Data analysis of recordings of slow earthquakes: Tectonic tremor, low-frequency earthquakes and slow slip events

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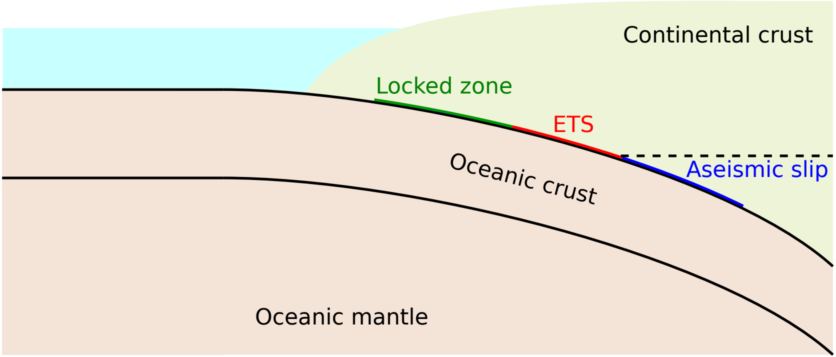
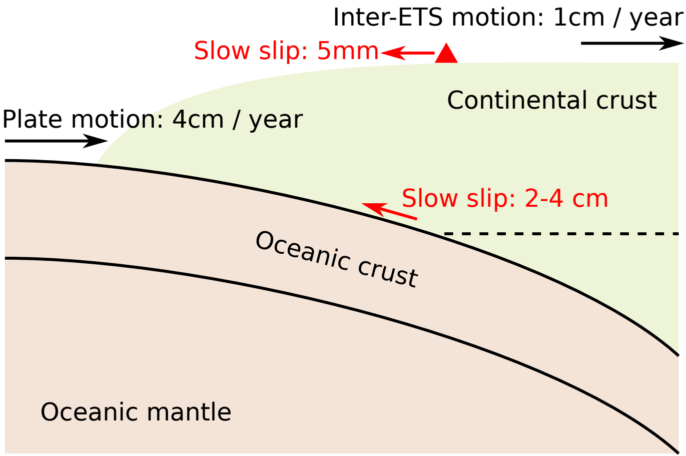
General Exam - October 25th 2019

Introduction

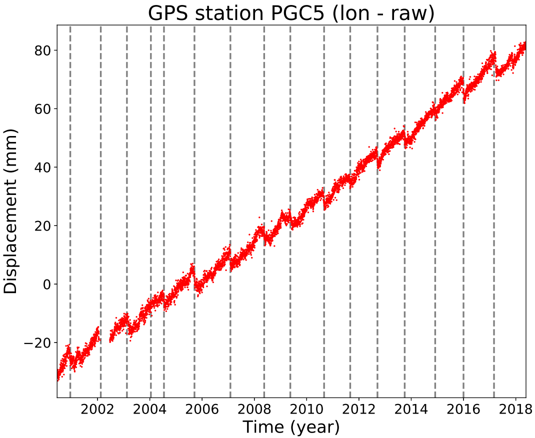
Slow earthquakes



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

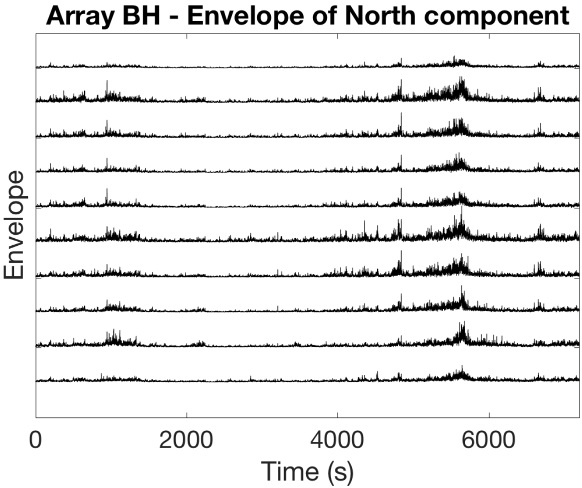
Slow slip


GPS station PGC5 (lon - raw)
Displacement (mm)
80
60
40
20
0
−20
2002
2004
2006
2008
2010
2012
2014
2016
2018
Time (year)

Tectonic tremor

- Long (several seconds to many minutes)
- Low amplitude
- Emergent onsets
- Absence of clear impulsive phases

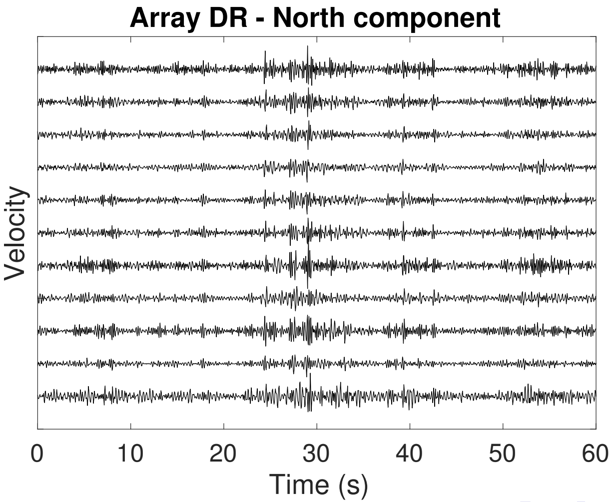
Tectonic tremor



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)



Episodic Tremor and Slip (ETS)

- Tectonic tremor observations spatially and temporally correlated with slow slip observations (Nankai, Cascadia)
- Only biggest tremor episode associated with slow slip
- No spatial or temporal correlation in other regions like New Zealand

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

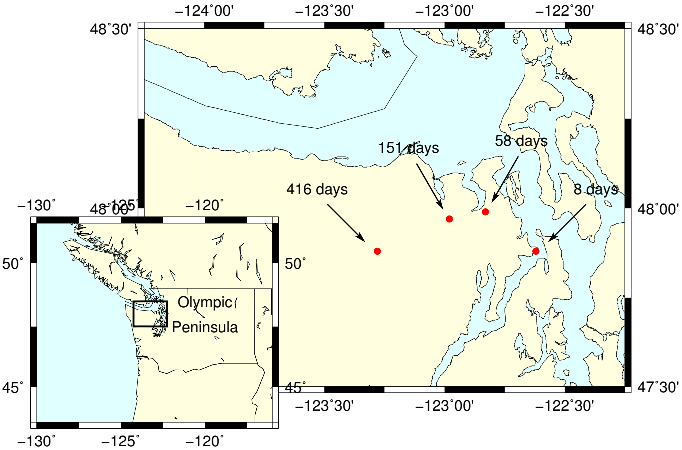
- Lack of impulsive phases → Difficult to determine the depth of the source of the tremor
- Tectonic tremor is at least partly made of a swarm of LFEs
- LFEs are located on the plate boundary

→ 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?

A low-frequency earthquake catalog for southern Cascadia

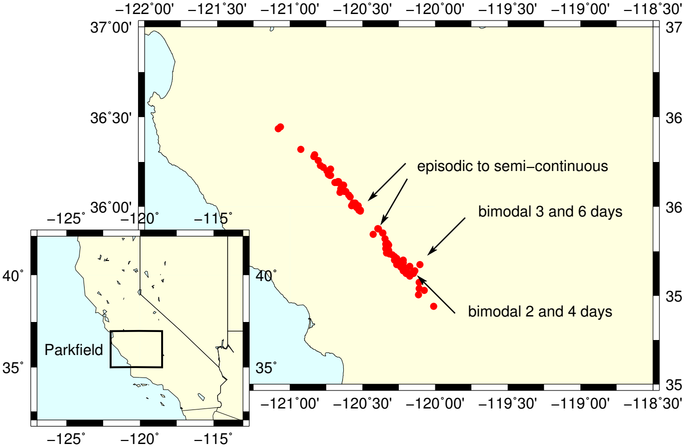
- LFEs grouped into families of events
- All the earthquakes of a given family originate from the same small patch on the plate interface
- LFEs recur more or less episodically in a bursty manner
- Wide range of recurrence behavior between seismic regions, and within the same seismic region

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.

A low-frequency earthquake catalog for southern Cascadia

- LFE families in southern Cascadia:
  - 34 LFE families on the subduction zone
  - 3 LFE families on two strike-slip faults from the San Andreas Fault system
- Wide range of recurrence behavior between Washington State and the San Andreas Fault, and within the San Andreas Fault zone

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

Detection of slow slip events in New Zealand

- Small (M $\sim$ 5) or long (several months) slow slip events are harder to detect
- In Cascadia, Mexico, tremor used as a proxy to study slow slip events
- Different pattern in northern new Zealand:
  - Tremor source located downdip of the slow slip on the plate boundary
  - Tremor activity does not seem to increase during slow slip events

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

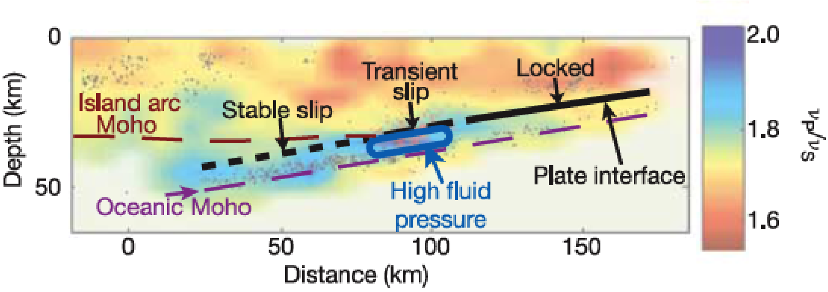
Depth of the source of the tectonic tremor

Tremor and LFEs

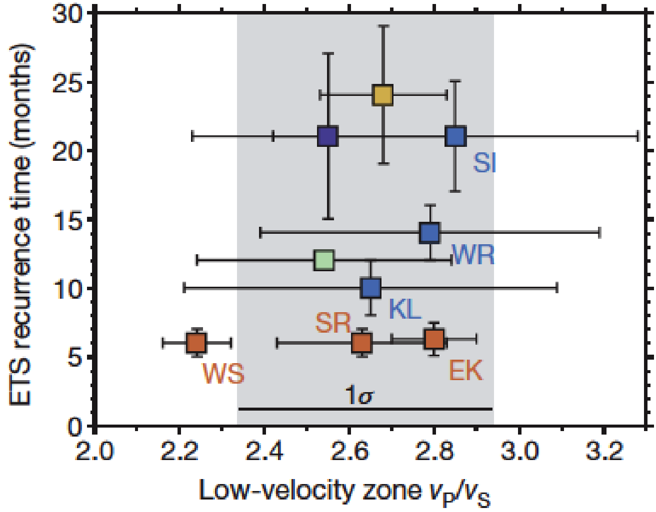
- Tremor can be explained as a swarm of LFEs
- LFE occur as shear faulting on the subduction-zone plate interface

Shelly et al. (2007), Ide et al. (2007)

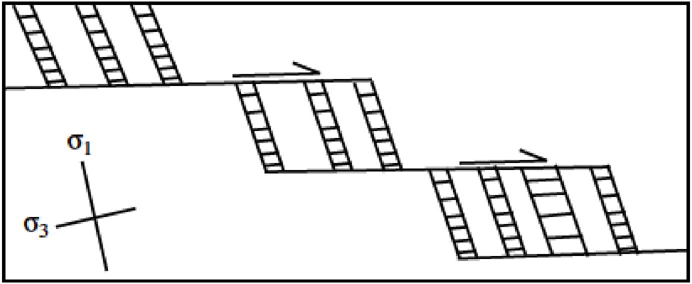
High pore fluid pressure in the oceanic crust



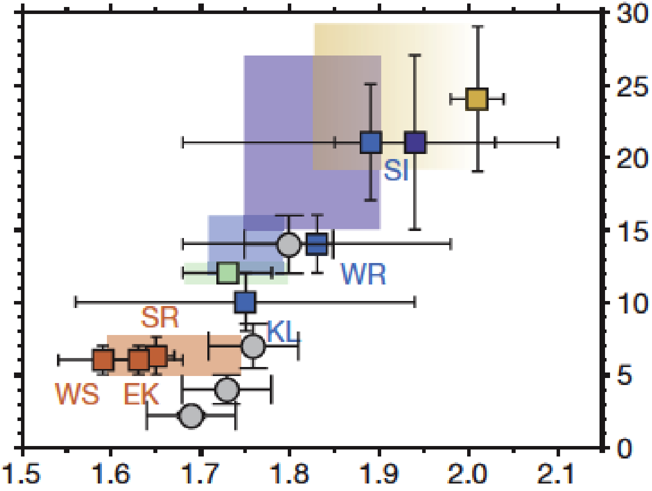
High pore fluid pressure in the oceanic crust



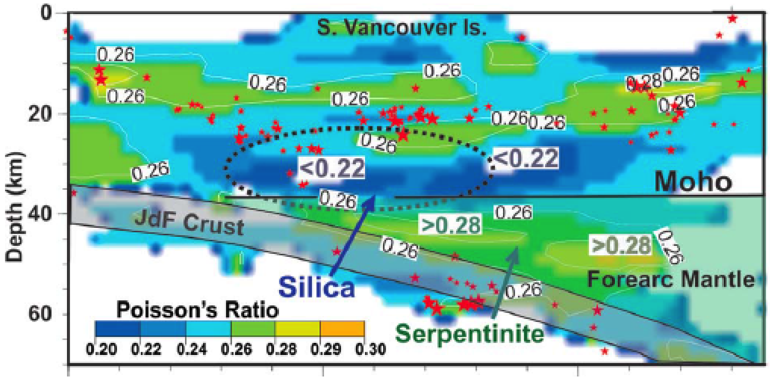
Fracture network



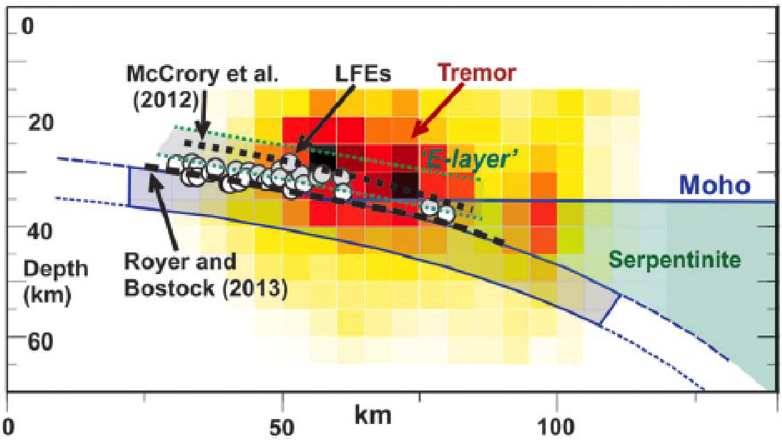
Low V_P/V_S ratio in subduction zones



Low V_P/V_S ratio in the overriding plate



Inferred location of the source of the tremor



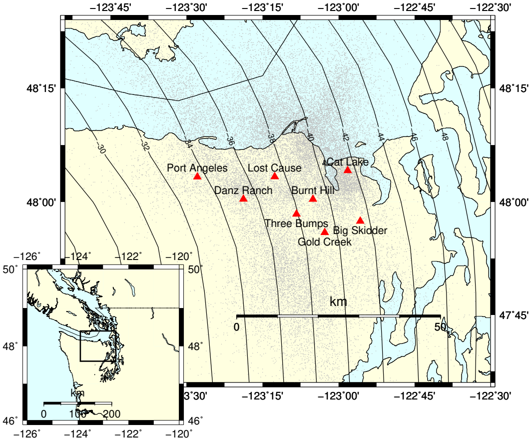
Where is the source of the tremor located?

- 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

→ How to constrain better 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

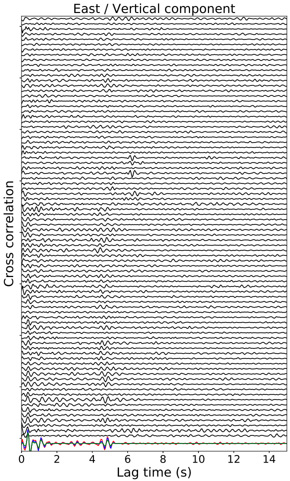
- 28902 one-minute-long time windows where tectonic tremor is recorded
- For each tremor window: Beginning time, latitude, longitude, and depth of the tremor source
- Start date: June 20^{th} 2009
- End date: September 30^{th} 2010

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

Stacking 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
- 70 one-minute-second-long time windows
- For each time window:
  - For each station, cross-correlate the horizontal component with the vertical component
  - Stack (linearly) the cross-correlation over all the stations of the array
- Plot all the 70 stacked cross-correlation
- Stack the 70 signals with a linear, power, or phase-weighted stack

Stacking of tremor recordings



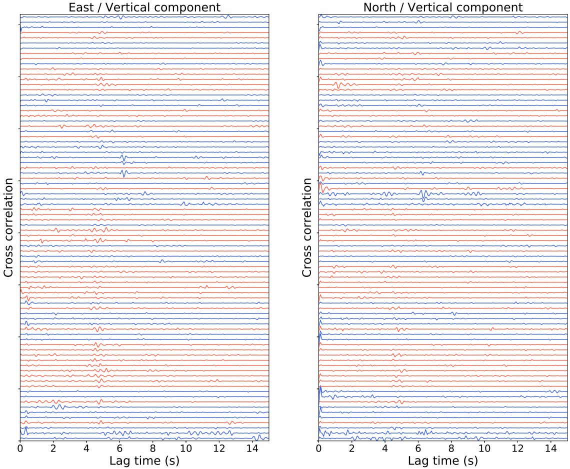
Clustering of cross correlation functions

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

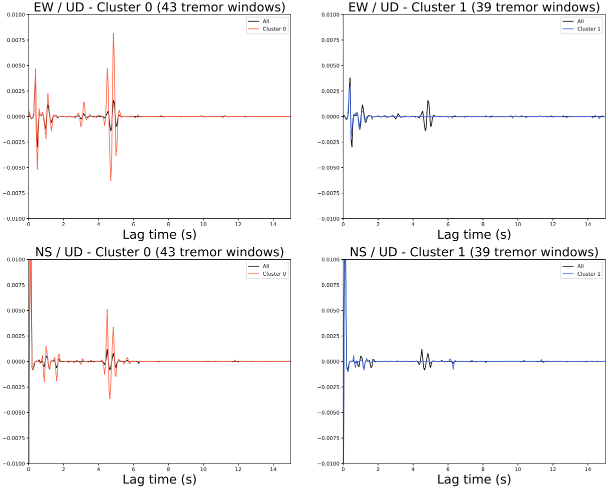
- Ratio RMS between 4 and 6 s / RMS between 12 and 14 s
- Cross-correlation between one cross-correlation and the stack:
    - Maximum cross-correlation value
    - Cross-correlation at time lag 0
    - Time lag corresponding to the maximum cross-correlation value

→ K-means clustering → Two clusters (good time windows / bad time windows)

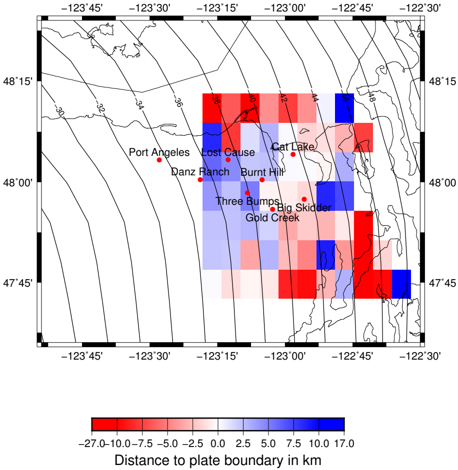
Clustering of cross correlation functions



Stacked cross correlation



Distance to plate boundary



Interpolation

- Number of tremor
- ratio peak cc / RMS
- Distance to array (strike / dip)

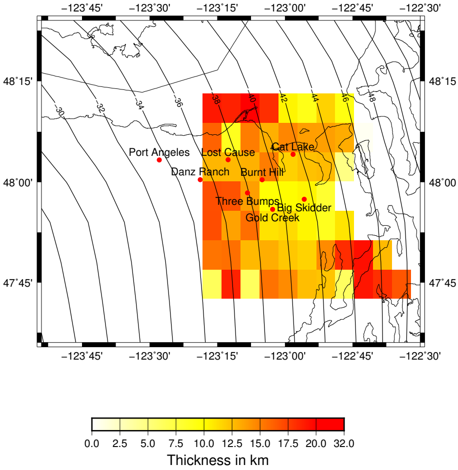
$\rightarrow$ Weights for interpolation of results from 8 arrays

Distance to plate boundary

Distribution of time lags

Width of the distribution

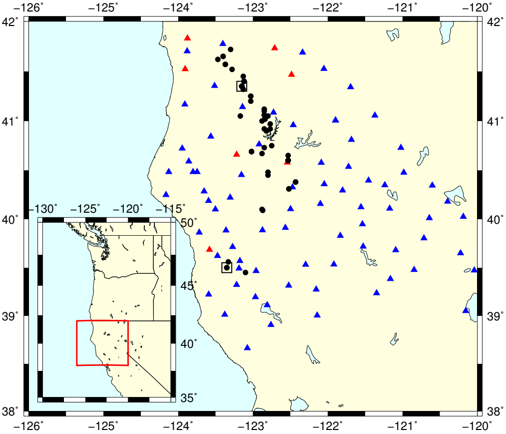
Thickness of the tremor zone



Conclusion

A low-frequency earthquake catalog for southern Cascadia

Current catalog



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

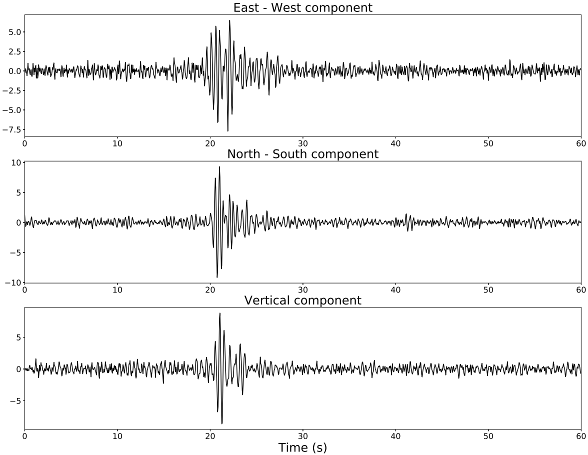
Current catalog

- 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

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

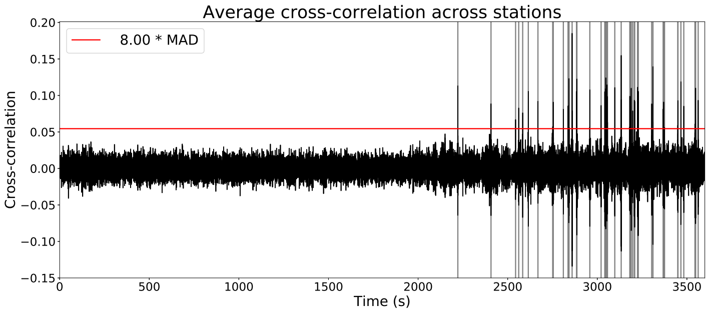
Templates for permanent station KRMB



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

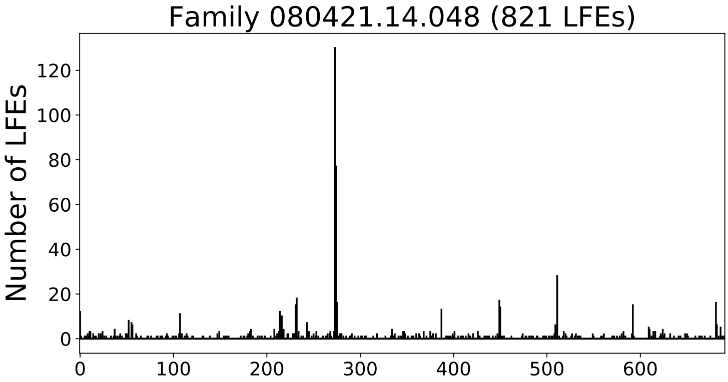


Comparison with existing catalog

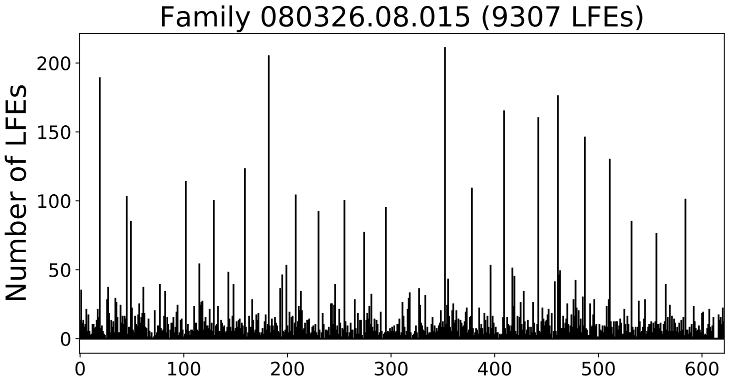
Family 080421.14.048

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

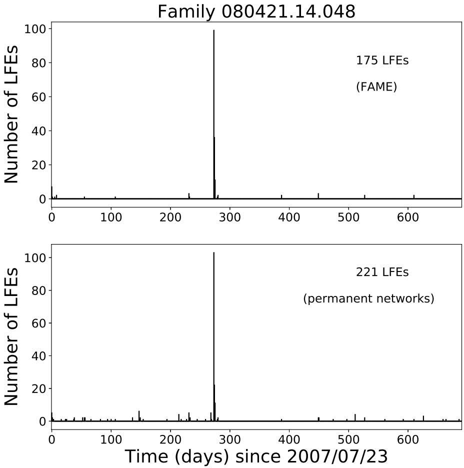
Extension of the catalog



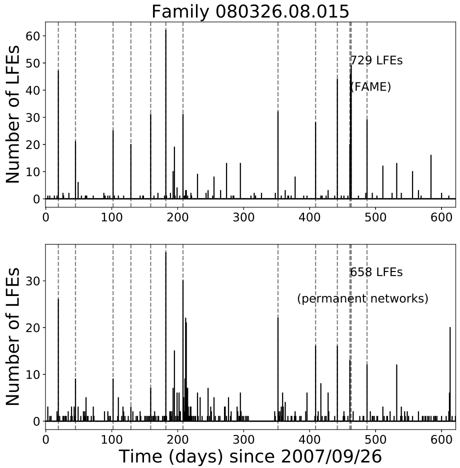
Extension of the catalog



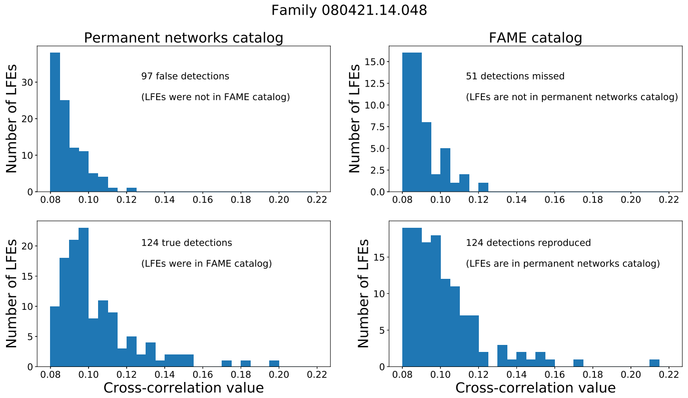
Detection of LFEs with permanent networks



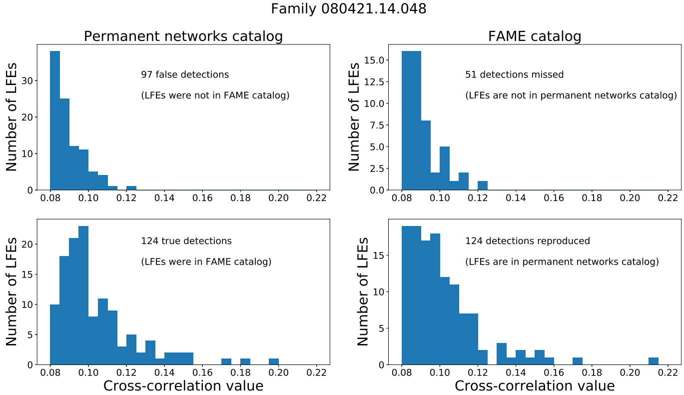
Detection of LFEs with permanent networks



Comparison FAME - permanent networks



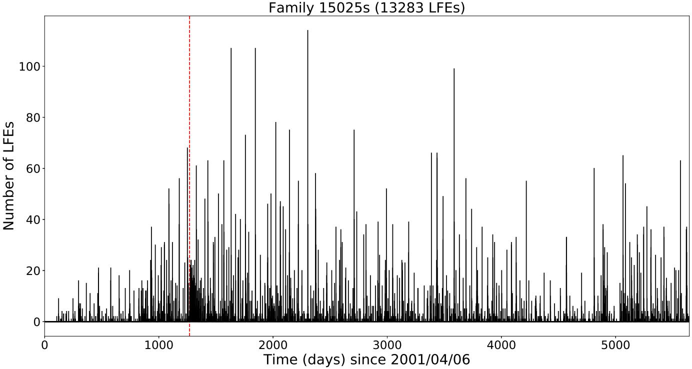
Comparison FAME - permanent networks



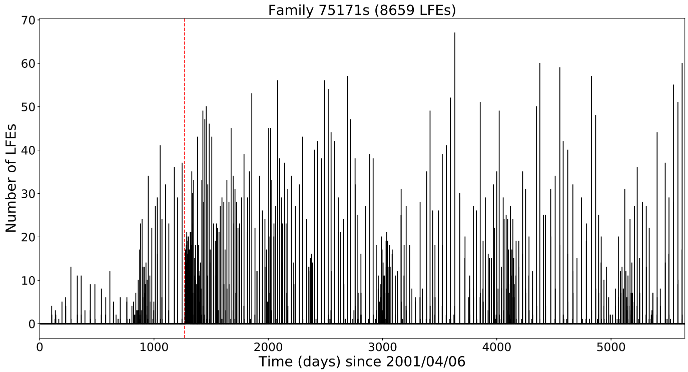
Future work

- 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

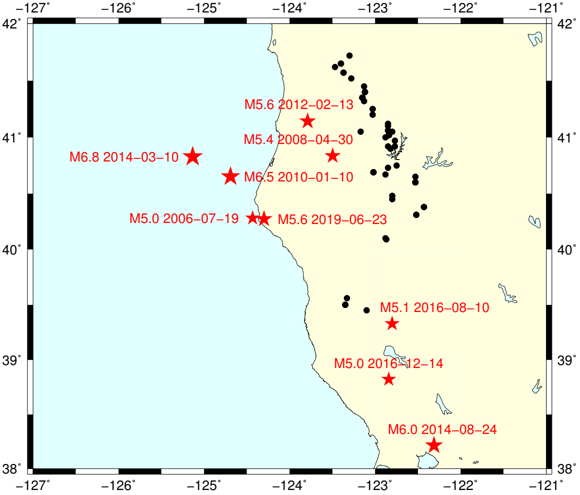
Effect of the 28 September 2004 M6.0 Parkfield earthquake



Effect of the 28 September 2004 M6.0 Parkfield earthquake



Moderate earthquakes in southern Cascadia



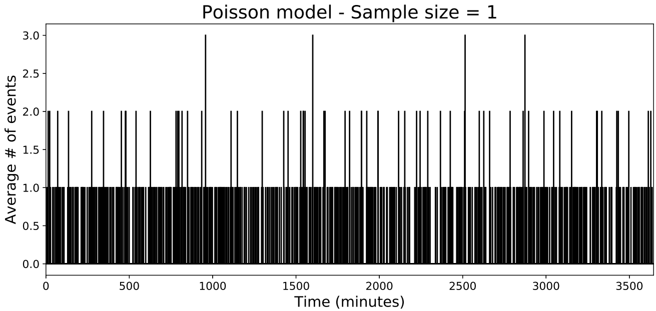
Future work

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

Long-range dependence

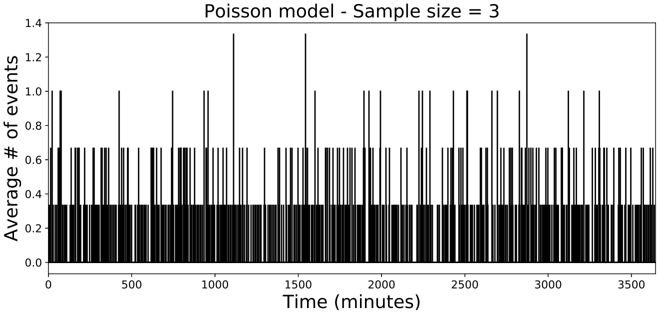
- Relates to the slow rate of decay of the statistical dependence between two points with increasing time interval between the points
- The fractional index d represents how fast the variance in the number of LFEs in a time window of a given length increases with the length of the time window considered
- $0 < d < 0.5$ is characteristic of long-range dependence

Homogeneous Poisson process



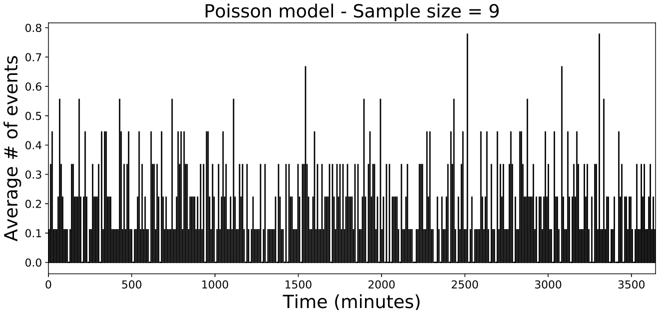
Number of events recorded during one day
$\rightarrow$ Variance over 3645 values $=$ 0.206

Homogeneous Poisson process



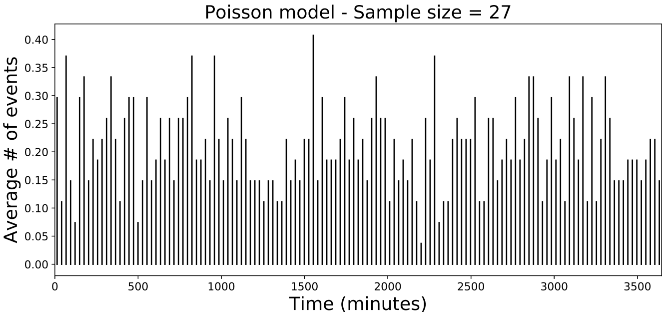
Number of events recorded during 3 days
$\rightarrow$ Variance over 1215 values $= 6.6210^{-2}$

Homogeneous Poisson process



Number of events recorded during 9 days
$\rightarrow$ Variance over 405 values $= 2.1410^{-2}$

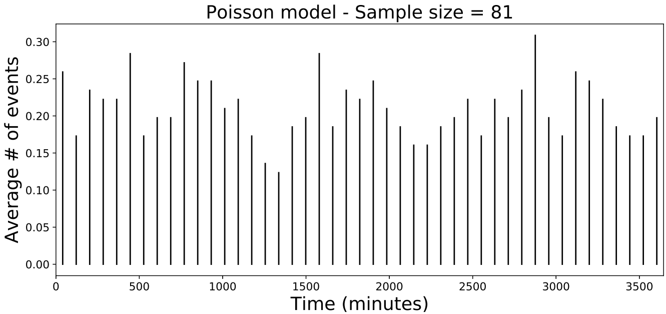
Homogeneous Poisson process



Number of events recorded during 27 days

$\rightarrow$ Variance over 135 values $= 5.5610^{-3}$

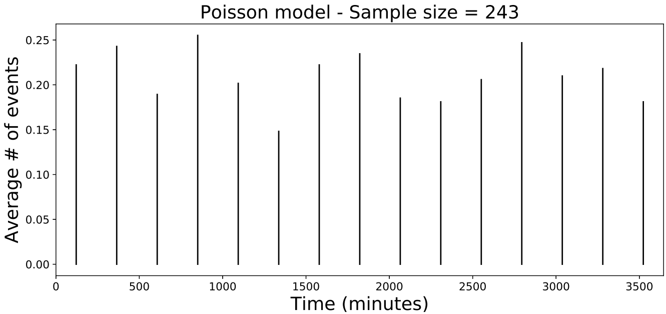
Homogeneous Poisson process



Number of events recorded during 81 days

$\rightarrow$ Variance over 45 values $= 1.5410^{-3}$

Homogeneous Poisson process



Number of events recorded during 243 days
$\rightarrow$ Variance over 15 values $= 8.0510^{-4}$

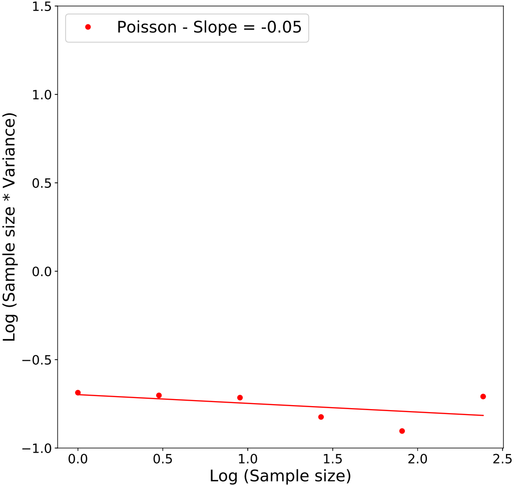
Variance vs Length of time window

V = Variance

m = Sample size

V behaves as m^{2d-1}

$\rightarrow d = 0$



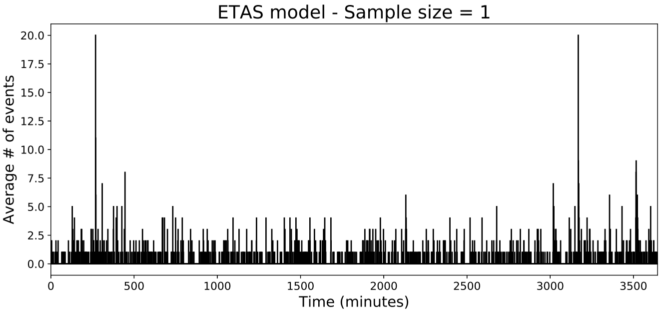
ETAS model

Epidemic-Type Aftershock Sequence (ETAS) model:

- Magnitude frequency distribution law of Gutemberg 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

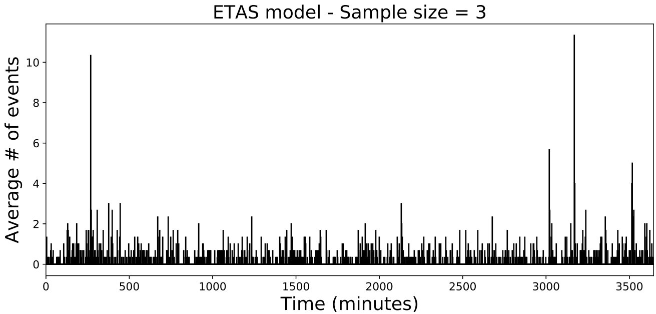
$$\lambda = \mu + A \sum_{t_i < t} e^{\alpha (M_i - M_0)} \left(1 + \frac{t - t_i}{c} \right)^{-p}$$

ETAS model



Number of events recorded during one day
$\rightarrow$ Variance over 3645 values $= 0.9636$

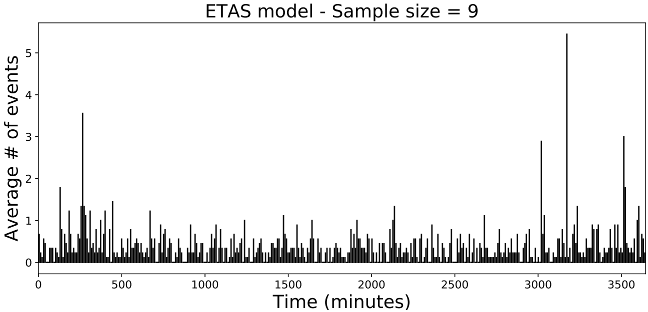
ETAS model



Number of events recorded during 3 days

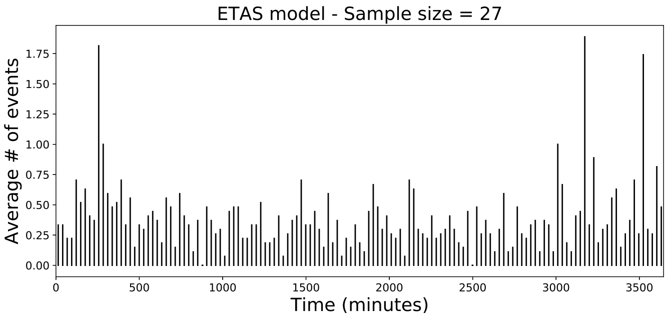
$\rightarrow$ Variance over 1215 values = 0.494

ETAS model



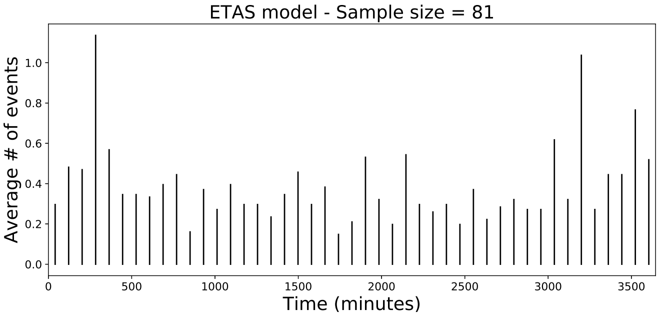
Number of events recorded during 9 days
$\rightarrow$ Variance over 405 values = 0.220

ETAS model



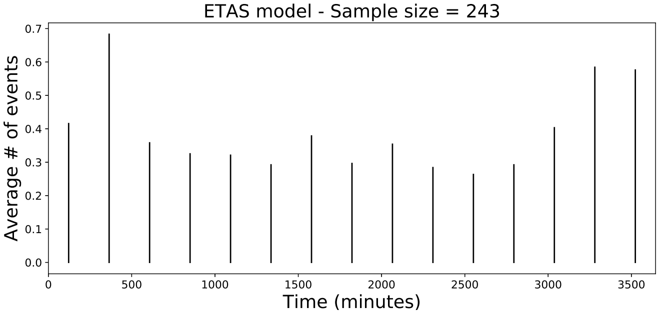
Number of events recorded during 27 days
$\rightarrow$ Variance over 135 values $= 0.0822$

ETAS model



Number of events recorded during 81 days
$\rightarrow$ Variance over 45 values $= 0.0381$

ETAS model



Number of events recorded during 243 days
$\rightarrow$ Variance over 15 values $= 0.0151$

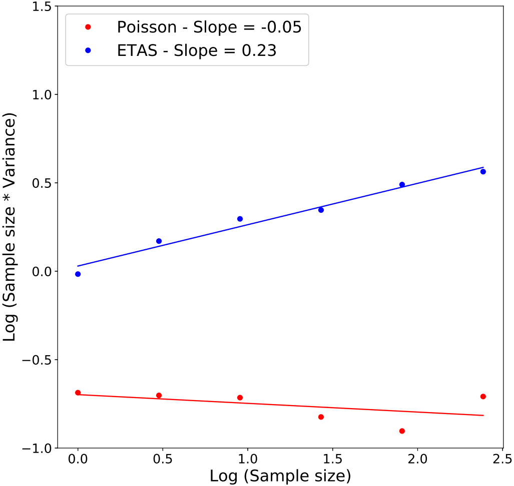
Variance vs Length of time window

V = Variance

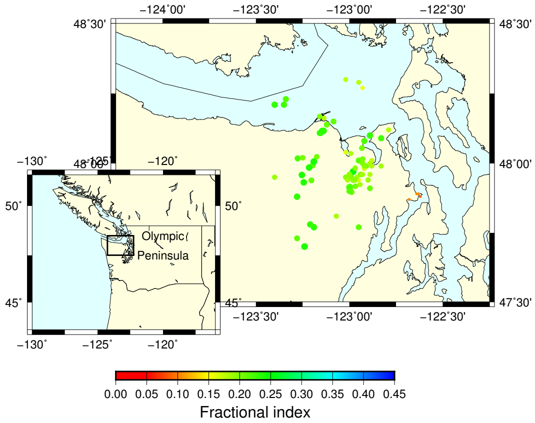
m = Sample size

V behaves as m^{2d-1}

$\rightarrow d = 0.117$

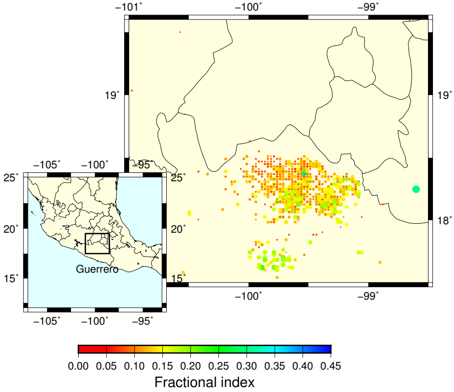


Northern Cascadia



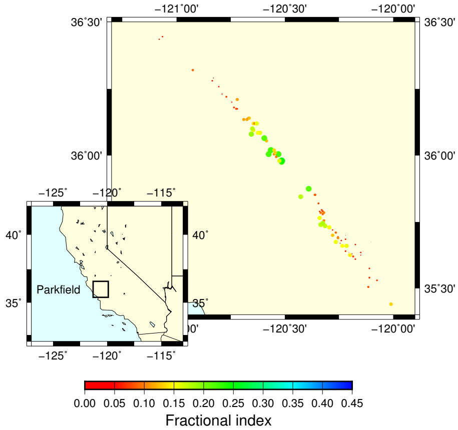
Catalogs from Sweet *et al.* (2019). G3, **20**, 1202-1217 and Chestler and Creager (2017). JGR Solid Earth, **122**, 3099-3114 and G3, **18**, 4690-4708.

Guerrero, Mexico



Catalog from Frank *et al.* (2014). JGR Solid Earth, **119**, 7686-7700.

San Andreas Fault



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

Future work

- Computation of the fractional index for the LFE families in southern Cascadia
- Quantification of the uncertainty on the value of the fractional index

ETAS model

Epidemic-Type Aftershock Sequence (ETAS) model:

- Magnitude frequency distribution law of Gutemberg 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

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

Future work

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

Detection of slow slip events in New Zealand

Tremor as proxy for slow slip

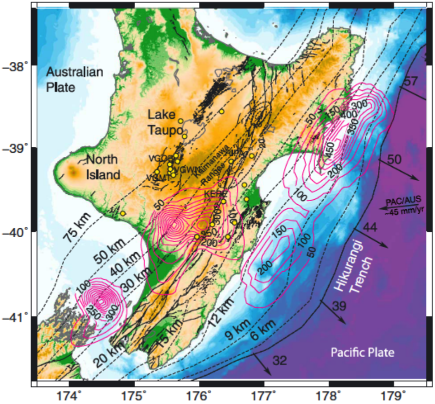
Episodic Tremor and Slip in Cascadia

- 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.

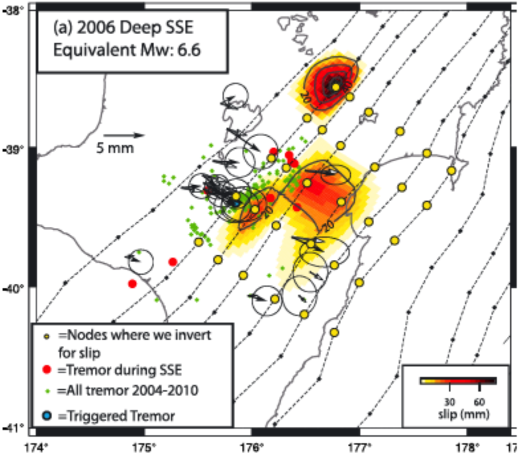
Slow slip events in northern New Zealand

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

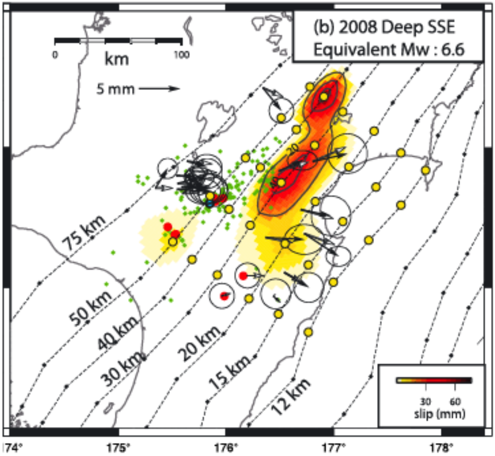
Wallace and Beavan (2010). JGR, **115**, B12402.
Todd and Schwartz (2016). JGR Solid Earth, **121**, 8706-8719.

Tremor accompanying deep slow slip events



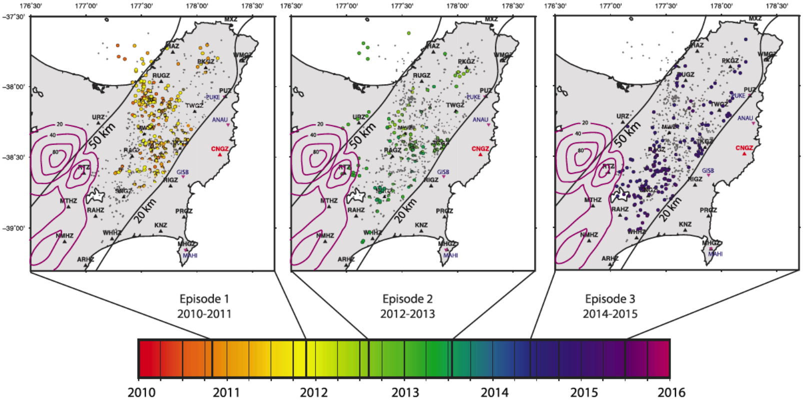
Wallace and Eberhart-Phillips (2013). GRL, **40**, 5393-5398.

Tremor accompanying deep slow slip events



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

Tremor with no detected slow slip event

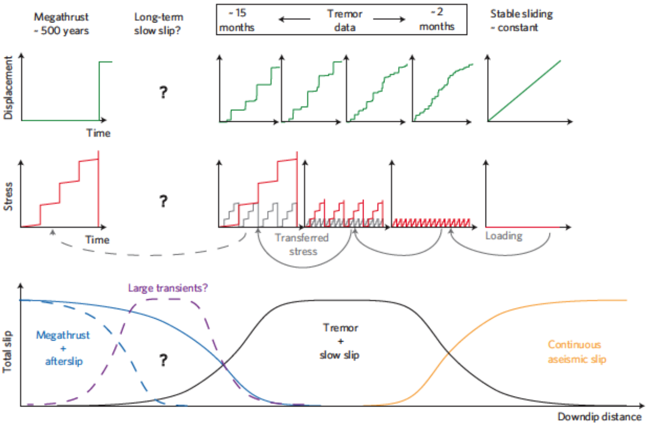


Todd and Schwartz (2016). JGR Solid Earth, **121**, 8706-8719.

Possible questions

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

Does the fault weakens with increasing depth?



Wech and Creager (2011). Nature Geoscience, **4**, 624-628.

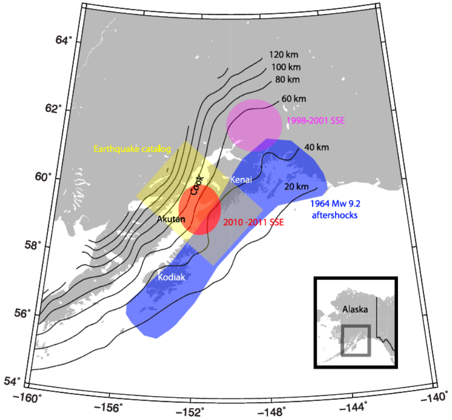
Does the fault weakens with increasing depth?

- 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).
- Hypothesis: Stable sliding at depth transfers stress to the base of the ETS zone, initiating frequent tremor and small slow slip. In a self-similar process, stress is then transferred updip of the fault, triggering less frequent tremor and larger slow slip, up toward the locked zone (Wech and Creager, 2011).

→ 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?



Wei *et al.* (2012). GRL, **39**, L15309.

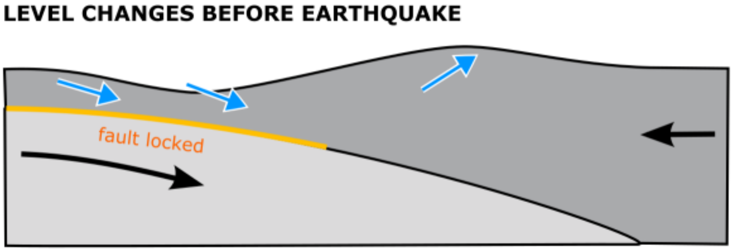
Is there a long term slow slip event accompanying tremor?

- 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?

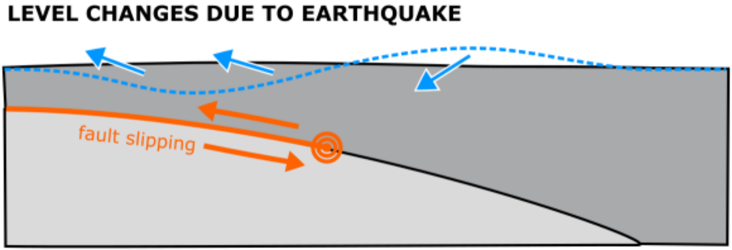
Wei *et al.* (2012). GRL, **39**, L15309.
Nuyen and Schmidt (2017). AGU Fall Meeting.
Todd and Schwartz (2016). JGR Solid Earth, **121**, 8706-8719.

Constraining the updip and downdip extent of slow slip



Source: http://all-geo.org/highlyallochthonous/

Constraining the updip and downdip extent of slow slip



Source: http://all-geo.org/highlyallochthonous/

Constraining the updip and downdip extent of slow slip

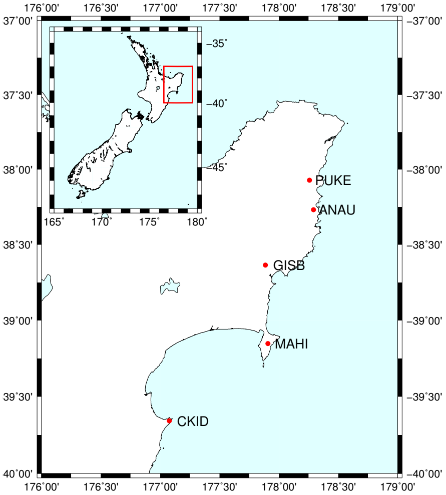
- Vertical component of the ground displacement is the most useful in constraining the updip and downdip extent of slip (Szeliga *et al.*, 2008)
- Downdip limit of the megathrust earthquake rupture
- Correlation with other geophysical data, such as porosity, temperature, and structure
- Smaller than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

$\rightarrow$ Can we better resolve the vertical component of the ground displacement?

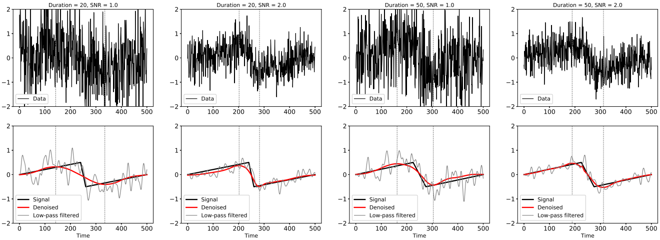
Szeliga *et al.* (2008). JGR, **113**, B04404.

Wavelet methods

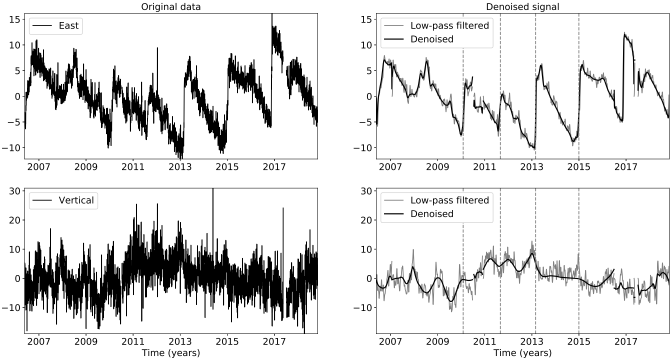
GPS stations in New Zealand



Denoising of GPS data



Denoising of GPS data



Questions?