Diurnal and sub-diurnal variations in slow slip in Cascadia:

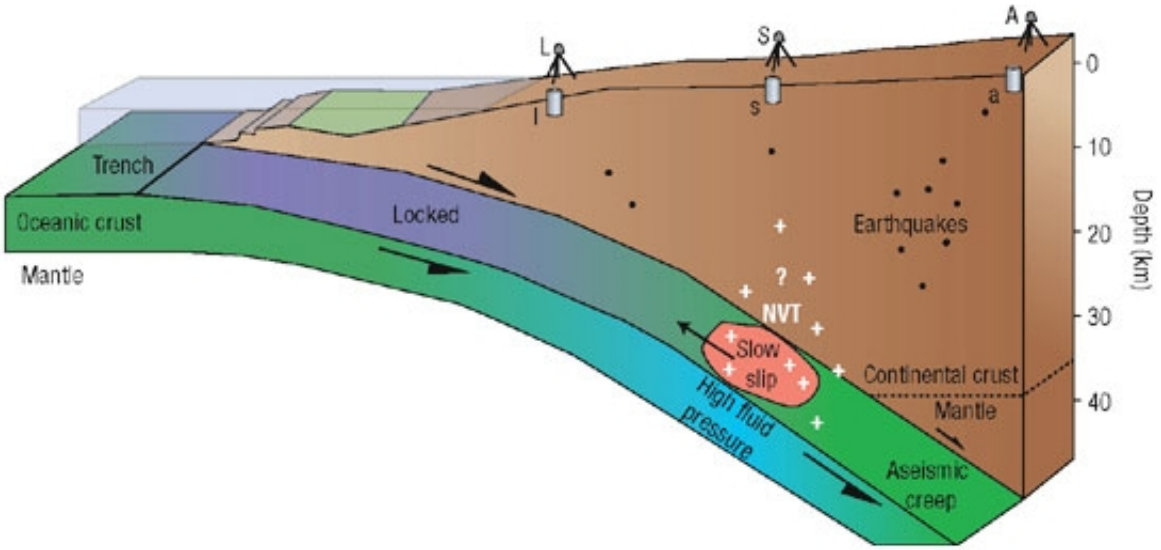
Comparison of PBO borehole strain observations with tidal loading and tremor

Jessica Hawthorne
Allan Rubin

Princeton University

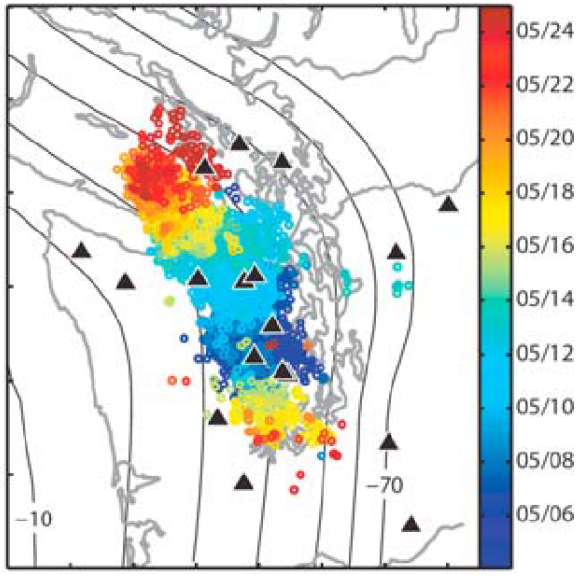
May 18, 2011

Slow slip in Cascadia



Brudzinski, 2007

May 2008 tremor

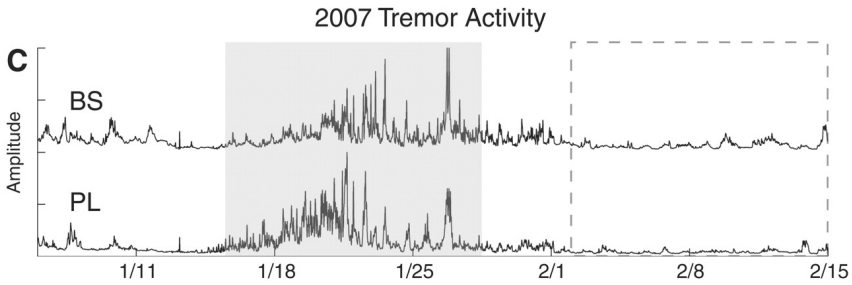


Wech et. al., 2009

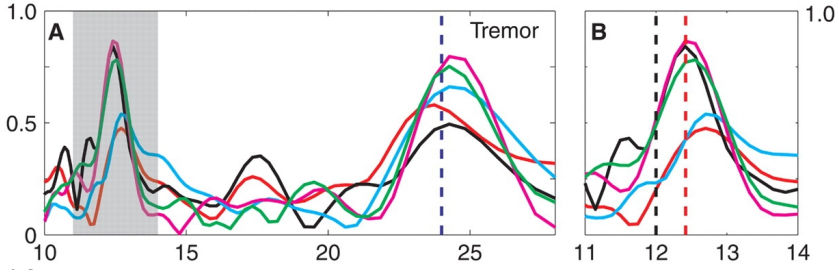
- 30-50 km depth
- Major events every 12-16 months
- 2-3 cm of slip in each event
- Events last 2-3 weeks
- Slip rates 10 to 100 times plate rate
- Tremor propagates along strike

Significant short timescale variability in tremor

Cascadia tremor envelope: large variation in amplitude



Envelope spectra: tidal modulation



Rubinstein et. al., 2008

Do we expect similar variability in slow slip?

- Major slow slip events in Cascadia coincide with large amounts of tremor.
- Moment released by tremor only ~0.1% of aseismic moment.

Further motivation to examine the details of slow slip

- Models proposed to explain slow slip events usually include only aseismic slip
- Make predictions about slip, not necessarily tremor

Outline

Goals for this talk

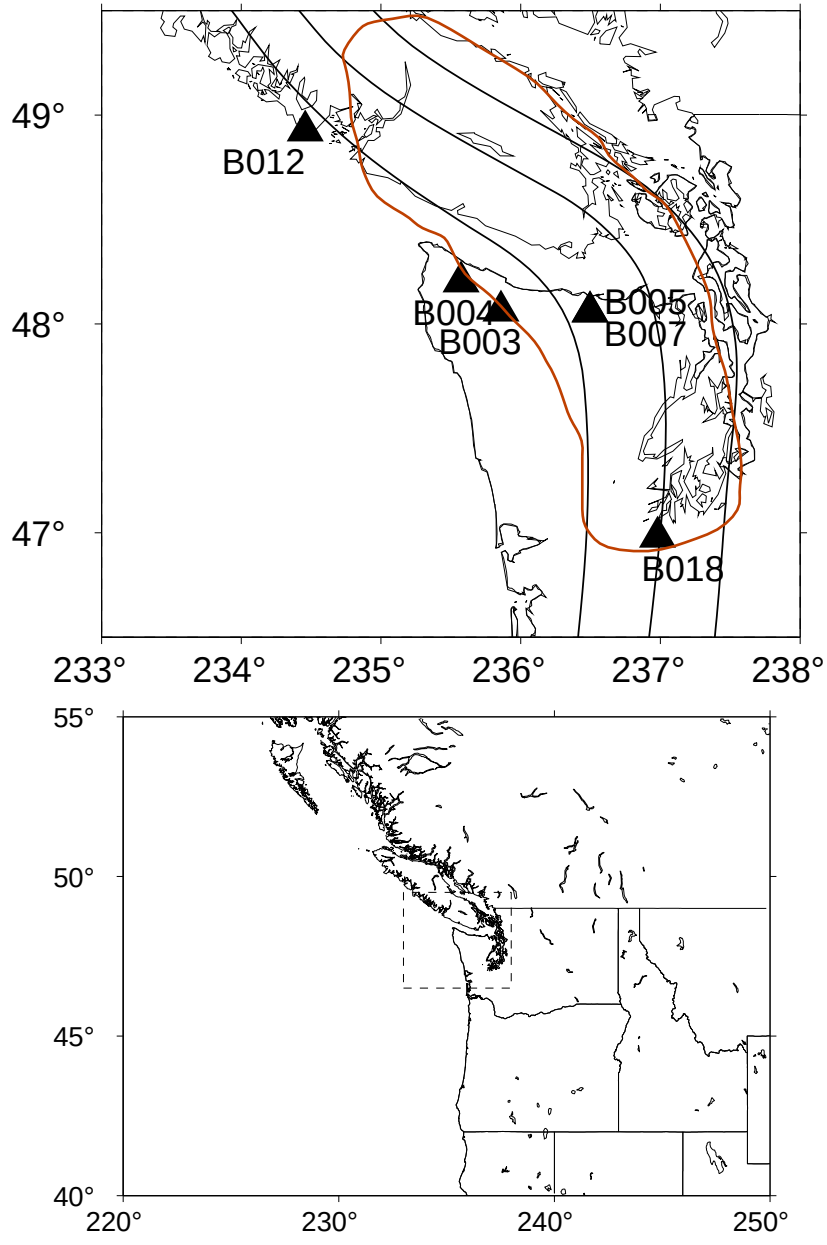
- Examine tidal modulation of slip in the strain data
- Look for a correlation between slip and tremor

Outline

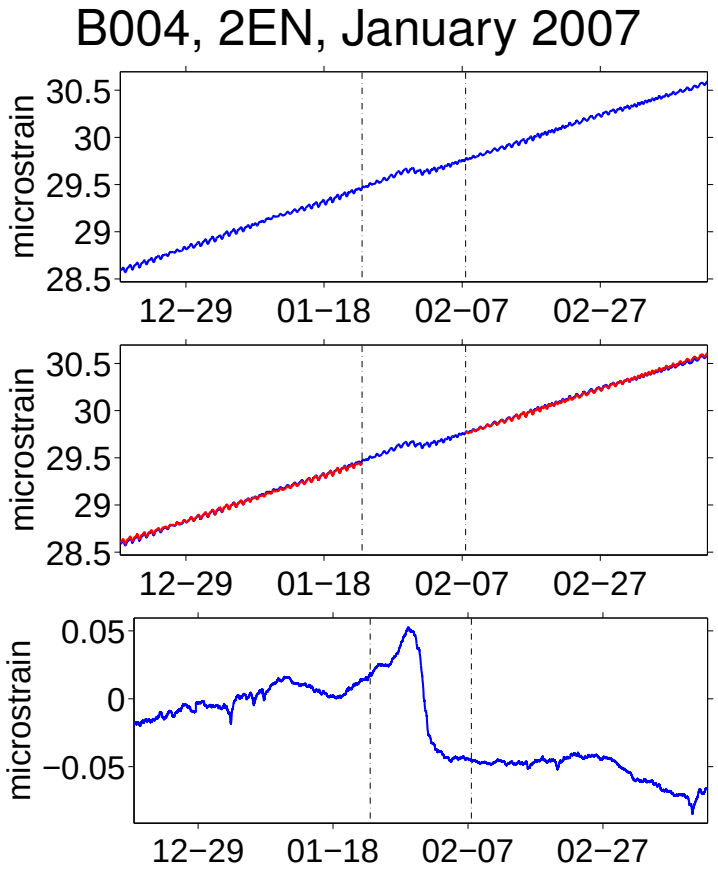
- Strain observations
- Strain data processing
- Tidal modulation of strain
  - Model for observing tidal modulation
  - Observed signal at the tidal periods
- Correlation of tremor and slip
  - Model for correlation with tremor
  - High strain rate coincides with large seismic amplitude

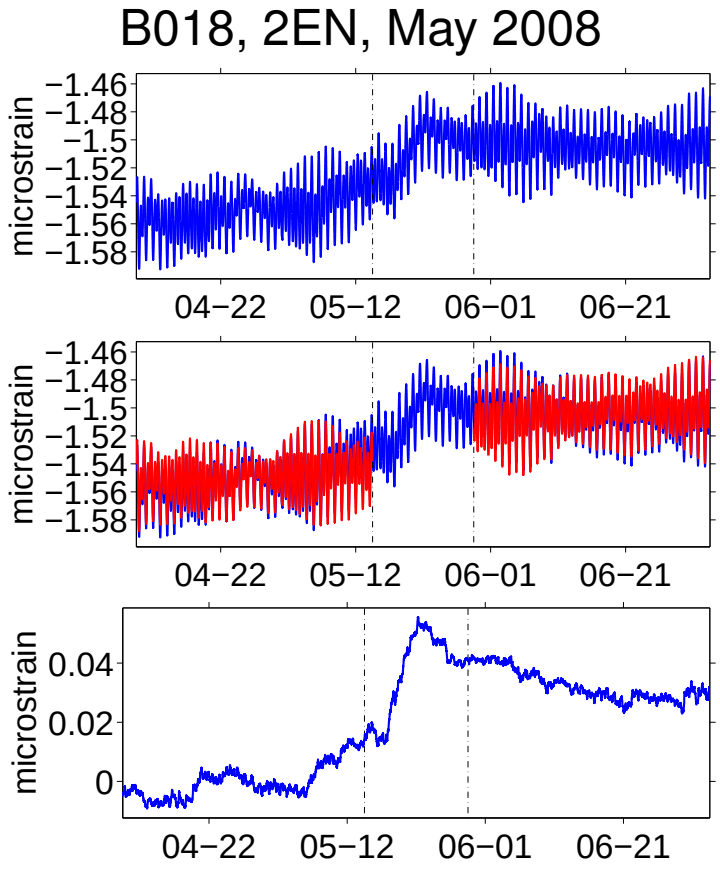
PBO borehole strainmeters

- 4 horizontal extensometers
- Depths of several hundred feet
- Processing by PBO:
  - calibrated to predicted tidal strain
  - converted to 3 horizontal strain components
- Use 2 horizontal shear strains
- Major events in January 2007, May 2008, May 2009, August 2010
- Smaller events in October 2007, March 2008



Strain data processing





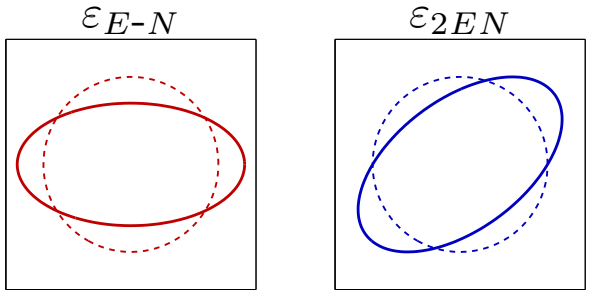
Identify a 15-day interval that includes most of the slow slip strain.

Remove empirical fit in 35 days before and after each slow slip event:

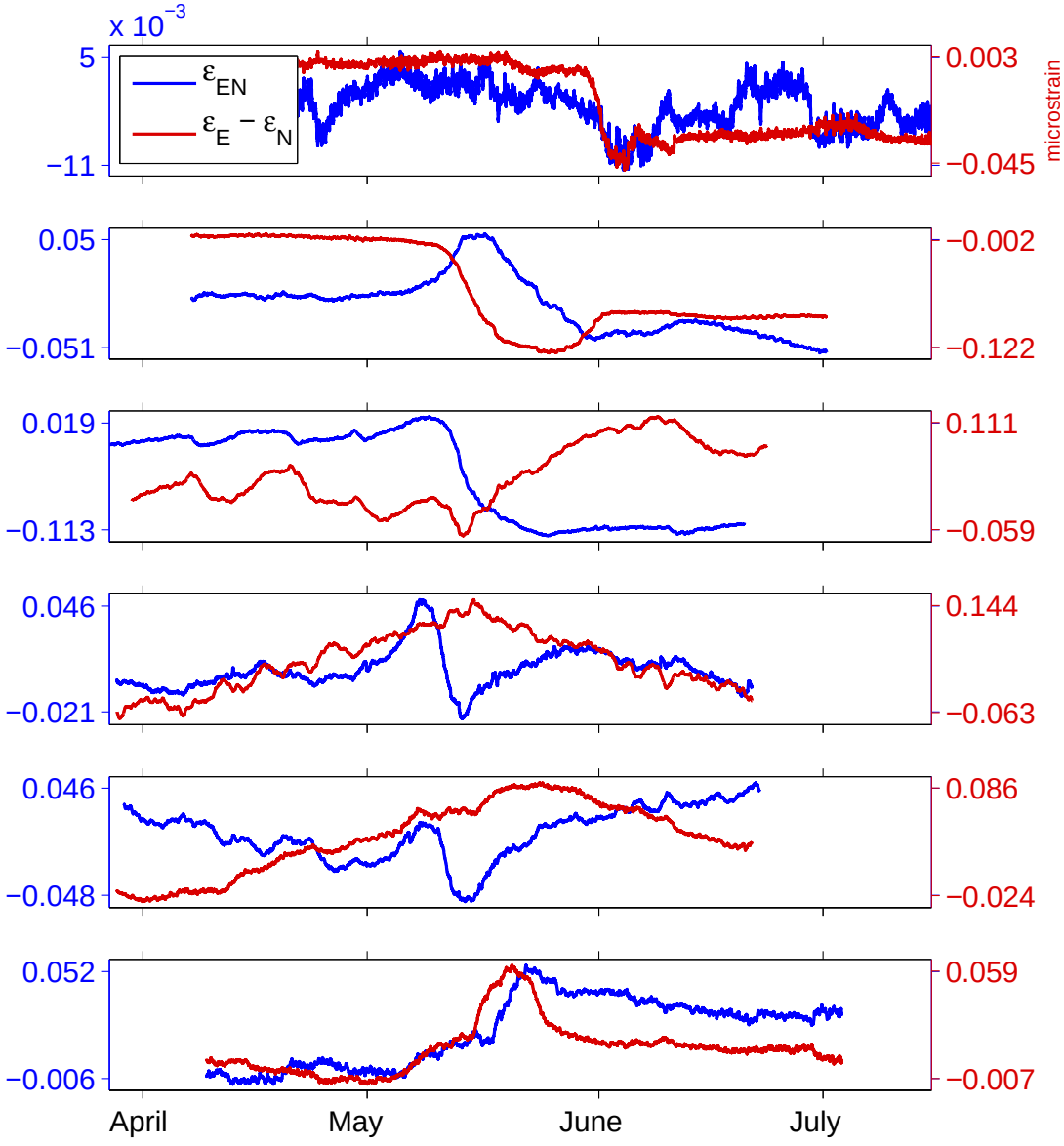
- Linear trend
- Direct tidal strain
- Linear correlation with atmospheric pressure

Slow slip as observed by strainmeters

- Sign of accumulating strain changes as location of slip moves.
- Assume strain rate is proportional to slip rate (moment rate).
- Noise level is such that we won't be able to extract information from a single record.

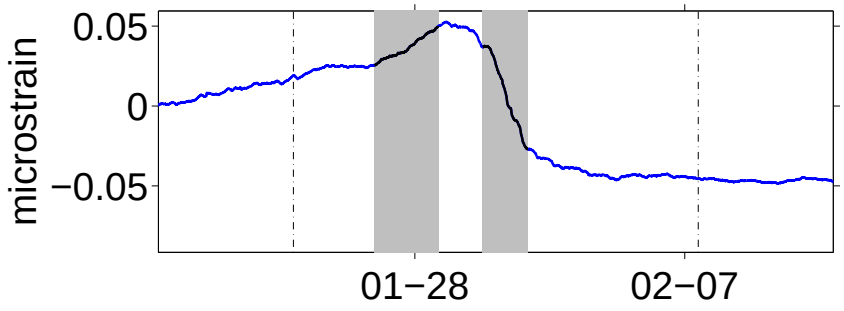


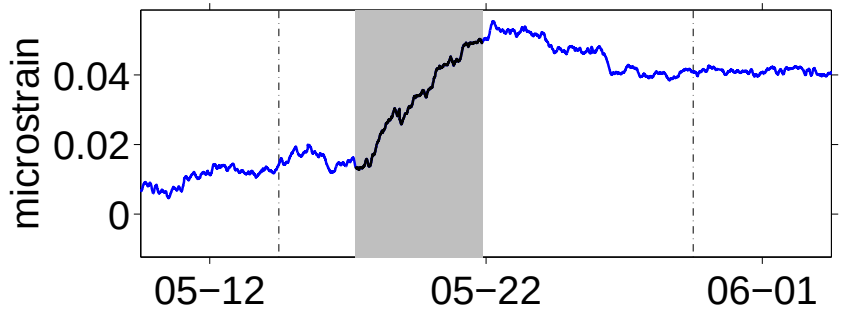
May 2008 strain records



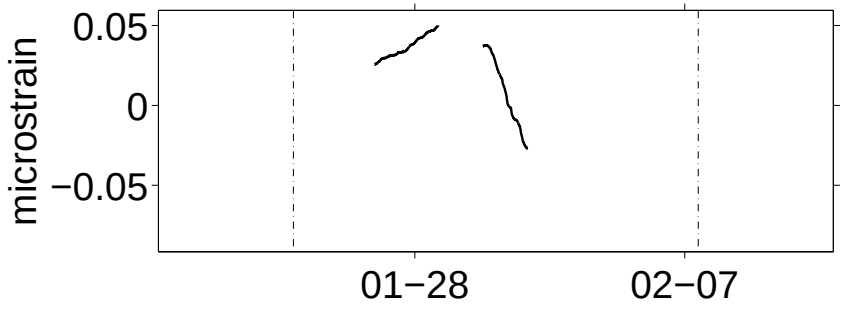
Extracting segments of the data to fit

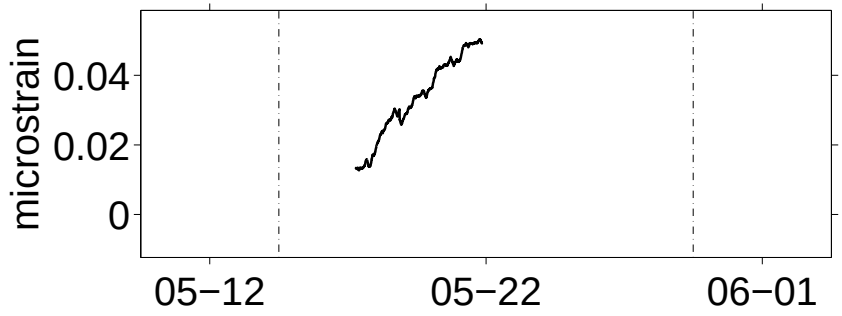
Changing sign of strain comes from change in location of slip





Only try to model simple portions of the data

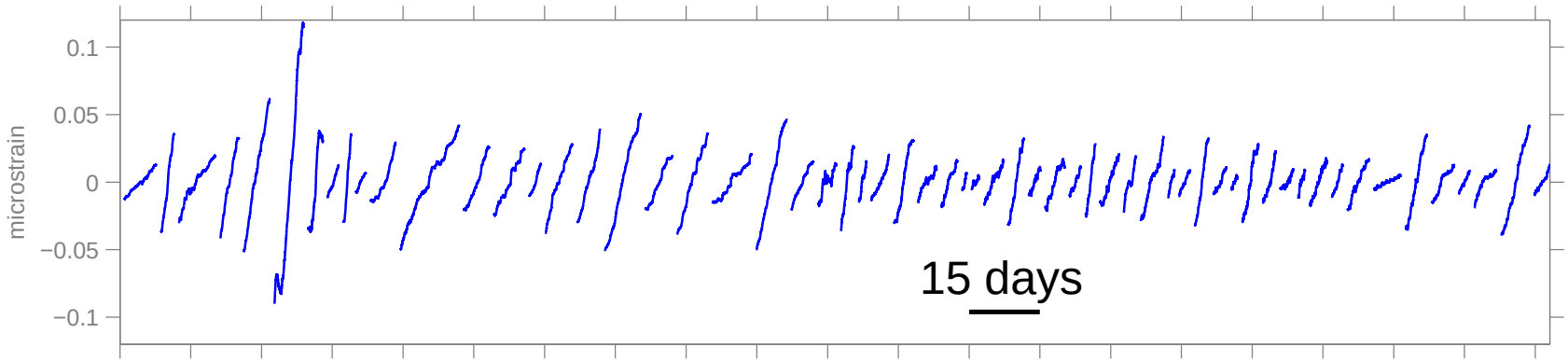




Extracted segments

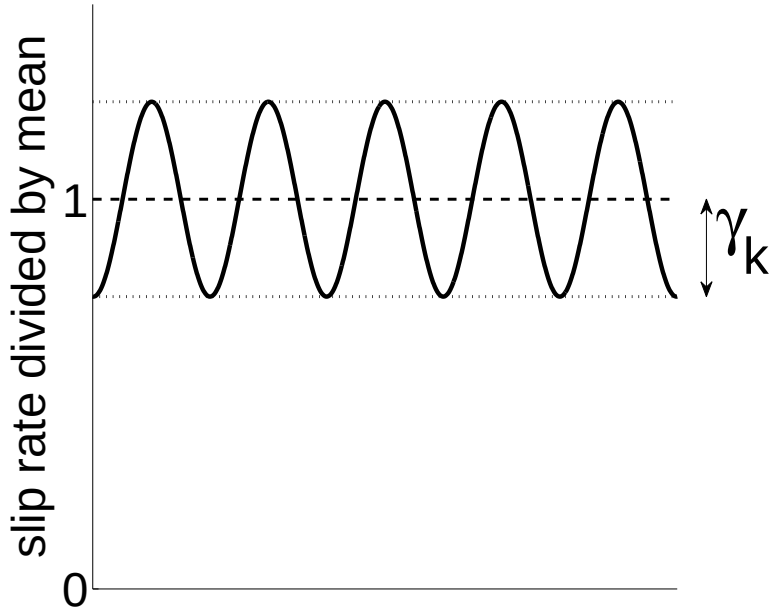
6 stations, 2 components, 4 events: 57 segments

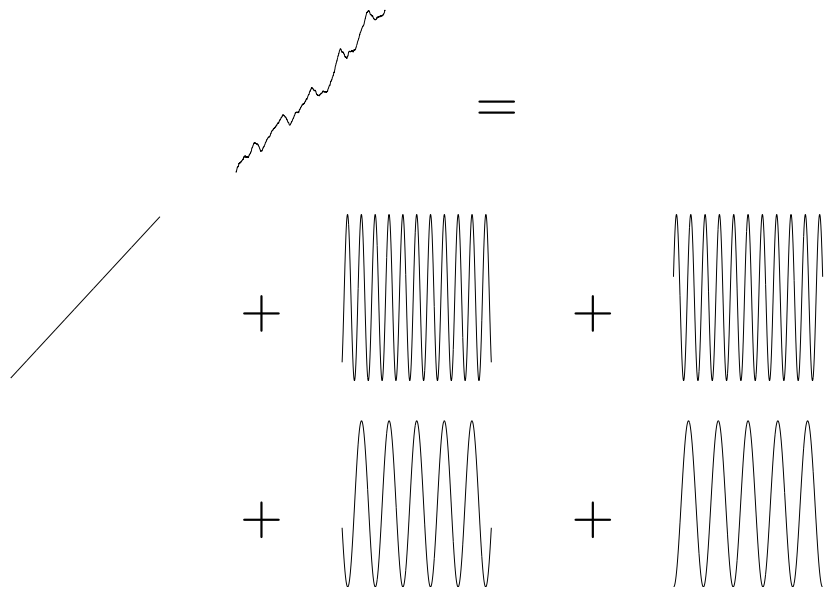
Approximately 240 days of data, 120 different days of data



Tidal modulation model

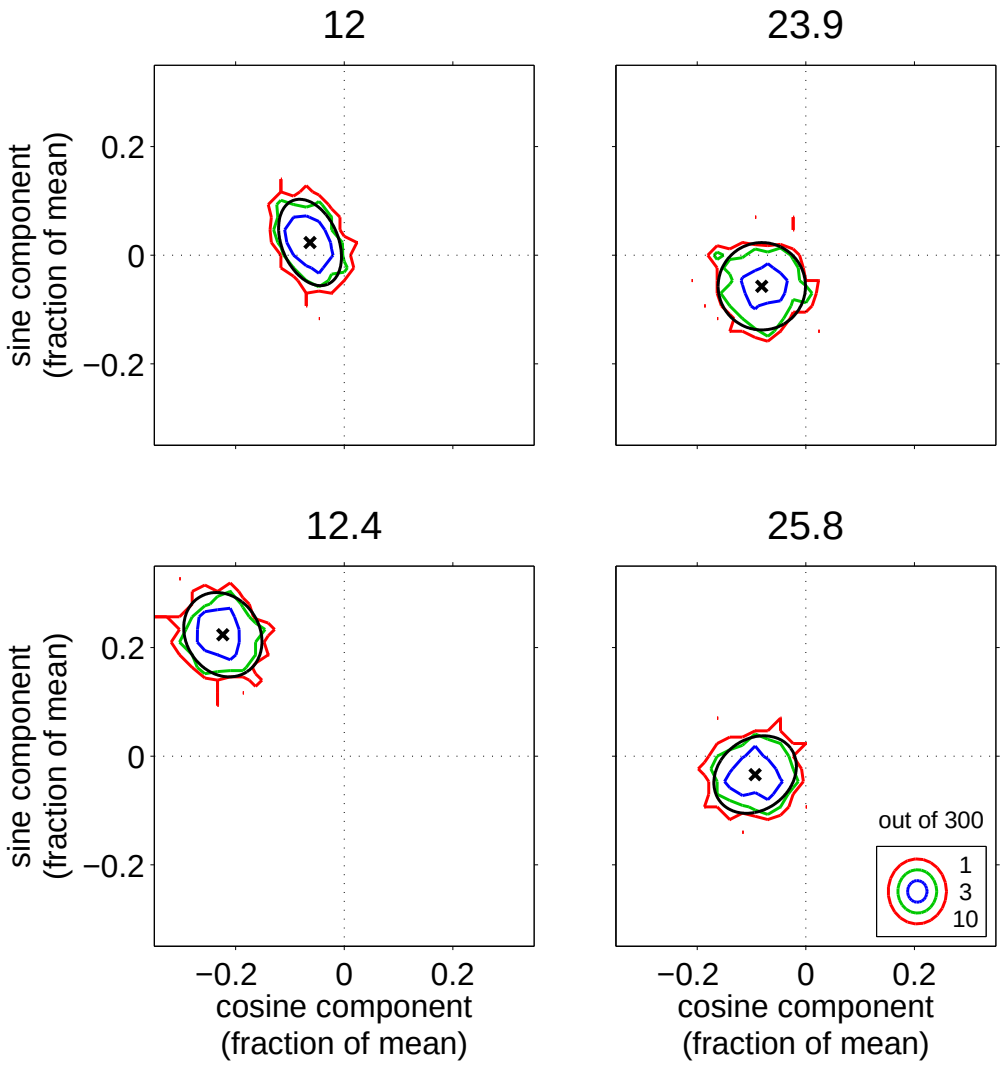
Assume the tides introduce sinusoidal variations in strain rate at the tidal periods with amplitudes proportional to the mean strain rate.





- 4 tidal periods: 12, 12.4, 23.9, and 25.8 hours
- Fit to strain data for all 57 segments
- Assume that the phase of modulation is the same in all segments

Results for tidal modulation



Obtain an amplitude and phase, or equivalently a cosine and sine component at each period.

- Signal at all four periods significant at 80-90% level
- Signal at 12.4 hours significant at 99% level

  Large amplitude at this period is consistent with 12.4-hour tide being strongest

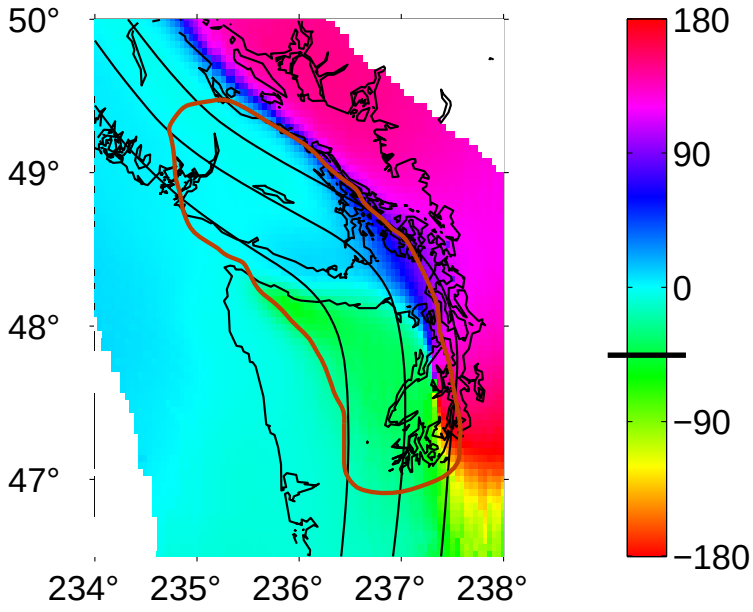
Bootstrap error estimates

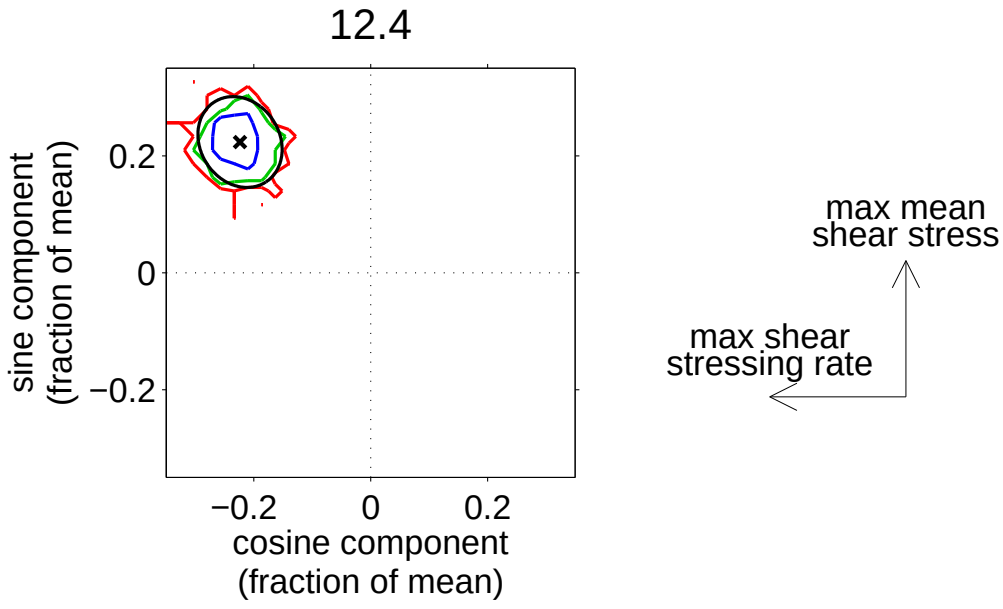
Ellipses include 90% of bootstrap estimates

Hawthorne and Rubin, JGR, 2010

12.4-hour tidal signal

Phase of maximum shear stress on the interface

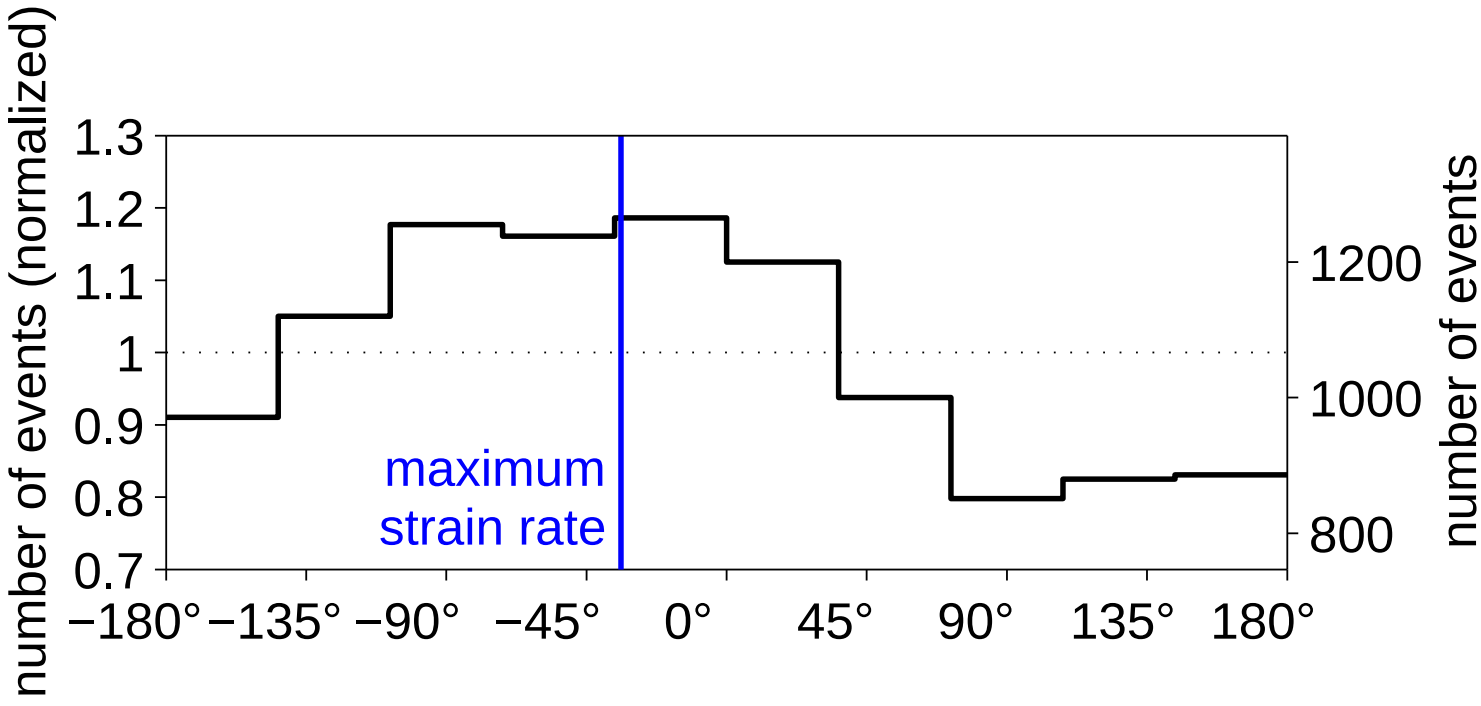




- Amplitude of signal at 12.4 hours is 20-30% of the mean strain rate
- Consistent with maximum strain rate at time of maximum shear or Coulomb stress or stressing rate, or sometime in between

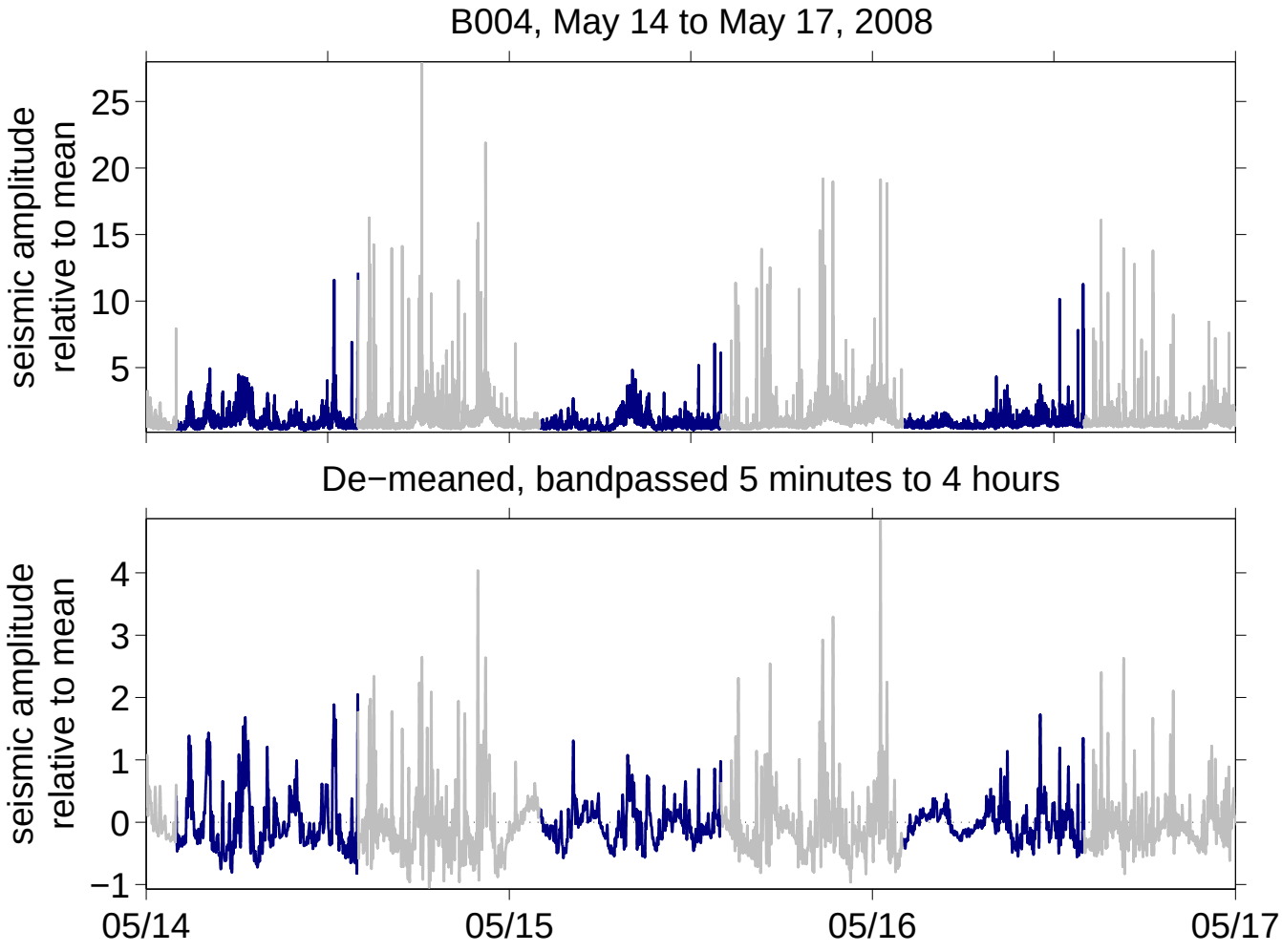
Comparing tidal modulation with tremor

Phases of 5-minute intervals with tremor (Wech and Creager, 2008)



- Phase of maximum strain rate similar to phase of maximum tremor rate at the 12.4-hour period.
- Amplitude at 12.4-hour period is 20 to 30% of the mean strain rate
- Consistent with maximum strain rate at time of maximum shear or Coulomb stress or stressing rate, or sometime in between

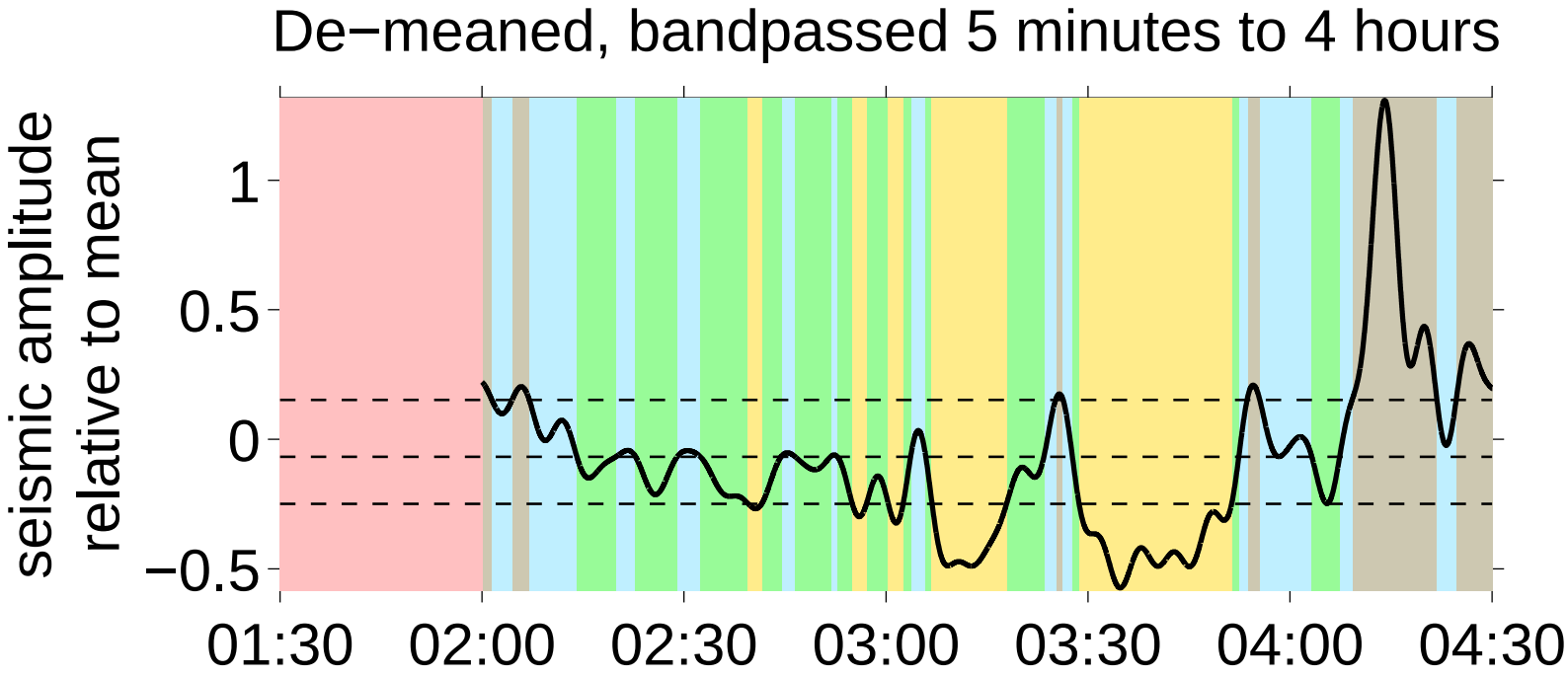
Comparing tremor and strain, step one: tremor amplitude



Proxy for tremor:

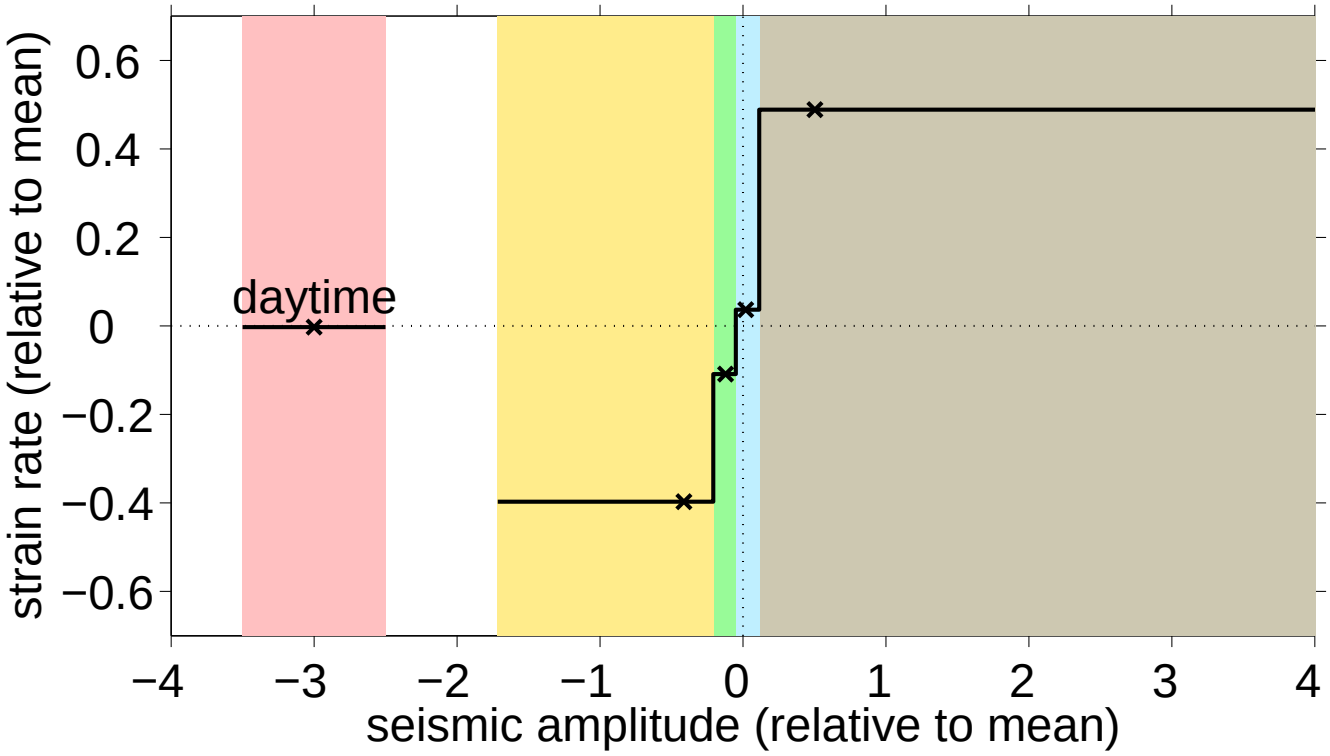
Amplitude of horizontal velocity seismograms

Mapping seismogram amplitude to strain rate



- Bin all times according to the seismic amplitude.
- Assume strain rate in each bin is a constant, equal to x_i.
- Write the forward model to compute the strain as a function of the as yet unknown strain rates x_i in each bin.
- Perform a fit to the strain data from multiple stations to find the preferred strain rates x_i.

Results from the fit



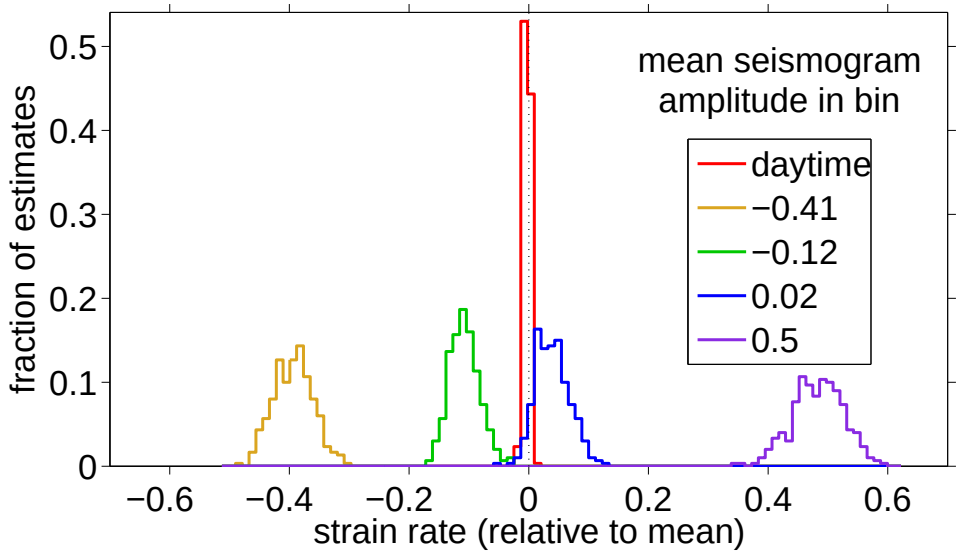
- Observe expected correlation: higher strain rate when the seismic amplitude is higher.
- Including periods from 5 minutes to 4 hours

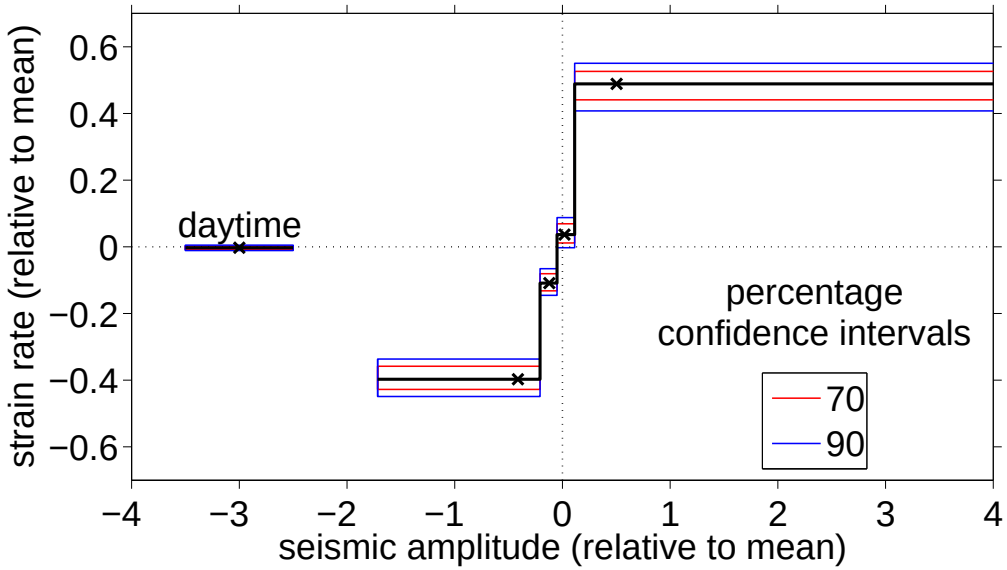
Bootstrap estimates

Strain rates in different bins are significantly different from each other.

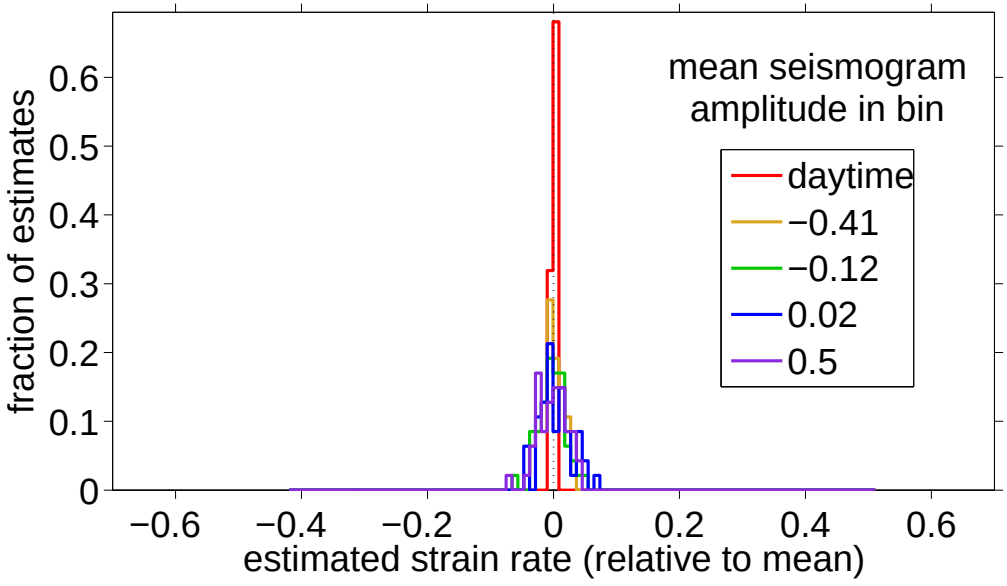
Magnitudes suggest at least a factor of 2 variation in moment rate on timescales shorter than 4 hours.

Histogram of strain rates for each bin



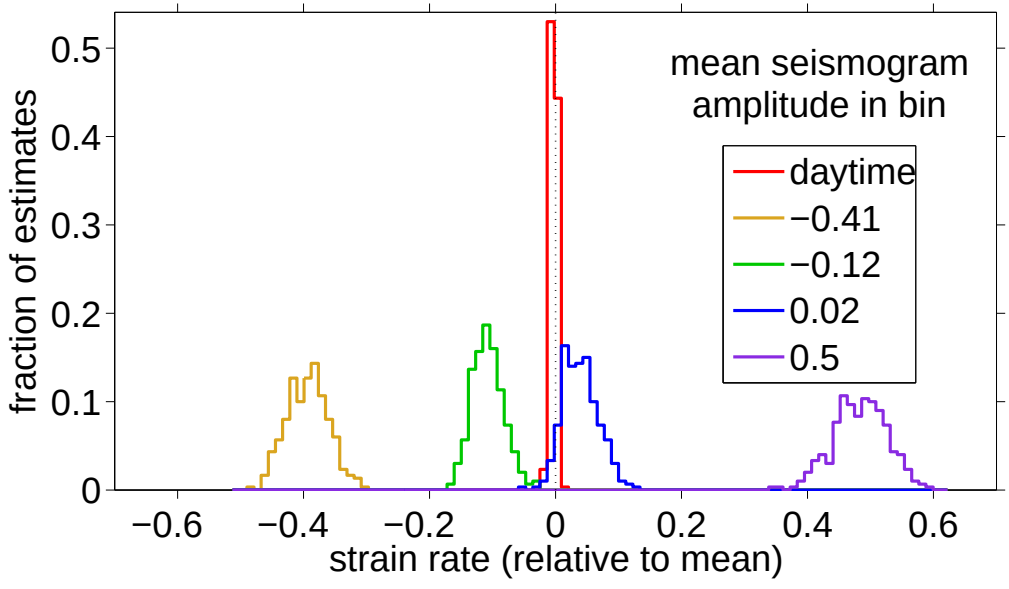


A coincidental correlation? Not likely.



Do the same analysis, but at times not during slow slip events. Use intervals 35 to 150 days after the defined segments.

Observe approximately the same strain rate in every bin when there is no slow slip.



Correlation at a wide range of periods

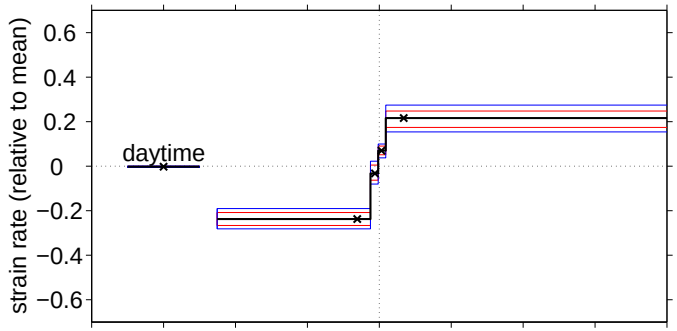
All events

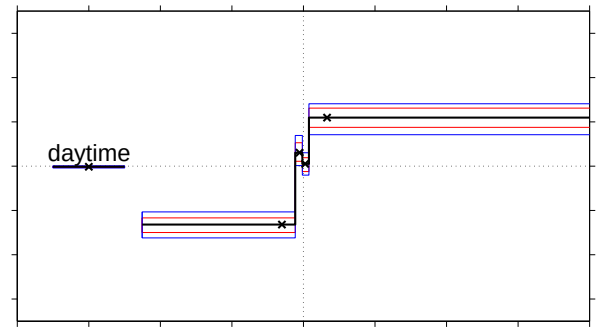
May 2008

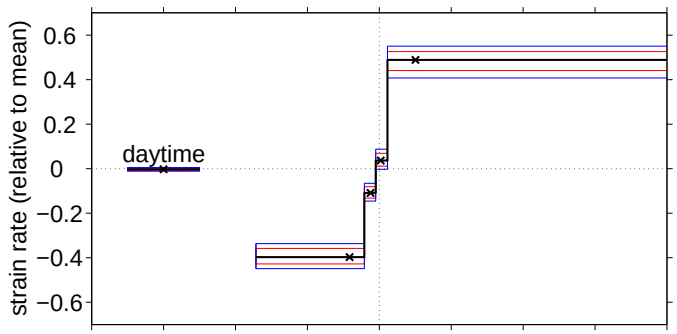
<1 hour

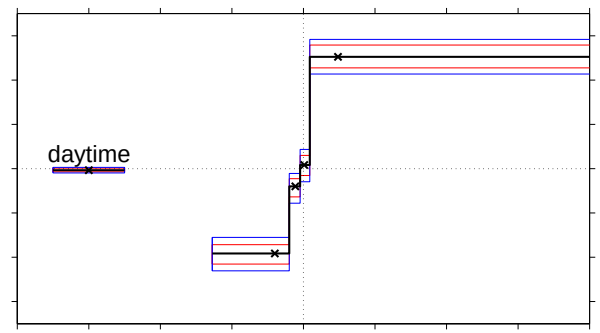
<4 hours

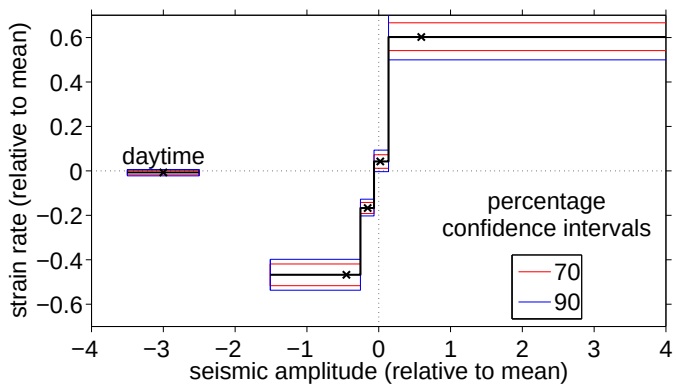
<10 hours

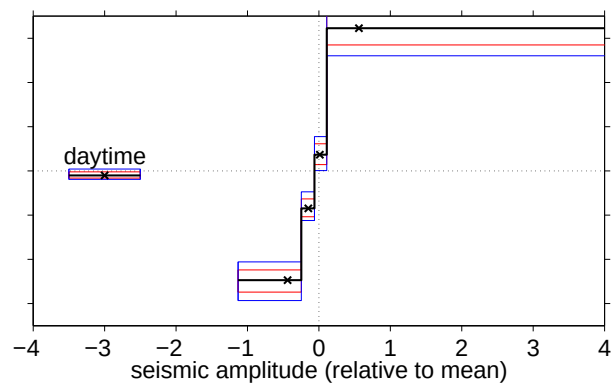












Conclusions and Implications

- Tremor and slow slip-induced strain are correlated on timescales from less than 1 hour to at least 12 hours
  - Constraint on interaction between tremor and slow slip
- Slow slip is tidally modulated, with an amplitude at the period of the strongest tide of 20 to 30% of the mean slip rate
  - Phase consistent with max stress, max stressing rate, or somewhere in between
  - Marginally significant signal at other tidal periods
- Large variations in the strain rate
  - Some subsets of the slow slip periods have mean strain rates 40% different from the mean
  - Implies a variation in moment rate larger than a factor of 2 on timescales less than 4 hours
  - Non-tidal variation larger than tidal modulation