Tools for monitoring the spatio-temporal evolution of seismic sequences: An application to the Azores triple junction

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Seismic activity in Azores and São Miguel island

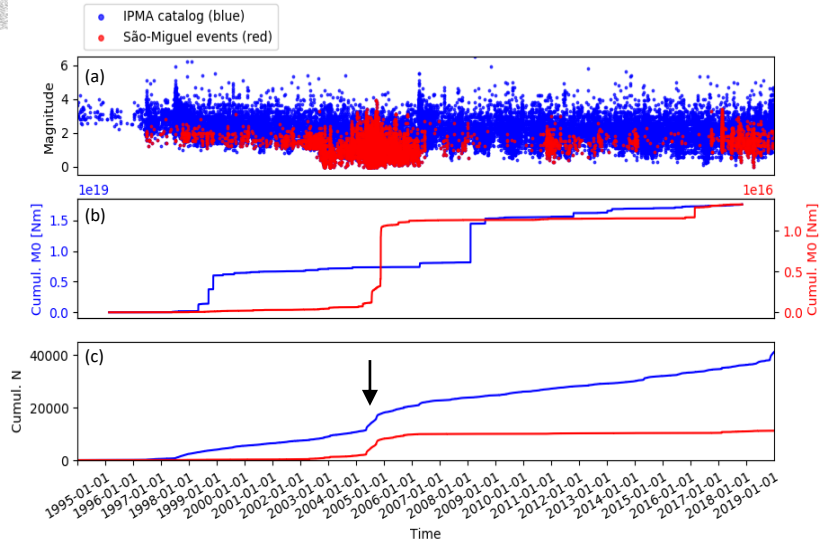
São Miguel plays a significant role in the seismic activity of the Azores region.

The seismicity that occur on São Miguel island is characterized by the occurrence of frequent seismic swarms. An example is the seismic activity recorded from 2002 and 2010.

Data: regional earthquake catalog provided by the *Instituto Português do Mar e da Atmosfera* (IPMA) with events from January 2, 1995, to December 31, 2019.

Objectives:

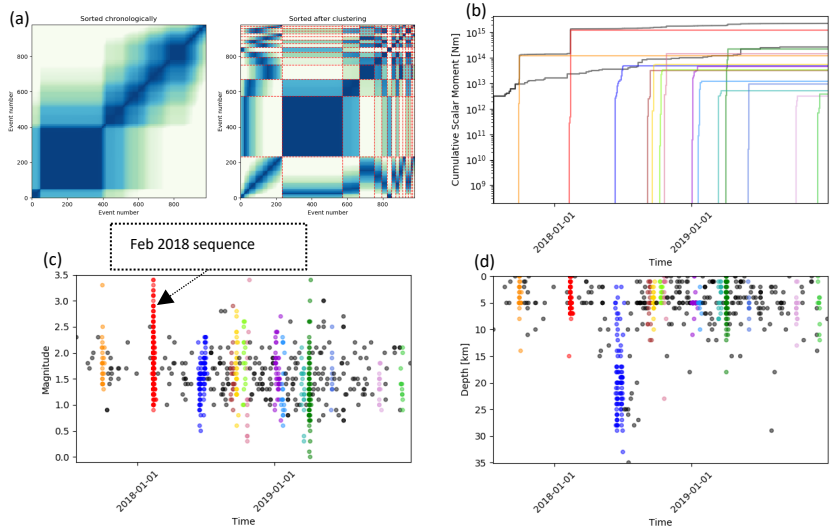
- Spatio-temporal evolution of the February 2018 seismic sequence which occurred in the island of São Miguel.
- Carry out detection and preliminary location of seismic events using Lassie, an open-source software for earthquake detection.



(a) Magnitude, (b) cumulative moment and (c) cumulative number of earthquakes with time listed on the IPMA catalog. Azores archipelago events are marked in blue, and events occurred on São Miguel island region are marked in red.

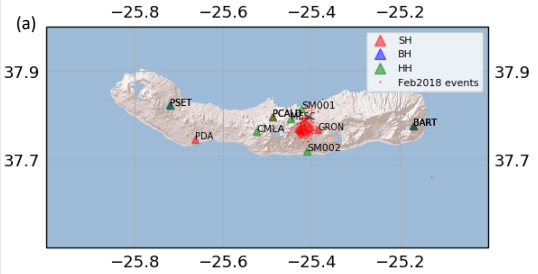
Earthquakes that occur in São Miguel island region correspond of approx. 1/3 of the total events present in the catalog.

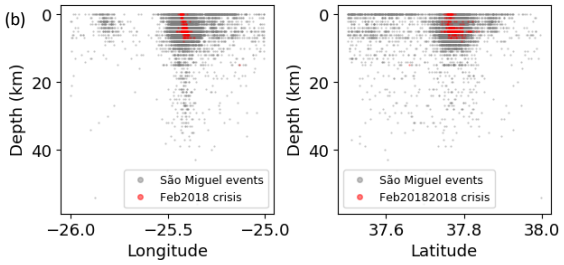
Applying a temporal clustering analysis using *seiscloud* software (https://git.pyrocko.org/cesca/seiscloud.git) we could recognize the February 2018 seismic sequence identified with the color red.

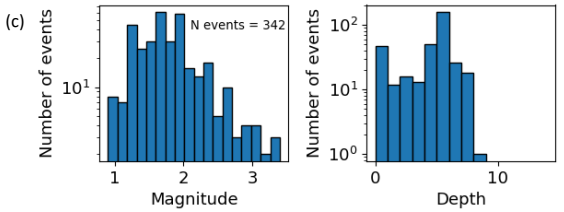


Cluster analysis of the seismic events events occurred in the São Miguel region in 2018. (a) Similarity matrix, (b) cumulative moment release and temporal evolution of the (c) magnitude and (d) depth of the seismic clusters.

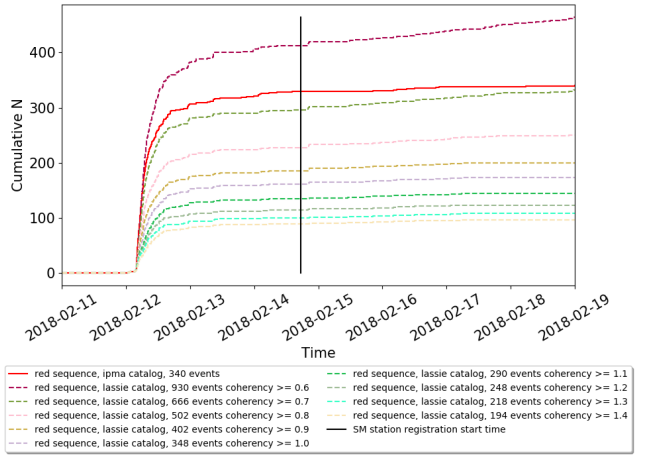
February 2018 seismic sequence







(a) Map view of seismic events registered during February 2018. (b) Cross-sections of latitude and longitude where all events inside the São Miguel region are in grey and February 2018 events are marked in red. (c) Magnitude and depth histograms.



Cumulative number of *Lassie* detected events over time for different values of coherency value. Earthquakes present in the IPMA catalog are represented by the solid red line and Lassie detections are marked by dashed lines. Vertical black solid line mark the time that stations SM001 and SM002 were deployed and started recording.

Key points:

- Earthquakes that occur in São Miguel island region, that correspond of approximately 1/3 of the total events present in the catalog, have lower magnitudes when compared with the whole archipelago.
- Most recent seismic activity of São Miguel island occurs on the centermost part of the island.
- We could clearly identify which the February 2018. This cluster is characterized by the highest cumulative scalar moment with 3.5 as the maximum magnitude and earthquakes constrained above 10km of depth.
- Applying *Lassie* to the *red cluster* that was identified in the clustering analysis we note that as the coherency value increases, the number of detections decreases.

References

- Custódio, S., Lima, V., Vales, D., Cesca, S., & Carrilho, F. (2016). Imaging active faulting in a region of distributed deformation from the joint clustering of focal mechanisms and hypocentres: Application to the Azores–western Mediterranean region. Tectonophysics, 676, 70-89.
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This work is funded by FCT through projects UIDB/50019/2020 – IDL and PTDC/CTAGEF/ 6674/2020 (RESTLESS).

Tools for monitoring the spatio-temporal evolution of seismic sequences: An application to the Azores triple junction

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1. Introduction

- The triggering mechanisms of earthquakes that occur in the Azores archipelago region are thought to be related to the interactions between a tectonic triple junction and a low-velocity (possibly hot) mantle anomaly. Thus, although most of the seismic activity in the Azores archipelago region is tectonic, there is evidence of seismic activity also related to hydrothermal and magmatic activity.

- São Miguel plays a significant role in the seismic activity of the Azores region. The seismicity that occurs in São Miguel island is characterized by the occurrence of frequent seismic swarms. An example is the seismic activity recorded from 2002 to 2010.

Objectives:

- We will then focus on the spatio-temporal evolution of the February 2018 seismic sequence, which occurred in the island of São Miguel.

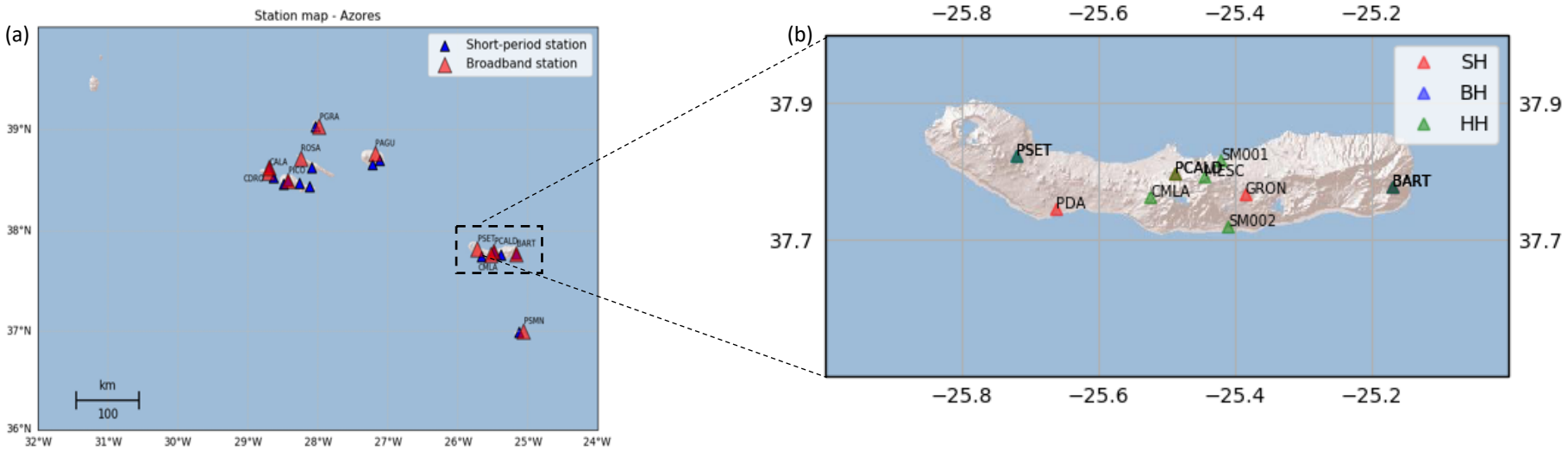
- We will carry out detection and preliminary location of seismic events using Lassie, an open-source software for earthquake detection.

- For future work we will also perform waveform similarity and clustering analysis to understand the detailed spatio-temporal evolution of the crisis.

3. Data

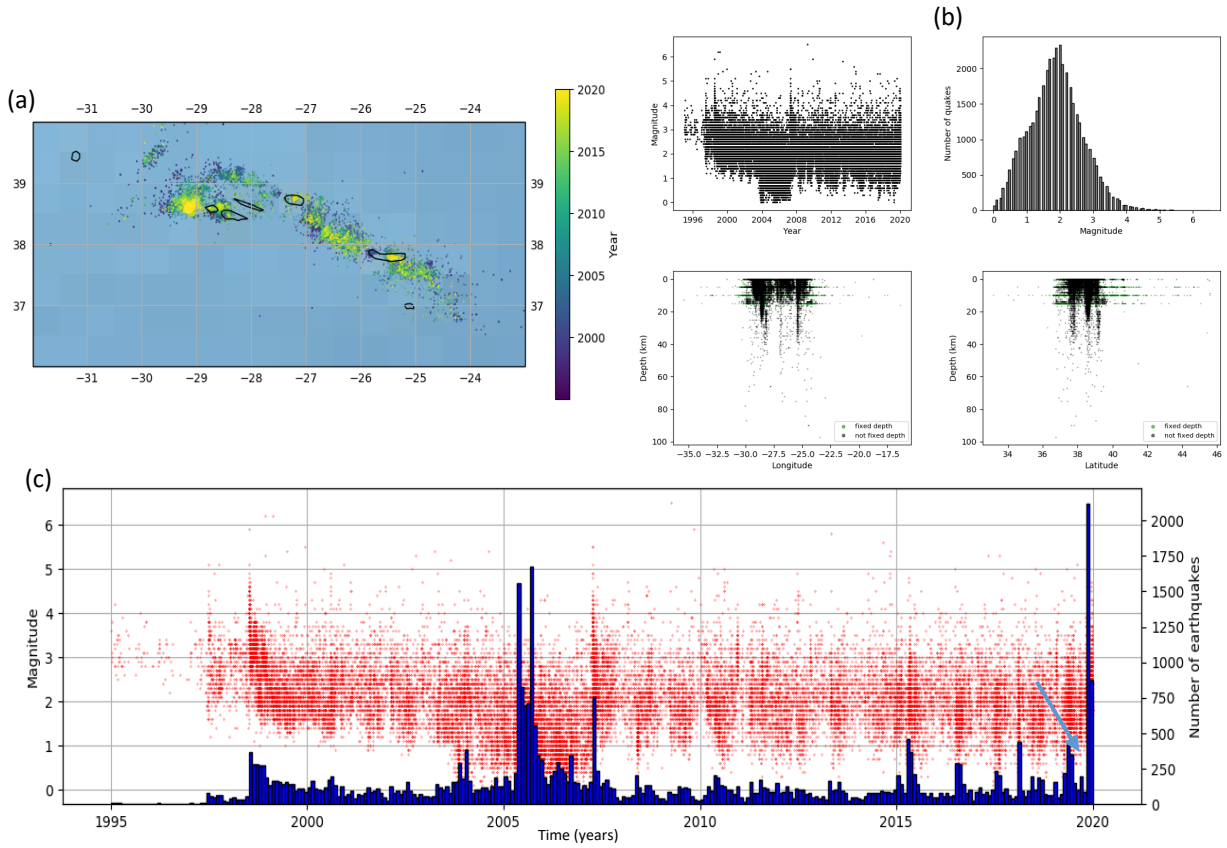
- We used a regional earthquake catalog provided by the *Instituto Português do Mar e da Atmosfera* (IPMA) with events from January 2, 1995, to December 31, 2019. This catalog contains the hypocentral location information for a total of 41539 events, located between -36º ≤ longitude ≤ -15º and 32º ≤ latitude ≤ 46º.

- We also used waveform data from February 12 to 19 of 2018 of the flowing seismic stations:
  - The permanent seismic network of the Azores region (PM), managed by the IPMA, which is composed by 25 stations: 11 of broadband stations and 14 short-period stations.
  - Two additional temporary stations installed by IPMA (with station codes SM001 and SM002) and one station from the University of the Azores (MESC).



(a) Seismic network map of the Azores region. (b) Seismic network map of São Miguel island used on this study. We considered São Miguel region: 37.5 ≤ latitude (degrees) ≤ 38.0 and : -26.0 ≤ longitude (degrees) ≤ - 25.0.

4. Seismicity of the Azores Archipelago

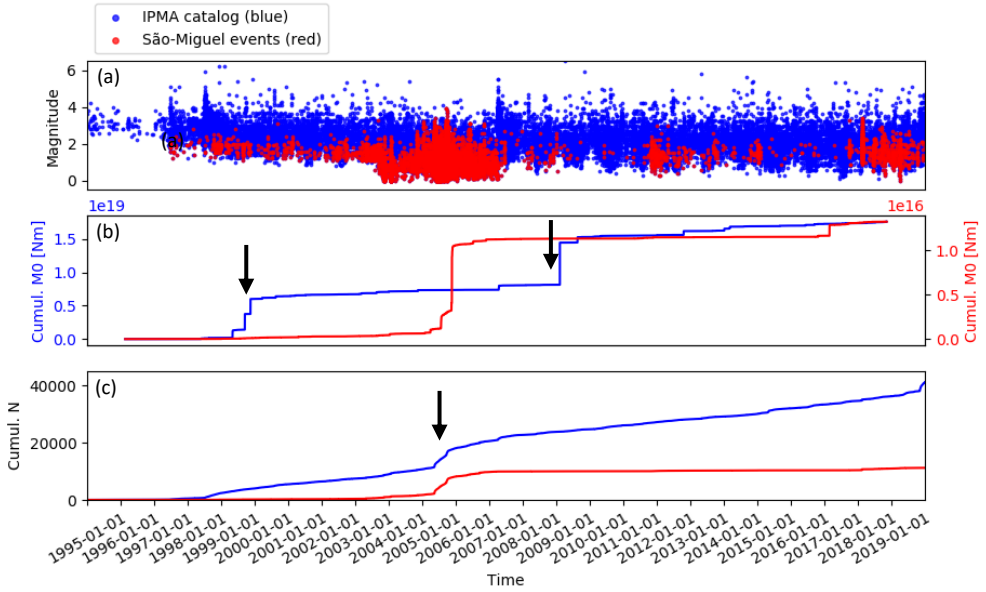


(a) Map indicating the time of the occurrence of earthquakes listed on the IPMA catalog. (b) Magnitude with time, magnitude histogram and cross sections in latitude and longitude of the same events. (c) Magnitude and histogram of the number of seismic events over time of the catalog displayed on the map. Earthquakes are marked with red dots and the blue bars represent the number of earthquakes per month. Blue arrow indicate the February 2018 seismic sequence.

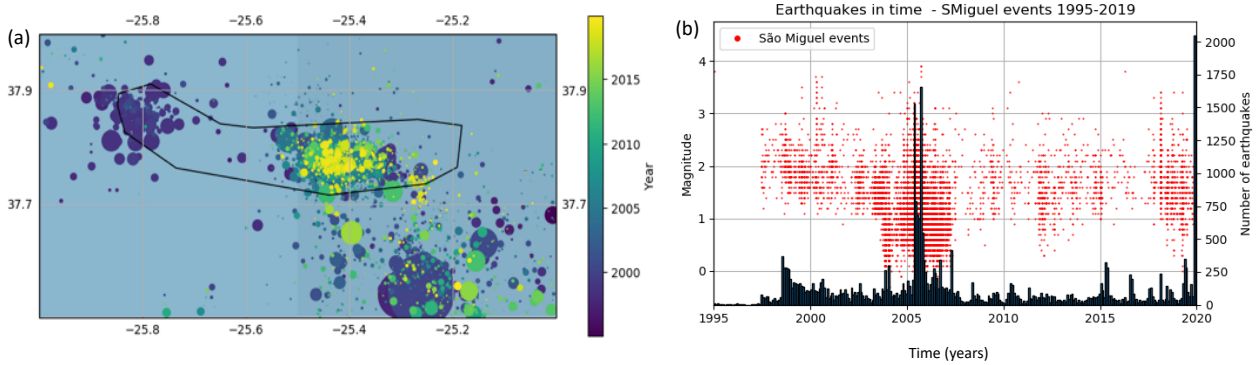
- Most recent events are observed in the region west of Faial and in the central-east São Miguel island.
- The number of observed events increases after 1998, due to network improvement.
- According to IPMS's catalog, earthquakes are concentrated mostly above 20 km depth and have relatively small magnitudes (between 1 and 4).
- We can notice some deep (approximately 20-40 km) earthquakes that correspond to, from east to west:
  - The center-east region of São Miguel island.
  - West of Terceira island.
  - And near the Graciosa island.

4. Seismicity of the Azores Archipelago

4.1 São Miguel Island



(a) Magnitude, (b) cumulative moment and (c) cumulative number of earthquakes with time listed on the IPMA catalog. Azores archipelago events are marked in blue, and events occurred on São Miguel island region are marked in red.

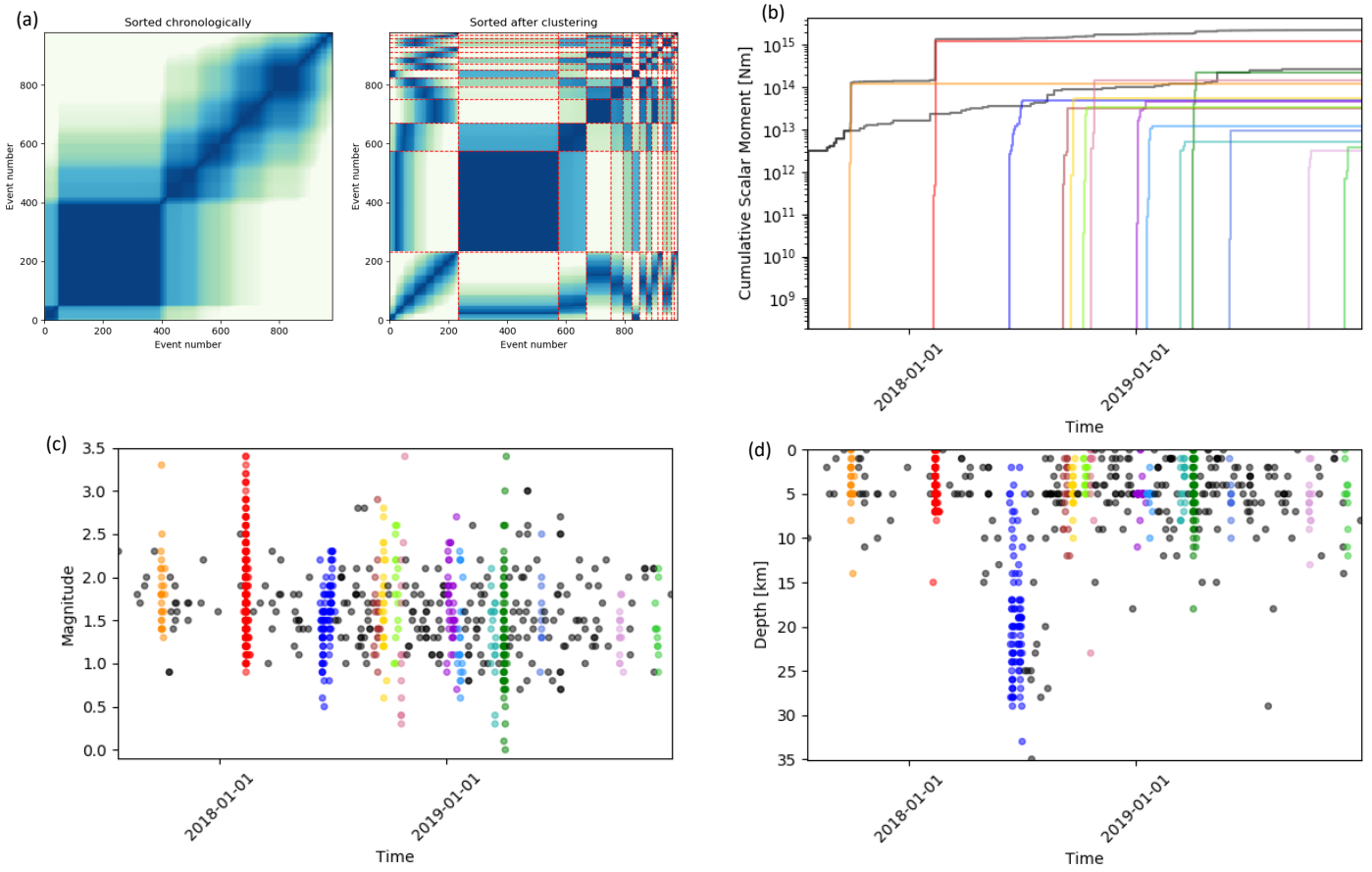


(a) Map showing time of occurrence of earthquakes in São Miguel island region, from January 2, 1995 and December 31, 2019. (b) Magnitude and histogram of the number of seismic events over time plot. Earthquakes are marked with red dots and the blue bars represent the number of earthquakes per month.

- The Azores region hosts some moderate-large magnitude earthquakes responsible for the abrupt increases in the cumulative moment M0 at certain times.
- There is an increase of the number of events on the year of 2005 that correspond to the May 2005 seismic crisis that occurred in São Miguel island.
- Earthquakes that occur in São Miguel island region, which correspond of approximately 1/3 of the total events in the catalog, have lower magnitudes when compared with the whole archipelago.
- We can see that in São Miguel there is a group of previous events on the west border of the island and that the more recent events are located on the center-east part of the island.

5. Seismicity of the São Miguel Island

5.1 Cluster analysis of the earthquakes occurred in 2018



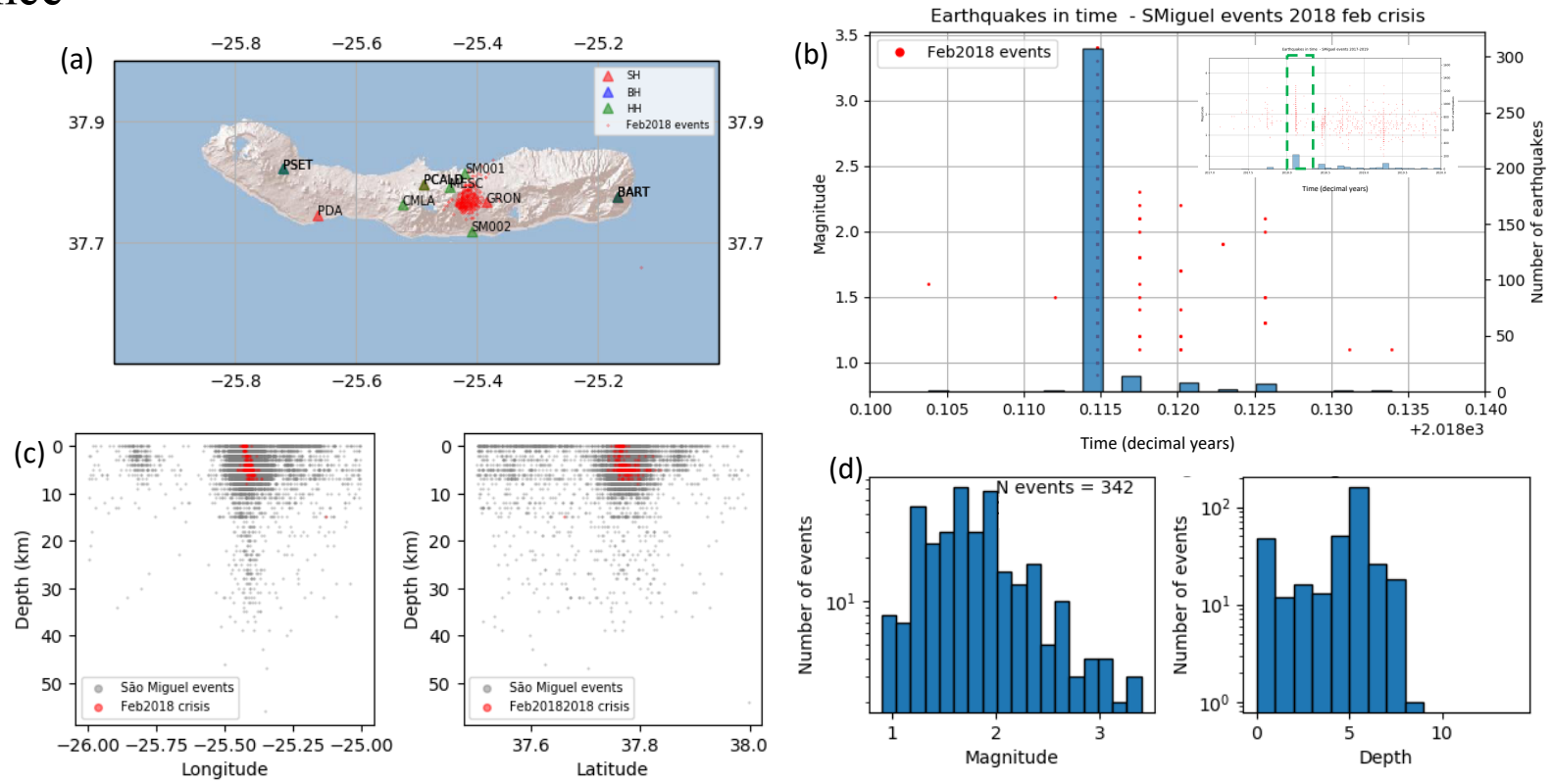
Cluster analysis of the seismic events events occurred in the São Miguel region in 2018. (b) Similarity matrix, (c) cumulative moment release and temporal evolution of the (d) magnitude and (e) depth of the seismic clusters.

- We applied a temporal clustering analysis on the São Miguel earthquakes occurred in 2018 using *seiscloud*, a clustering software based on the DBSCAN approach (https://git.pyrocko.org/cesca/seiscloud.git).
- There are more than 10 clusters identified, with the February 2018 seismic sequence identified with the color red.
- Note that the red cluster:
  - has the highest cumulative scalar moment, which is associated with existence of more earthquakes with relatively high magnitudes (approximately between 2.5 and 3.5) compared with the other clusters.
  - and has almost all earthquakes above 10 km of depth.

5. Seismicity of the São Miguel Island

5.2 February 2018 seismic sequence

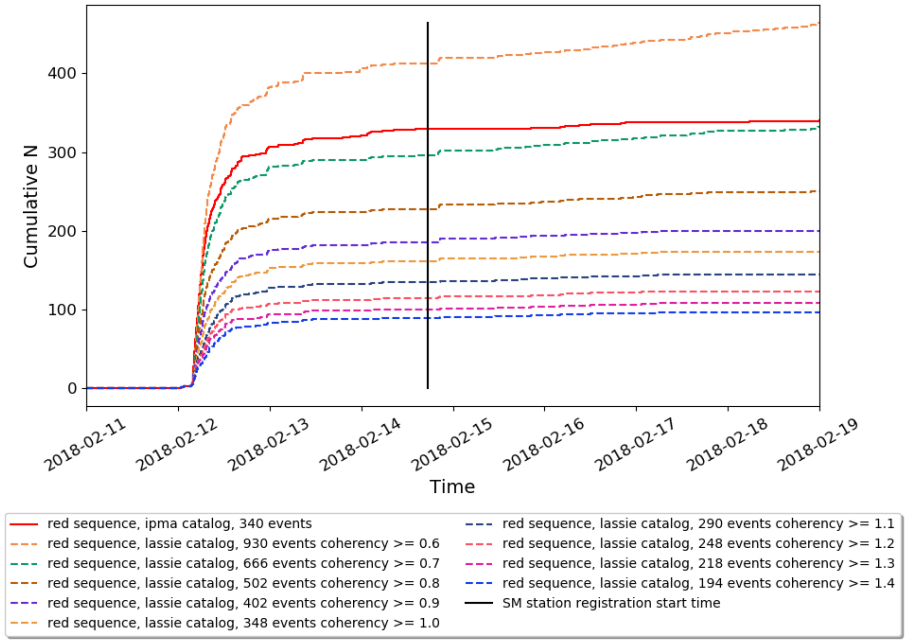
- Earthquakes of the February 2018 seismic sequence are:
  - clustered on the center of the island.
  - limited to above 10 km depths.
  - have a maximum magnitude of 3.5.



(a) Map view of seismic events registered during February 2018. (b – inside plot) Magnitude and histogram of the number of seismic events over time plot between 2017 and 2020 where the February 2018 seismic sequence is noticeable. (b – outside plot) Magnitude and histogram of the number of seismic events occurred in February 2018. (c) Cross-sections of latitude and longitude where all events inside the São Miguel region are in grey and February 2018 events are marked in red. (d) Magnitude and depth histograms.

6. February 2018 seismic sequence

6.1 Preliminary Lassie Detection



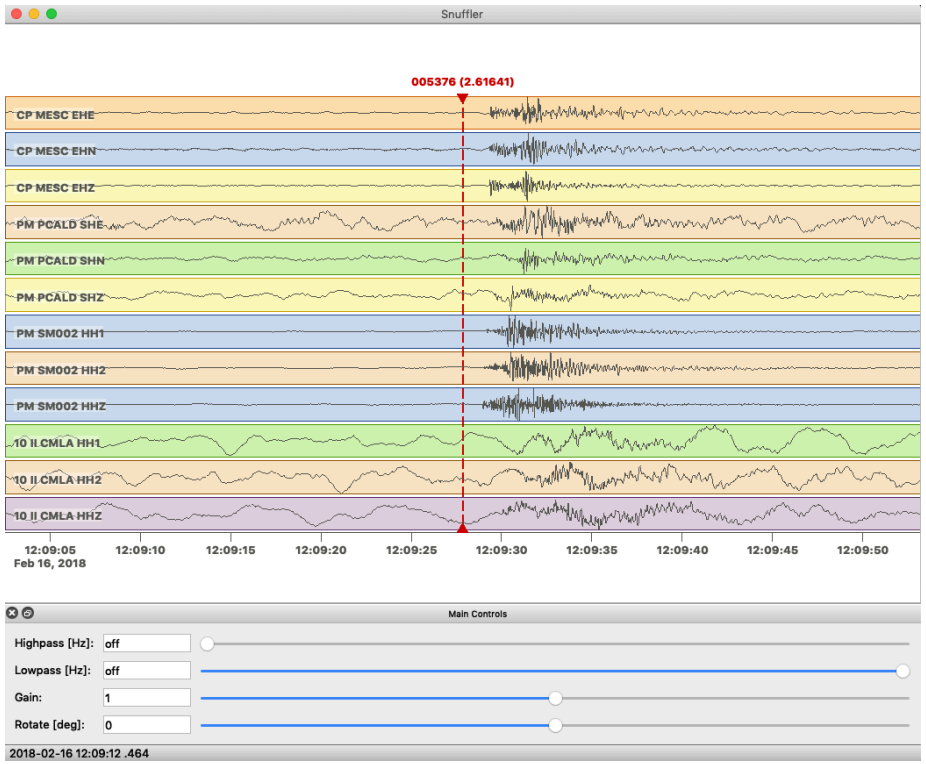
Cumulative number of *Lassie* detected events over time for different values of coherency value. We used waveform data of a set of the closest stations that includes CMLA, MESC, PCALD and SM002 (see slide 4) in a time window that contains the cluster of events of February 2018 that was identified in the clustering analysis as the *red cluster* (see slide 7). Earthquakes present in the IPMA catalog are represented by the solid red line and Lassie detections are marked by dashed lines. Vertical black solid line mark the time that stations SM001 and SM002 were deployed and started recording.

- Applying *Lassie*, a software of earthquake detection based on Grid Search method (https://gitext.gfz-potsdam.de/heimann/lassie), to the *red cluster* that was identified in the clustering analysis we note that:
  - The line pattern coincides with the events registered on the IPMA catalog. Such indicates that the detections seems coherent (i.e., there are more “real events” detected than “false events”).
  - The number of detections increases significatively on February 12 and, it is also the day with the largest number of events. Thus, implying that this is day with the highest release of energy.
  - As the coherency value increases the number of detections decreases.

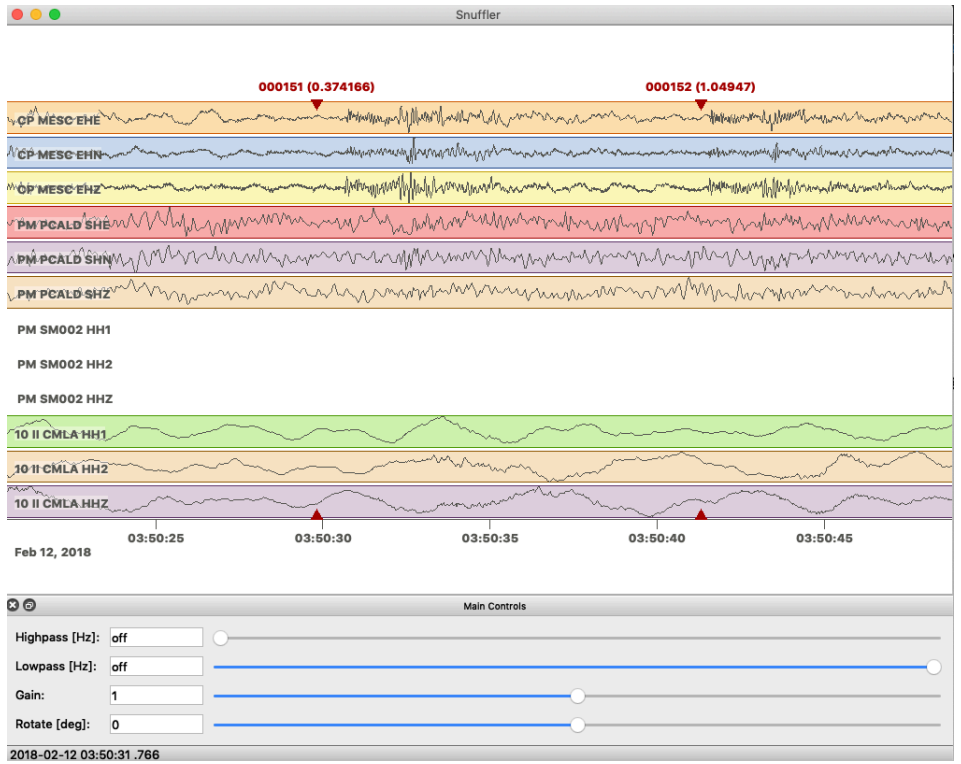
6. February 2018 seismic sequence

6.1 Preliminary Lassie Detection and Location

- We note also the presence of detections with a signal that is different from a “conventional” earthquake (see examples below).



Waveform data visualization with Snuffler (https://pyrocko.org/docs/current/apps/snuffler/manual.html). Example of a detection that represents a ”real” and “conventional” earthquake.



Waveform data visualization with Snuffler (https://pyrocko.org/docs/current/apps/snuffler/manual.html). Example of a detections that represents a signal that is different from a “conventional” earthquake.

7. Key Points

- Earthquakes that occur in the São Miguel island correspond to approximately 1/3 of the total events present in the catalog and have lower magnitudes when compared with the whole archipelago.

- The most recent seismic activity in the São Miguel island occurs on the centermost part of the island.

- We could clearly identify the February 2018 cluster using *seiscloud*. This cluster is characterized by the highest cumulative scalar moment, with 3.5 as the maximum magnitude, and earthquakes are limited to above 10 km depth.

- Applying *Lassie* to the *red cluster* that was identified in the clustering analysis we note that as the coherency value increases, the number of detections decreases.

8. References

- Custódio, S., Lima, V., Vales, D., Cesca, S., & Carrilho, F. (2016). Imaging active faulting in a region of distributed deformation from the joint clustering of focal mechanisms and hypocentres: Application to the Azores–western Mediterranean region. Tectonophysics, 676, 70-89.
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Thank you!