Isolating and Quantifying Tectonic Signals in Borehole Strainmeter Data

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Topics

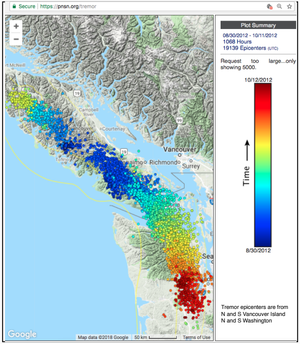
1. Tectonic and non-tectonic signals in strainmeter data
2. Seasonal variations
3. Isolating and validating a small tectonic strain signal
4. Calibration matrices from coupling coefficients; Gauge subsets
5. Orientation corrections
6. Issues with areal strains

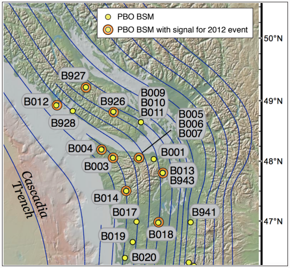
Tectonic and non-tectonic signals in strainmeter data

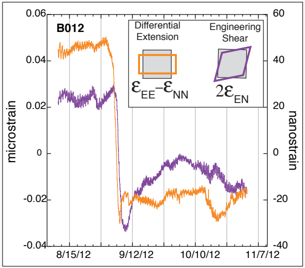
Overview

- What signals are we looking for?
- What other variations in strain data are obscuring those signals?
- How can we isolate the signals of interest?

Example signal: 2012 Northern Cascadia Episodic Tremor and Slip (ETS) event



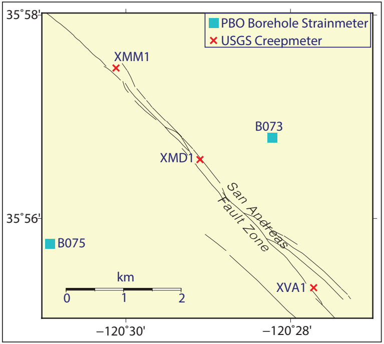


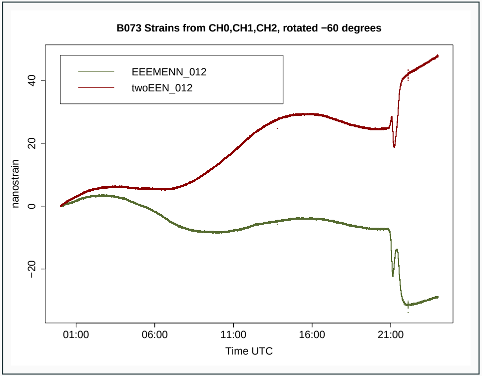


Trend, tides, atmospheric pressure removed

- Differential extension at B012 is about 60 nanostrain
- Signal takes place over about 5 days
- There are net offsets associated with both shears
- 84 days of data used to isolate signal

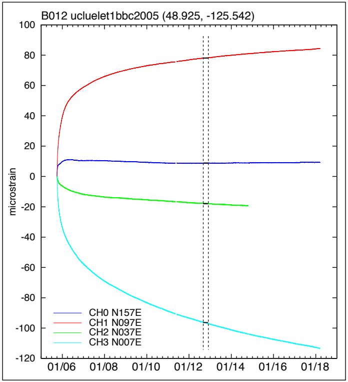
Example signal: Central San Andreas Creep Event

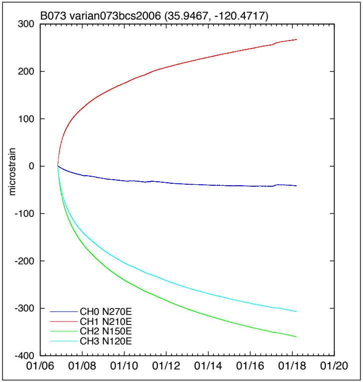




- Shear strain signals at B073 are about 30 nanostrain
- Signal takes place over about 5 hours
- There are net offsets associated with shear strains
- Visible in 1 day of unprocessed data

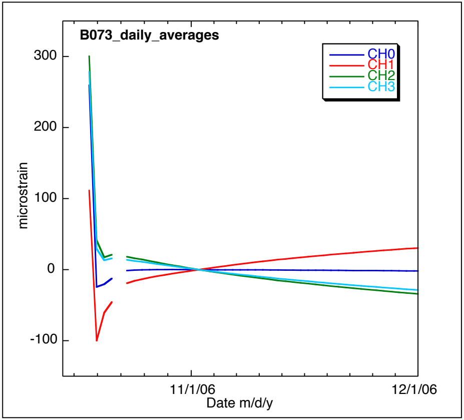
Long-term gauge elongations: B012 and B073

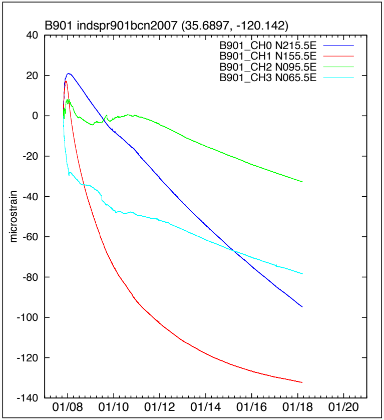




- The tectonic signals are dwarfed by long-term gauge elongations
- Long-term rates are typically 10's of microstrain/year
- Often similar shapes on the 4 gauges of one GTSM
- Elongation rates typically become constant but not zero
- In general, elongations continue for life of instrument
- Gauge elongations are not measurements of tectonic strain rate

Long-term gauge elongations: Post-installation

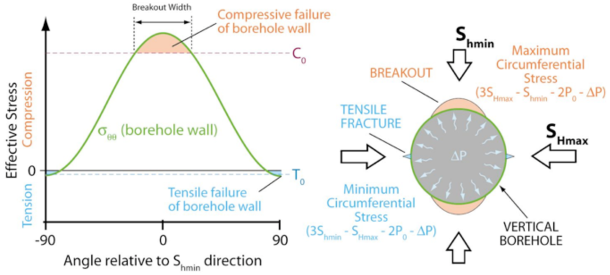




- During first weeks-months, trends are complex and non-monotonic:
  - Curing grout expands and gives off heat
  - Pore pressure around borehole re-equilibrates after drilling/installation disturbance
- Data are difficult to use in this phase
- Some BSMs take more than 1 year to perform well

What causes long-term trends to continue?

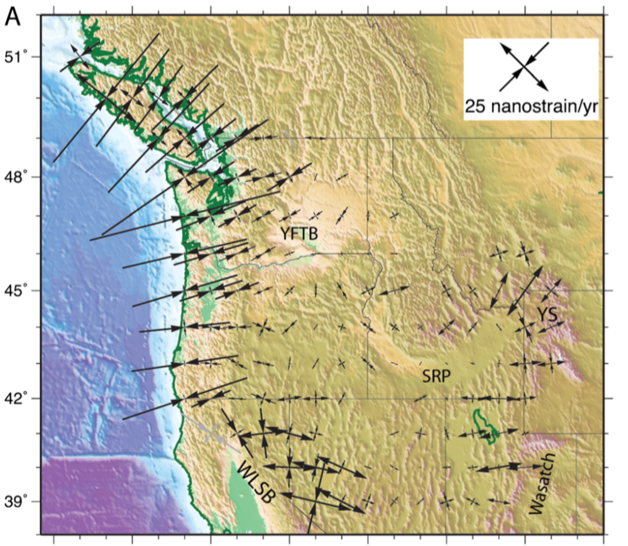
STRESS AROUND A BOREHOLE PROMOTES THE DEFORMATION OF THE BOREHOLE WALL. THAT DEFORMATION RECORDS MODERN DAY STRESS STATE.



Stress concentration around a borehole coinciding with one of the principal stresses based on the Kirsch equations.

- Drilling the borehole and installing the strainmeter creates a stress field that varies around the borehole
- BSM gauges measure localized formation creep caused by these stresses

Gauge elongation rates far exceed tectonic strain rates



McCaffrey, R., R. W. King, S. J. Payne, and M. Lancaster (2013), Active tectonics of northwestern U.S. inferred from GPS-derived surface velocities, JGRSE, 118.

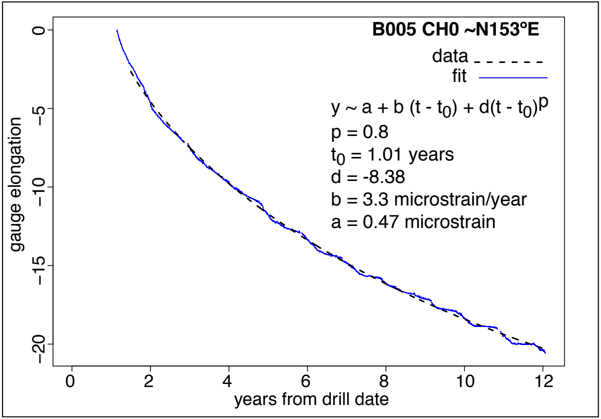
Long-term gauge elongations: Fitting

A function that can fit the gauge extension time series $e(t)$ for many PBO BSMs is:

$e(t) =$
$a + b(t - t_0) + d(t - t_0)^p$

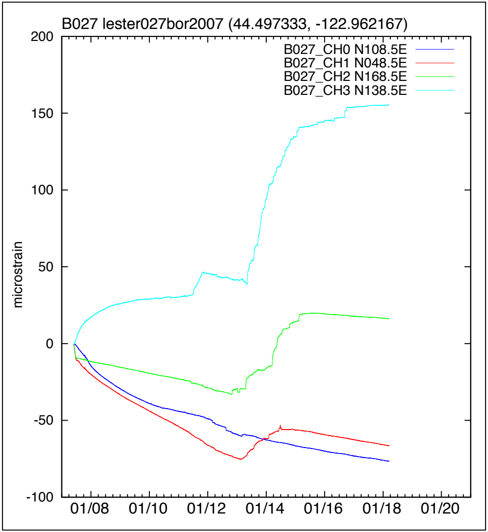
where:

t = time, t_0 = reference time
a = arbitrary reference value
b = constant elongation rate
d = power term coefficient
p = exponent with
$0 < p < 1$

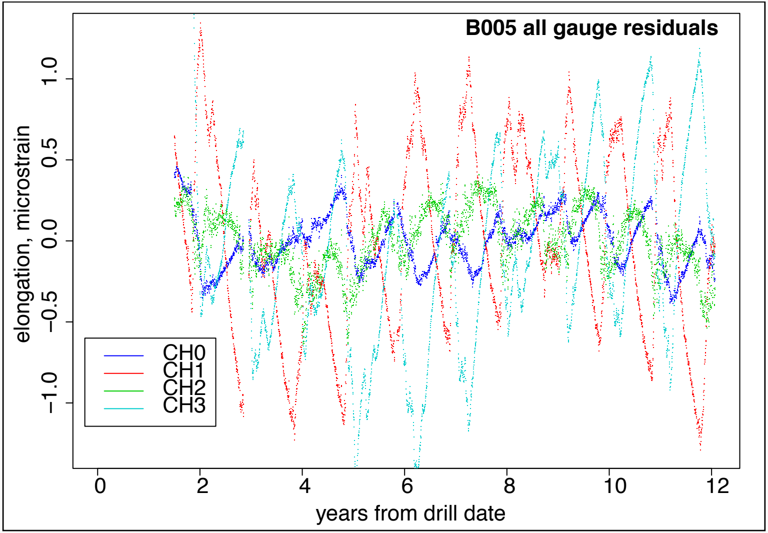


Long-term gauge elongations: Difficult cases

- For some strainmeters, the long-term elongations cannot be easily modeled
- Not necessarily a problem, since generally need to work with only a short interval of data



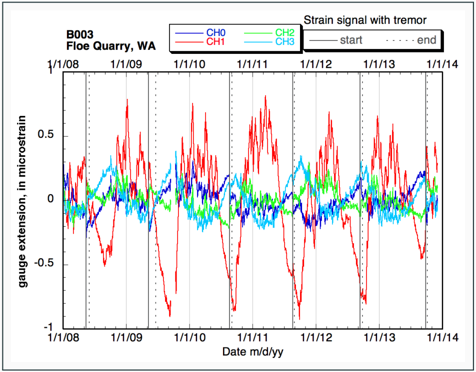
What's left after subtracting the long-term trend?



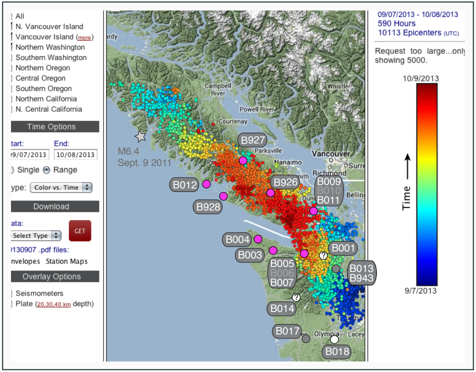
Seasonal variations

Seasonal variations compared with slip-event signals

B003 after removing long-term trend



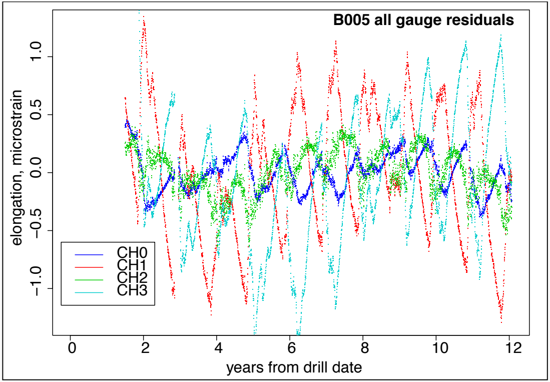
2013 Northern Cascadia tremor



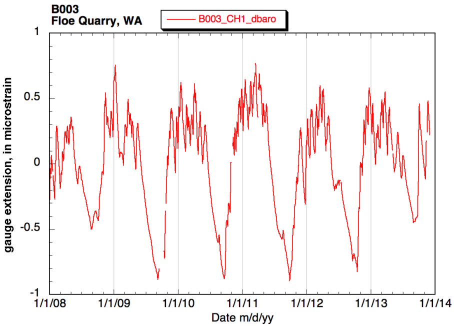
Seasonal variations often dwarf slip-event signals

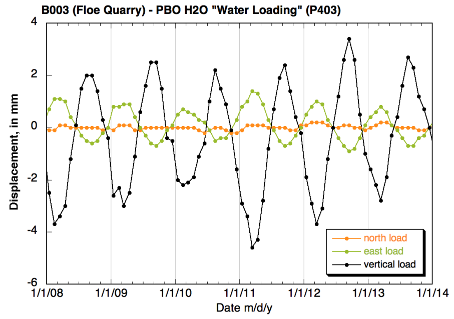
Seasonal variations in gauge data

- Seasonal variations differ among the gauges of a BSM
- Measured parameters may correlate with seasonal variations:
    - atmospheric pressure
    - downhole temperature
    - pore pressure
    - seasonal vertical displacement
    - depth of surface-water
- Groundwater pumping that affects strainmeters may also occur seasonally (see B009 and B011)



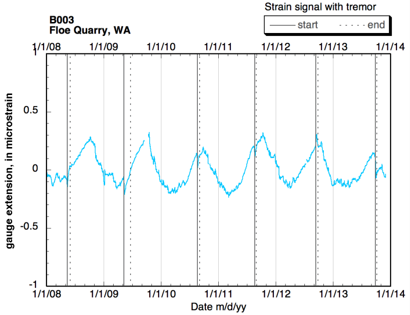
Seasonal variations and GPS-derived seasonal displacements

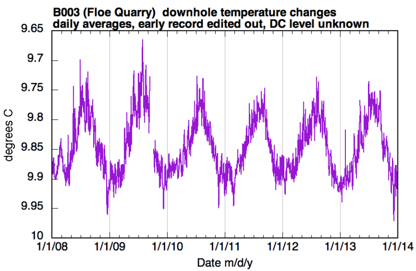




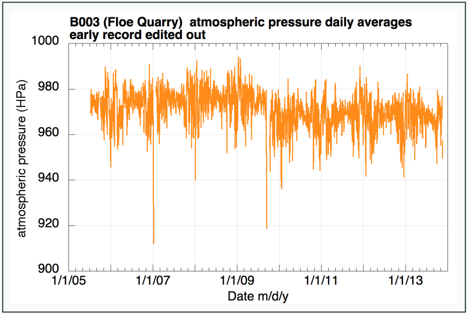
Seasonal gauge elongations and downhole temperature

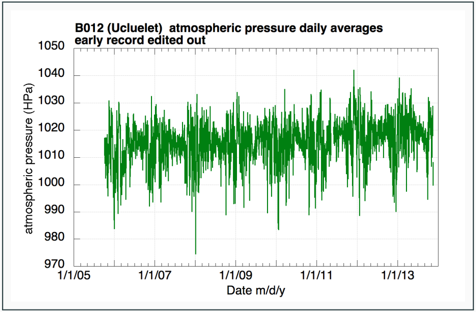
- Peak extension on B003 CH3 lags peak downhole temperature by about two months
- Coefficient about 2.5 microstrain/°C
- For comparison, coefficients of thermal expansion:
    - Steel 9.9-17 microstrain/°C
    - Concrete 12 microstrain/°C





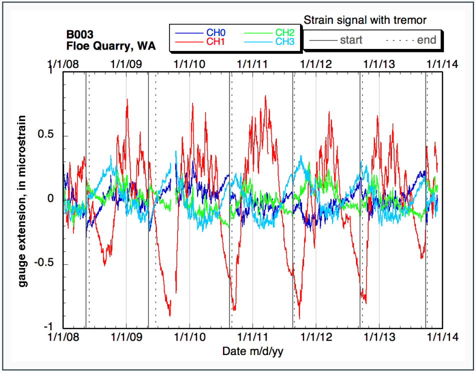
Atmospheric pressure contributes some seasonal variation



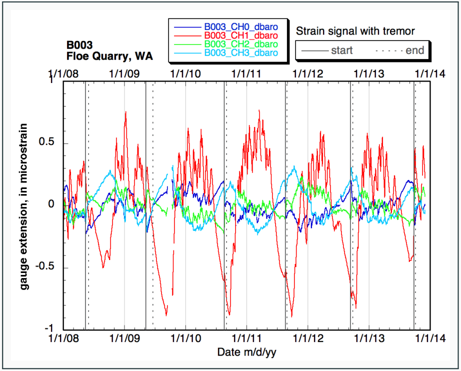


- Atmospheric pressure influence on gauge data can be greatly reduced using linear regression
- First check for and correct artificial offsets and/or drift in long-term barometer data

Seasonal variations after removing atmospheric pressure



No pressure correction



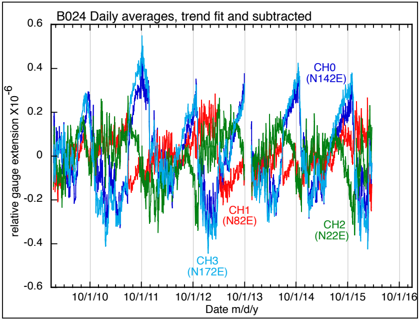
After pressure correction

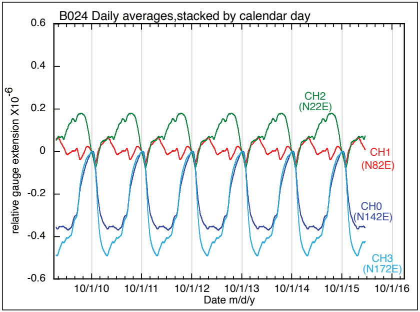
Approaches to modeling/removing seasonal variations

In approximate decreasing order of effectiveness...

- For repeatable seasonal signals, stack years of data
- STL ("Seasonal Trend decomposition based on Loess")
- Model the strain caused by precipitation infiltration
- Regress against other measured parameters
- Fit sinusoids

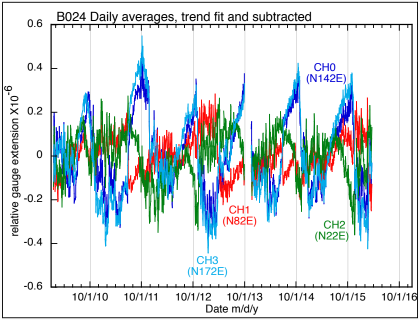
Example: Stacking repeatable seasonal signals

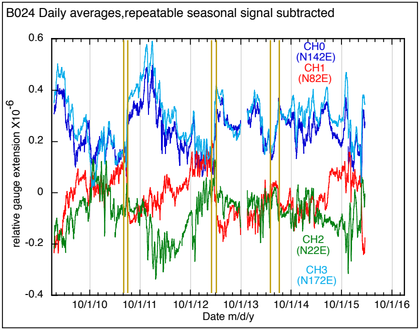




Form a 365-day time series by averaging values on each calendar day over all years of data

Example: Stacking repeatable seasonal signals

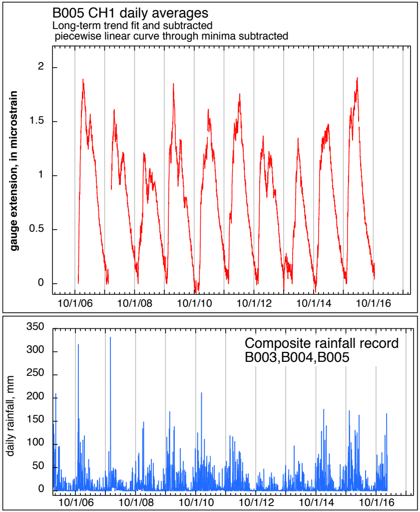




Gold lines on right-hand plot are times when tremor was observed

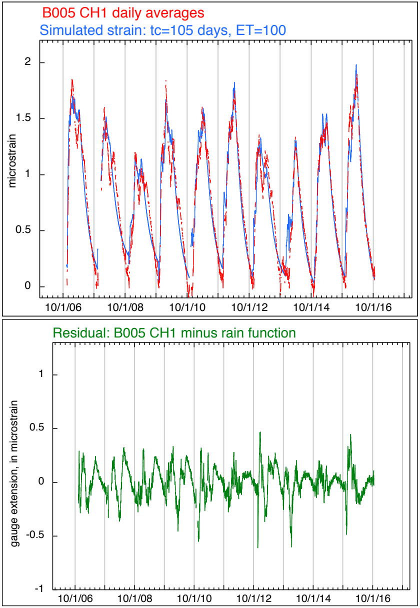
Strain excursions at these times are more obvious after removing seasonal signals

Example: Modeling strain caused by precipitation



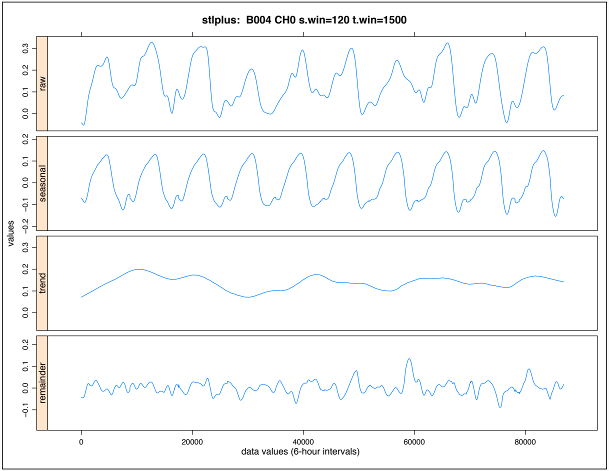
- Groundwater recharge from precipitation is a cause of seasonal strain
- Precipitation record can be used to simulate strain
- Note: It can be difficult to assemble a consistent record of precipitation

Example: Modeling strain caused by infiltrating precipitation



- To calculate simulated strain from daily precipitation:
  - Reduce daily rainfall for evapotranspiration (ET) during summer
  - Infiltration begins after a threshold cumulative amount of precip
  - After ET and above threshold, each day's precip is added to simulated strain
  - Each day's contribution decays with time
- This is a trial-and-error fit
- Variance is reduced but sharp onset of seasonal is poorly modeled

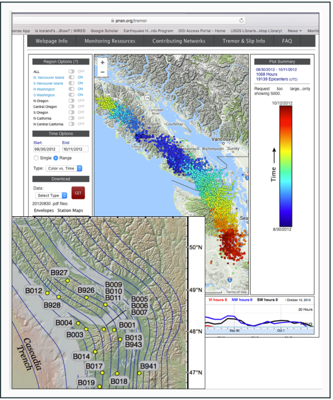
Example: STL "loess" seasonal adjustment

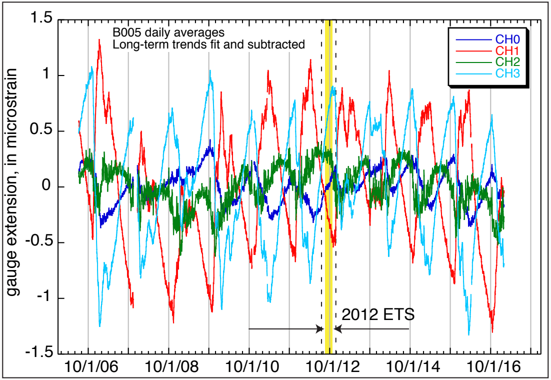


- STL algorithm from Cleveland et al., J. Official Statistics, 1990
- implemented as R "STL+" algorithm by R.P. Hafen

Isolating and validating a small tectonic strain signal

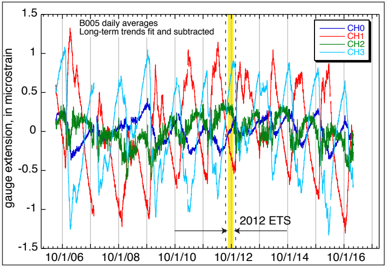
Example signal: 2012 Northern Cascadia ETS on B005

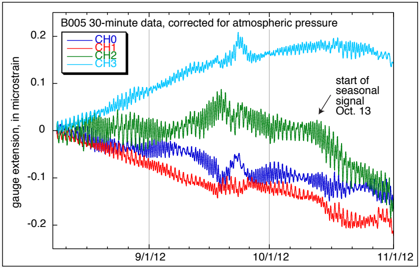




- Tremor identified August 30 to October 11 (42 days)
- Period to analyze ends near onset of seasonal signals

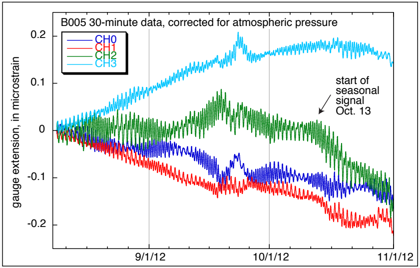
Example signal: 2012 Northern Cascadia ETS on B005

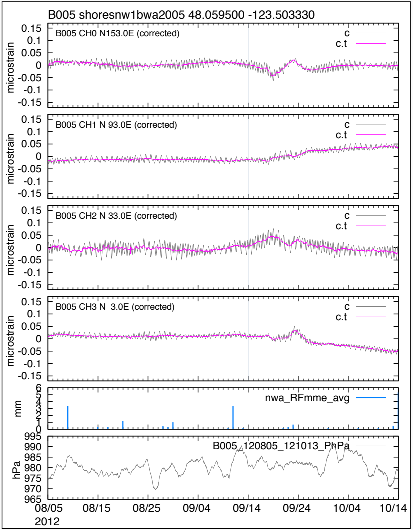




- Tremor identified August 30 to October 11 (42 days)
- Period to analyze ends near onset of seasonal signals
- Here it is possible to just delete the seasonal signal from the analysis

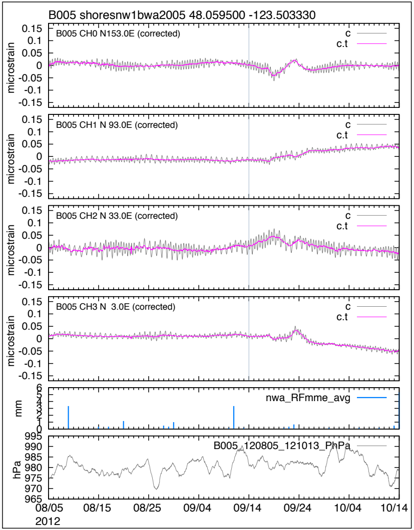
Example signal: 2012 Northern Cascadia ETS on B005

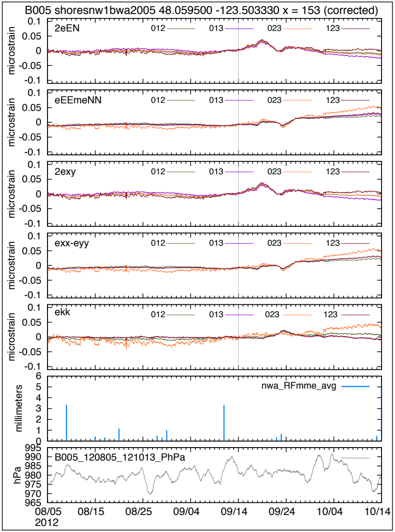




- Delete data after 13 October
- Correct for tides
- Detrend over period before event
  - Use care: choice of detrending period changes signal shape.
  - Experiment for robust result

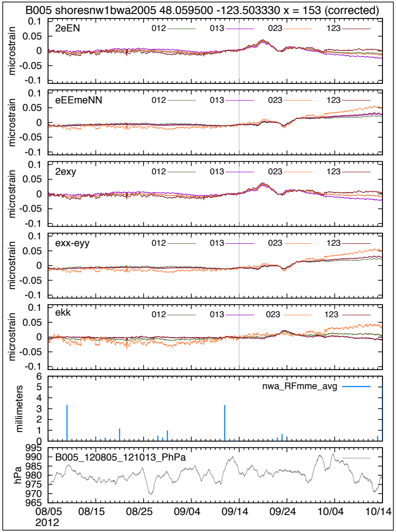
Example signal: 2012 Northern Cascadia ETS on B005

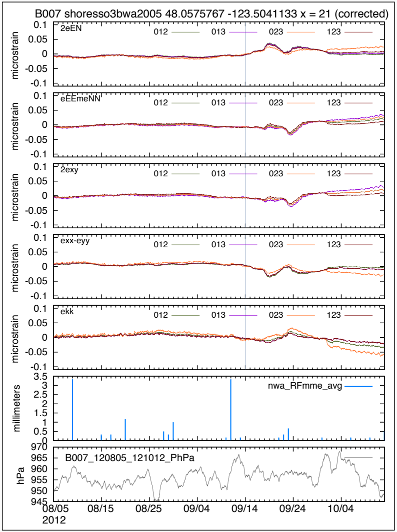




Combine elongations to get strains, using all possible subsets

Compare: 2012 N Cascadia ETS on co-located B005 and B007





Calibration matrices from coupling coefficients; Gauge subsets

3 gauge elongations to 3 strain components

- 3 identical gauges 120° apart $(CH0, CH1, CH2) = (e_0, e_1, e_2)$
- Express elongations in CH1-parallel coordinates:

$$e_0 = C(\epsilon_{x_1x_1} + \epsilon_{y_1y_1}) + Dcos(240^\circ)(\epsilon_{x_1x_1} - \epsilon_{y_1y_1}) + Dsin(240^\circ)(2\epsilon_{x_1y_1})$$
$$e_1 = C(\epsilon_{x_1x_1} + \epsilon_{y_1y_1}) + D(\epsilon_{x_1x_1} - \epsilon_{y_1y_1})$$
$$e_2 = C(\epsilon_{x_1x_1} + \epsilon_{y_1y_1}) + Dcos(-240^\circ)(\epsilon_{x_1x_1} - \epsilon_{y_1y_1}) + Dsin(-240^\circ)(2\epsilon_{x_1y_1})$$

- Solve for strain components:
  $(\epsilon_{x_1x_1} + \epsilon_{y_1y_1}) = (e_0 + e_1 + e_2)/3C$
  $(\epsilon_{x_1x_1} - \epsilon_{y_1y_1}) = [(e_1 - e_0) + (e_1 - e_2)]/3D$
  $2\epsilon_{x_1y_1} = (e_2 - e_0)/[2(0.866D)]$
- Areal strain is proportional to average of outputs from equally spaced gauges
- Shear strains are proportional to differences among gauge outputs

More general coupling and calibration matrices

- Coupling coefficients C_i, D_i, and F_i (or $\tilde{C}_i$) are estimated from gauge response to "known" strains
- The equations expressing the responses of all the gauges to strain in common (x, y) coordinates are assembled as rows of a "coupling matrix", **C**, in which θ_i is angle of e_i CCW from x:

$$\begin{bmatrix} e_0 \\ e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} C_0 & D_0 \cos 2\theta_0 & D_0 \sin 2\theta_0 \\ C_1 & D_1 \cos 2\theta_1 & D_1 \sin 2\theta_1 \\ C_2 & D_2 \cos 2\theta_2 & D_2 \sin 2\theta_2 \\ C_3 & D_3 \cos 2\theta_3 & D_3 \sin 2\theta_3 \end{bmatrix} \begin{bmatrix} \epsilon_{xx} + \epsilon_{yy} \\ \epsilon_{xx} - \epsilon_{yy} \\ 2\epsilon_{xy} \end{bmatrix} = \mathbf{C} \begin{bmatrix} \epsilon_{xx} + \epsilon_{yy} \\ \epsilon_{xx} - \epsilon_{yy} \\ 2\epsilon_{xy} \end{bmatrix}$$

- The "calibration matrix", **S**, "inverts" the coupling matrix to express the strains in terms of the gauge elongations

$$\begin{bmatrix} \epsilon_{xx} + \epsilon_{yy} \\ \epsilon_{xx} - \epsilon_{yy} \\ 2\epsilon_{xy} \end{bmatrix} = \mathbf{S} \begin{bmatrix} e_0 \\ e_1 \\ e_2 \\ e_3 \end{bmatrix}$$

Calibration matrices

$$\begin{bmatrix} \epsilon_{xx} + \epsilon_{yy} \\ \epsilon_{xx} - \epsilon_{yy} \\ 2\epsilon_{xy} \end{bmatrix} = \mathbf{S} \begin{bmatrix} e_0 \\ e_1 \\ e_2 \\ e_3 \end{bmatrix}$$

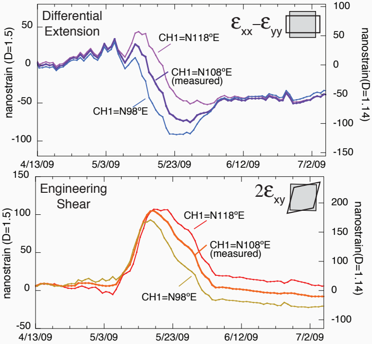
- The "calibration matrix", **S**, depends on
  - Coordinate system (x, y)
  - Gauge subset used (all 4, or any subset of 3)
- For identical gauges, the coupling matrices for subsets of 3 gauges can be inverted analytically to obtain calibration matrices
- In general, the coupling matrices must be inverted numerically
- If all 4 gauges are used, the inverse is a "generalized" inverse

Why use a subset of the gauges?

- One gauge may stop working or have a noisy period
- Disagreement among strains from gauge subsets may indicate incorrect calibration

Orientation corrections

Need for orientation corrections

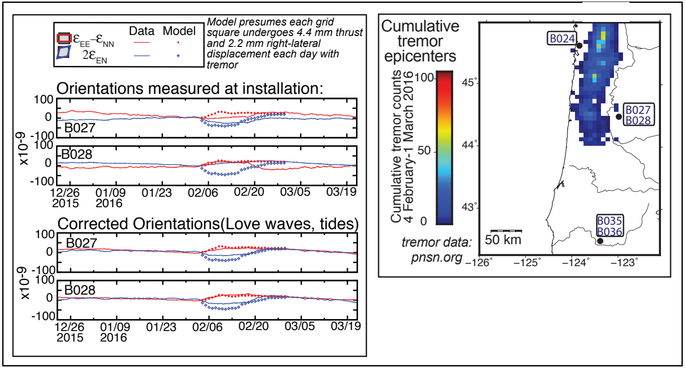


B004 shear strains for 2009 Cascadia aseismic slip event

- The strain tensor is a function of π (not 2π)
- 10° misorientation for a GTSM is twice as large relative to full-scale as same misorientation for a seismometer
- PBO GTSM measured orientations may require correction
- Some orientations were not measured at installation
- see Hodgkinson et al., JGR, 2012

Sources of orientation corrections

- Tidal calibrations (Roeloffs, JGR 2010; Hodgkinson et al., JGR, 2012)
- Teleseismic Love waves (Roeloffs, in preparation)
- Where both methods have been applied, orientation corrections agree



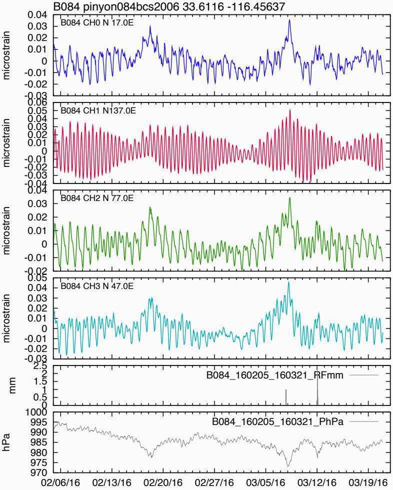
B027 shear strains for 2016 tremor/slip event in Oregon

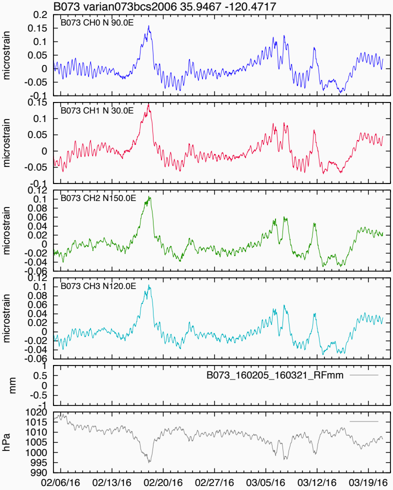
Issues with areal strains

Why emphasize shear strains?

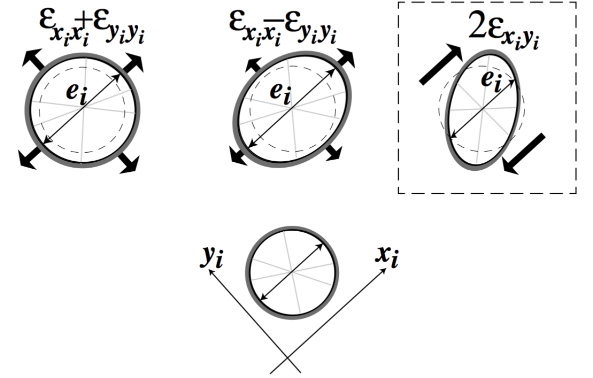
- Areal strains average gauge outputs, so stack common-mode noise
    - Shear strains are differences among gauge outputs; common-mode noise is reduced
- Vertical coupling reduces areal strain response coefficients for some BSMs

Evidence for vertical coupling: Large atmospheric pressure response





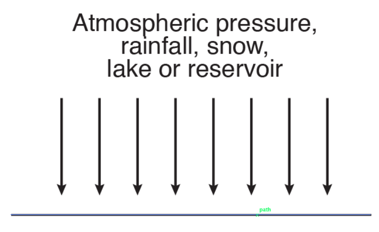
More general coupling formulation

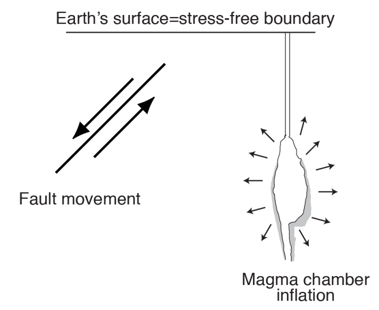


$$e_i = C_i(\epsilon_{x_ix_i} + \epsilon_{y_iy_i}) + D_i(\epsilon_{x_ix_i} - \epsilon_{y_iy_i}) + F_i\epsilon_{zz}$$

- Each gauge has its own coupling coefficients
- Coupling to vertical strain is included
- Note: No coupling to $2\epsilon_{x_iy_i}$ in gauge-parallel coordinates

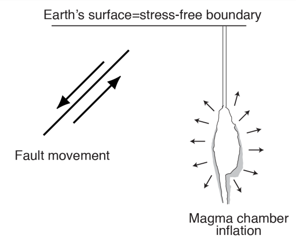
Effect of the free surface





Strainmeter responds differently to a surface load than to a source from within the earth

Effect of vertical coupling on areal strain response



$$\epsilon_{zz} = \frac{-\nu}{1-\nu}(\epsilon_{xx} + \epsilon_{yy}) = \frac{-\nu}{1-\nu}(\epsilon_{x_i x_i} + \epsilon_{y_i y_i})$$

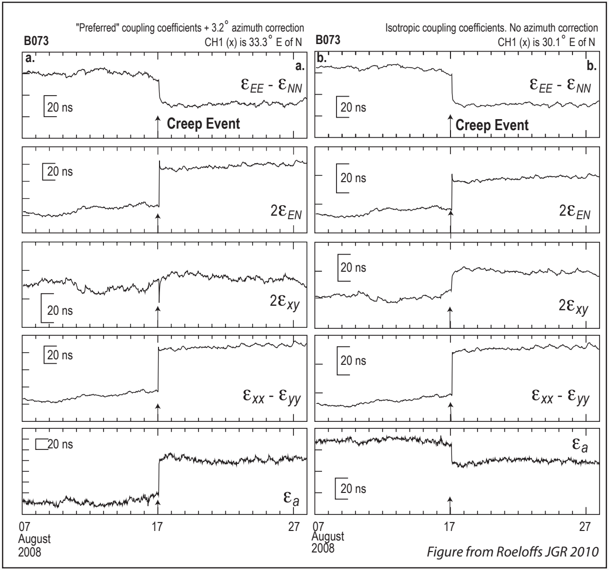
$$e_i = [C_i - \frac{\nu}{1-\nu} F_i](\epsilon_{x_i x_i} + \epsilon_{y_i y_i}) + D_i(\epsilon_{x_i x_i} - \epsilon_{y_i y_i})$$

Define an apparent areal strain coupling coefficient $\tilde{C}_i = [C_i - \frac{\nu}{1-\nu} F_i]$

$$e_i = \tilde{C}_i(\epsilon_{x_i x_i} + \epsilon_{y_i y_i}) + D_i(\epsilon_{x_i x_i} - \epsilon_{y_i y_i})$$

- For sources much deeper than strainmeter:
  - Vertical coupling reduces apparent areal strain response
  - Apparent areal strain response can even be negative

Example: B073 Areal Strain



Time for questions...