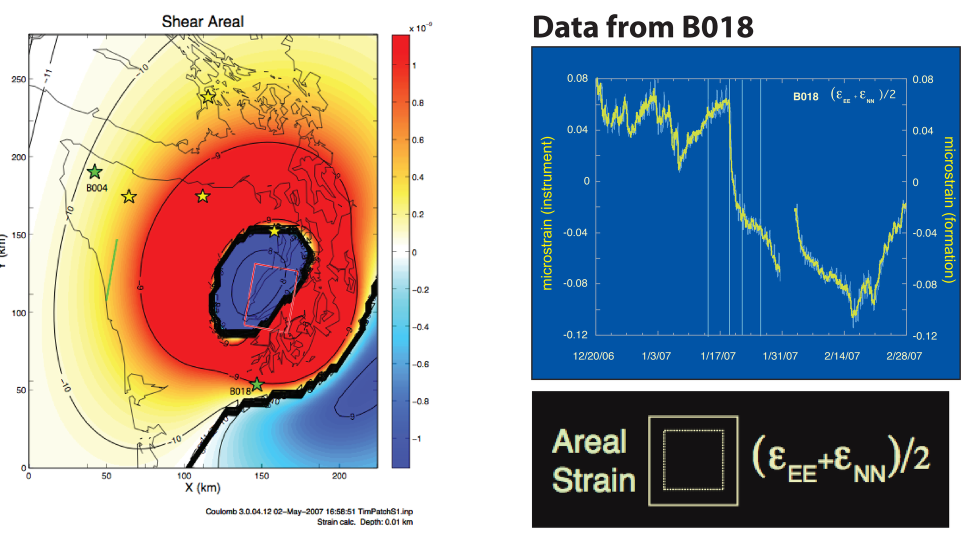
Contour Plot of Shear Strain from Model



Differential Extension from Model



Areal Strain from Model



Conclusions- Instruments

Strainmeters clearly recorded the January 2007 Cascadia slow slip event.
Strainmeters record the time history of slow slip event which is useful for refining geodetic models.
Strainmeters are capable of recording large teleseismic events, and moderate size local earthquakes.
Ratio of Areal to Shear coupling is smaller than what PBO is using. In instrument strain, shear appears larger than it is.

Conclusions- Slip Event

B004 recorded the slip event several days later than B018, indicating that the slip event migrated from south to north, which is consistent with the migration of the tremor epicenters.
There is no temporal overlap between the signal at B018 and at B004, therefore we can only model one station at a time. B013 will help fill this gap.
Sense of shear is different at B004 and B018 indicating the stations have a different spatial relationship to the slip surface.
The two shear components have different time histories indicating that the source geometry changed or moved.
The reversal of the EN shear component at B018 indicates that the source initiated south of the station and then moved northward.