Slow earthquakes: Tectonic tremor, low-frequency earthquakes and slow slip events

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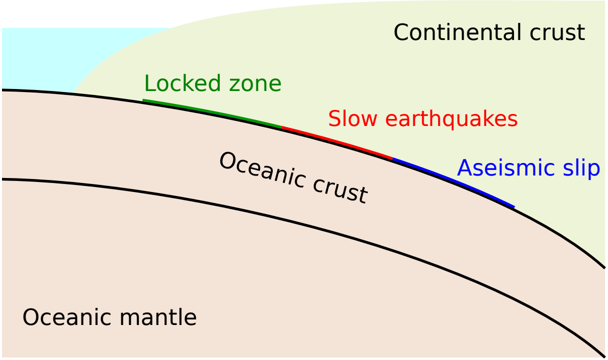
General Exam - October 25th 2019

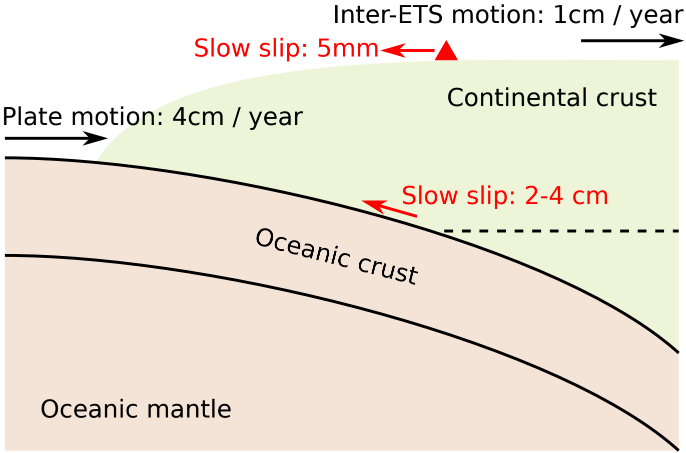
Introduction

Slow earthquakes (Subduction zones and strike-slip faults)

- Short duration (minutes), long recurrence time (hundreds of years)
- Long duration (a few days to several years), short recurrence time (months to years)



Slow slip


Inter-ETS motion: 1cm / year
Slow slip: 5mm
Continental crust
Plate motion: 4cm / year
Slow slip: 2-4 cm
Oceanic crust
Oceanic mantle

Tectonic tremor

- Long (several seconds to many minutes)
- Low amplitude
- Emergent onsets
- Absence of clear impulsive phases → Difficult to determine the depth of the tremor source

Low-frequency earthquakes (LFEs)

- Small magnitude earthquakes (M $\sim$ 1)
- Frequency content (1-10 Hz) lower than for ordinary earthquakes (up to 20 Hz)
- Source located on the plate boundary,
- Focal mechanism: Shear slip on a low-angle thrust fault dipping in the same direction as the plate interface

Research questions

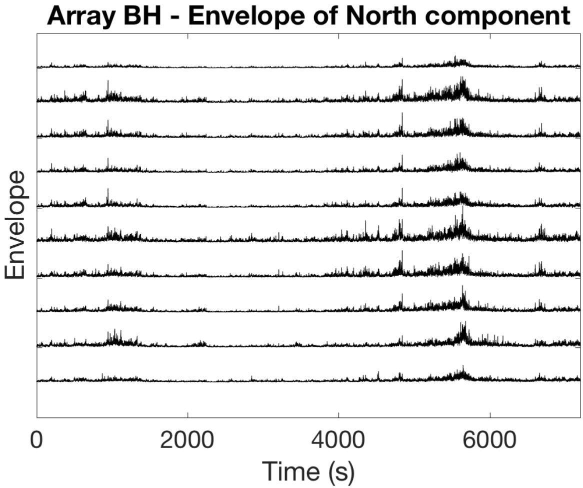
- Is the source of the tectonic tremor located on the plate boundary? What is the depth extent of the location of the source of the tremor?
- Do low-frequency earthquakes families behave similarly or differently in southern Cascadia, compared to Washington State and the San Andreas Fault?
- Can we detect smaller and / or longer slow slip events using geodetic data in the absence of spatially and temporally correlated tectonic tremor?

Depth of the source of the tectonic tremor

Tectonic tremor

- Long (several seconds to many minutes)
- Low amplitude
- Emergent onsets
- Absence of clear impulsive phases $\rightarrow$ Difficult to determine the depth of the tremor source

Tectonic tremor



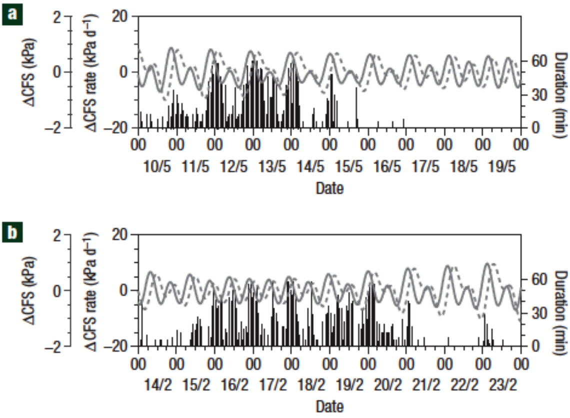
Tectonic tremor and low-frequency earthquakes

- At least part of the tremor is made of a swarm of small, low-frequency earthquakes (LFEs)
- LFE source located on the plate boundary
- LFE focal mechanism: Shear slip on a low-angle thrust fault

$\rightarrow$ Tremor source assumed to be also located close to the plate boundary

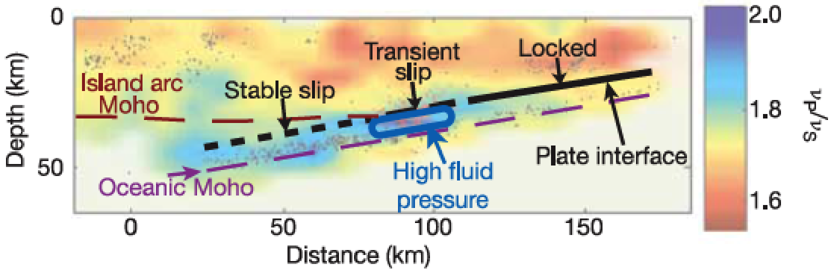
Ide *et al.* (2007). GRL, **34**, L03308.
Shelly *et al.* (2007) Nature, **446**, 305-307.

Link between tremor occurrence and tidal cycles



Nakata *et al.* (2008). Nature Geoscience, **1**, 676-678.

High pore fluid pressure near the source of the tremor



Shelly *et al.* (2006). Nature, **442**, 188-192.

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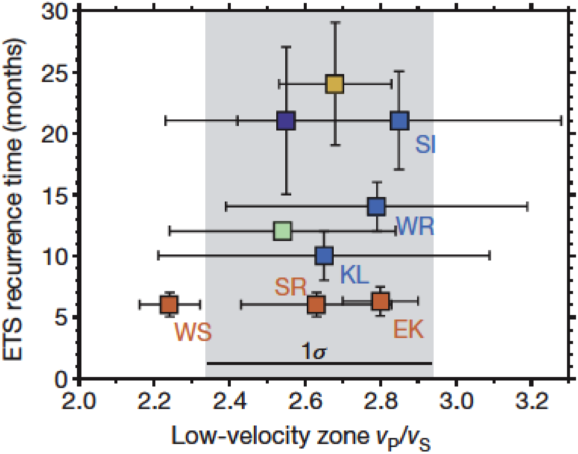


Audet and Bürgmann (2014). Nature, **510**, 389-393.

How could fluids generate tectonic tremor?

1. Hydraulic fracturing or coupling between rock and fluid flow $\rightarrow$ Fluid movement $\rightarrow$ Tremor generation

   Slip triggered by the same fluid movement / Fluid flow is a response to changes in stress and strain induced by the slip

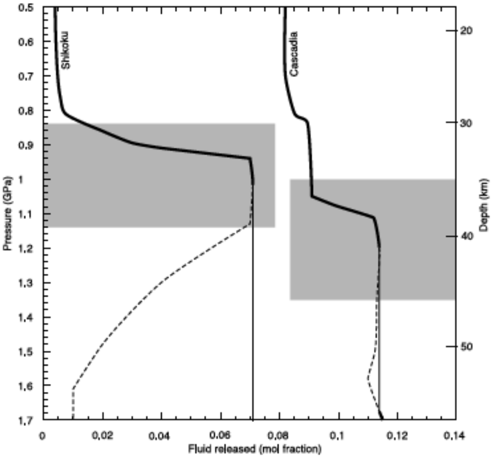
2. Irregularities on the plate interface $\rightarrow$ Slip acceleration $\rightarrow$ Tremor generation

   Fluids alter the conditions on the plate interface to enable transient slip events

Shelly *et al.* (2006). Nature, **442**, 188-192.

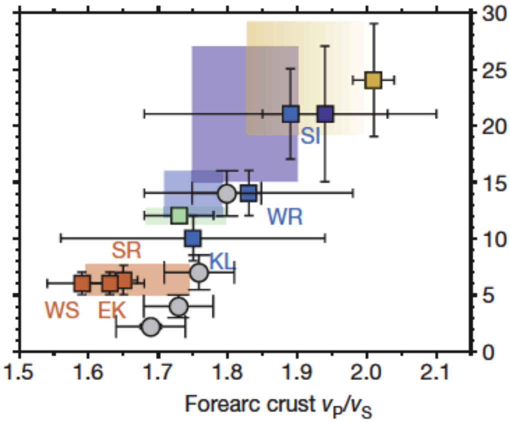
Mineral model predicts significant water release

- Shikoku:
  Lawsonite → Epidote
- Cascadia:
  Chlorite and glaucophane → Hornblende and epidote



Fagereng and Diener (2011). GRL, **38**, L15302.

Abundance of quartz in the forearc crust



Audet and Bürgmann (2014). Nature, **510**, 389-393.

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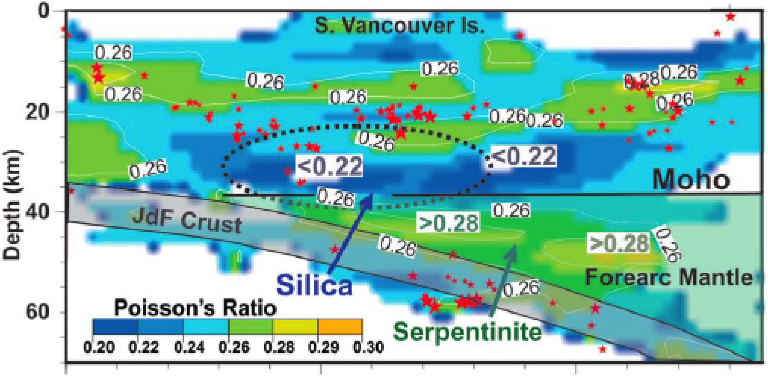


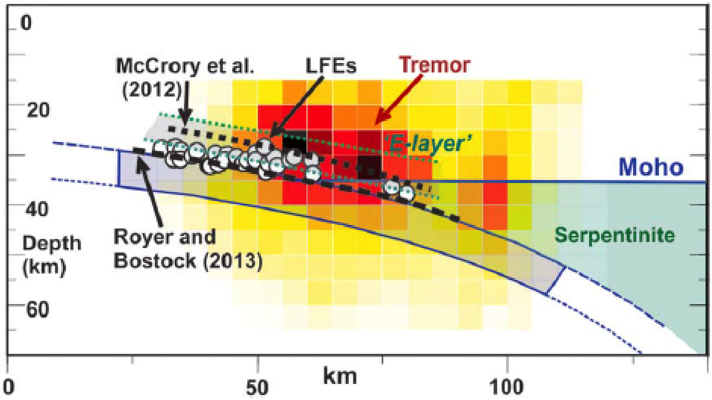
Hyndman *et al.* (2015). JGR Solid Earth, **120**, 4344-4358.

Quartz veins in exhumed subduction zones

- Foliation-parallel veins formed by viscous shear flow
  → Shear stain rate due to the flow compatible with slow slip strain rate
- Discordant veins formed by brittle deformation caused by locally elevated fluid pressure
  → Size of the structures where brittle deformation is observed compatible with size of LFE asperity

Fagereng *et al.* (2014). GRL, **41(12)**, 4159-4167.

Large vertical extent of the source of the tremor



Hyndman *et al.* (2015). JGR Solid Earth, **120**, 4344-4358.

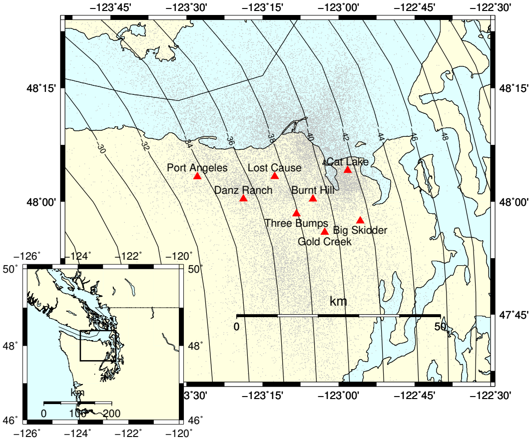
Depth of the source of the tectonic tremor in the northeastern Olympic Peninsula

- Same location as LFEs → Very thin layer at the plate boundary
- Same location as quartz → Thick layer above the plate boundary, in the continental crust
- Same location as the fluid → Oceanic crust

→ Research question: Is the source of the tectonic tremor located on the plate boundary? What is the depth extent of the location of the source of the tremor?

Cascadia Array of Arrays

- Cascadia Array of Arrays experiment (2009-2010)
- Eight arrays of seismic stations in the Olympic Peninsula
- Recorded the main ETS event in August 2010, and the 2011 ETS event
- Tremor located just under the arrays



Tremor catalog

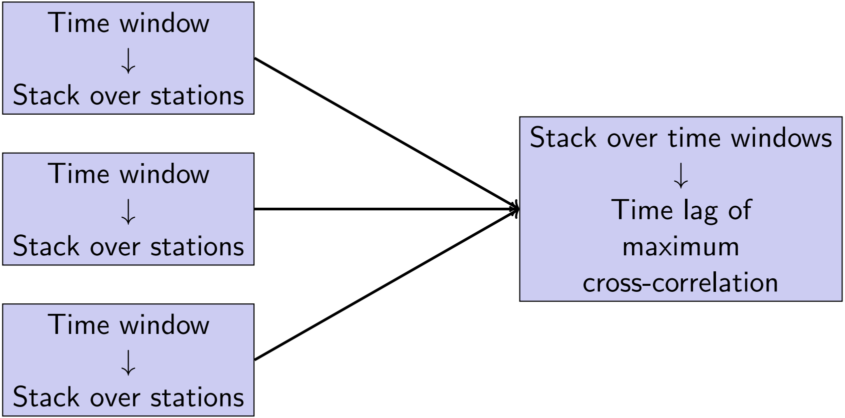
- Two data sets:
  - From June 20th 2009 to September 30th 2010: 28902 one-minute-long time windows where tectonic tremor is recorded
  - From August 10th 2011 to September 6th 2011: 5600 one-minute-long time windows where tectonic tremor is recorded
- For each tremor window: Beginning time, end time, latitude and longitude of the source of the tremor

Ghosh A., Vidale J.E., Creager K.C. (2012). *JGR*, **117**, B10301.

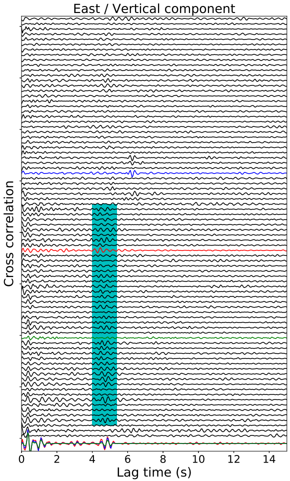
Cross-correlation of tremor recordings

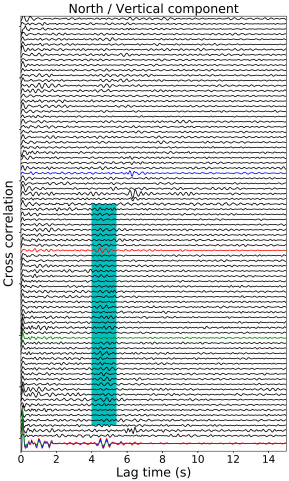
- Tectonic tremor recorded at the Big Skidder array and which source is located in a 5x5 km cell just under the array
- 82 one-minute-second-long time windows
- For each time window:
  - For each station, cross-correlate the horizontal component with the vertical component
  - Stack the cross-correlation over all the stations of the array
- Plot all the 82 stacked cross-correlation
- Stack the 82 signals with a linear, power, or phase-weighted stack

Summary of signal processing



Cross-correlation of tremor recordings (linear stack)





Cross-correlation of tremor recordings (linear stack)

- Peak at about 4.7 s
- P-wave energy higher on the vertical component
- S-wave energy higher on the horizontal component
- Time lag between the direct P-wave arrival and the direct S-wave arrival
- For $V_P = 6.4 km/s$ and $V_S = 3.6 km/s$, and a source located on the plate boundary ($d = 42 km$), we expect $t_{lag} = 5.1 s$

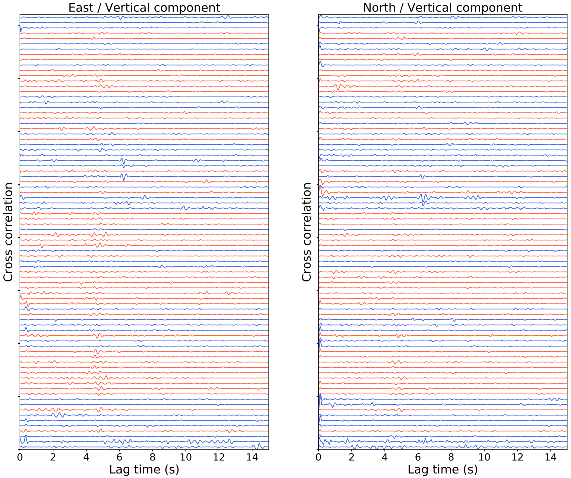
Clustering of cross-correlation functions

Does the cross-correlation for a given one-minute-long time windows look like the stack over all time windows?

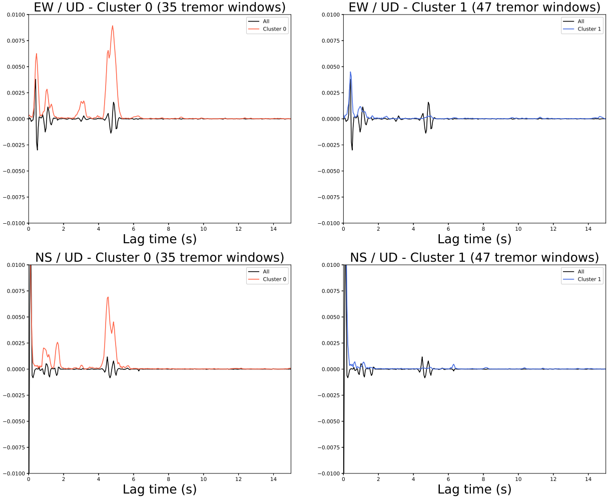
- Ratio cross-correlation peak / RMS between 12 and 14 s
- Cross-correlation between one cross-correlation and the stack:
  - Maximum cross-correlation value
  - Cross-correlation at time lag 0
  - Time lag corresponding to the maximum cross-correlation value

$\rightarrow$ K-means clustering$\rightarrow$ Two clusters (good time windows / bad time windows)

Selected tremor recordings (phase-weighted stack)



Stacking for the two clusters (phase-weighted stack)

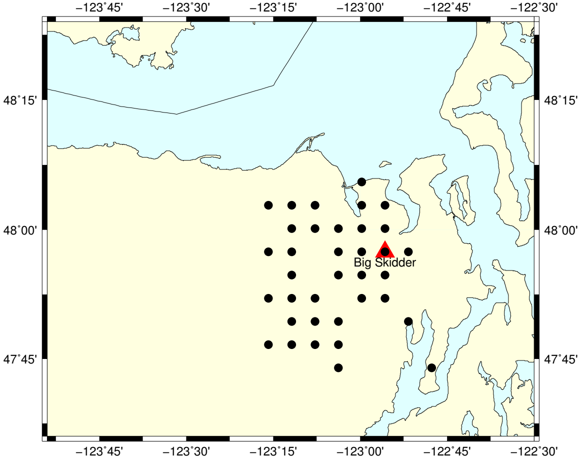


Where is the method applicable?

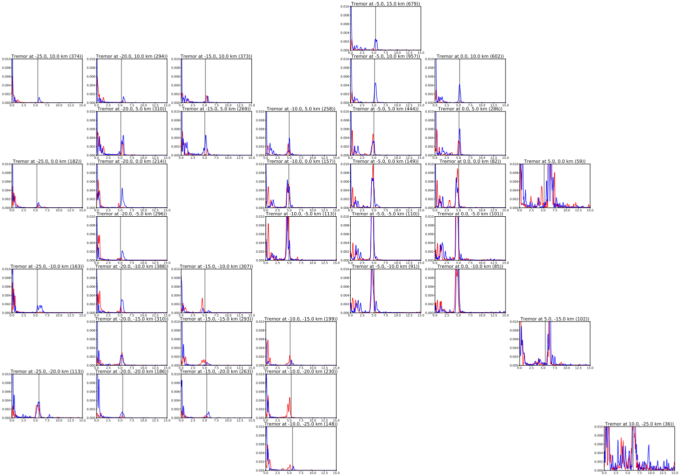
- Areas badly covered, only a few tremor were recorded
- Moving tremor source (tremor streaks): Method will not work for stations located more than 18km updip of the tremor source

  $\rightarrow$ We keep only the grid cells with more than 30 tremor, and a ratio max envelope / RMS higher than 100

Ratio max envelope / RMS > 100 (Big Skidder array)



Ratio max envelope / RMS > 100 (Big Skidder array)



Future work

- Check for possible anisotropy in the continental crust → Compare time lags for the EW and the NS components
- Evaluate the uncertainty on the depth of the tremor source → Use the half-width of the envelope to compute the uncertainty on the time lag
- Interpolate the results from the 8 arrays, using the ratios max envelope / RMS as weights
- Compute the histogram of the time lags for each grid cell, and the associated width to determine the thickness of the tremor zone

Future work

Time line:

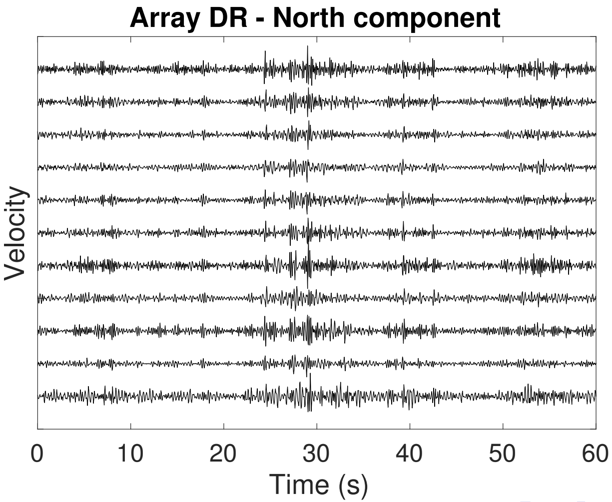
- Chapter 1: About 80 % of work done

A low-frequency earthquake catalog for southern Cascadia

Low-frequency earthquakes (LFEs)

- Small magnitude earthquakes (M $\sim$ 1)
- Frequency content (1-10 Hz) lower than for ordinary earthquakes (up to 20 Hz)
- Source located on the plate boundary,
- Focal mechanism: Shear slip on a low-angle thrust fault dipping in the same direction as the plate interface

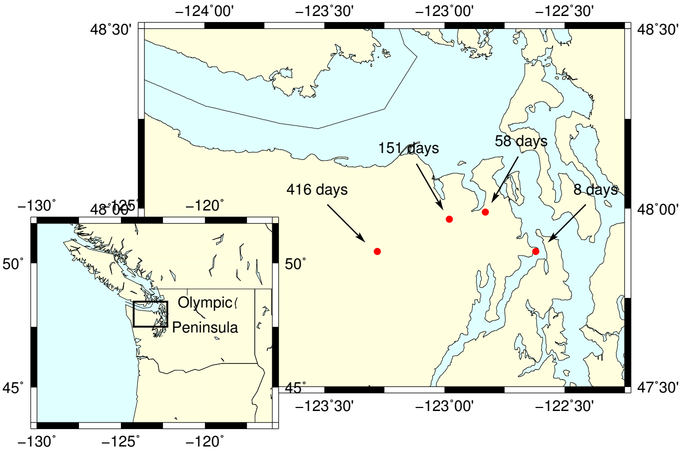
Low-frequency earthquakes (LFEs)



A low-frequency earthquake catalog for southern Cascadia

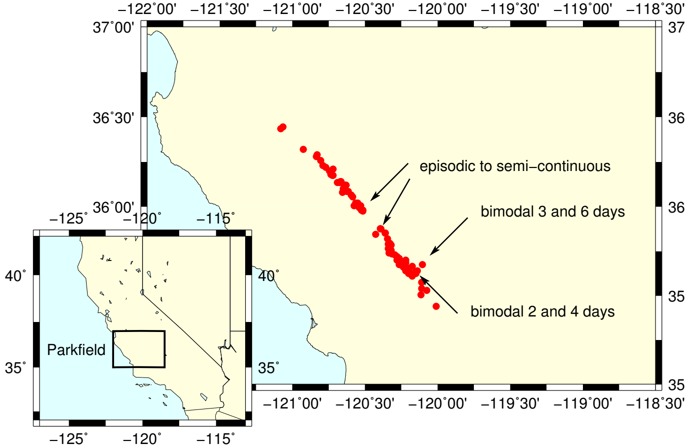
- LFEs grouped into families of events
- All the earthquakes of a given family originate from the same small patch on the plate interface
- LFEs recur more or less episodically in a bursty manner
- Wide range of recurrence behavior between seismic regions, and within the same seismic region

LFEs in Washington State



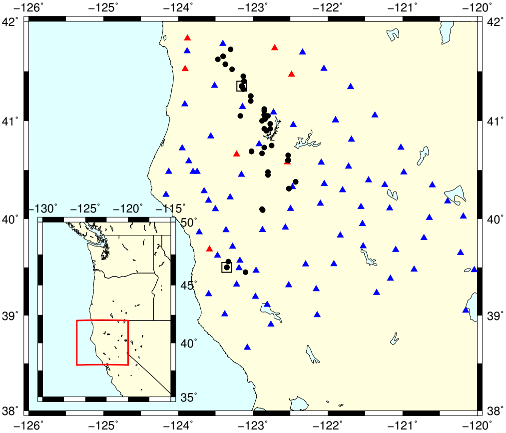
Sweet *et al.* (2019). G3, **20**, 1202-1217.

LFEs on the San Andreas Fault



Shelly (2017). JGR Solid Earth, **122**, 3739-3753.

Current catalog



Plourde *et al.* (2015). GRL, **42**, 4849-4855.

Current catalog

- Subduction zone families
  - 34 families
  - Period covered: April 2008
  - One burst of LFEs lasting a few days and propagating from south to north
- Strike-slip fault families
  - 3 families
  - Period covered: March and April 2008
  - Active all the time, several bursts of LFEs

Research question

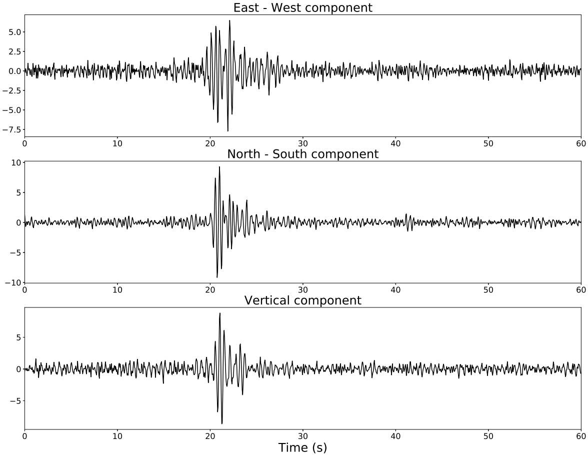
→ Do low-frequency earthquake families behave similarly or differently in southern Cascadia, compared to Washington State and the San Andreas Fault?

- 34 LFE families on the subduction zone → Same behavior as Washington State?
- 3 LFE families on two strike-slip faults from the San Andreas Fault system → Same behavior as San Andreas Fault around Parkfield?

Creating templates

- Download a one-minute-long time window of data around the detection time of each LFE
- Detrend
- Taper the first and last 5 seconds with a Hann window
- Remove the instrument response
- Bandpass filter between 1.5 and 9 Hz
- Resample to 20 Hz
- Linearly stack all the seismograms for each station and each channel

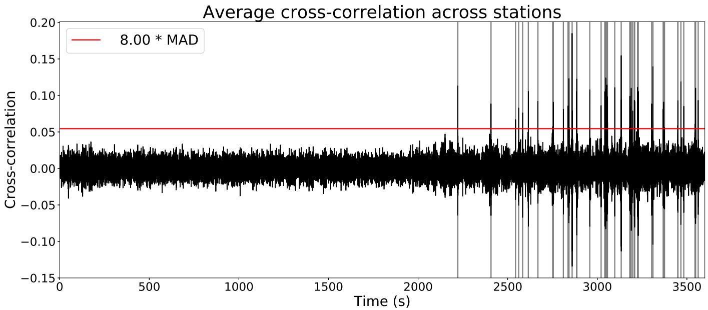
Templates for permanent station KRMB



Finding new LFEs

- Download one hour of data
- Cross correlate the one-hour-long signal with the one-minute-long template for the given station and channel
- Stack the cross correlation signal over all the channels and all the stations
- Value of the average cross correlation higher than a threshold $\rightarrow$ LFE detection
- Threshold $=$ 8 times the median absolute deviation (MAD)

Analysis of one hour of seismic data

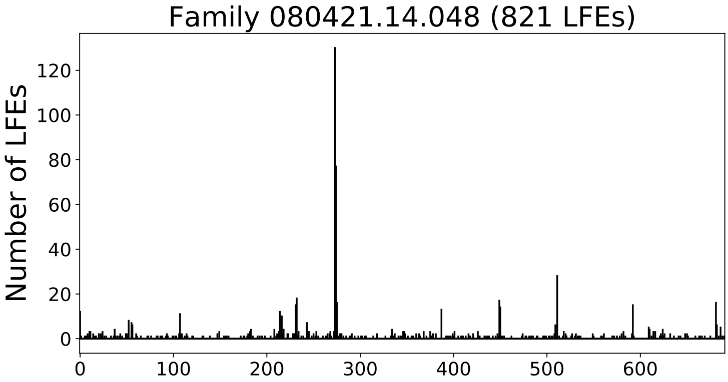


Comparison with existing catalog (April 2008)

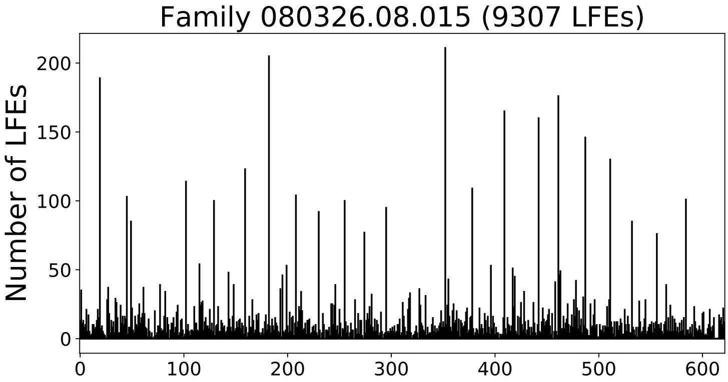
Family 080421.14.048

Number of LFEs in my catalog	236
Number of LFEs in the catalog by Plourde *et al.*	225
Number of LFEs added in my catalog	13
Number of LFEs missing in my catalog	2
Number of LFEs present in both catalogs	223

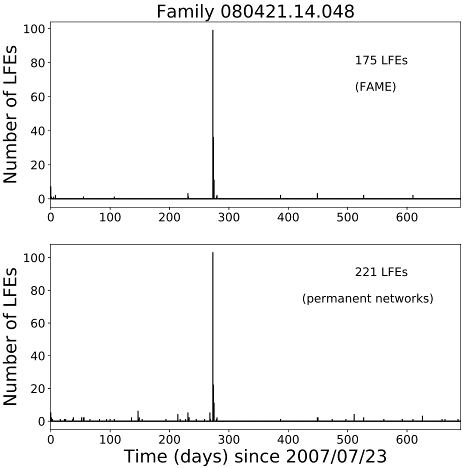
Extension of the catalog



Extension of the catalog



Detection of LFEs with permanent networks



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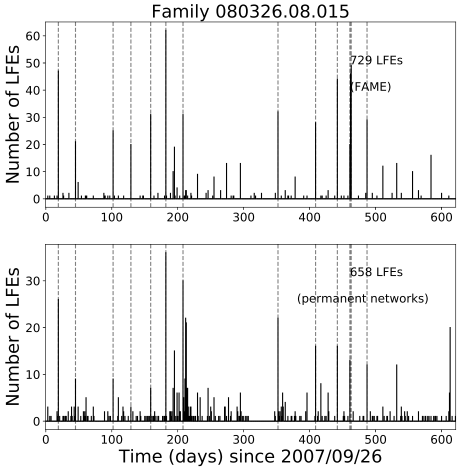
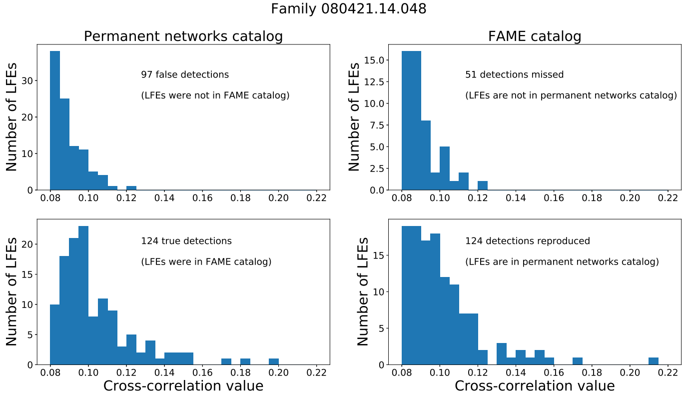


Comparison FAME - permanent networks



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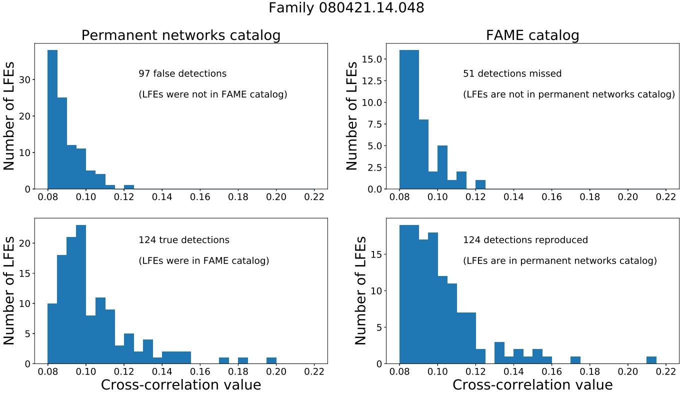
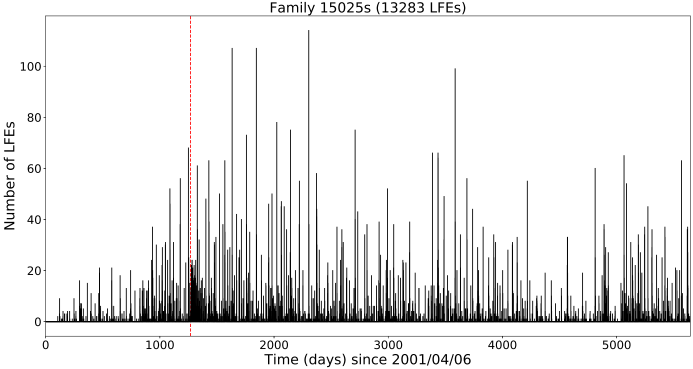


Future work

- Two-year-long catalog for all LFE families
- Computation of new templates for the permanent networks
- Whenever possible, extension of the LFE catalog to 2009-2019

Effect of the 28 September 2004 M6.0 Parkfield earthquake



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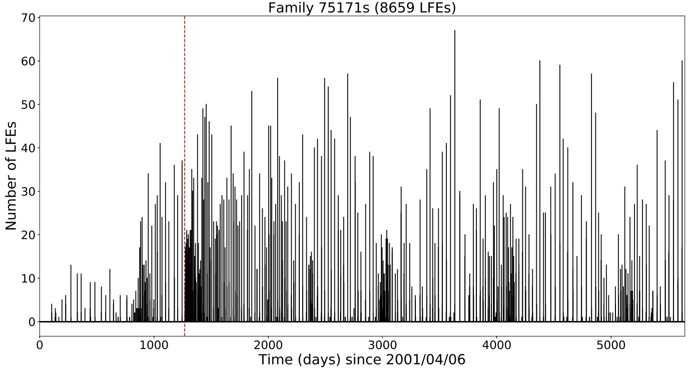
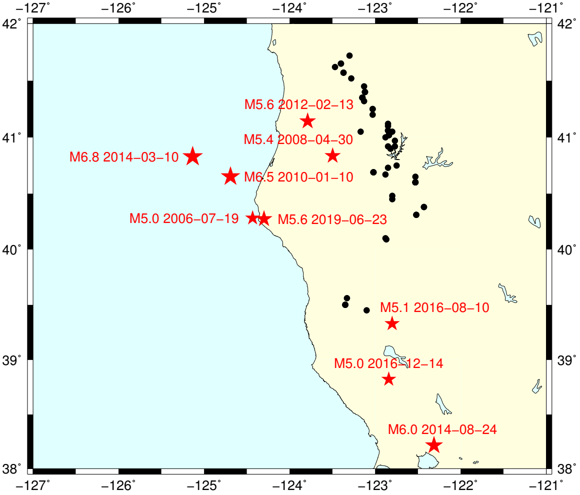


Moderate earthquakes in southern Cascadia



Future work

- LFE event rate before the earthquake
- LFE event rate after the earthquake
- Comparison between two event rates: Likelihood Ratio Test (LRT)

ETAS model

Epidemic-Type Aftershock Sequence (ETAS) model:

- Magnitude frequency distribution law of Gutenberg and Richter
- Omori-Utsu law of aftershock decay
- Each event, irrespective of whether it is a small or a big event, can trigger its own offspring

$$\lambda = \mu + A \sum_{t_i < t} e^{\alpha(M_i - M_0)} \left(1 + \frac{t - t_i}{c} \right)^{-p}$$

- $p = 0.9 - 1.5$ (regular earthquakes)

Future work

- Fit ETAS model on existing LFE families
- Two available R packages: bayesianETAS and PtProcess

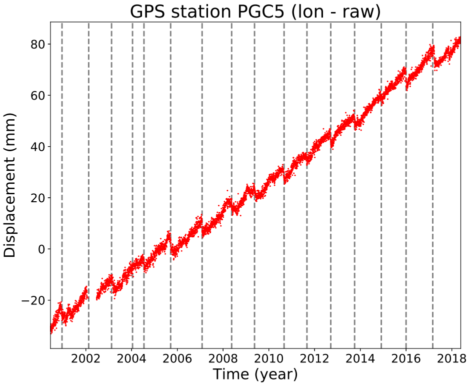
Future work

Time line:

- Chapter 2: About 50 % of work done

Detection of slow slip events in New Zealand

Slow slip = Reversal of the direction of motion at GPS stations, compared to the secular motion



Tremor as proxy for slow slip

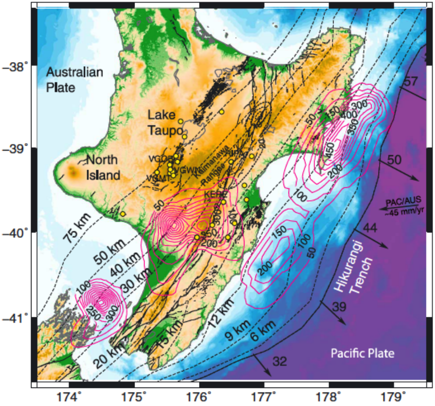
In Cascadia and Mexico, tremor used as a proxy to study slow slip events:

- Tremor occurrence rate → Moment of slow slip events not detectable in the GPS data (Aguiar *et al.*, 2009)
- Stacking of GPS data when LFEs are detected (Frank, 2016)

→ How can we detect small slow slip events when tremor is not correlated with slow slip?

Aguiar *et al.* (2009). JGR, **114**, B00A05.
Frank (2016). GRL, **43**, 2774-2779.

Slow slip events in northern New Zealand



Wallace and Eberhart-Phillips (2013). GRL, **40**, 5393-5398.

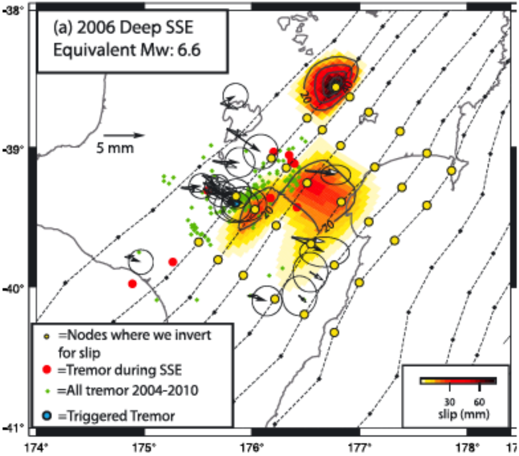
Slow slip events in northern New Zealand

Two types of slow slip events:

- Shallow (10-15 km depth), shorter (1-3 weeks), usually smaller (Mw 6.3-6.8)
  $\rightarrow$ Observed every 18-24 months in the northern part of the margin
- Deeper (35-60 km depth), longer (12-18 months) larger (Mw 7.0)
  $\rightarrow$ Observed every 5 years in the southern part of the margin

Wallace and Beavan (2010). JGR, **115**, B12402.
Todd and Schwartz (2016). JGR Solid Earth, **121**, 8706-8719.

Tremor accompanying deep slow slip events



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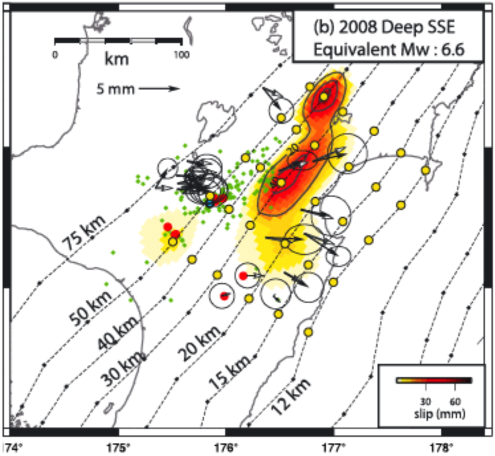
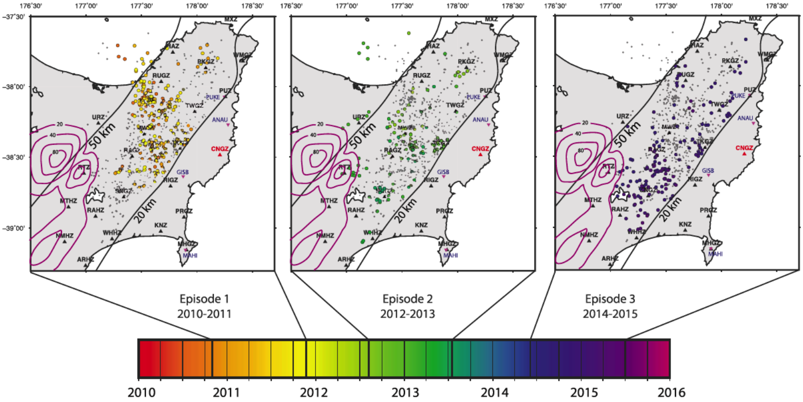
Tremor accompanying deep slow slip events



Wallace and Eberhart-Phillips (2013). GRL, **40**, 5393-5398.

Tremor with no detected slow slip event



Todd and Schwartz (2016). JGR Solid Earth, **121**, 8706-8719.

Research question

In northern new Zealand, tremor and slow slip are not spatially / temporally correlated:

- Tremor source located downdip of the slow slip on the plate boundary
- Tremor activity does not seem to increase during slow slip events

→ Can we detect smaller and / or longer slow slip events in the absence of spatially and temporally correlated tectonic tremor?

Wavelet methods

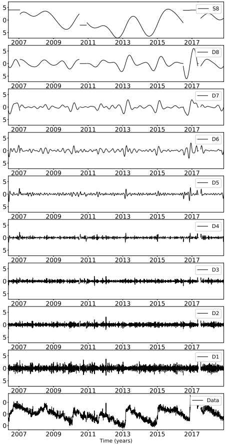
Time series X_t $\rightarrow$ Wavelet coefficients $W_j (j = 1, ..., J)$

Wavelet vector W_j associated with changes on scale $\tau_j = dt 2^{j-1}$

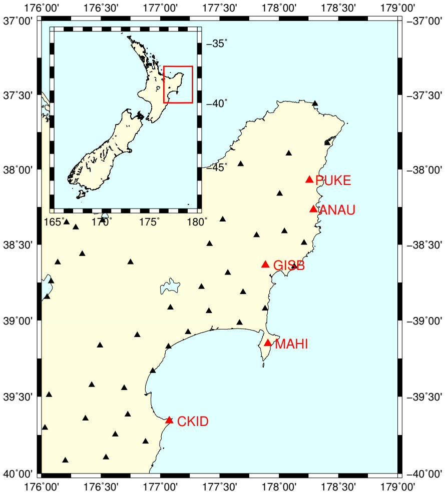
Scaling vector V_J associated with averages in scale $\lambda_J = dt 2^J$

$\rightarrow$ Compute wavelet details $D_j (j = 1, ..., J)$ and wavelet smooth S_J

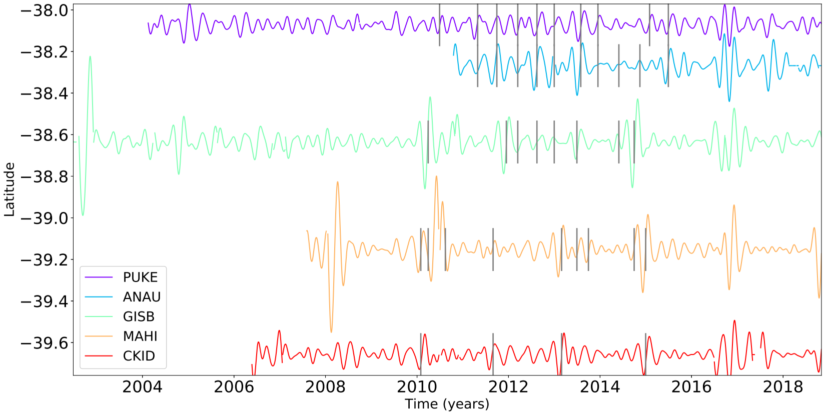
Multiresolution analysis (MRA):
$X = \sum_{j=1}^{J} D_j + S_J$



GPS stations in New Zealand

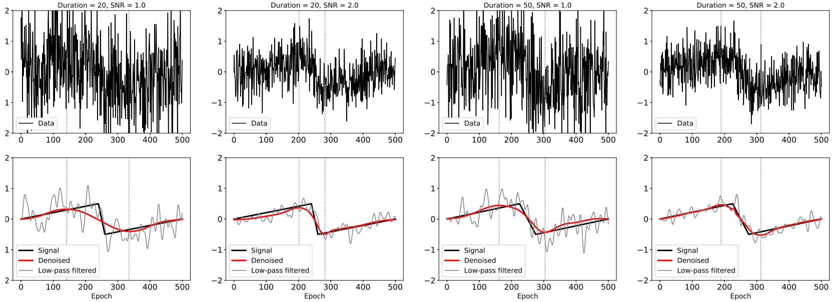


6th level detail of GPS times series in New Zealand

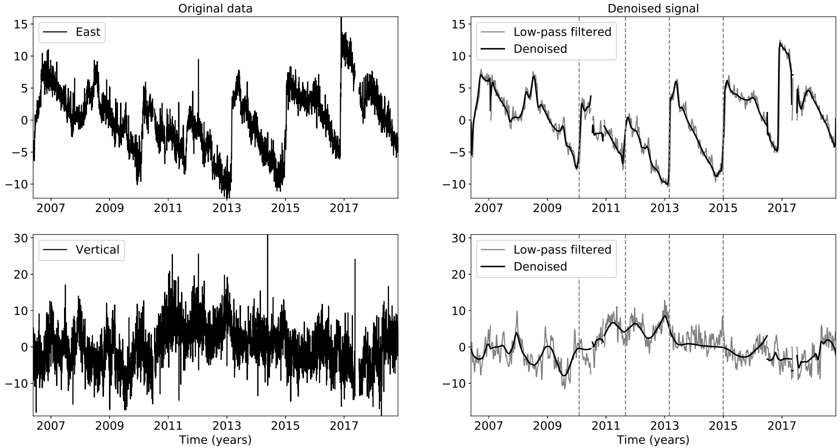


Timing of slow slip events by Todd and Schwartz (2016). JGR Solid Earth, **121**, 8706-8719.

Denoising of synthetic GPS data



Denoising of GPS time series in New Zealand



Possible questions

- Detecting smaller, currently undetected slow slip events
- Detecting longer term slow slip events
- Better measuring of the vertical displacement at the Earth's surface during slow slip events

Does the fault weakens with increasing depth?

- Tremor: Frequent episodes with small spatial and temporal extent / infrequent episodes with large spatial and temporal extent (Wech and Creager, 2011)
- LFEs: Downdip swarms happen nearly weekly / updip families active only during the yearly ETS events (Sweet *et al.*, 2019).

→ Does the same pattern exist for slow slip?

Wech and Creager (2011). Nature Geoscience, **4**, 624-628.
Sweet *et al.* (2019). G3, **20**, 1202-1217.

Is there a long term slow slip event accompanying tremor?

- Long term slow slip events in Japan, Mexico, Alaska (Wei *et al.*, 2012), and possibly Cascadia (Nuyen and Schmidt, 2017)
- New Zealand: Deep tremor between 20 and 50 km depth with unclear origin (Todd and Schartz, 2016)

→ Is there an undetected deep long-term slow slip event?

Wei *et al.* (2012). GRL, **39**, L15309.
Nuyen and Schmidt (2017). AGU Fall Meeting.
Todd and Schwartz (2016). JGR Solid Earth, **121**, 8706-8719.

Constraining the updip and downdip extent of slow slip

- Vertical component of the ground displacement is the most useful in constraining the updip and downdip extent of slip (Szeliga *et al.*, 2008)
- Downdip limit of the megathrust earthquake rupture
- Correlation with other geophysical data, such as porosity, temperature, and structure
- Smaller than the horizontal displacement, and generally hard to resolve

→ Can we better resolve the vertical component of the ground displacement?

Szeliga *et al.* (2008). JGR, **113**, B04404.

Future work

- **Detecting smaller, currently undetected slow slip events:** Combine MRA of several channels and several stations, and stack them with some time shift.
- **Detecting longer term slow slip events:** Replace the missing data points by synthetic data points obtained by a combination of linear or more complex interpolation and random Gaussian noise.
- **Better measuring of the vertical displacement at the Earths surface during slow slip events:** Improve wavelet-based methods of denoising, by applying thresholding, scaling, or shrinkage of the wavelet coefficients.

Future work

Time line:

- Chapter 3: About 20 % of work done

Time line

Time	PhD Work	Other Activities
Fall 2019	General exam	Present slow slip work at AGU Fall Meeting
Winter 2020	Write paper on tremor in northern Cascadia	
Spring 2020	Write paper on LFE catalogs in southern Cascadia	Present work on LFEs at SIAM Conference on Mathematics of Data Science
Summer 2020		
Fall 2020	Write paper on statistical analysis of LFE catalog	
Winter 2021		
Spring 2021	Write paper on wavelet analysis of slow slip	
Summer 2021	Defend by mid-summer	Present work on statistical analysis of LFEs catalog at Workshop on Statistical Seismology

Questions?