Analysis of the 2017 Valparaiso Earthquake Sequence

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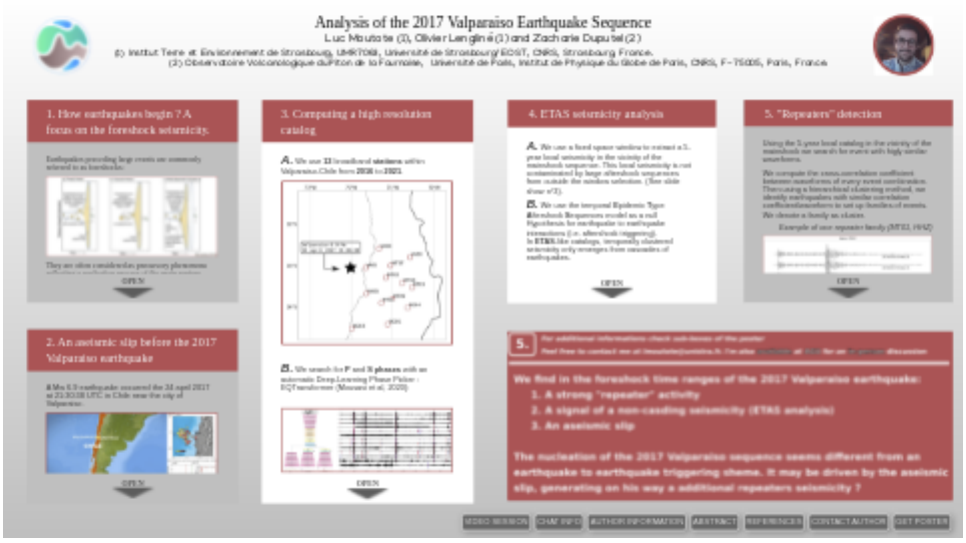
November 23, 2022

Abstract

One of the key questions in fault mechanics is how do earthquakes begin ? This is central to our understanding of earthquakes, including the long controversial issue of their predictability. Earthquakes preceding large events are commonly referred to as foreshocks. They are often considered as precursory phenomena reflecting a nucleation process of the main rupture potentially driven by an underlying slow pre-slip. On the other hand, some studies suggest that foreshock sequences may only be explained by cascades of triggered events. In this work, we choose to test the cascading hypothesis against the foreshock seismicity observed during a previously reported slow slip event preceding the 2017 Mw=6.9 Valparaiso earthquake. We build a very complete 5 years long earthquake catalog of the sequence using refine detection and location algorithms. We test the detected seismicity against the Epidemic Type Aftershock Sequences model. We identify time windows with anomalously high seismic activity compared to what is expected by the typical earthquake interactions. We analyze statistically these anomalies over 5 years to understand if the Mw=6.9 foreshock sequence presents a specific anomalous activity. In addition, using a hierarchical clustering method, we identify earthquakes with similar waveforms to evidence any repeating ruptures. We analyze the time distribution of these clusters over 5 years to understand if unusual rates of repeating events emerge during foreshock time ranges. The conjoint analysis of seismicity rate anomalies and repeating events along with the results of previous pre-slip studies allows to accurately describe the nucleation process and evolution of the 2017 Valparaiso earthquake sequence.

Analysis of the 2017 Valparaiso Earthquake Sequence



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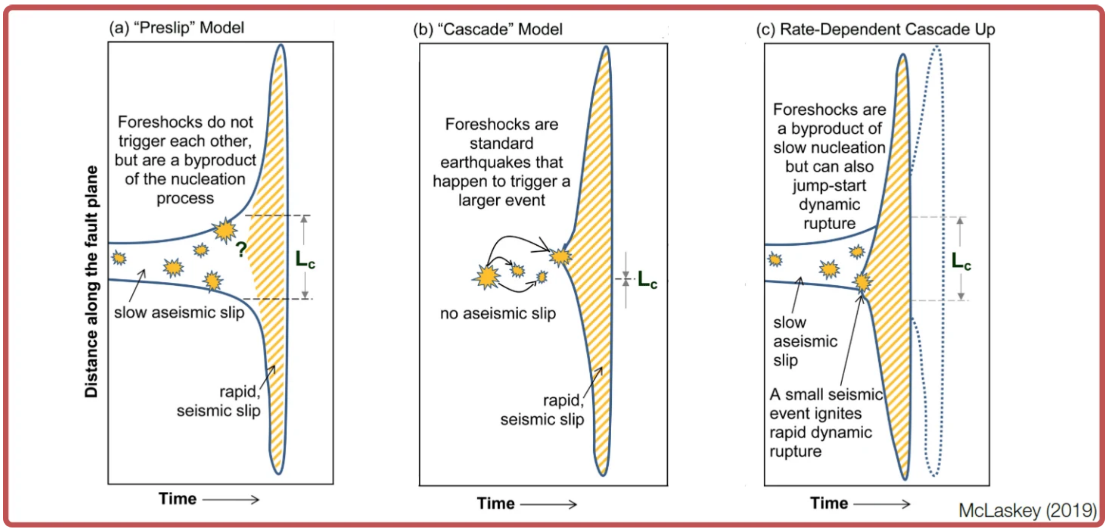
PRESENTED AT:

1. HOW EARTHQUAKES BEGIN ? A FOCUS ON THE FORESHOCK SEISMICITY.

Earthquakes preceding large events are commonly referred to as foreshocks:



They are often considered as precursory phenomena reflecting a nucleation process of the main rupture potentially driven by an underlying slow pre-slip. On the other hand, some studies suggest that foreshock sequences may only be explained by cascades of triggered events. A go-between model is also likely to reflect the ongoing processes, with a seismicty mainly driven by an aseismic slip but enhanced by earthquake to earthquake interactions.

In this work, we test the cascading hypothesis against the foreshock seismicity observed during a previously reported slow slip event preceding the 2017 Mw=6.9 Valparaiso earthquake.

2. AN ASEISMIC SLIP BEFORE THE 2017 VALPARAISO EARTHQUAKE

A Mw 6.9 earthquake occurred the 24 april 2017 at 21:30:38 UTC in Chile near the city of Valparaiso.

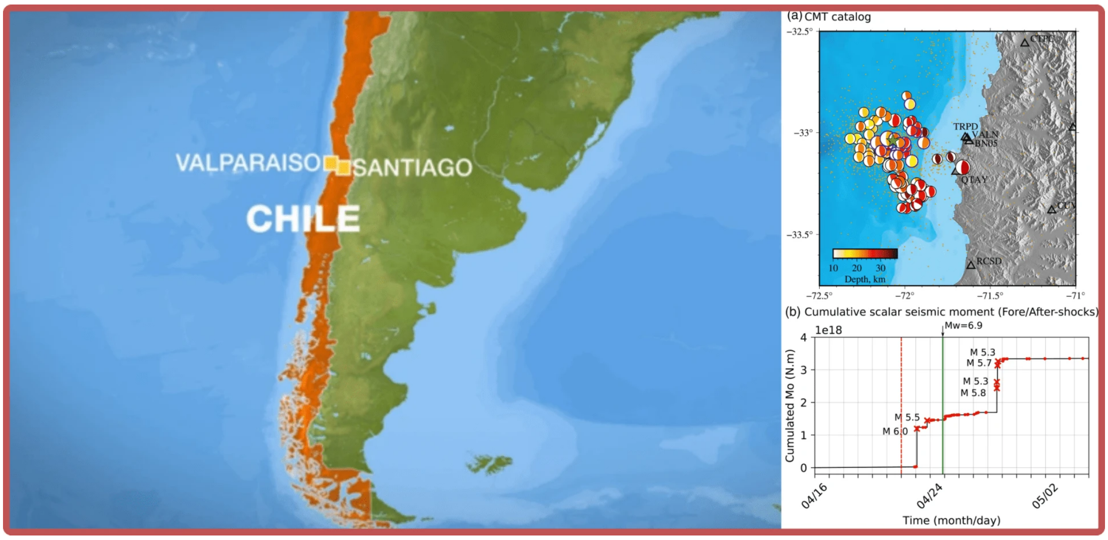


Fig. from (Caballero et al, 2021)

This mainshock take part in a intense sequence of earthquakes. It was preceded by a 2-days long seismic activity, with foreshocks up to Mw 6.0.

Previous studies (Ruiz et al, 2015; Caballero et al,2021) have reported an aseismic slip from GPS data, up to 3 days before the mainshock starting before the foreshock seismic activities.

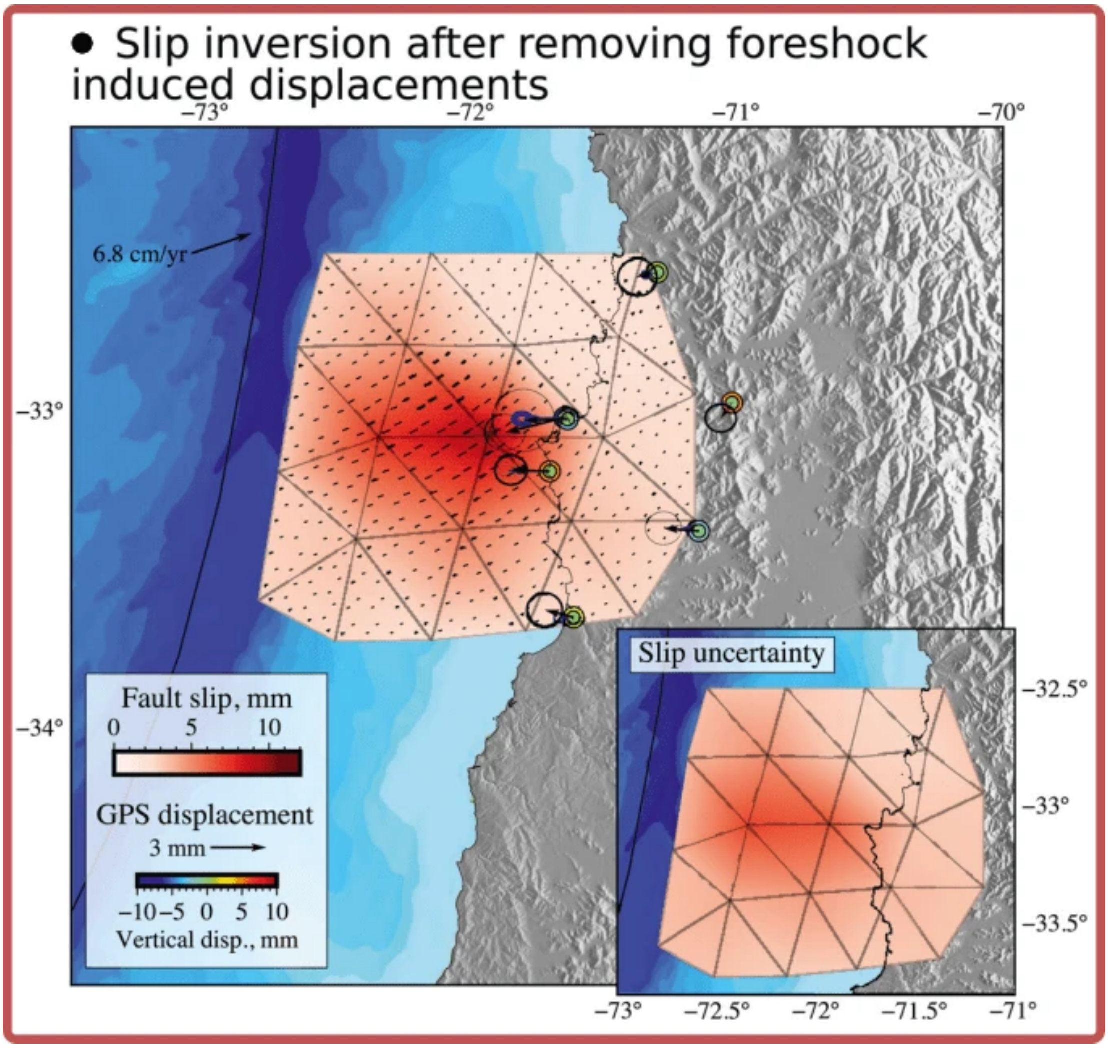


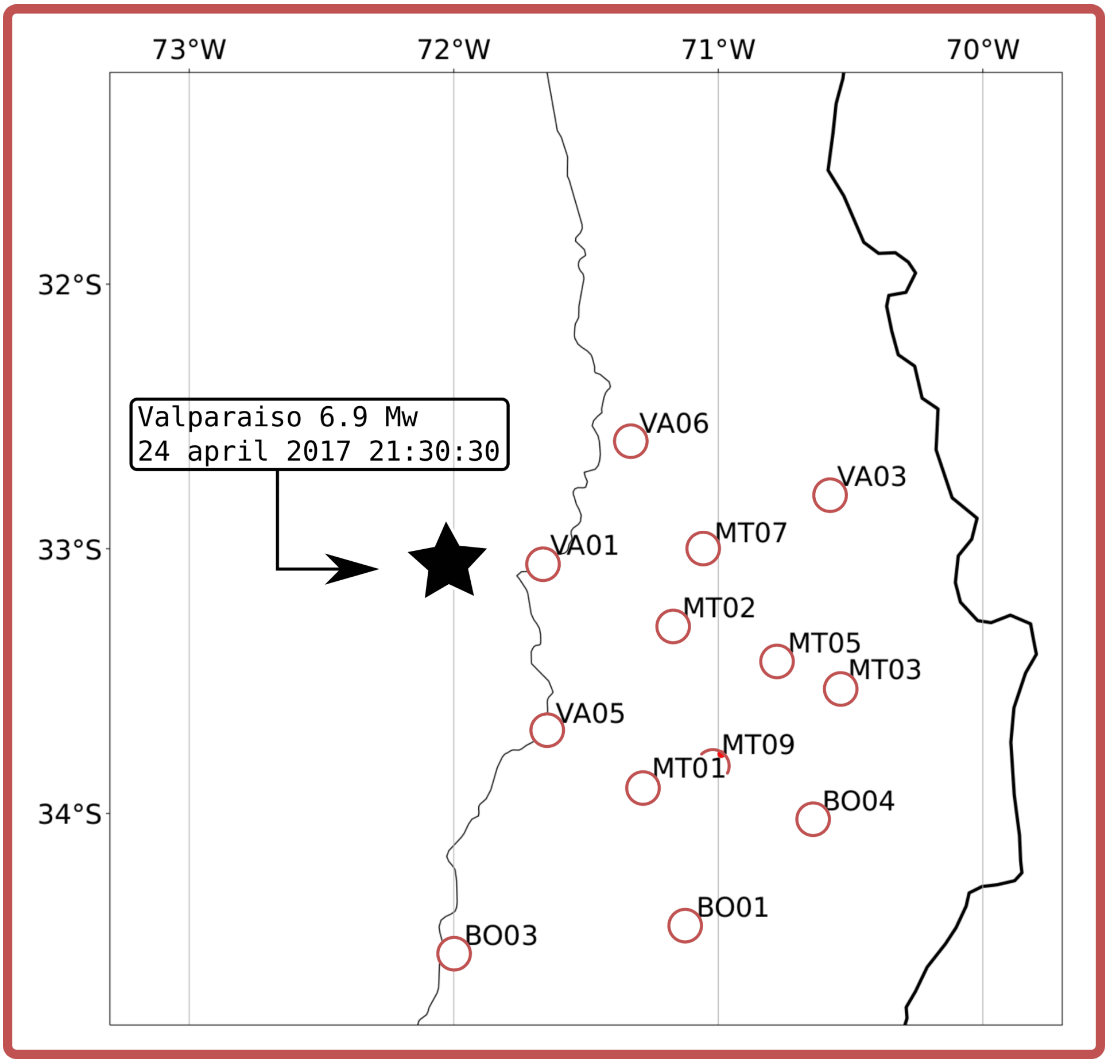
Fig. from (Caballero et al, 2021)

We believe that a fine analysis of the foreshock seismcity may carry usefull informations on processes ongoing during the Vaparaiso earthquake sequence. We test if the foreshock seismicty is consistent with a simple model of cascading earthquakes or if there is additional seismic activities that can be attributed to the aseismic slip.

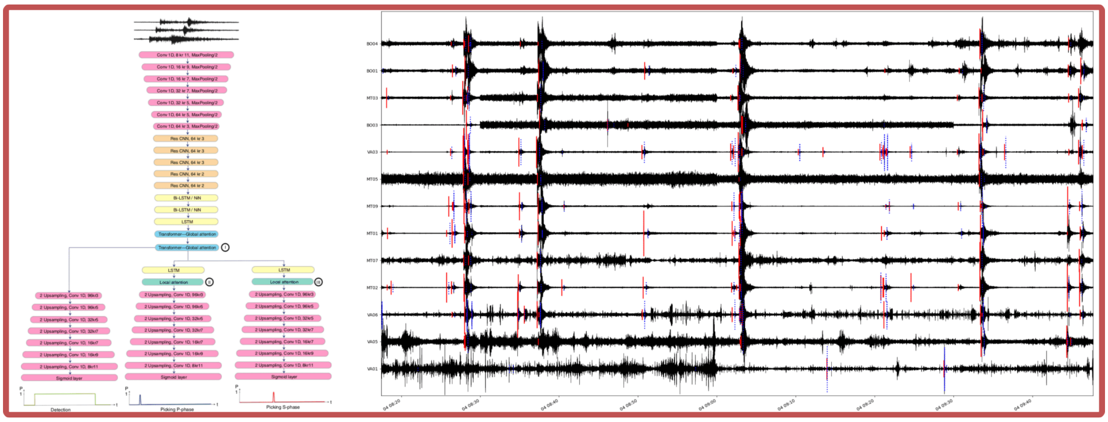
1. For that we build a very complete 5 years long earthquake catalog of the region using refine detection and location algorithms.
2. We test the detected seismicity against the Epidemic Type Aftershock Sequences model as a null hypothesis for earthquake to earthquake interactions and detect anomalously high seismicty rates.
3. We also search for events with similar waveforms by cross-correlation to indentify families of repeating rupture.

3. COMPUTING A HIGH RESOLUTION CATALOG

A. We use **13** broadband **stations** within Valparaiso-Chile from **2016** to **2021**.



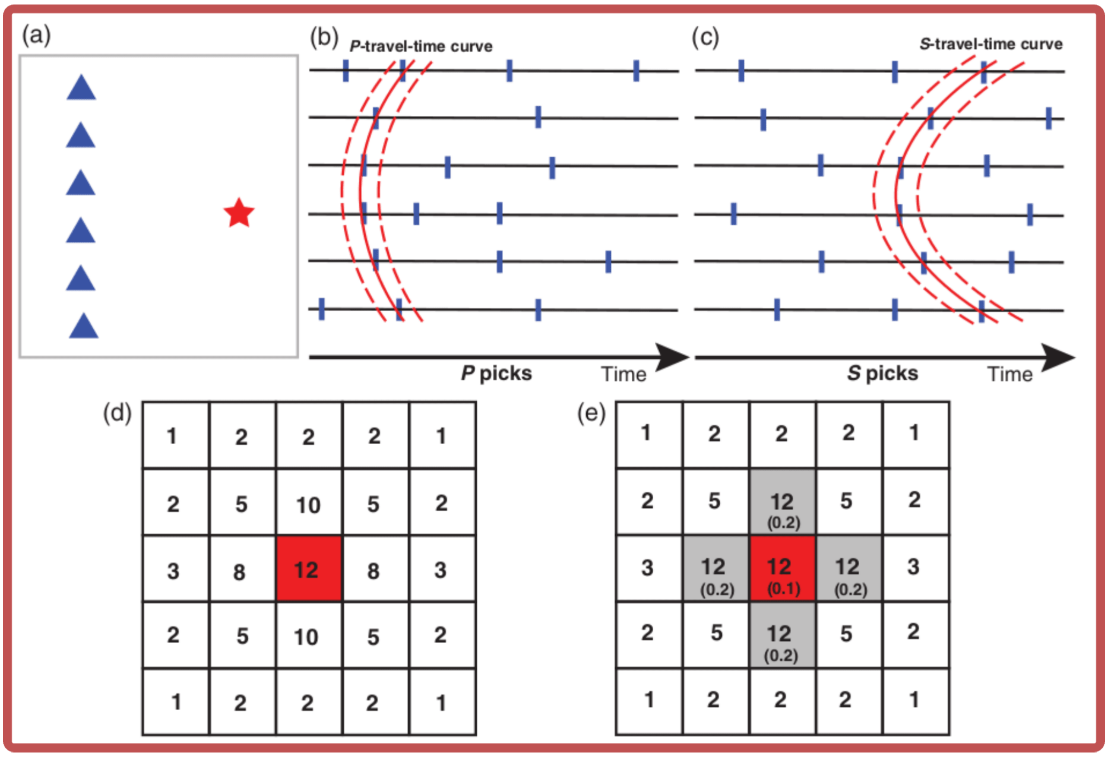
B. We search for **P** and **S phases** with an automatic Deep-Learning Phase Picker : EQTransformer (Mousavi et al, 2020):



C. We associate P and S phases observed over stations with **REAL** (*Zhang et al, 2019)*:

- 3D grid-search with **TauP** travel times

- 1 event = At least 3 station with P + S pick



D. We locate the hypocenter of every event using NonLinLoc (*Lomax et al, 2000*)

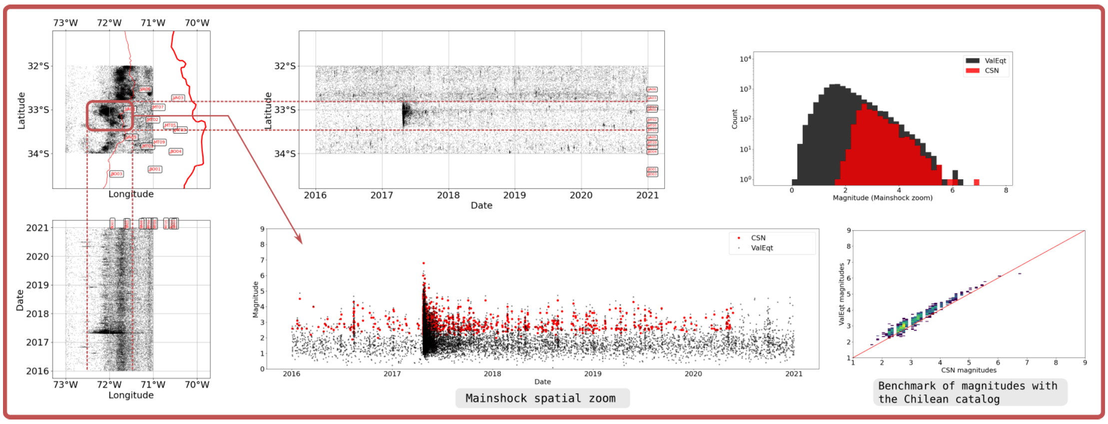
- Using a 3D velocity model (*B. Potin, personal communication*)

- Posterior Probability Density Fonction of hypocenter

E. Local Magnitude estimation with Richter approach on a Wood Anderson instrumental response.

We focus on the seismicity within the region of the 2017 Valparaiso sequence. We extract a local and 'isolated' catalog of the mainshock region over 5-year.

The ValEqt catalog



- We indentify more than 7000 earthquakes in the vicinity of the mainshock over 5 years

- This local catalog is complete for magnitude above 1.9
- Magnitude estimation are consistant with the official chilean catalog (CSN). (Only the mainshock magnitude was understimated by the local magnitude, we manually define it's value to 6.9 (from the CSN value))

4. ETAS SEISMICITY ANALYSIS

A. We use a fixed space window to extract a 5-year local seismicity in the vicinity of the mainshock sequence. This local seismicity is not contaminated by large aftershock sequences from outside the window selection. (See slide show n°3).

B. We use the temporal **E**pidemic **T**ype **A**ftershock **S**equences model as a null Hypothesis for earthquake to earthquake interactions (i.e. aftershock triggering).
In **ETAS**-like catalogs, temporally clustered seismicity only emerges from cascades of earthquakes.

C. After removing events below the magnitude of completness, we extract ETAS parameters over the 5-year seismicity with an Expectation-Maximization algorithm.
It depicts the average number of aftershocks that an earthquake can trigger, depending on its magnitude.

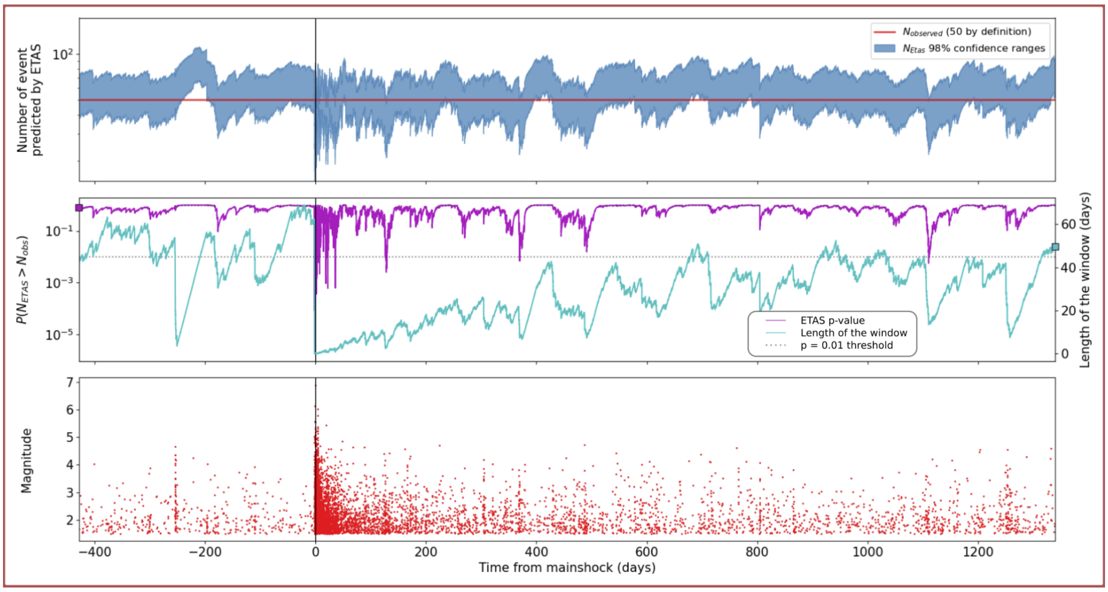
With ETAS estimates and for any short time window within the catalog:

1. We can compute the number of event expected by the ETAS model. The ETAS expected number of event is Poisson distributed. (*see Moutote et al, 2021*)
2. We compare this distribution with the actual number of event observed within the window.
3. We can extract a p-value that the observed number of event is consistent with the expected ETAS seismicty.
4. A window with a low p-value (<0.01) reflects a number of event unexplain by ETAS earthquake to earthquake interactions.

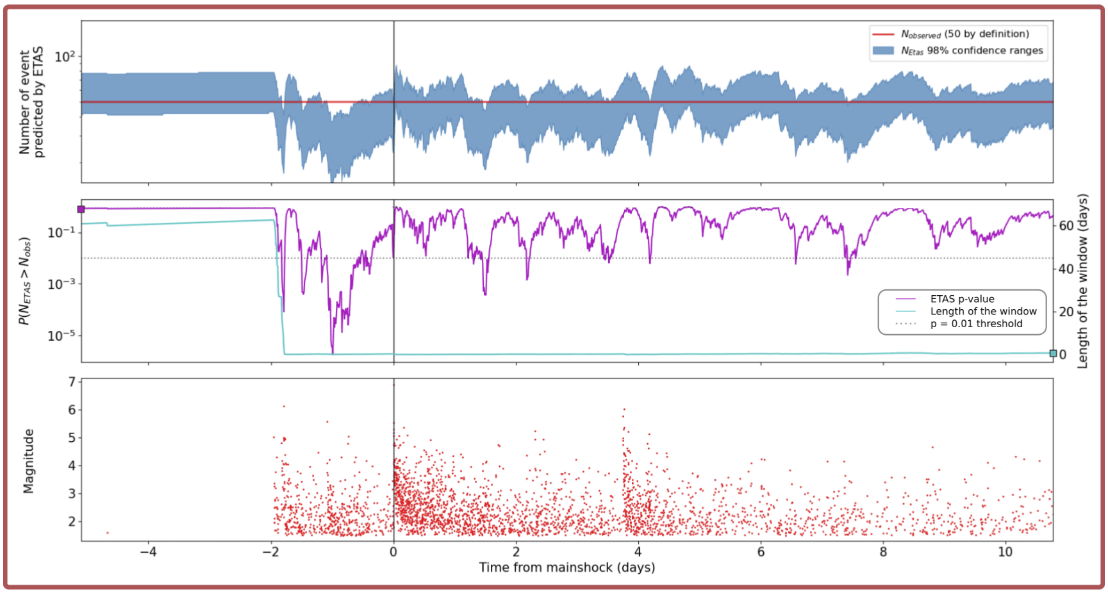
D. We use a slinding window over the full length of the catalog to detect any ETAS anomalies over 5 years.

The length of the window is adapted along the slinding steps to cover the last 50 observed event. Unlike a fixed length, it allow to properly sample the Poisson distribution when the seismicity is very low.

Full catalog lentgh



Zoom around the mainshock



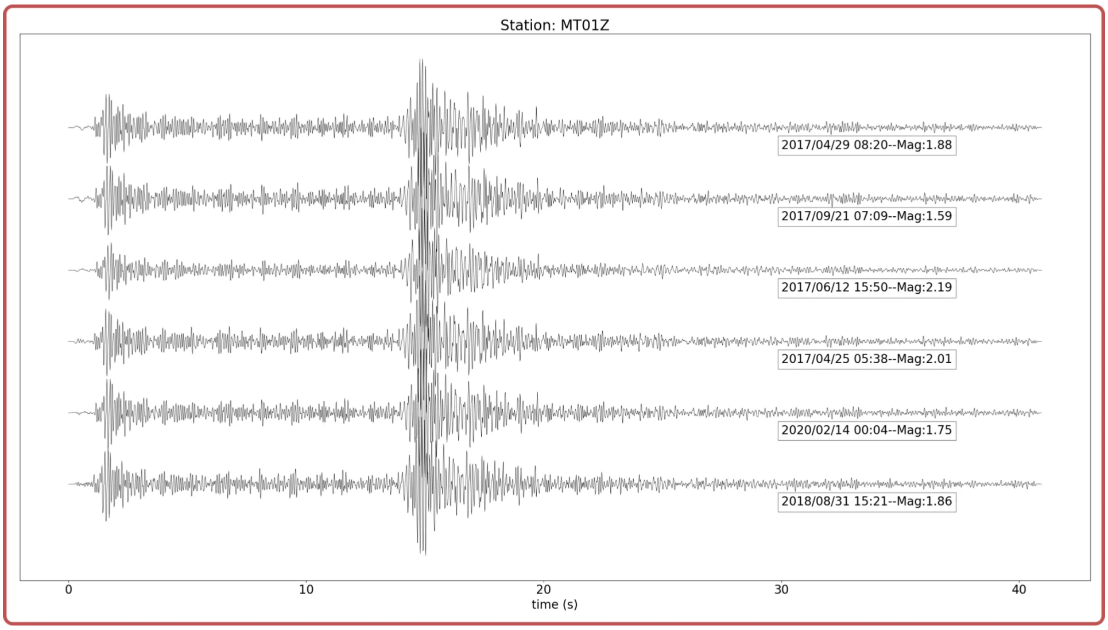
1. The strongest ETAS anomalies are located in the foreshock sequence, 1 day before the mainshock.
2. The rest of the catalog is more consistent with ETAS, even after large magnitude earthquakes (e.g., after the Mw=6.9 mainshock)

5. "REPEATERS" DETECTION

Using the 5-year local catalog in the vicinity of the mainshock we search for event with higly similar waveforms.

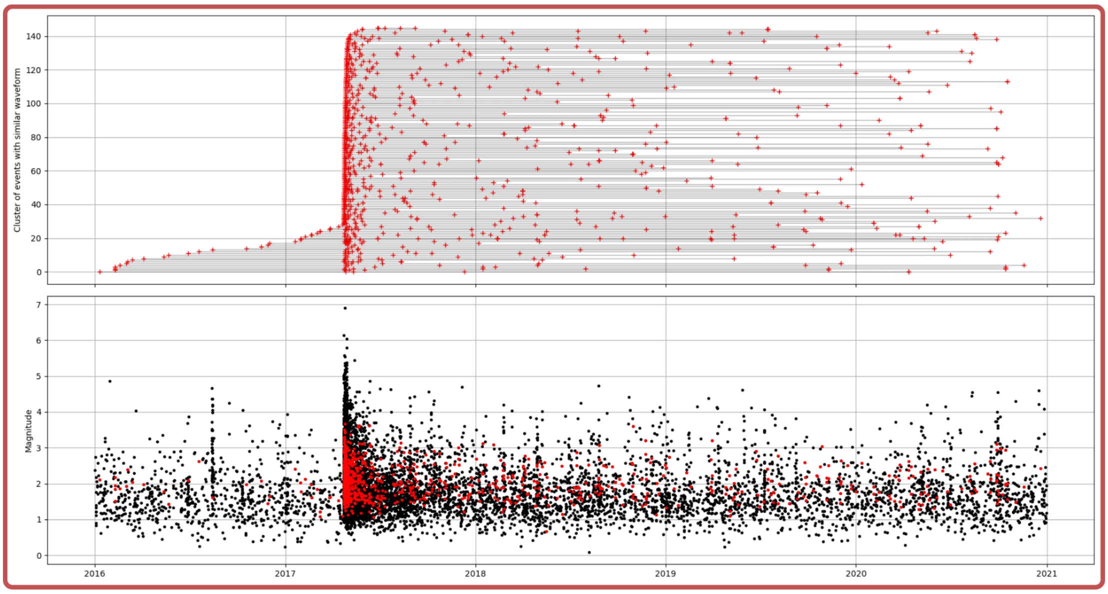
We compute the cross-correlation coefficient between waveforms of every event combination. Then using a hierarchical clustering method, we identify earthquakes with similar correlation coefficient/waveform to set up families of events. We denote a family as cluster.

Example of one repeater family (MT01, HHZ)

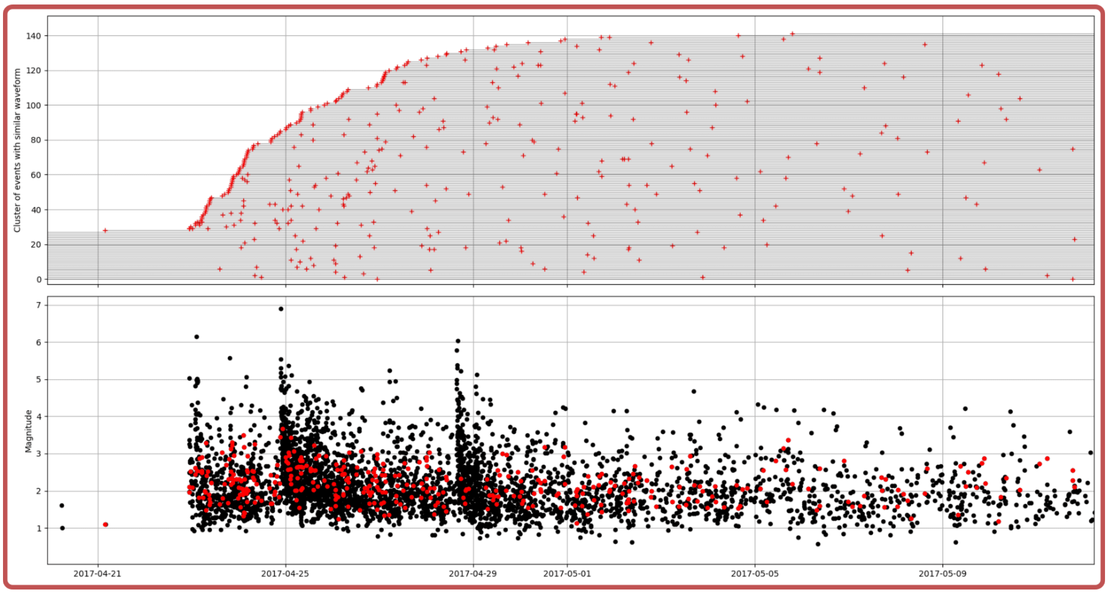


We isolate ~150 cluster of events with a median correlation coefficent above 0.8 and with at least 5 events. :

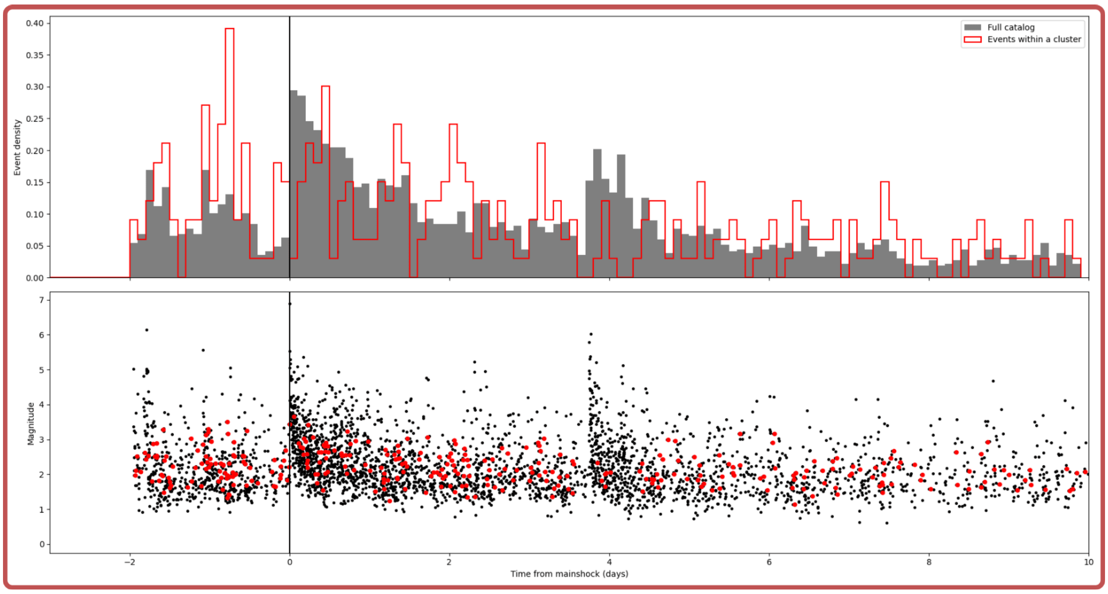
Similar Waveforms cluster sort by first event:



Mainshock Zoom



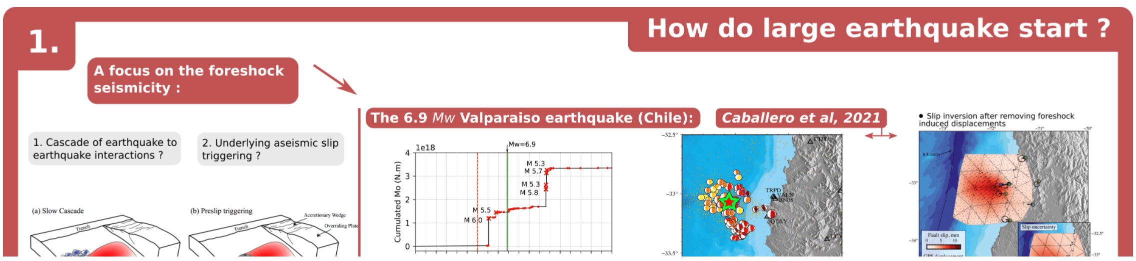
Cluster Event density during the 2017 sequence

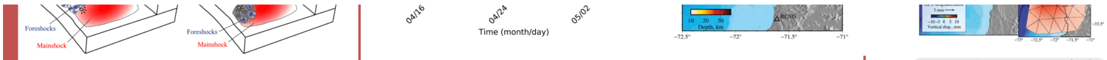


[Event density = counts_in_bin / (sum_all_counts) * bins_width) i.e. like a probability density , integrate to 1]

We find that:

- The rate of repeater does not correlate with the occurrence of large magnitude events. (See just after mainshock and 4 days after the mainshock)
- The higest rate occur within the foreshock sequence, 1 day before the mainshock.
- A lot of repeating ruptures are triggered during the foreshock time ranges.
- This strong repeater activity is correlated with a strong non-ETAS activity (see section 4.)
- Therefor, repeater activity may be related to the aseismic slip detected by Ruiz et al, 2017; and Caballero et al, 2021.



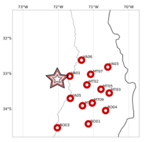


→ A **intense foreshock activity** before the Mw 6.9 Earthquake + A prevously reported **aseismic slip (Ruiz et al, 2017; Caballero et al, 2021)**

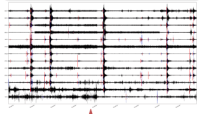
Is there any seismicity anomalies within the aseismic slip of the 2017 Valparaiso earthquake ?

2. Computing a high resolution catalog of Valparaiso

A **13 broadband stations** within Valparaiso-Chile from **2016** to **2021**

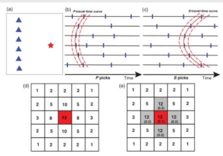


B **EQTransformer** phases picker: Automatic P and S Phase picking



A Neural Network trained over a Worldwide database

C Association of phases : **REAL**
Space Grid-Search with Taup Travel-Times



1 event = Associated P ans S phases

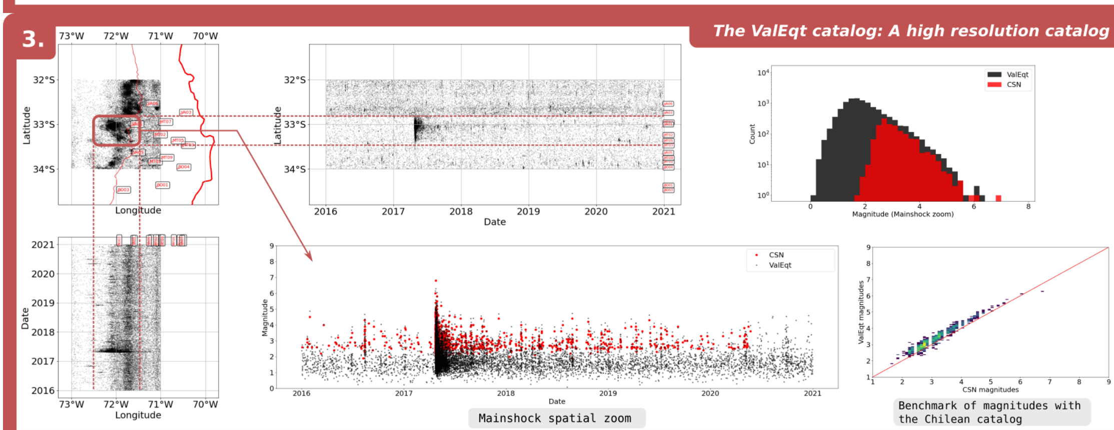
3D velocity model (B. Potin)

D **NLLoc performs earthquake locations in 3D models using non-linear search techniques.**

E **Local magnitude (ML) estimation over Wood-Anderson seismometer**

The ValEqt catalog

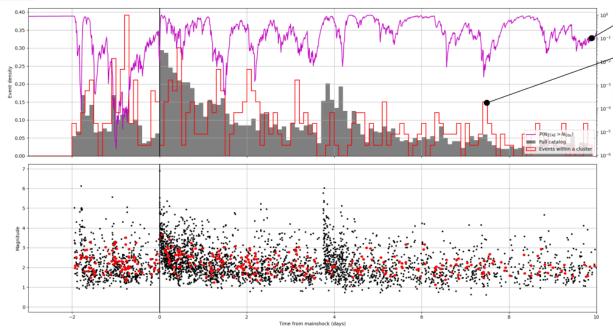
3. *The ValEqt catalog: A high resolution catalog*



Mainshock spatial zoom

Benchmark of magnitudes with the Chilean catalog

4. Seismicity analysis of the 2017 sequence



ETAS anomaly (The p-value scale the ability of the ETAS model to explain the last 50 event, ***see section 4***.)

Events listed as repeaters (Families of events with similar waveforms, ***see section 5.***)

1. The seismicity within the foreshock sequence is strongly unexplained by the ETAS model. (Null hypothesis for the nucleation cascade model).

2. The foreshock sequence contains the higest rate of repeaters events.

3. An aseismic slip was detected within the foreshock sequence

5.

For additional informations check sub-boxes of the poster

Feel free to contact me at lmoutote@unistra.fr. I'm also available at AGU for an in-person discussion

We find in the foreshock time ranges of the 2017 Valparaiso earthquake:

1. **A strong "repeater" activity**
2. **A signal of a non-casding seismicity (ETAS analysis)**
3. **An aseismic slip**

The nucleation of the 2017 Valparaiso sequence seems different from an earthquake to earthquake triggering sheme. It may be driven by the aseismic slip, generating on his way a additional repeaters seismicity ?

AUTHOR INFORMATION

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See me at AGU during in-person poster session ! (Seismology, Technophysics, Minerals and rocks physics for example)

I'll bring my computer in-person somewhere in the poster hall to present my work ;)

ABSTRACT

One of the key questions in fault mechanics is how do earthquakes begin ? This is central to our understanding of earthquakes, including the long controversial issue of their predictability. Earthquakes preceding large events are commonly referred to as foreshocks. They are often considered as precursory phenomena reflecting a nucleation process of the main rupture potentially driven by an underlying slow pre-slip. On the other hand, some studies suggest that foreshock sequences may only be explained by cascades of triggered events. In this work, we choose to test the cascading hypothesis against the foreshock seismicity observed during a previously reported slow slip event preceding the 2017 Mw=6.9 Valparaiso earthquake. We build a very complete 5 years long earthquake catalog of the sequence using refine detection and location algorithms. We test the detected seismicity against the Epidemic Type Aftershock Sequences model. We identify time windows with anomalously high seismic activity compared to what is expected by the typical earthquake interactions. We analyze statistically these anomalies over 5 years to understand if the Mw=6.9 foreshock sequence presents a specific anomalous activity. In addition, using a hierarchical clustering method, we identify earthquakes with similar waveforms to evidence any repeating ruptures. We analyze the time distribution of these clusters over 5 years to understand if unusual rates of repeating events emerge during foreshock time ranges. The conjoint analysis of seismicity rate anomalies and repeating events along with the results of previous pre-slip studies allows to accurately describe the nucleation process and evolution of the 2017 Valparaiso earthquake sequence.

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