

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

Ariane Ducellier

University of Washington

General Exam - October 25th 2019

# Introduction

## 1 Introduction

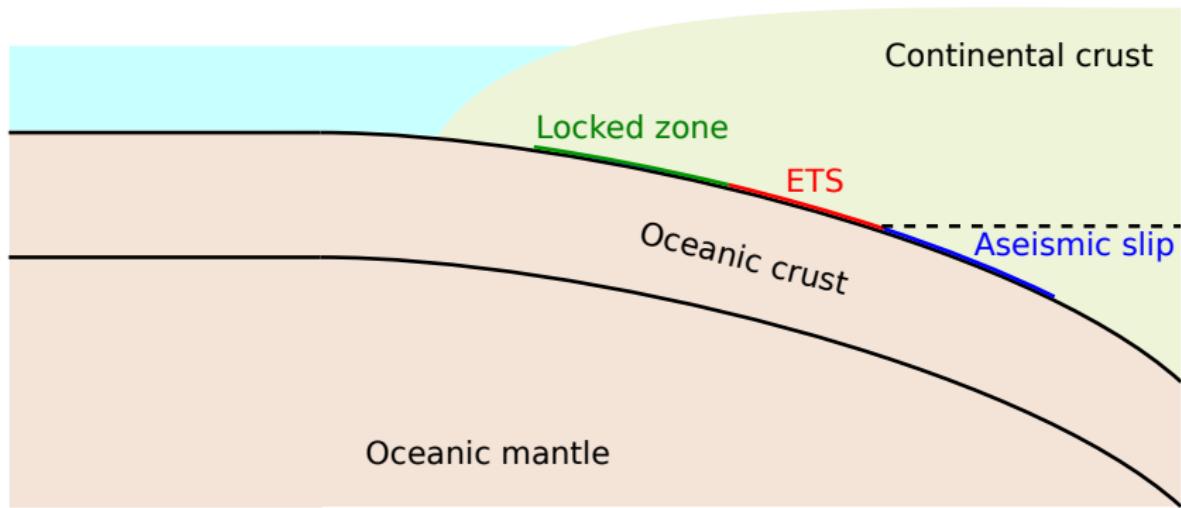
- Slow slip
- Tectonic tremor
- Low-frequency earthquakes (LFE)
- Episodic Tremor and Slip (ETS)
- Research questions

## 2 Depth of the source of the tectonic tremor

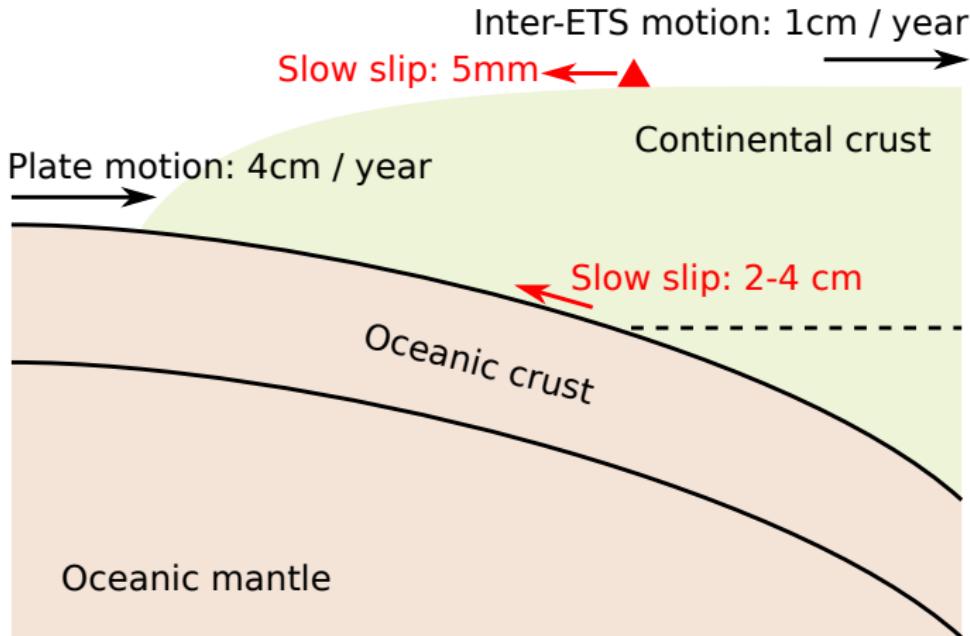
## 3 A low-frequency earthquakes catalog for southern Cascadia

## 4 Detection of slow slip events in New Zealand

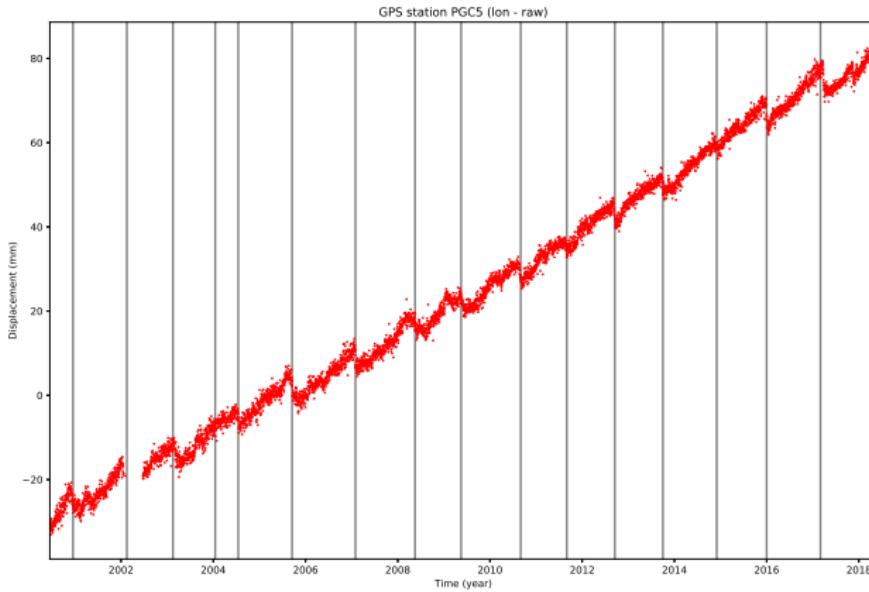
# Slow earthquakes



# Slow slip



# Slow slip

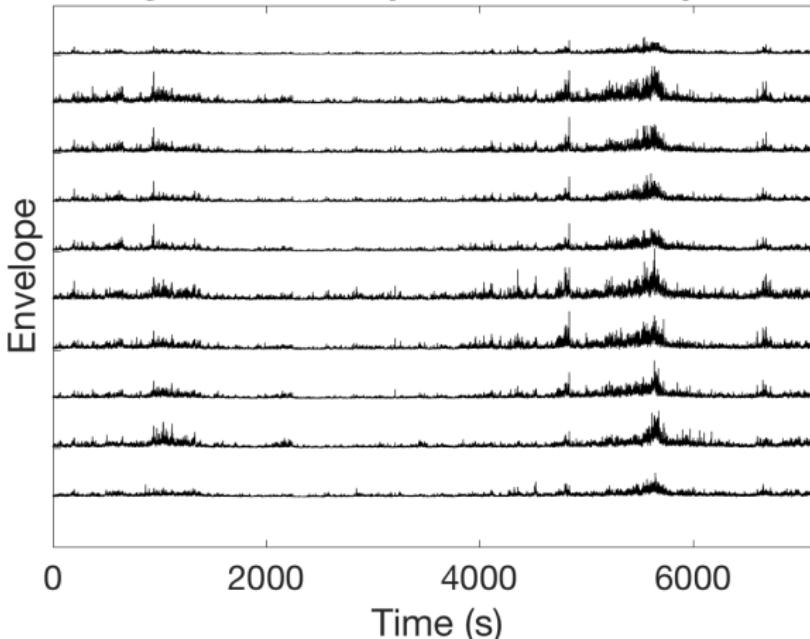


# Tectonic tremor

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

# Tectonic tremor

**Array BH - Envelope of North component**

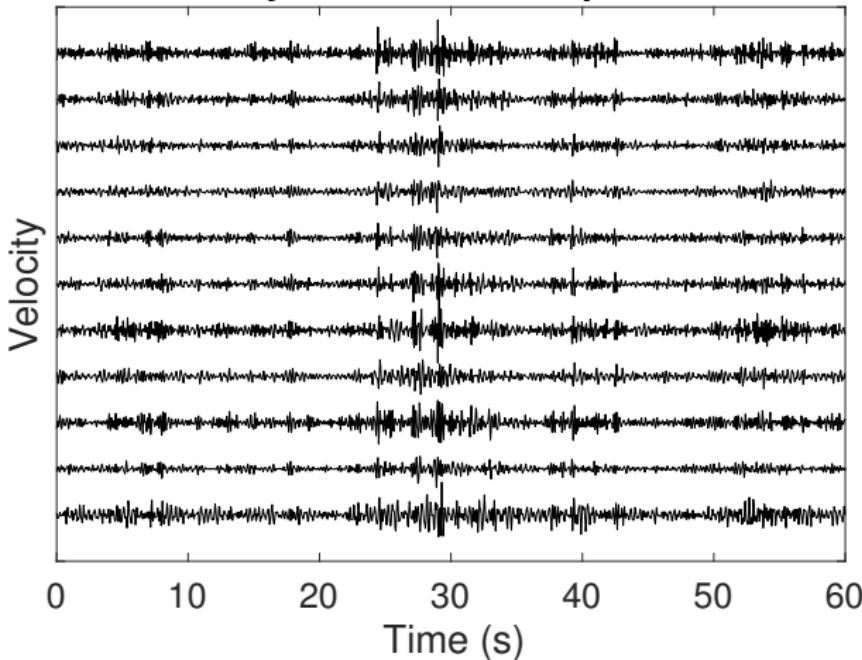


# Low-frequency earthquakes (LFE)

- 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)

Array DR - North component



# 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

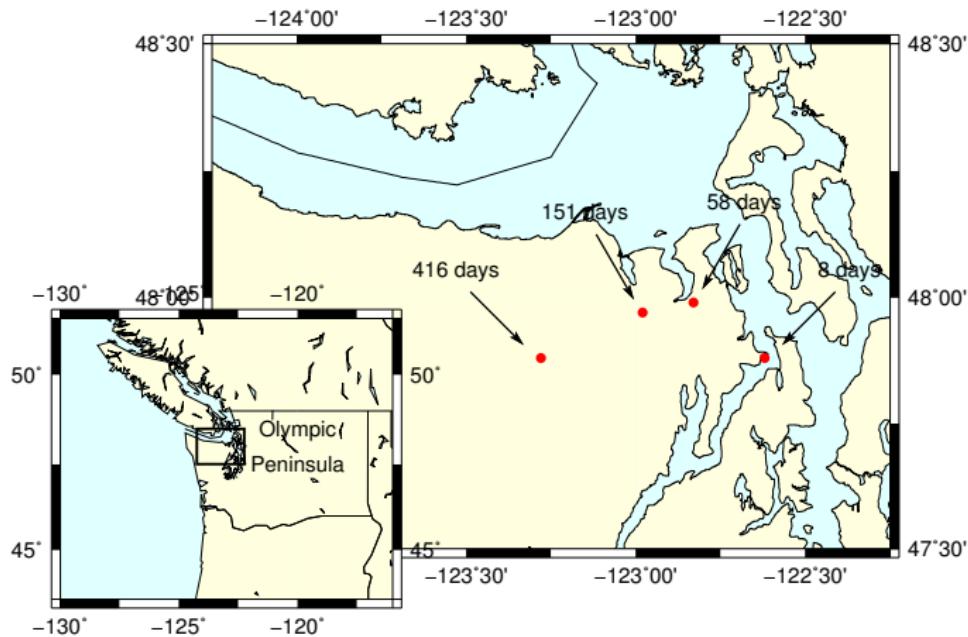
- Lack of impulsive phases → Difficult to determine the depth of the source of the tremor
- Tectonic tremor is at least partly made of a swarm of LFEs
- LFEs are located on the plate boundary

→ 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?

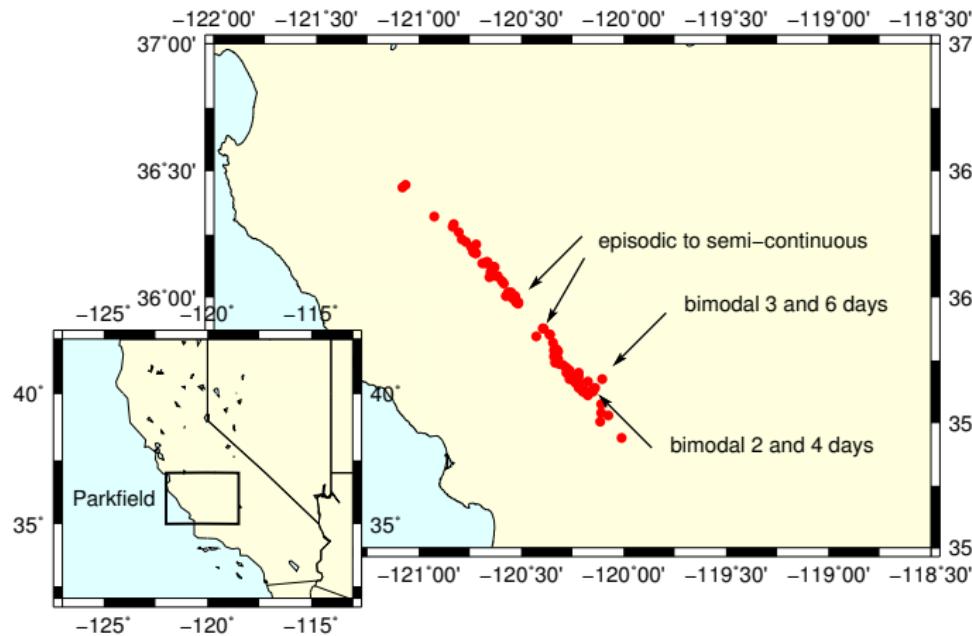
# A low-frequency earthquake catalog for southern Cascadia

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

# LFE in Washington State



# LFE on the San Andreas Fault



# A low-frequency earthquakes 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 earthquakes 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

→ 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

## 1 Introduction

## 2 Depth of the source of the tectonic tremor

- Motivation
- Data
- Method
- Results
- Discussion and Conclusion

## 3 A low-frequency earthquakes catalog for southern Cascadia

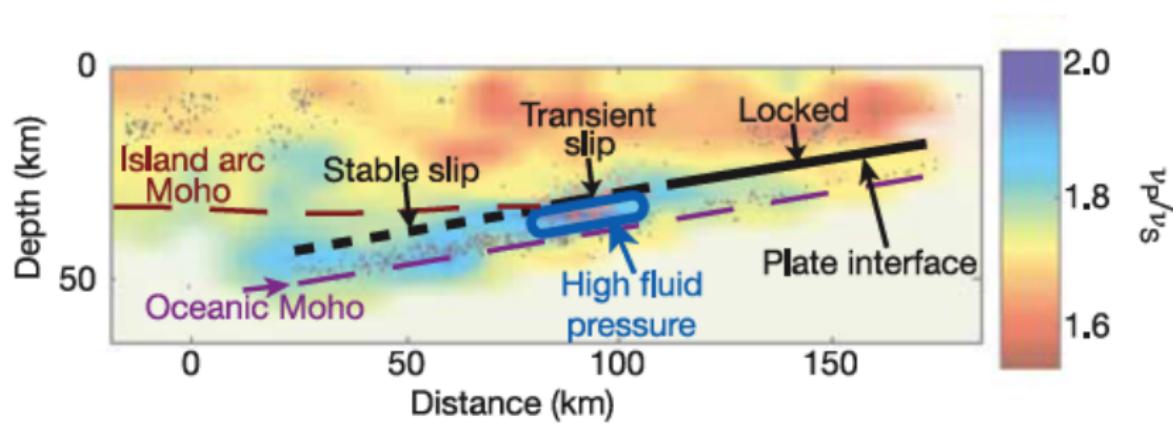
## 4 Detection of slow slip events in New Zealand

# Tremor and LFEs

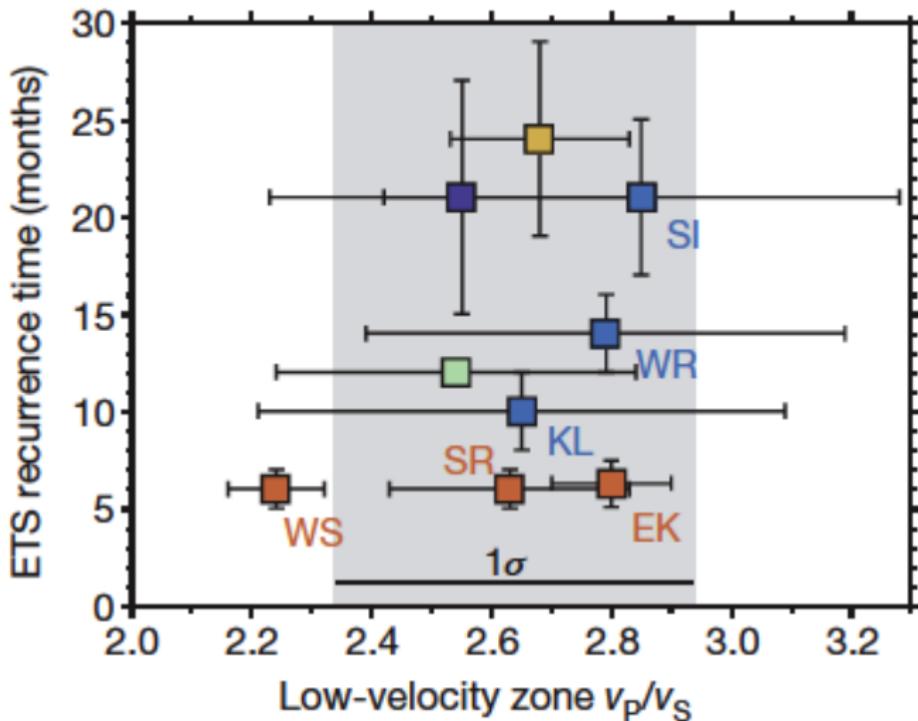
- Tremor can be explained as a swarm of LFEs
- LFE occur as shear faulting on the subduction-zone plate interface

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

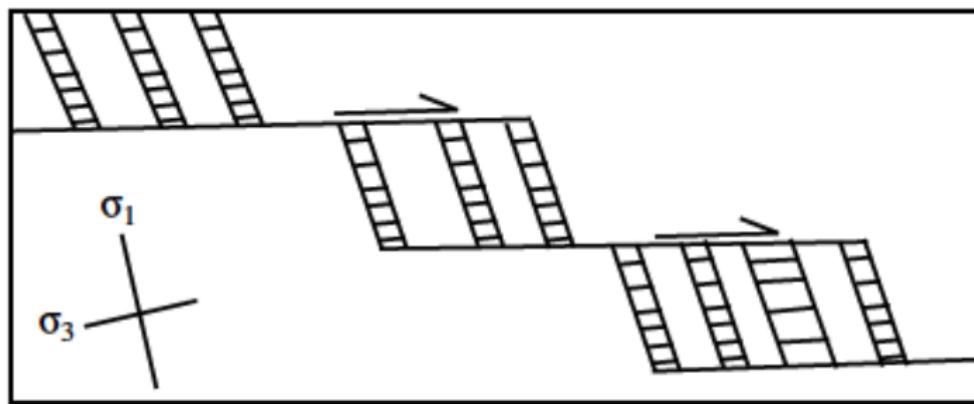
# High pore fluid pressure in the oceanic crust



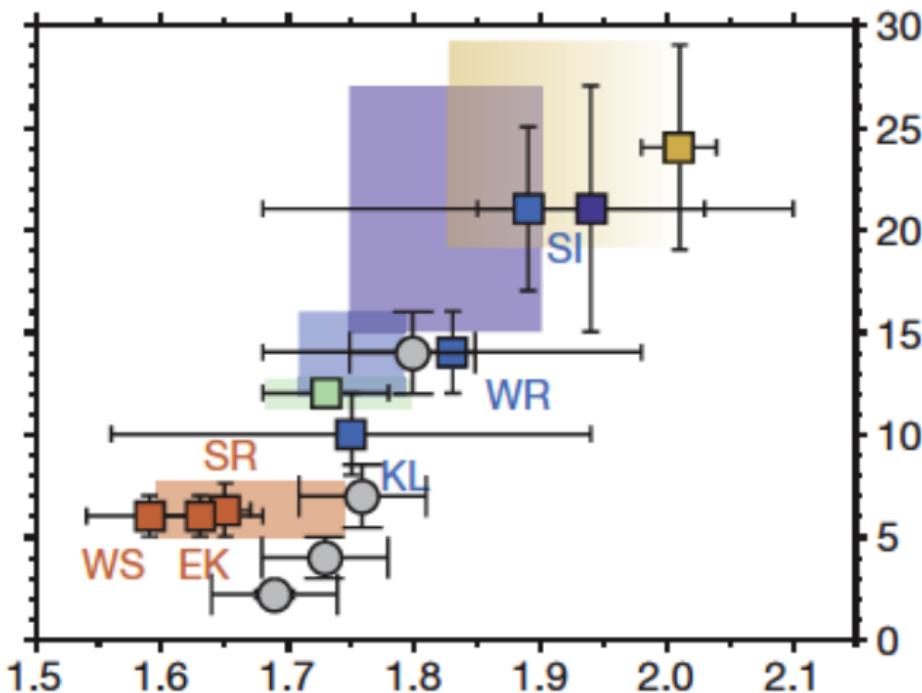
# High pore fluid pressure in the oceanic crust



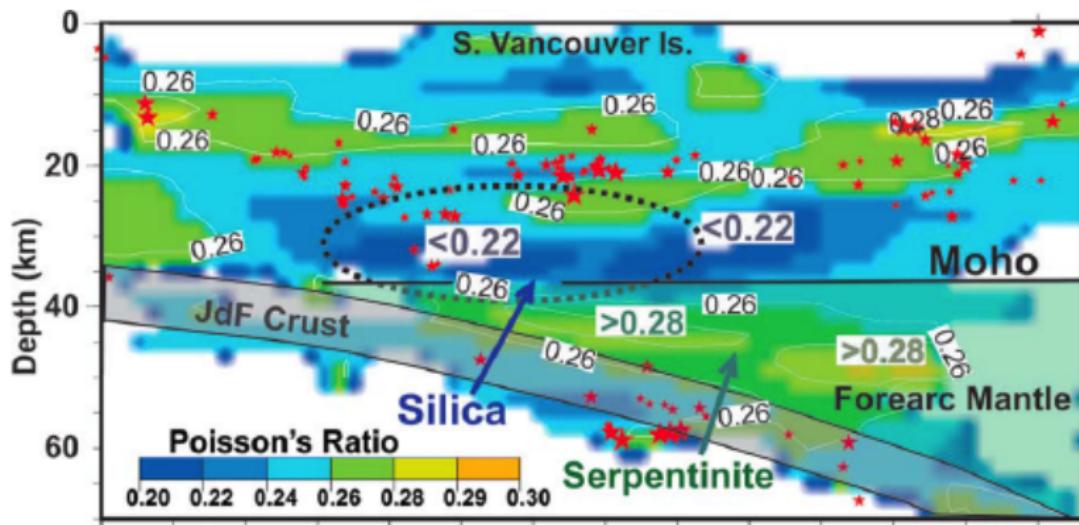
# Fracture network



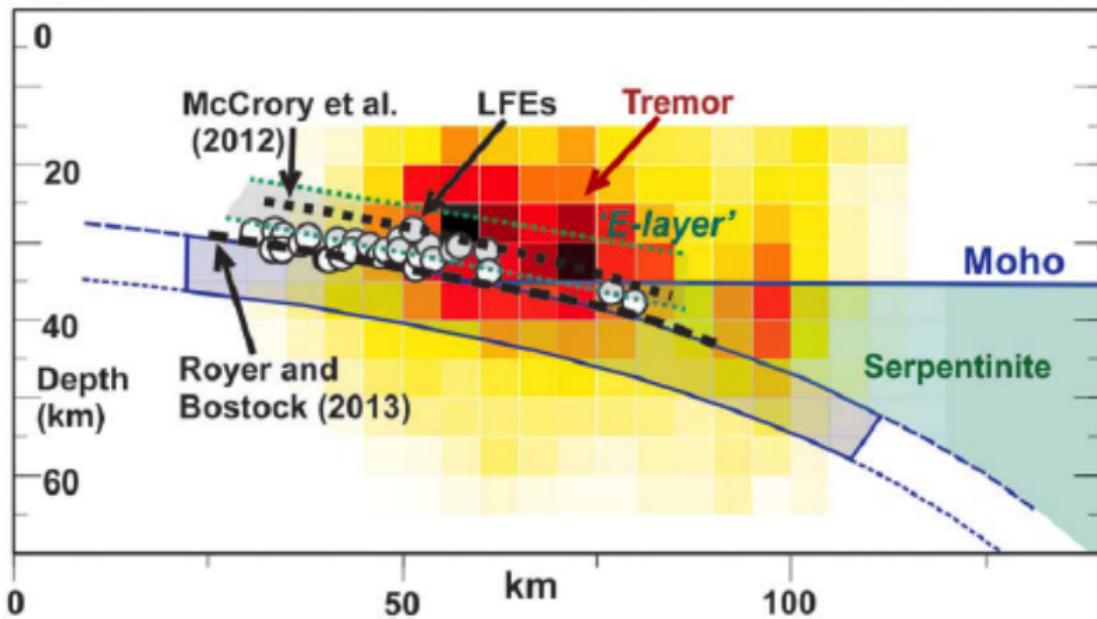
# Low $V_P/V_S$ ratio in subduction zones



# Low $V_P/V_S$ ratio in the overriding plate



# Inferred location of the source of the tremor



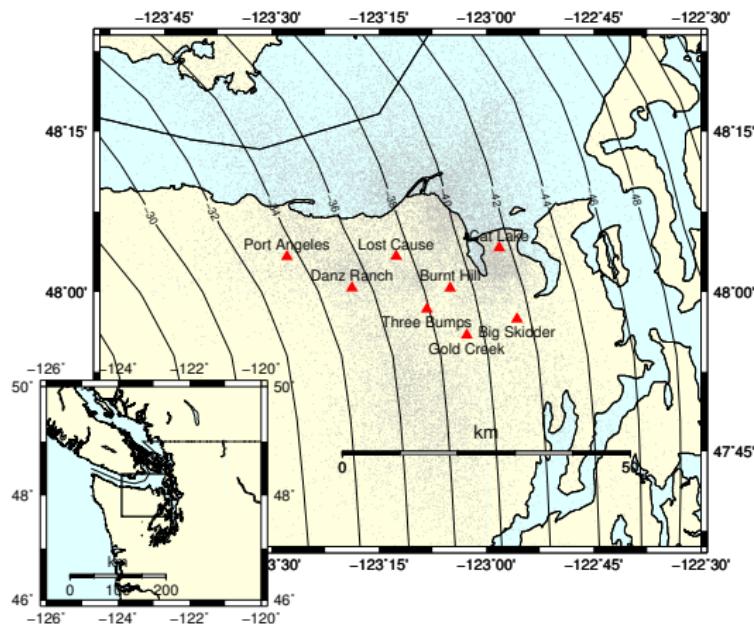
# Where is the source of the tremor located?

- 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



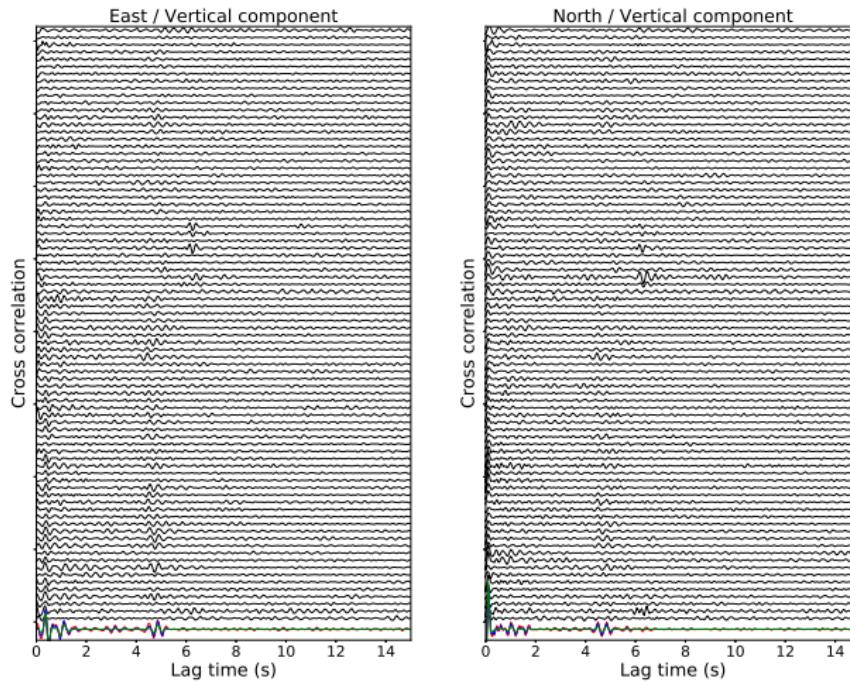
# Tremor catalog

- 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<sup>th</sup> 2009
- End date: September 30<sup>th</sup> 2010

# 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



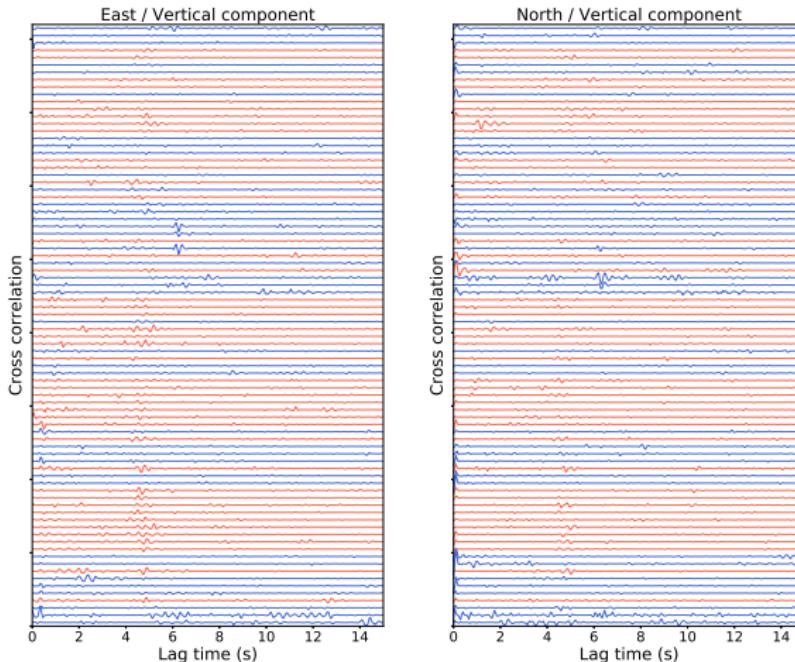
# Clustering of cross correlation functions

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

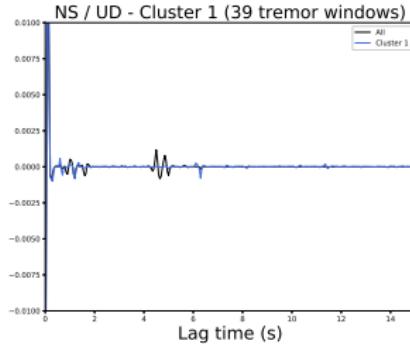
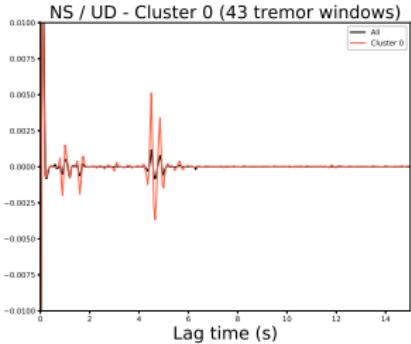
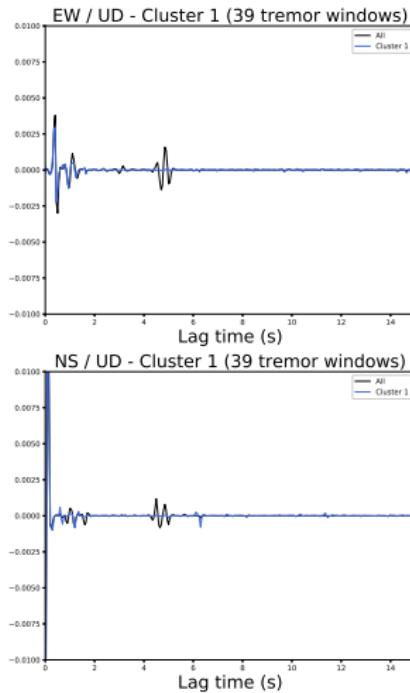
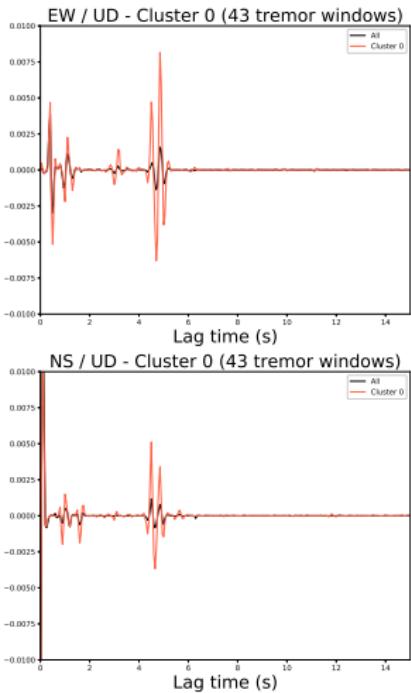
- Ratio RMS between 4 and 6 s / RMS between 12 and 14 s
- Cross-correlation between one cross-correlation and the stack:
  - Maximum cross-correlation value
  - Cross-correlation at time lag 0
  - Time lag corresponding to the maximum cross-correlation value

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

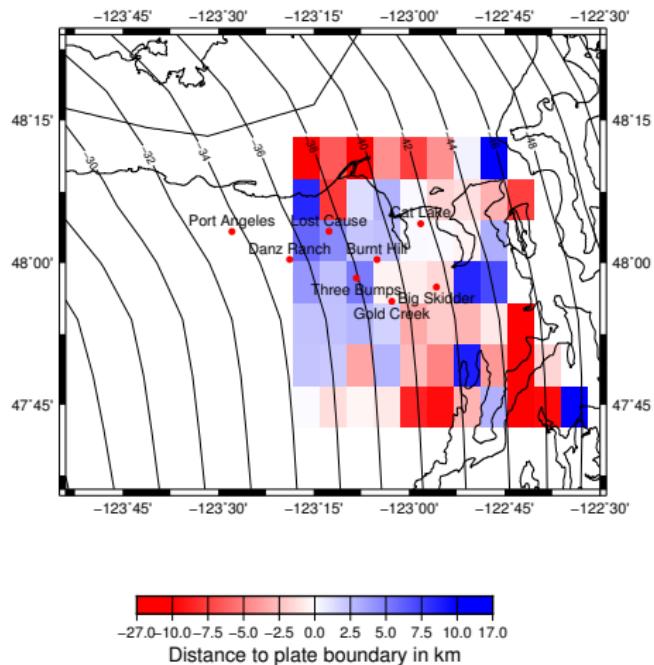
# Clustering of cross correlation functions



# Stacked cross correlation



# Distance to plate boundary



# Interpolation

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

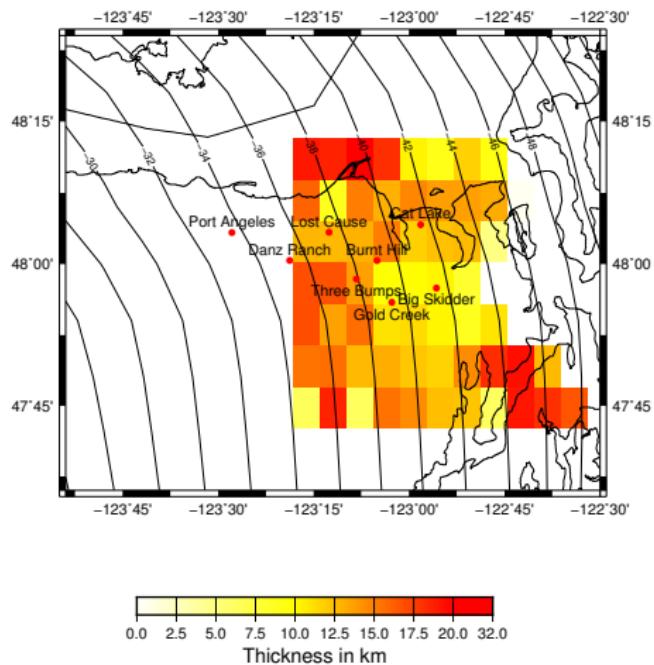
→ Weights for interpolation of results from 8 arrays

# Distance to plate boundary

# Distribution of time lags

# Width of the distribution

# Thickness of the tremor zone



# Conclusion

# A low-frequency earthquakes catalog for southern Cascadia

## 1 Introduction

## 2 Depth of the source of the tectonic tremor

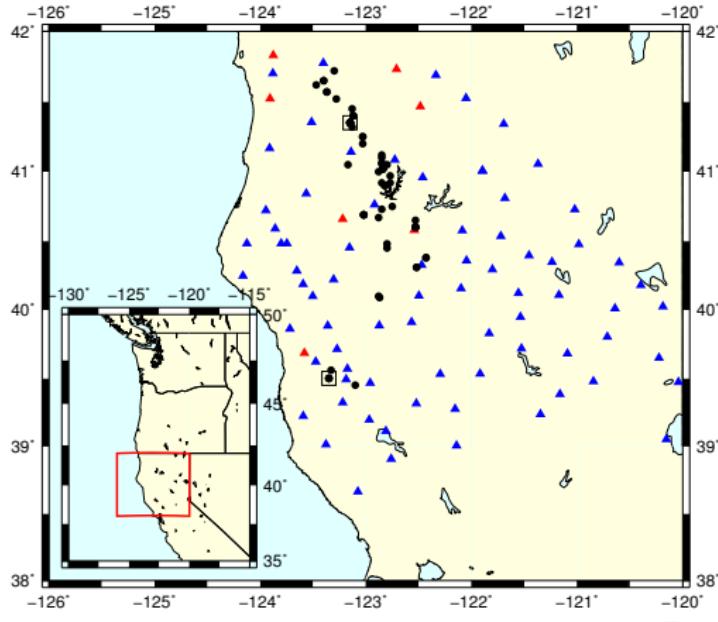
## 3 A low-frequency earthquakes catalog for southern Cascadia

- Extension of an LFE catalog for southern Cascadia
- Effect of nearby earthquakes on LFE activity
- Characterization of LFE clustering
- Temporal model of LFE occurrence rate

## 4 Detection of slow slip events in New Zealand

## 5 Time line

# Current catalog

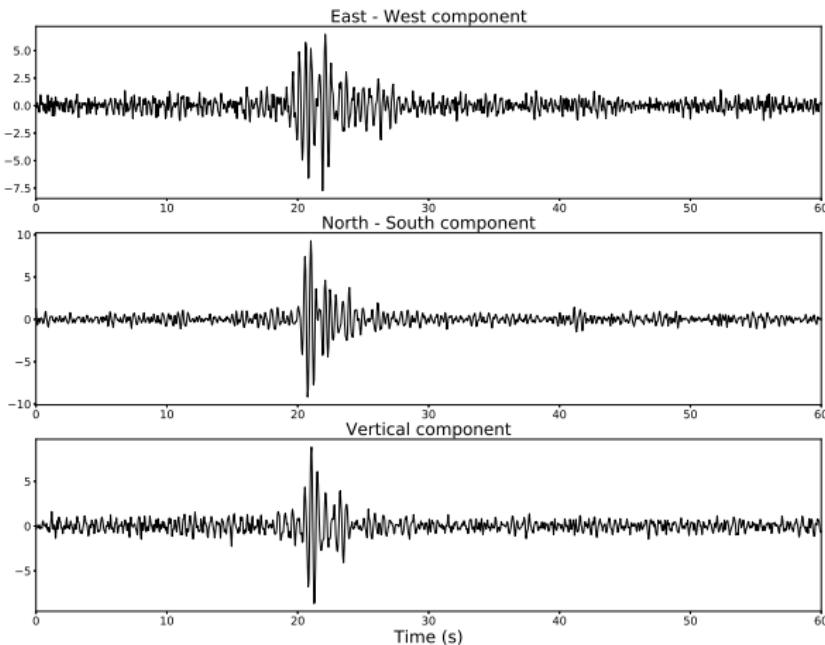


# Current catalog

- Subduction zone families
  - 34 families
  - Period covered: April 2008
  - One burst of LFE 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 LFE

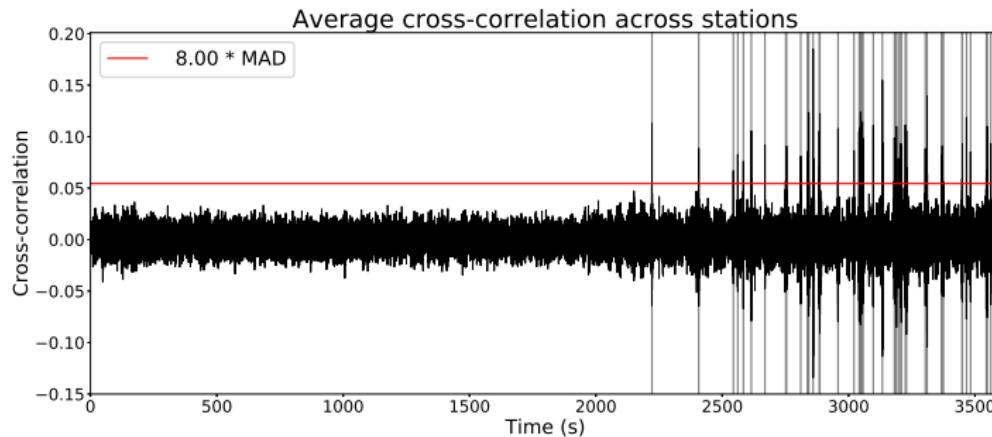
# Creating templates

# Templates for permanent station KRMB



# Finding new LFE

# Analysis of one hour of seismic data

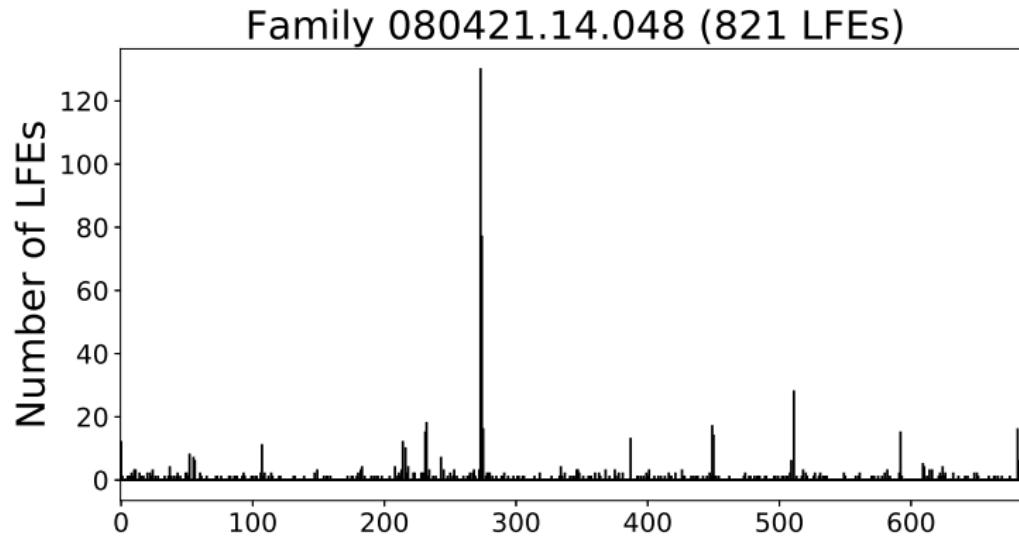


## Comparison with existing catalog

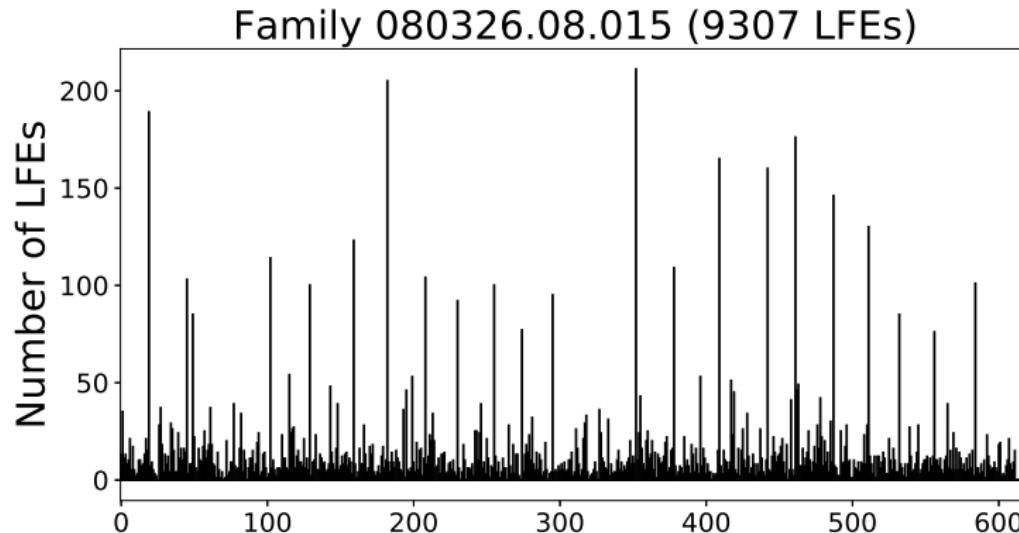
Family 080421.14.048

Number of LFE in my catalog	236
Number of LFE in the catalog by Plourde <i>et al.</i>	225
Number of LFE added in my catalog	13
Number of LFE missing in my catalog	2
Number of LFE present in both catalogs	223

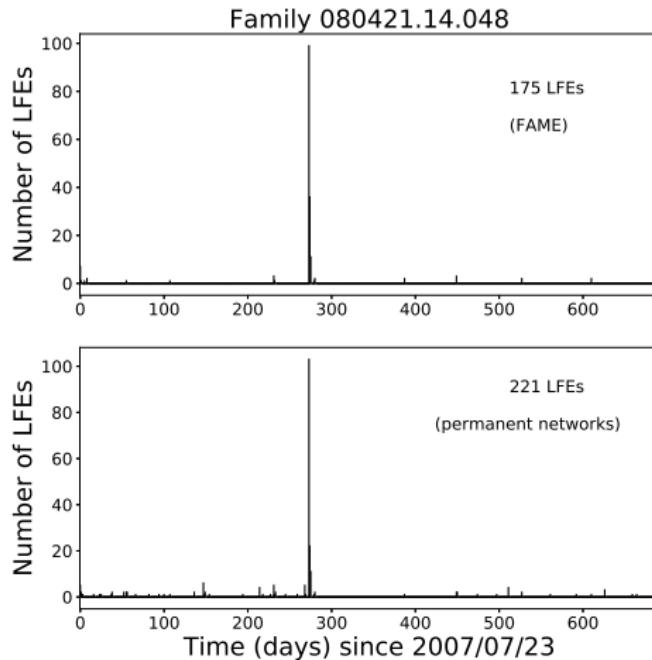
## Extension of the catalog



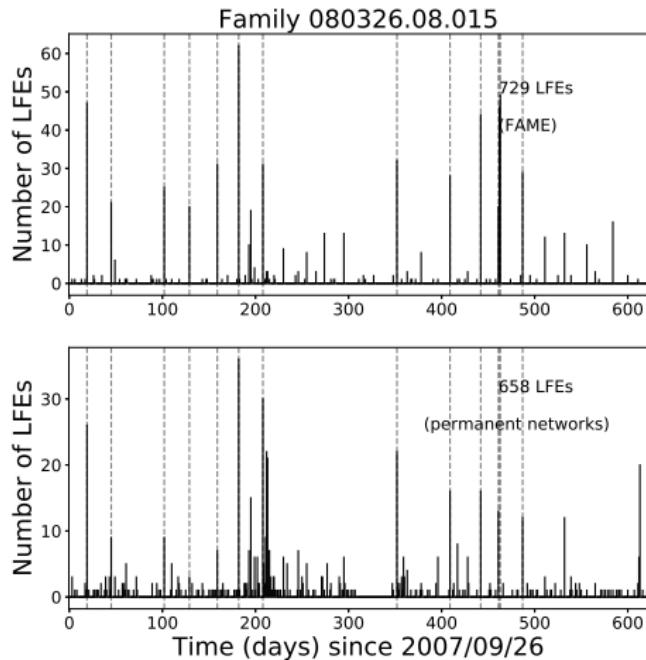
## Extension of the catalog



# Detection of LFE with permanent networks

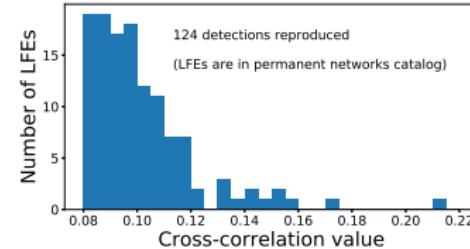
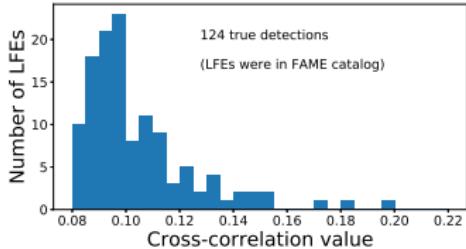
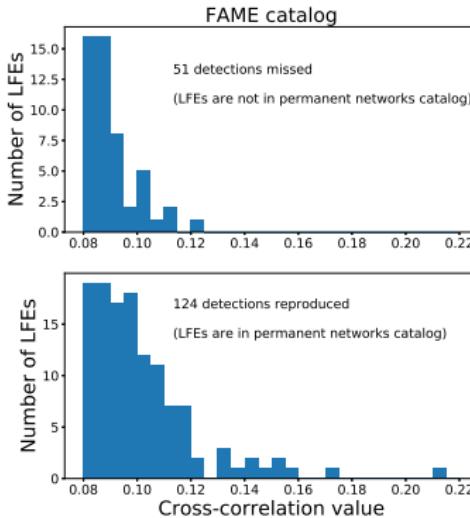
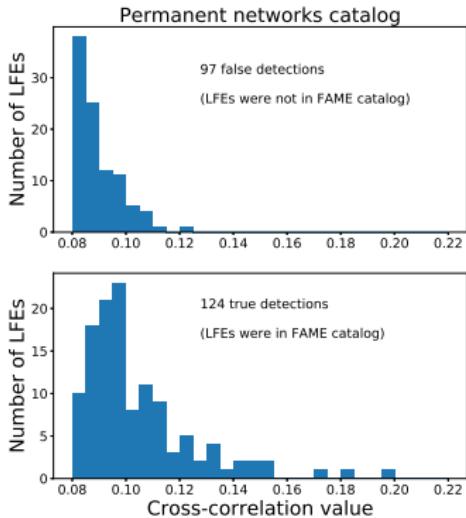


# Detection of LFE with permanent networks



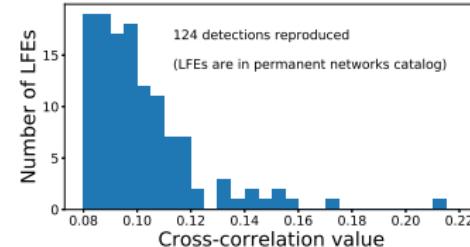
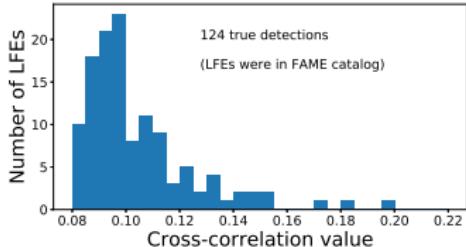
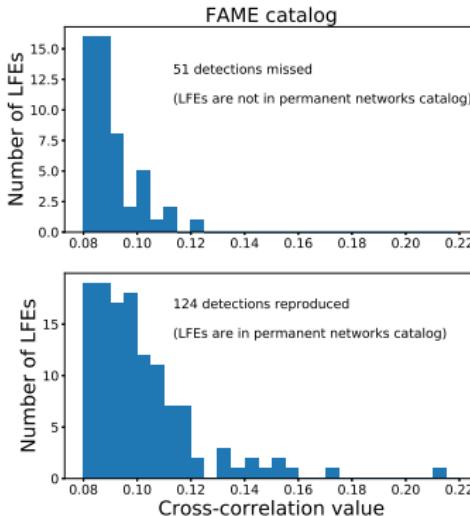
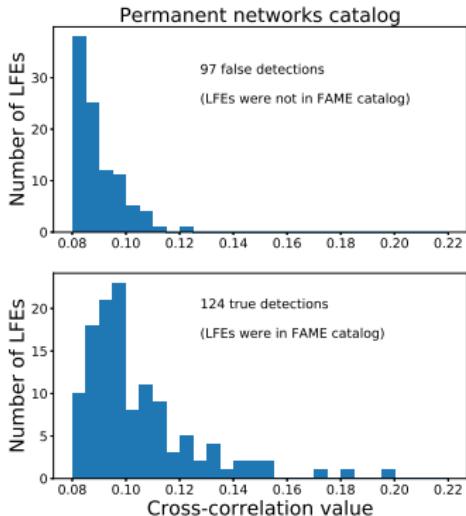
# Comparison FAME - permanent networks

Family 080421.14.048



# Comparison FAME - permanent networks

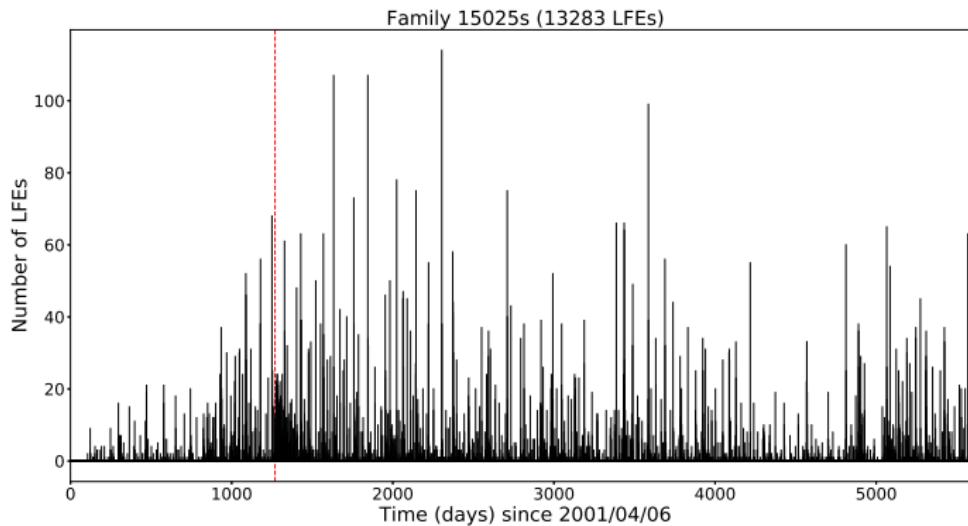
Family 080421.14.048



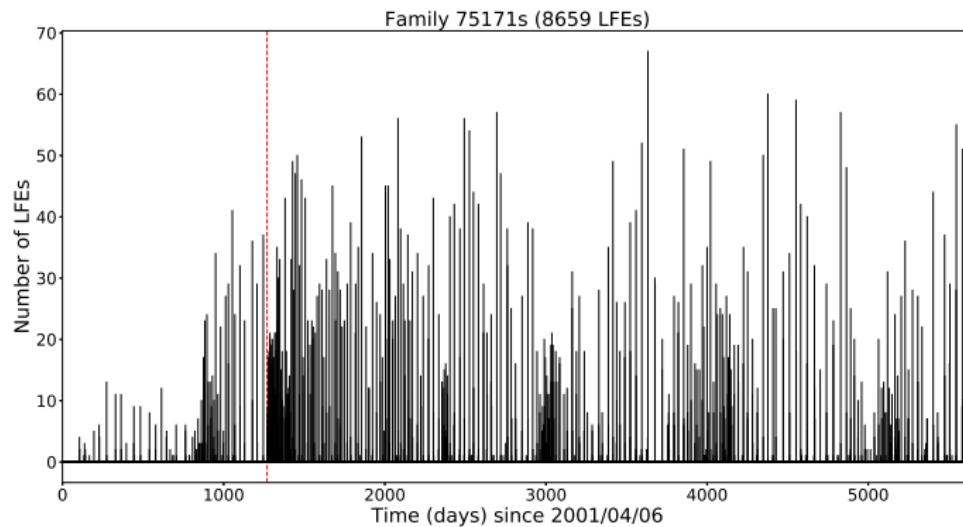
# Future work

- 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

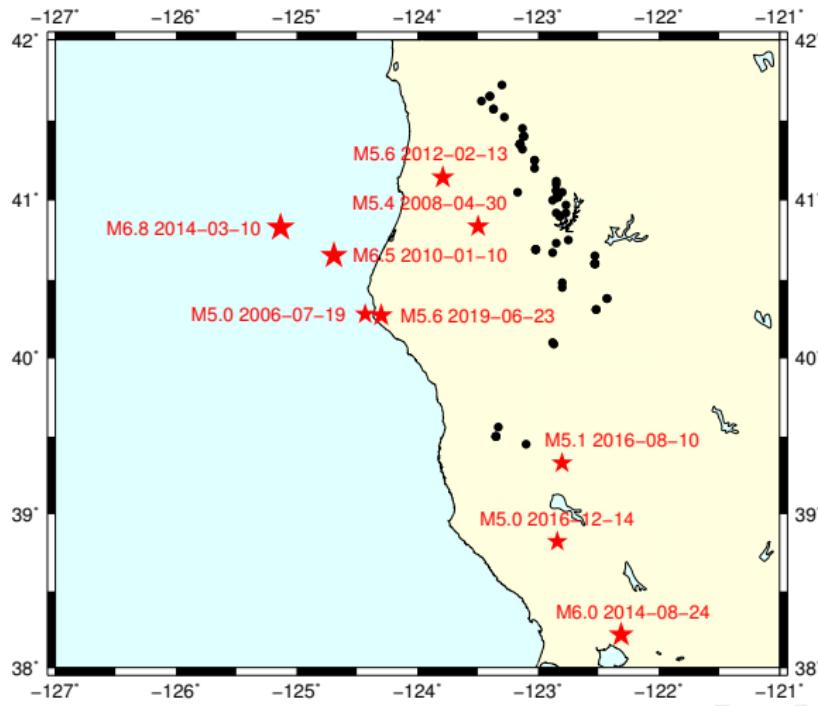
# Effect of the 28 September 2004 M6.0 Parkfield earthquake



# Effect of the 28 September 2004 M6.0 Parkfield earthquake



# Moderate earthquakes in southern Cascadia



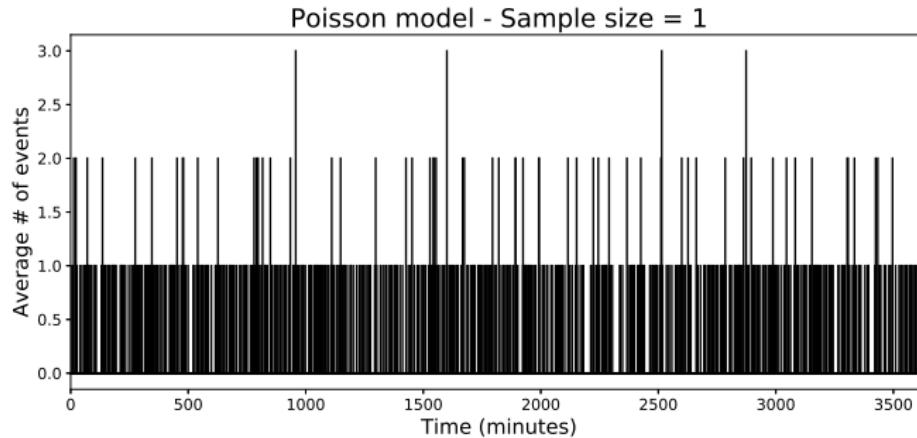
# Future work

- Event rate before the earthquake
- Event rate after the earthquake
- Comparison between two event rates: Computation of likelihood ratio

# 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

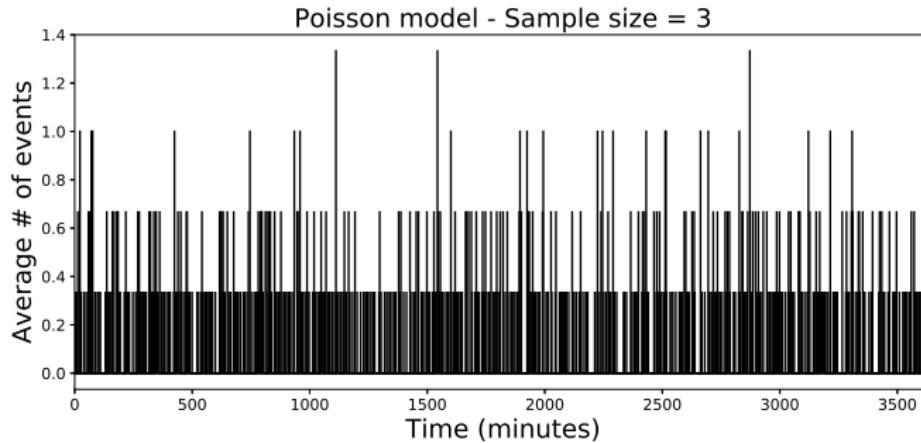
# Homogeneous Poisson process



Number of events recorded during one day

→ Variance over 3645 values = 0.206

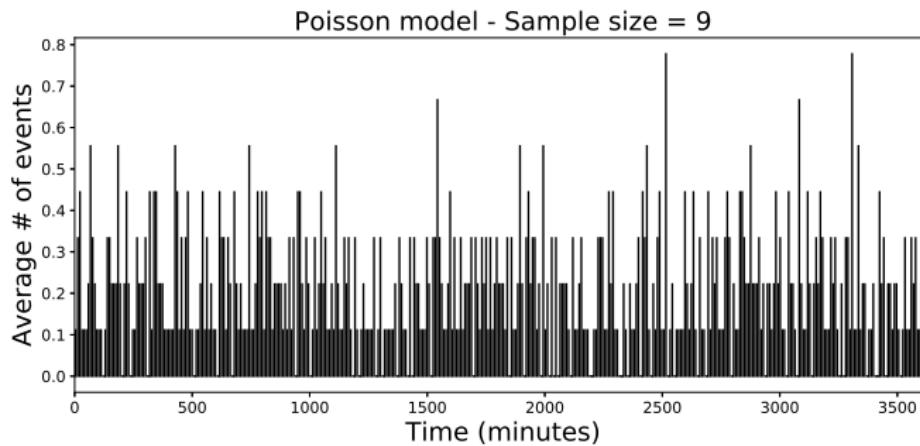
# Homogeneous Poisson process



Number of events recorded during 3 days

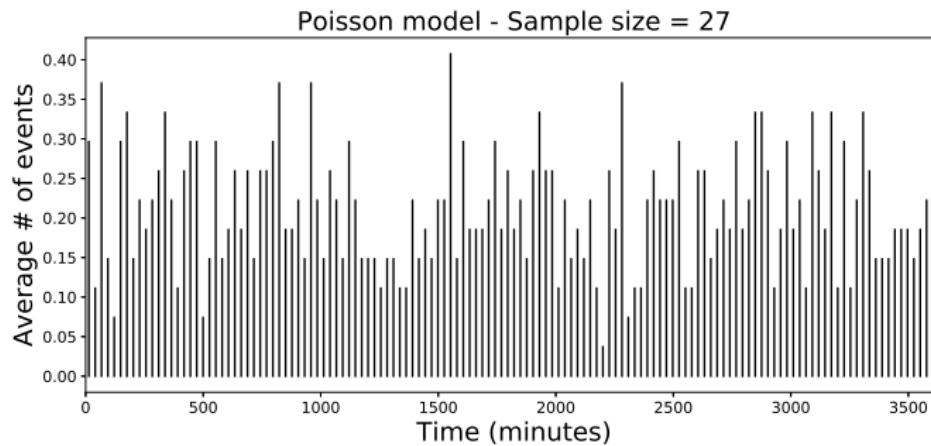
→ Variance over 1215 values =  $6.62 \cdot 10^{-2}$

# Homogeneous Poisson process



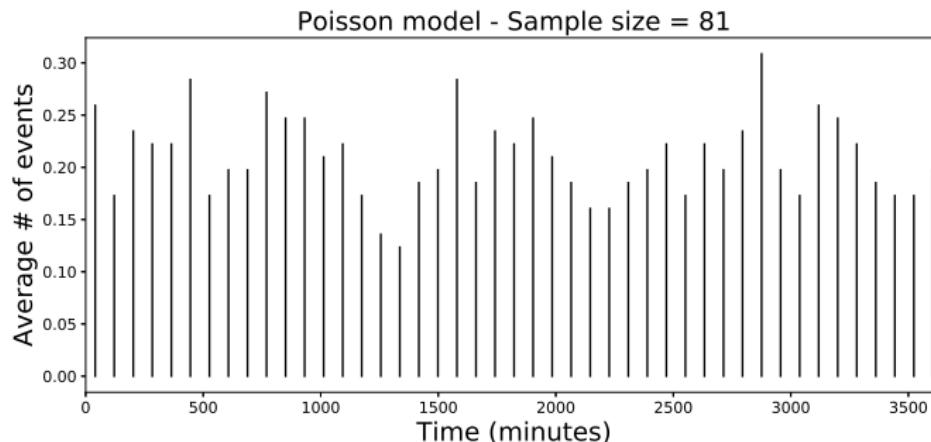
Number of events recorded during 9 days  
 → Variance over 405 values =  $2.14 \cdot 10^{-2}$

# Homogeneous Poisson process



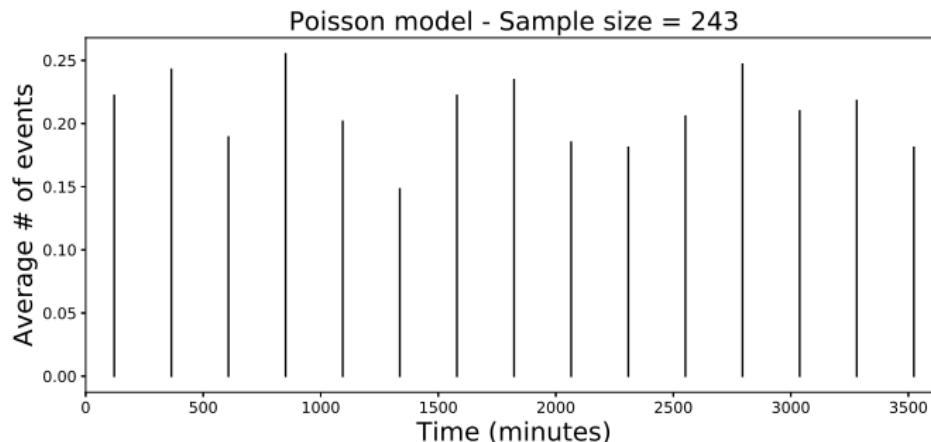
Number of events recorded during 27 days  
 → Variance over 135 values =  $5.56 \cdot 10^{-3}$

# Homogeneous Poisson process



Number of events recorded during 81 days  
→ Variance over 45 values =  $1.54 \cdot 10^{-3}$

# Homogeneous Poisson process



Number of events recorded during 243 days  
 → Variance over 15 values =  $8.05 \cdot 10^{-4}$

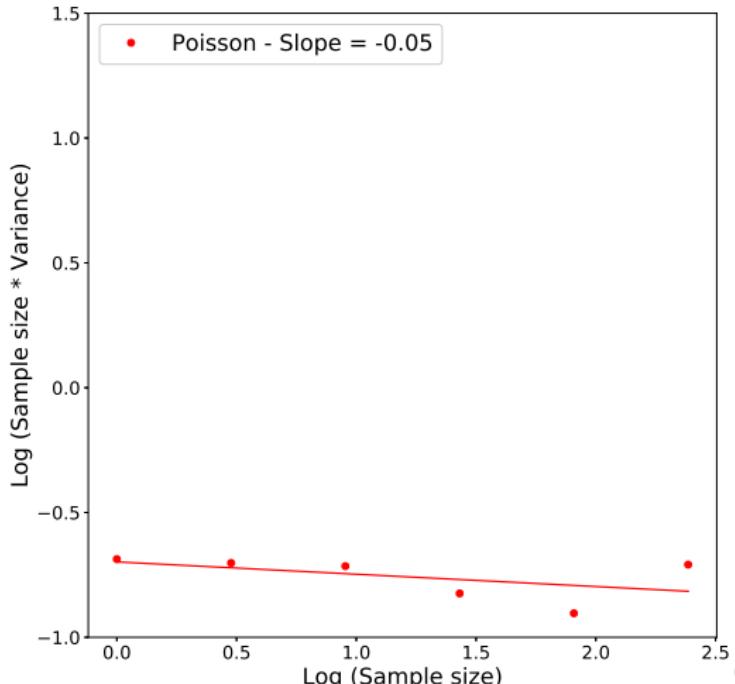
# Variance vs Length of time window

$V = \text{Variance}$

$m = \text{Sample size}$

$V$  behaves as  $m^{2d-1}$

$\rightarrow d = 0$



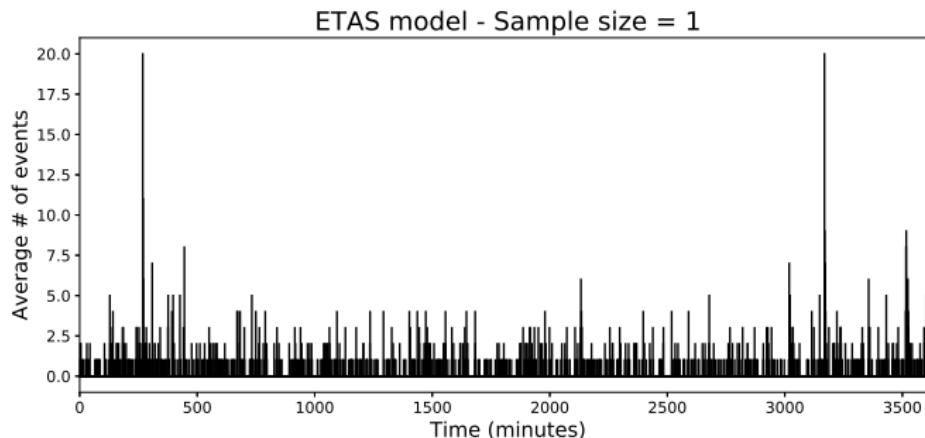
# ETAS model

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

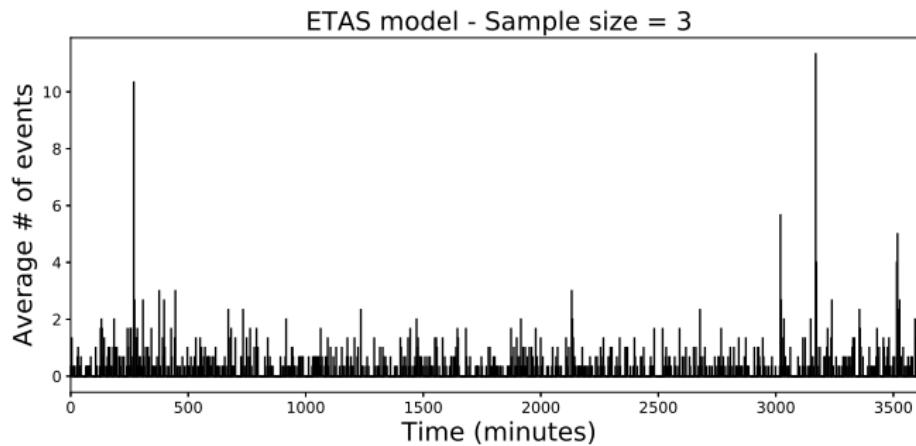
$$\lambda = \mu + A \sum_{t_i < t} e^{\alpha(M_i - M_0)} \left(1 + \frac{t - t_i}{c}\right)^{-\rho} \quad (1)$$

# ETAS model



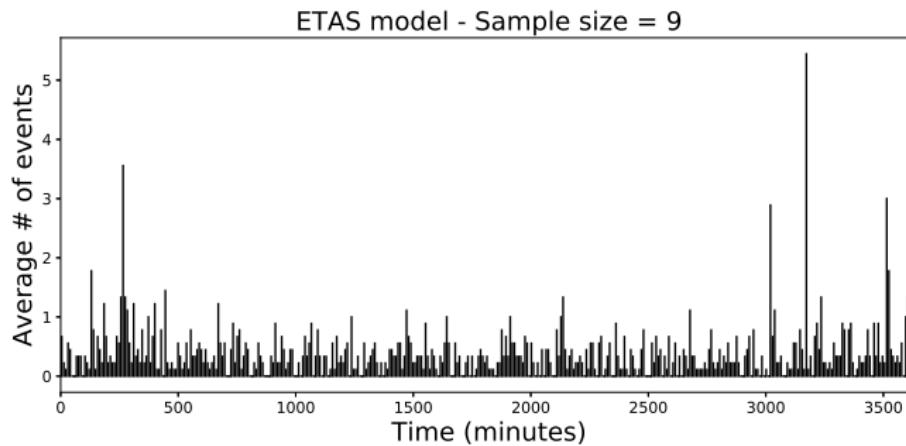
Number of events recorded during one day  
→ Variance over 3645 values = 0.9636

# ETAS model



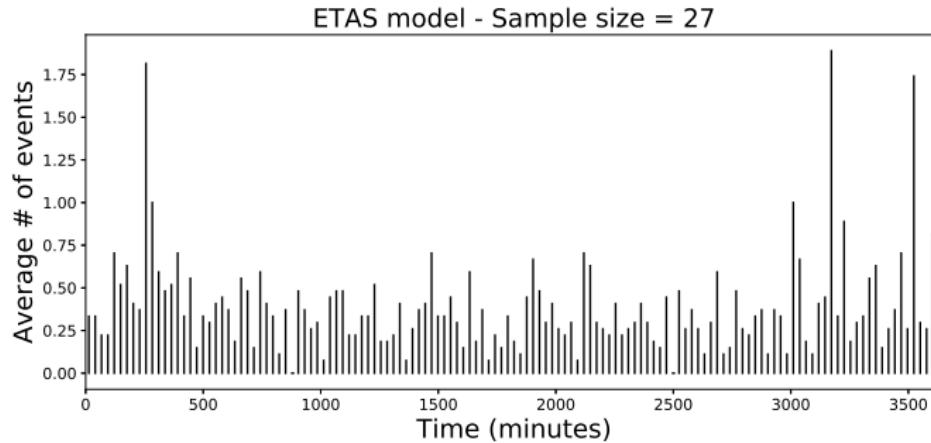
Number of events recorded during 3 days  
→ Variance over 1215 values = 0.494

# ETAS model



Number of events recorded during 9 days  
→ Variance over 405 values = 0.220

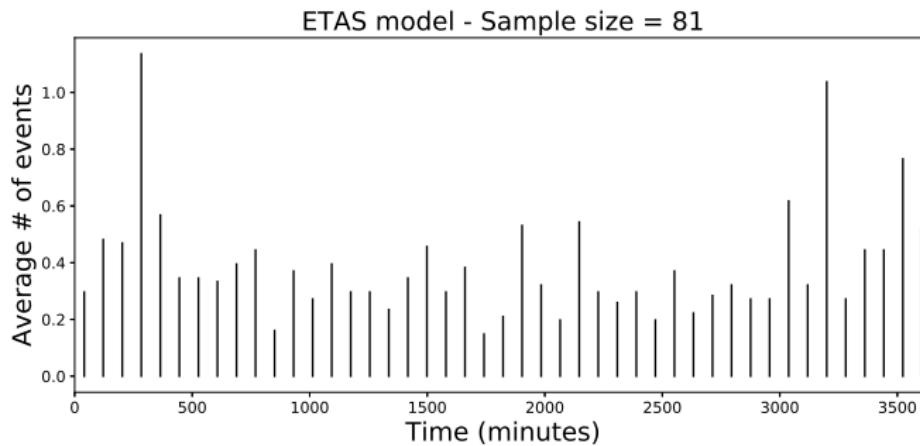
# ETAS model



Number of events recorded during 27 days

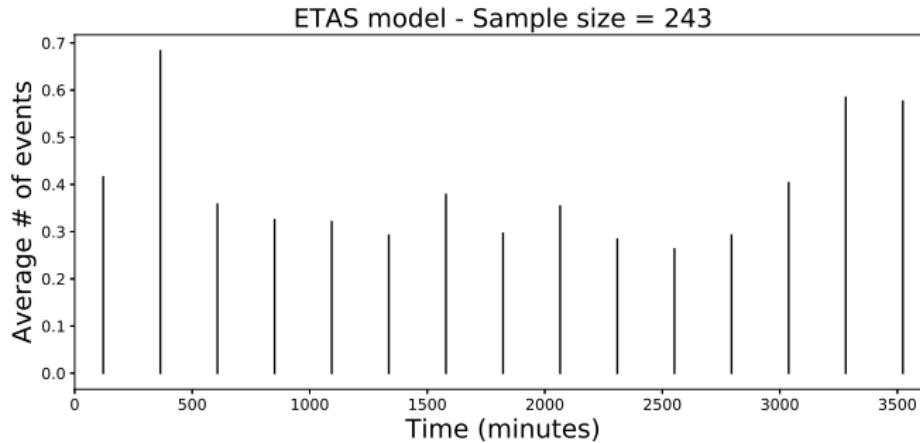
→ Variance over 135 values = 0.0822

# ETAS model



Number of events recorded during 81 days  
→ Variance over 45 values = 0.0381

# ETAS model



Number of events recorded during 243 days

→ Variance over 15 values = 0.0151

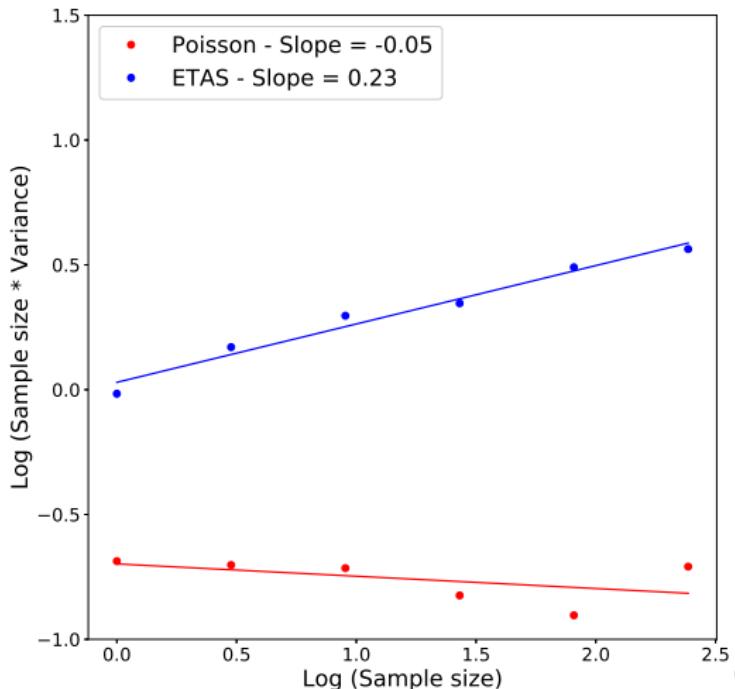
# Variance vs Length of time window

$V = \text{Variance}$

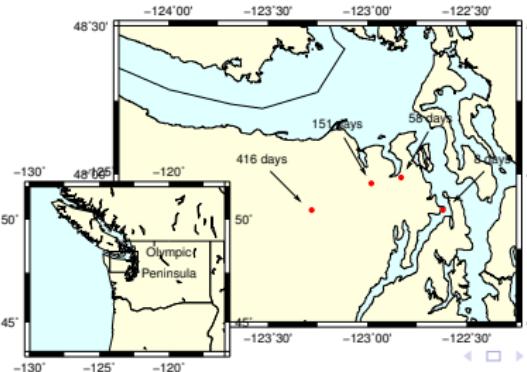
$m = \text{Sample size}$

$V$  behaves as  $m^{2d-1}$

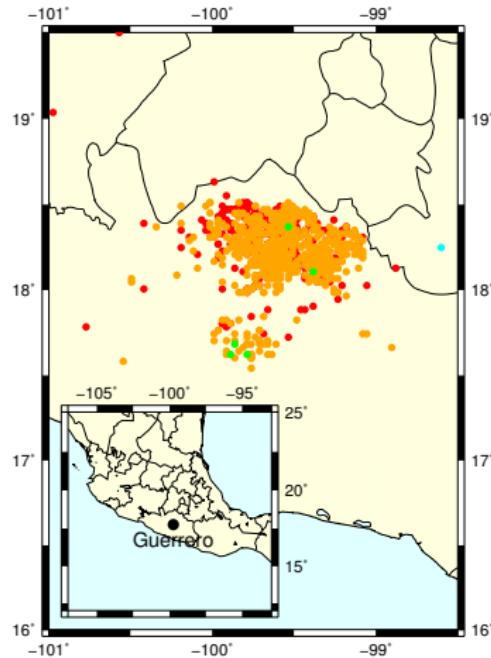
$$\rightarrow d = 0.117$$



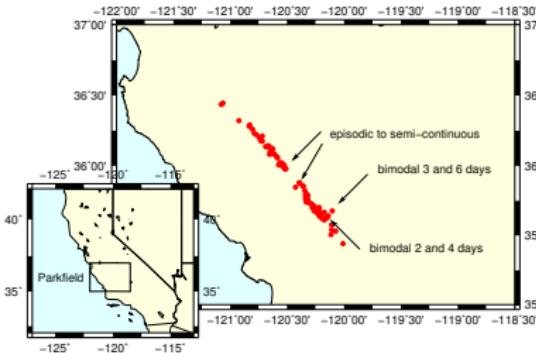
# Northern Cascadia



# Guerrero, Mexico



# San Andreas Fault



# Future work

- Computation of fractional index  $d$  for the southern Cascadia catalog
- Fit ETAS model on existing LFE families

# Detection of slow slip events in New Zealand

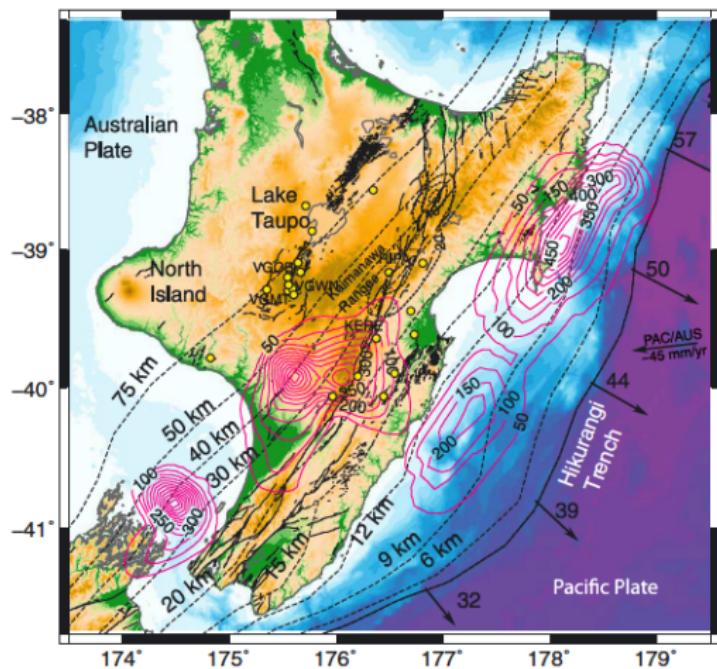
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- 5 Time line

# Tremor as proxy for slow slip

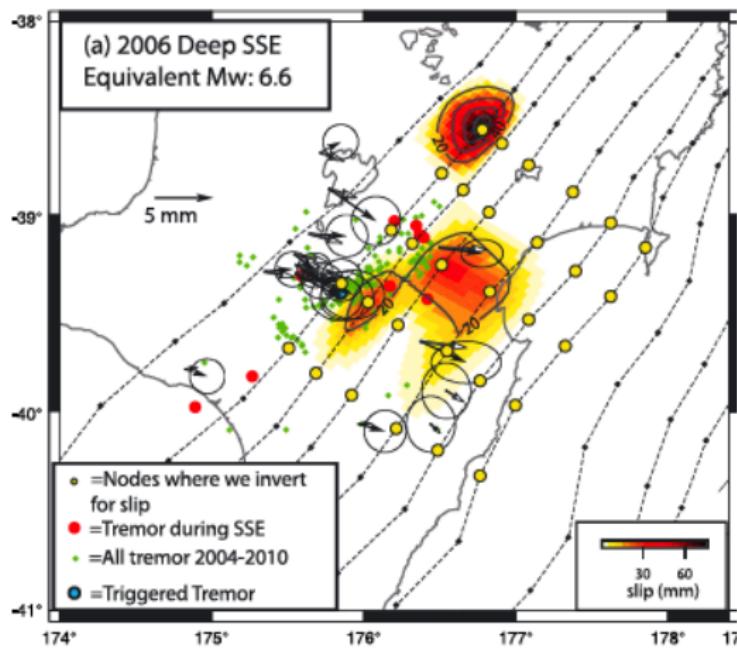
## Episodic Tremor and Slip in Cascadia

- Tremor occurrence rate → Moment of slow slip events not detectable in the GPS data (Aguiar, 2009)
  - Stacking of GPS data when LFEs are detected (Frank, 2016)
- What do we do when tremor is not correlated with slow slip?

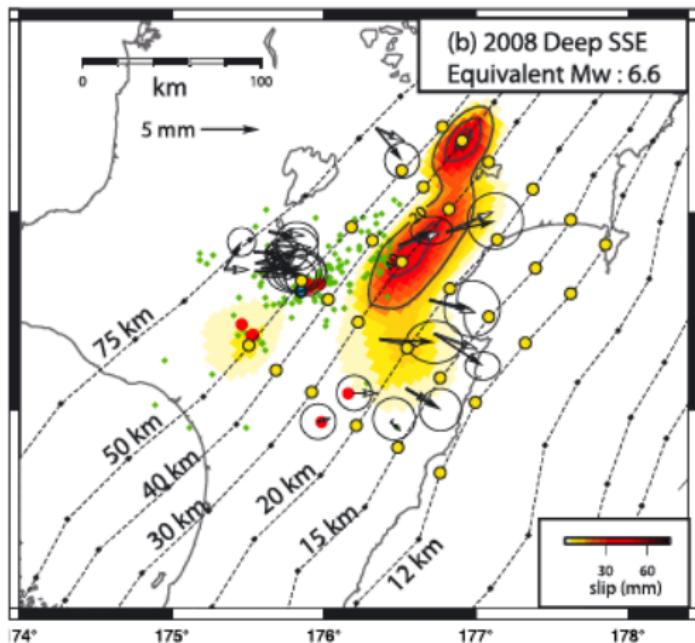
# Northern New Zealand



# Tremor during deep slow slip events



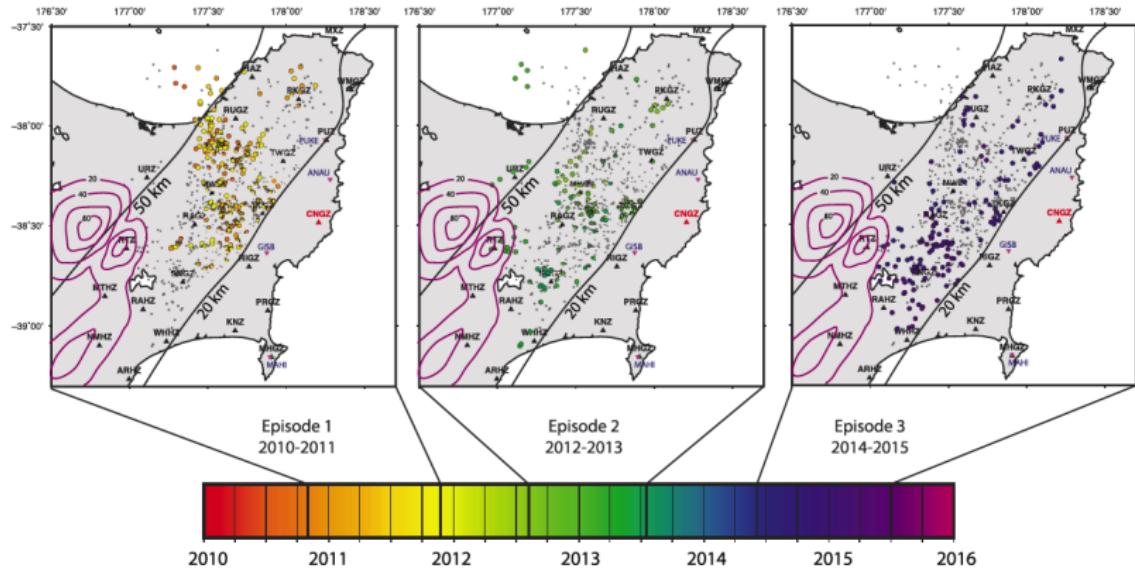
# Tremor during deep slow slip events



## Introduction

Depth of the source of the tectonic tremor  
A low-frequency earthquakes catalog for southern Cascadia  
Detection of slow slip events in New Zealand  
Time line

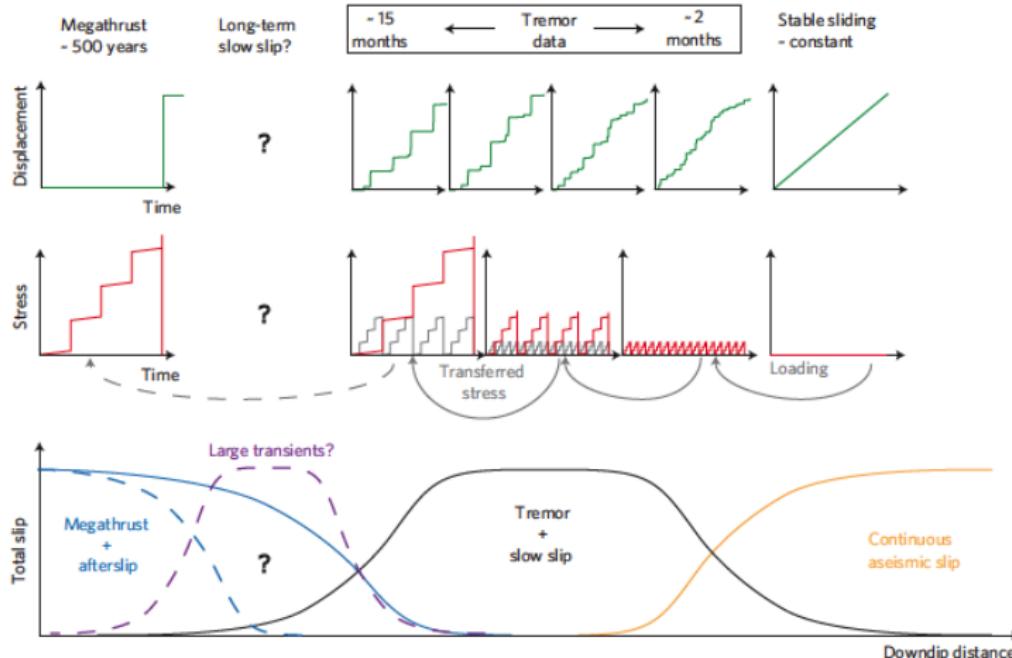
# Tremor with no detected slow slip event



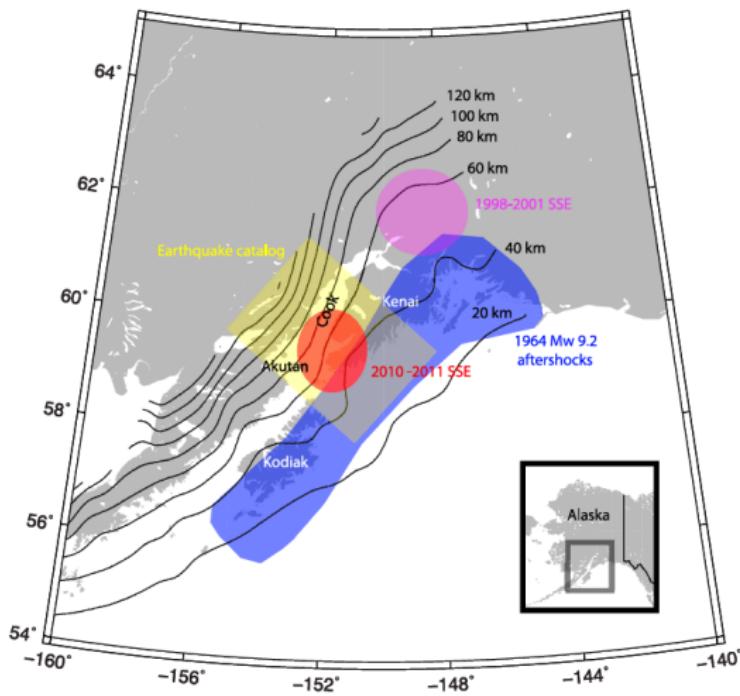
# Possible questions

- 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

# Detecting smaller, currently undetected slow slip events

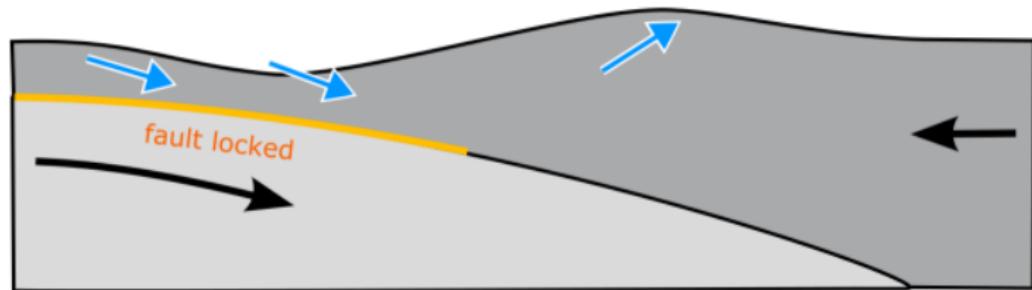


# Detecting longer term slow slip events



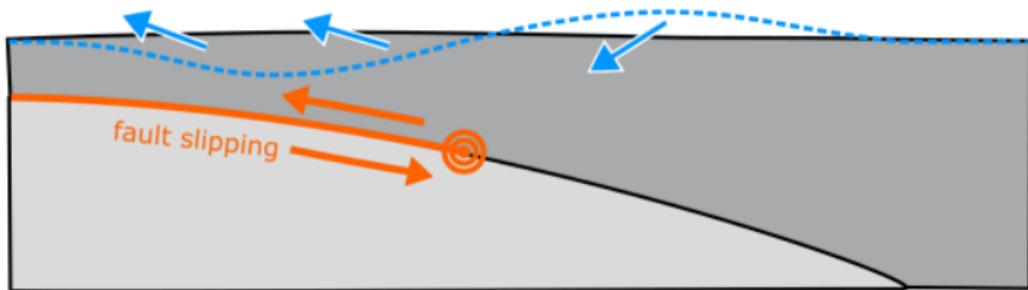
# Better measuring of the vertical displacement at the Earths surface during slow slip events

## LEVEL CHANGES BEFORE EARTHQUAKE

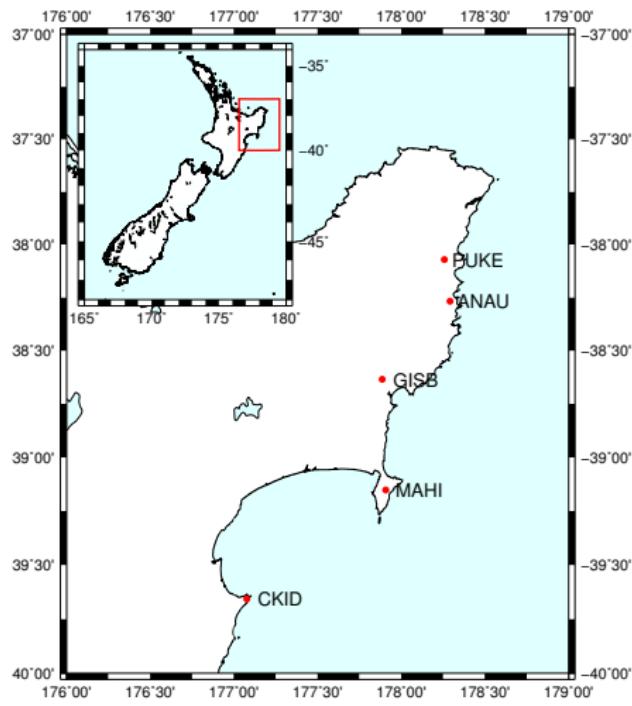


# Better measuring of the vertical displacement at the Earths surface during slow slip events

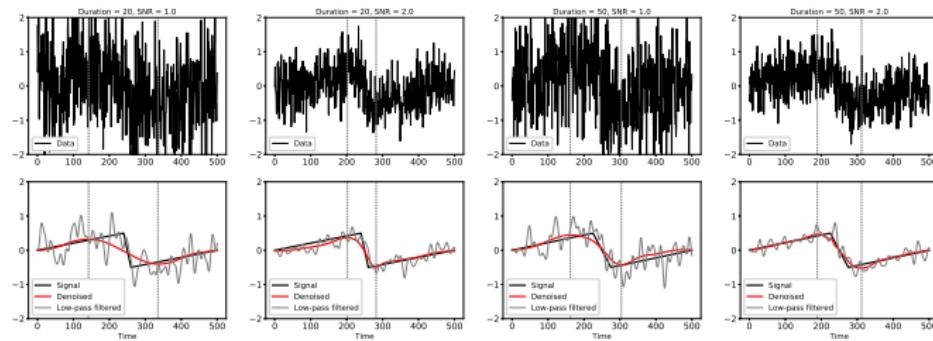
## LEVEL CHANGES DUE TO EARTHQUAKE



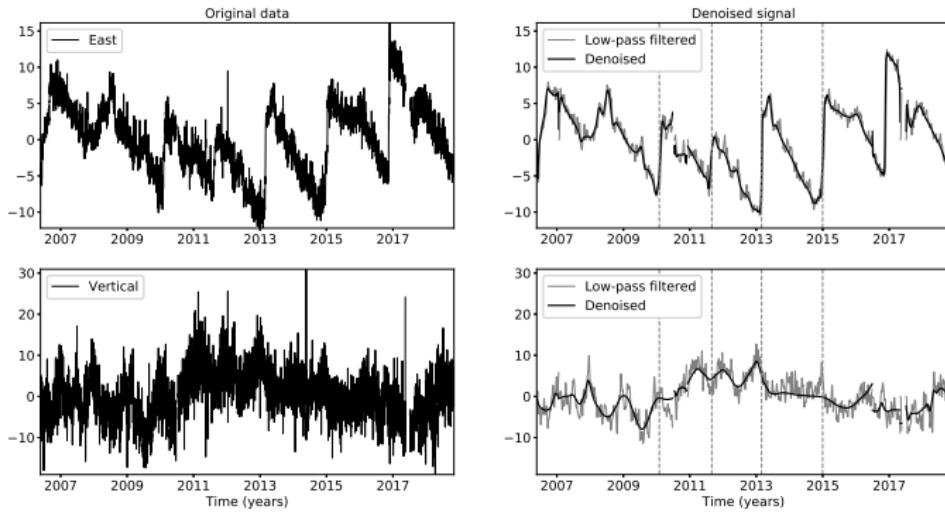
# GPS stations in New Zealand



# Denoising of GPS data



# Denoising of GPS data



# Questions?