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Seismic activity along a Cretaceous magmatic intrusion in SW Iberia

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Introduction

※ Iberia and its offshore areas, in the southwestern tip of Europe, display a complex pattern of seismic activity, with most known active faults slipping at low rates (< 1 mm/yr) (Fernades et al., 2003; Noquet, 2012).

※ The most active seismic cluster in Portugal is very localized (small spatial extent) and lays on the Monchique late Cretaceous magmatic intrusion (Carrilho et al., 2004; Custódio et al., 2015; González-Clavijo and Valadares, 2003).

※ This magmatic intrusion, in addition to creating a strong rheological contrast between the intruded magmatic rocks and the surrounding Palaeozoic rocks, is further the locus of abundant natural water springs (Lourenço, 1998; Veludo et al., 2017).

Introduction

※ In this presentation, we re-analyze in detail the seismic data recorded by the regional permanent seismic network, in order to better understand the relationship between seismic activity and igneous intrusion. In particular,

1. We re-locate earthquakes using NonLinLoc and the IGN reference model used at IPMA (Instituto Português do Mar e da Atmosfera), PRISM3D, a 3D velocity model for the region and the velocity model from Veludo et al., 2017.

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2. Perform a clustering analysis based on waveform similarity.

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3. Then, we re-locate earthquakes using the double difference method implemented on hypoDD software:

1) using only catalog information and, 2) joint the catalog information and the waveform cross-correlation results.

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4. Lastly, we compute focal mechanisms for the region.

Objectives

※ Several pertinent questions remain to be answered concerning earthquakes in Monchique, namely:

- Why there are earthquakes in Monchique? Response to tectonic stresses?
- Is there a relationship between earthquake activity and fluid circulation?
- Do fluids play a role in facilitating slip in existing fractures? Or conversely, do existing fractures facilitate the circulation of fluids? Or both?
- Are there hazardous faults in Monchique?
- In this region, earthquakes are generated by large faults (big structures) with small localized rupture? Or generated by the slip of small non-oriented fractures (shear zone)?

Purpose of this work: Clarify the relationship between seismic activity and the geological structure of the Monchique region.

Geological Context

※ The Monchique massif is a structure of the upper Cretaceous with 72 Ma (K-Ar Method) (Machintyre and Berger, 1982).

※ Miranda et al. (2009) associates the genesis of this igneous complex with other onshore magmatic bodies such as the alkaline masses of Sines and Sintra and offshore intrusions such as the Fontanelas seamount all belonging to Iberian Alkaline Igneous Province.

※ A singularity of the Monchique complex, in relation to the other massifs, is the fact that it is the only one that is placed on Paleozoic sediments that were not affected by the rifting associated with the opening of the North Atlantic ocean (González-Clavijo and Valadares, 2003; Miranda, 2010).

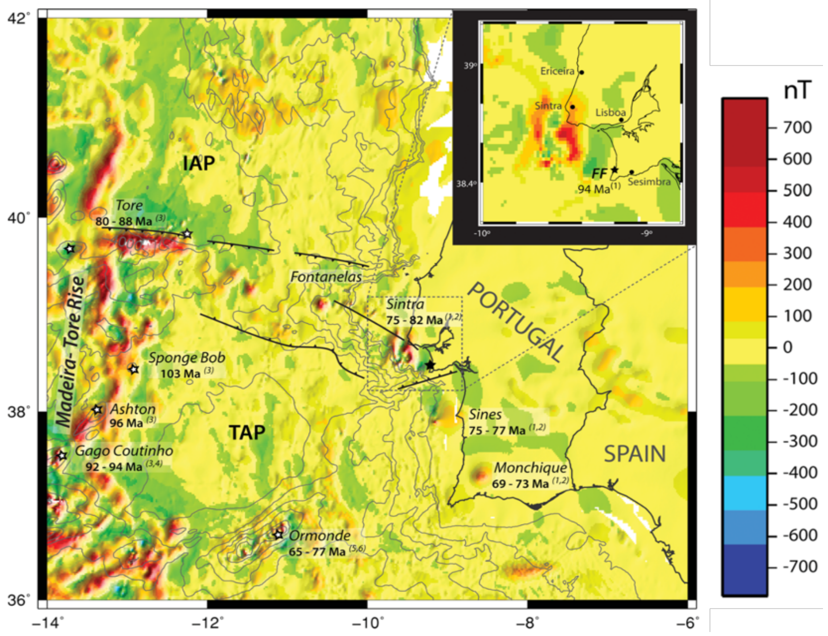


Figure 1 – Magnetic anomalies of West Iberia: magnetic data from the compilation of Luis & Miranda (2008) and earthquakes epicenters from Custódio et al. (2016) (blue dots). The onshore plutons (Monchique, Sines, Sintra) have strong magnetic signatures that extend offshore in the case of Sines and Sintra. Note that Monchique also hosts an earthquake cluster. Several punctual magnetic highs, such as the Fontanelas seamount, form a lineament that extends from Sintra to the Tore seamount. [Adapted from Neres et al 2014].

Data

※ We used a catalog for the Monchique region with a total of 1487 events recorded between 01/26/2007 and 12/28/2018 by the national seismic network (code PM), led by IPMA plus records form a few stations belonging to other seismic networks that operate in the region (ES, GE, IP, LX, SS, WM) (Fig. 2a).

※ We plot earthquake catalog locations, location quality parameters and seismic arrivals in Figure 1. As we can see:

- ※ the earthquakes appear to align along two directions, E-W and NNE-SSW;
- ※ the cluster has a tapered shape in depth;
- ※ most events occur between 10-15km depth.

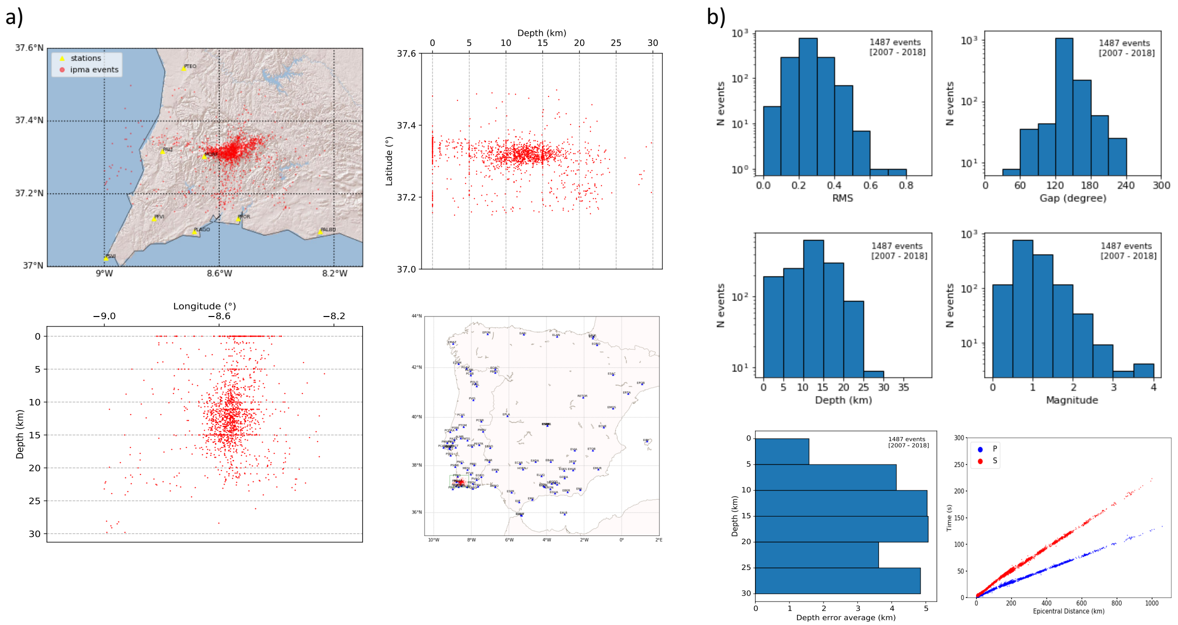


Figure 2 – IPMA earthquake catalog data for Monchique region, Portugal from 01/26/2007 to 12/28/2018 with a total of 1487 events. Map view (upper left) showing epicenters (red dots) and seismic stations (yellow triangles). Depth profiles N-S (upper center) and E-W (bottom left). Map view (bottom right) with events in the select study region (red dots) and all stations (blue triangles). Histograms of RMS, azimuthal Gap, depth and magnitude (upper right) and average depth error in function of depth (bottom center). Travel time table for P (blue dots) and S (red dots) waves (bottom right).

Earthquake Location - NonLinLoc

Gutenberg & Richter Law

※ Using the Zmap software, we did a first analysis of the data by calculating the Gutenberg and Richter Law for the study region. The results are presented below.

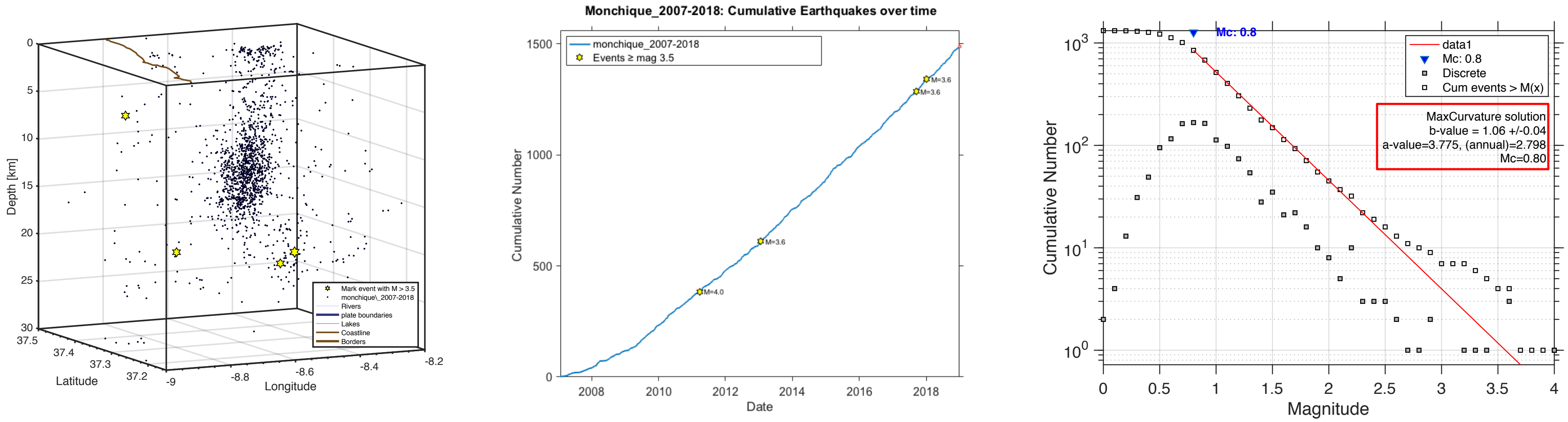


Figure 3 – 3D view of Monchique events (left). It shows four earthquakes with magnitude larger than 3.5 (yellow stars). Cumulative rate (middle) and Maximum curvature solution of the Gutenberg & Law Richter (right), showing that the magnitude of completeness is 0.8 and that, in this region, *b-value* = 1.06 ± 0.04 and *a-value* = 3.775 ± 0.001. Note that larger events (events with mag ≥ 3.5) occur on the edges of the cluster. Is also evident that there is a significant abundance of small-magnitude earthquakes (0.8 ≥ mag ≥ 2.5) that can possibly suggest a hydrothermal control in this region.

1. Earthquake Location with NonLinLoc

Earthquake Location - NonLinLoc

Velocity Models

※ For the absolute earthquake re-location with NonLinLoc, we use PRISM3D and IGN reference model (IGN1D) shown below.

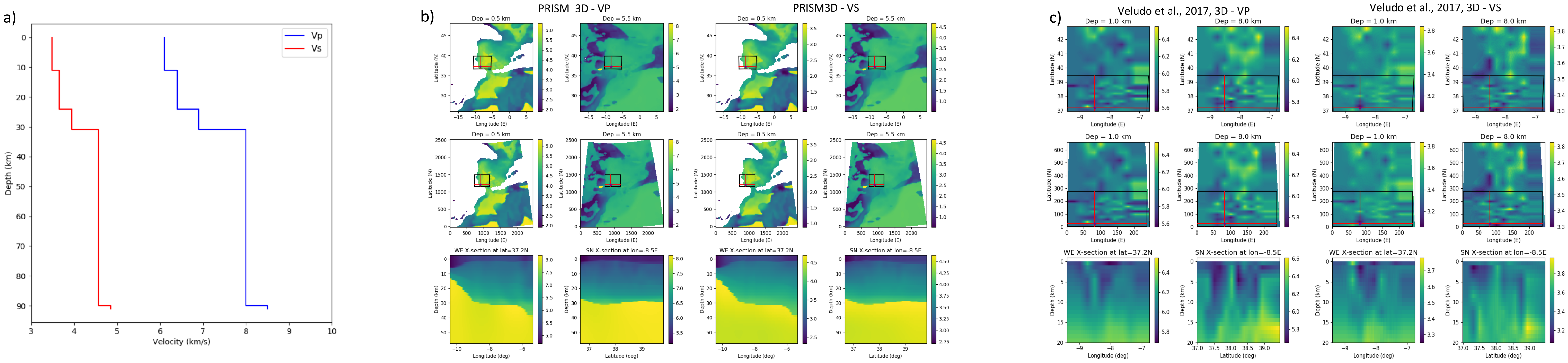


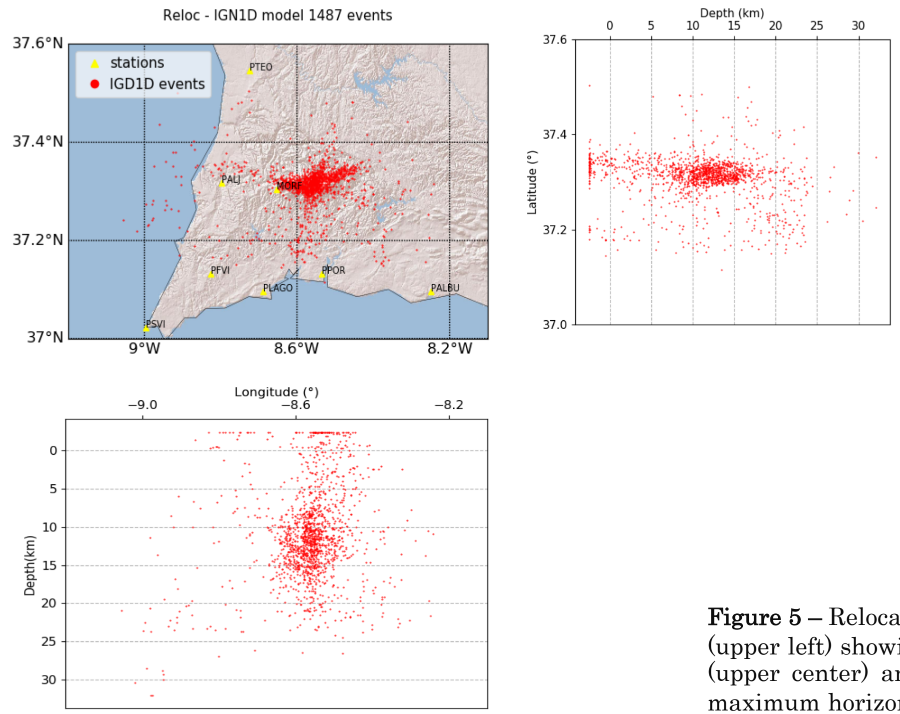
Figure 4 – Velocity models for P and S waves. a) IGN reference model (IGN1D). Values for P (blue line) and S (red line) waves. b) PRISM3D velocity model for Iberia. Velocities values at depths of 0.5 (1st raw) and 5.5 km (2nd raw) and vertical profiles E-W and N-S with origin point in Monchique P=37.32 N, 8.55 W (3rd raw). c) Velocity model for Portugal from Veludo et al. 2017. Velocities values at depths of 1.0 and 8.0 km (1st and 2nd raw) and vertical profiles E-W and N-S with origin point in Monchique P=37.32 N, 8.55 W (3rd raw).

Earthquake Location - NonLinLoc

Results

※ Re-location using IGN1D.

a)



b)

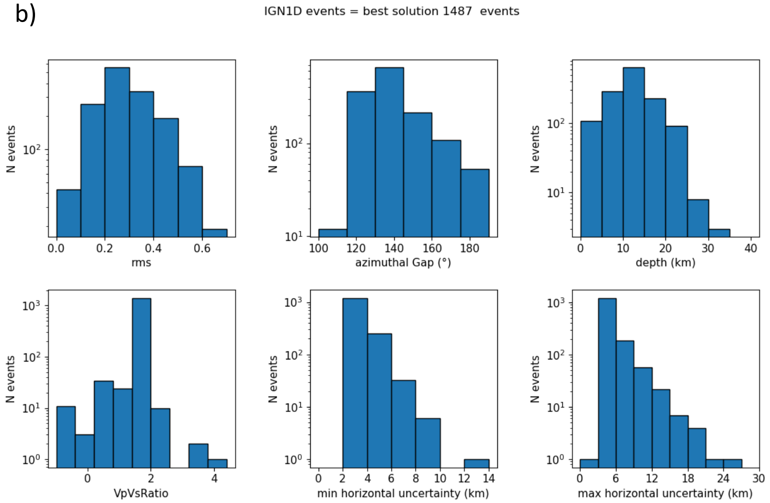
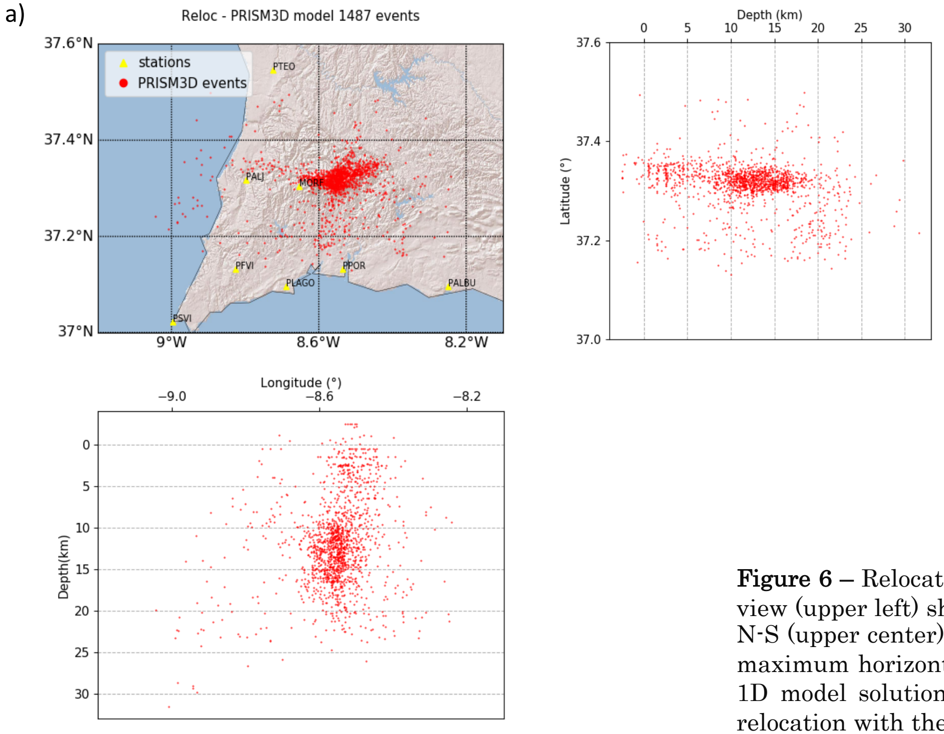


Figure 5 – Relocated events for Monchique region using IGN1D velocty model, Portugal. a) Map view (upper left) showing epicenters (red dots) and seismic stations (yellow triangles). Cross sections: N-S (upper center) and E-W (bottom left). b) Histograms of RMS, azimuthal Gap, depth, VpVsRatio, maximum horizontal uncertainty and minimum horizontal uncertainty (right). The relocated events distribution (in map view and depth) and the previously highlighted alignments are very consistent when compared with the IPMA original location.

Earthquake Location - NonLinLoc

Results

※ Re-location using PRISM3D.



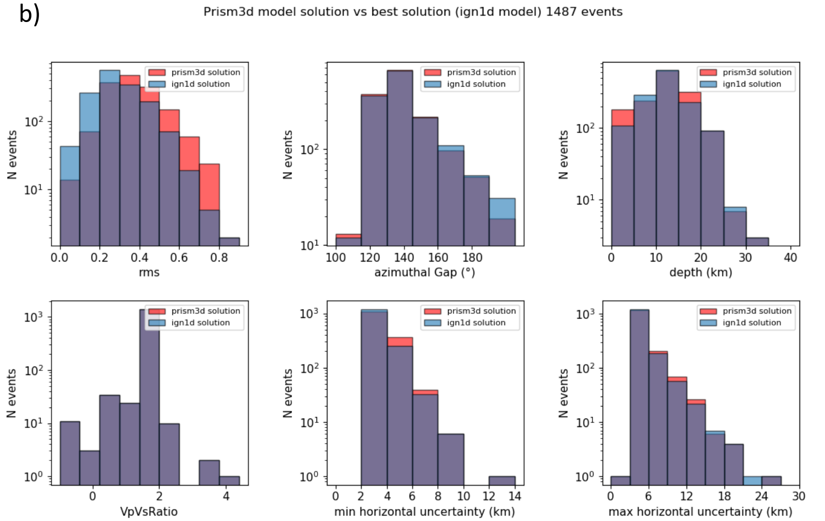


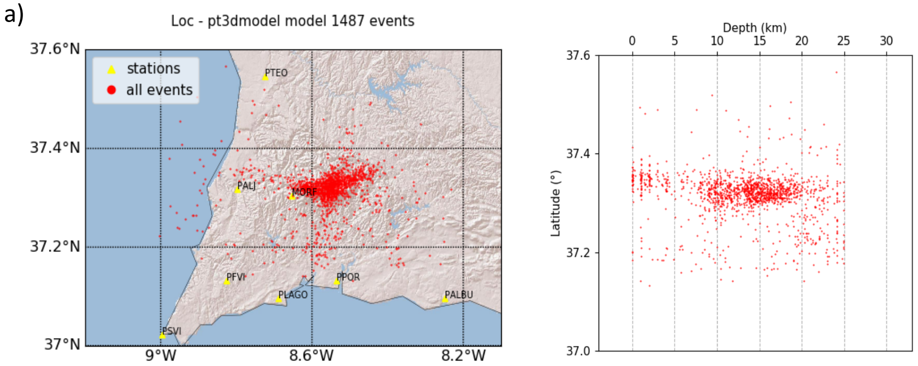
Figure 6 – Relocated events for Monchique region, Portugal using PRISM3D velocity model. a) Map view (upper left) showing epicenters (red dots) and seismic stations (yellow triangles). Cross sections: N-S (upper center) and E-W (bottom left). b) Histograms of RMS, azimuthal Gap, depth, VpVsRatio, maximum horizontal uncertainty and minimum horizontal uncertainty (right) *vs* histograms of the 1D model solution. The results using PRISM3D velocity model reveals to be very similar to the relocation with the 1D model with only slight differences. Note that RMS_1Dmodel < RMS_3Dmodel and with the 3D model the number of earthquakes with negative depth decrease substantially.

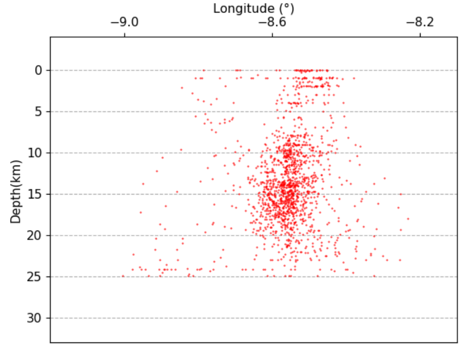
Earthquake Location - NonLinLoc

Results

※ Re-location using the velocity model from Veludo et al., 2017.

a)





b)

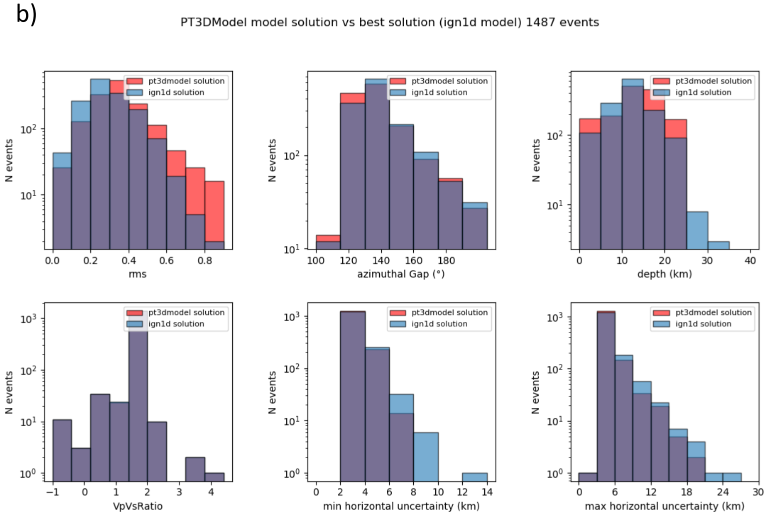


Figure 7 – Relocated events for Monchique region, Portugal using Veludo et al., 2017 velocity model. a) Map view (upper left) showing epicenters (red dots) and seismic stations (yellow triangles). Cross sections: N-S (upper center) and E-W (bottom left). b) Histograms of RMS, azimuthal Gap, depth, VpVsRatio, maximum horizontal uncertainty and minimum horizontal uncertainty (right) *vs* histograms of the 1D model solution. In comparison with the 1D model, the model from Veludo et al., 2017 only appears to decrease the RMS. Because the depth limit of this model is 30km, the earthquakes are confined at the 25km depth however, in the other re-locations (with IGN1D and PRISM3D) there is very few events with depth larger than 25km.

3. Clustering Analysis

Earthquake Location

Velocity Models

※ We used the SEISAN tool to perform waveform cross-correlation analysis to search for families of similar earthquakes.

※ We used 8 high quality stations and a sub-set of 560 events that contains events with:

- ※ RMS <= 0.5; azimuthal Gap <= 180; magnitude >= 1.0; and recorded in at least 7 stations

※ The cross-correlation was executed for the P phase, recorded on Z component, filtered from 3 to 15 Hz. We restricted the distance between each pair of events to be less than 40 km and 140km to be the maximum distance event-station. The cross-correlation matrix is obtained by combining the results of the cross-correlation at each station.

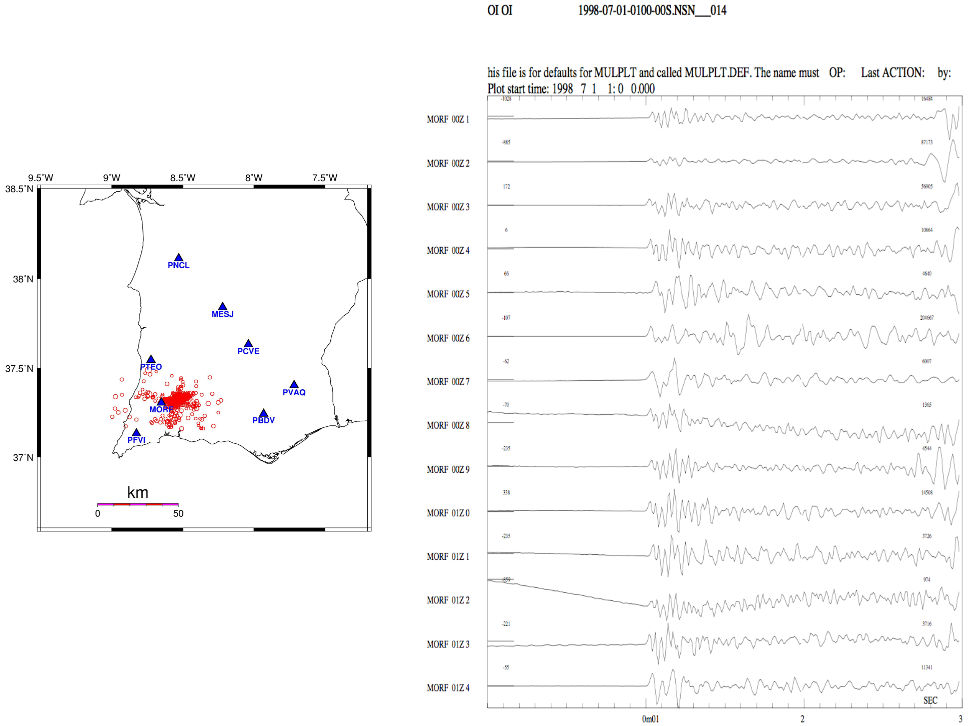


Figure 8 – Map view of the selected events (red circles) and the station used in the cross-correlation analysis (left). Examples of waveform cross-correlation (CC) for the P phase, 2 s record length plus 0,25 s pre-event time, for the closest station to the cluster MORF (right).

Earthquake Location

Velocity Models

※ A sequence of earthquakes is recognized when it has 3 or more elements with cross-correlation coefficient (CC) bigger or equal to 0.75 in 8 stations. In total, 76 sequences were identified with only 3 of them with 10 or more events.

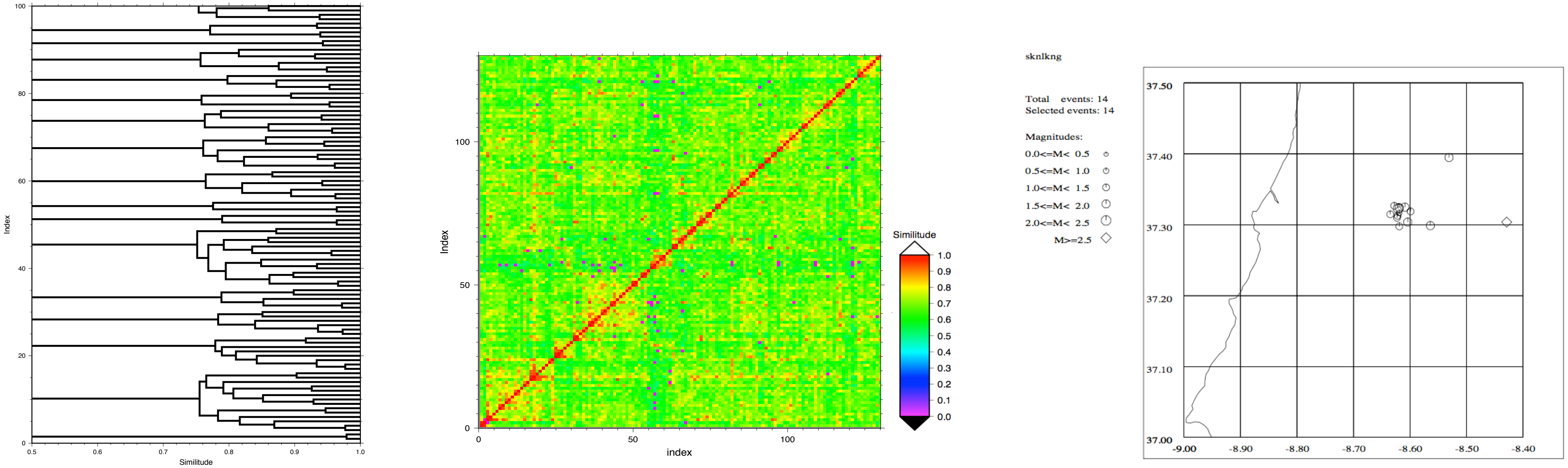
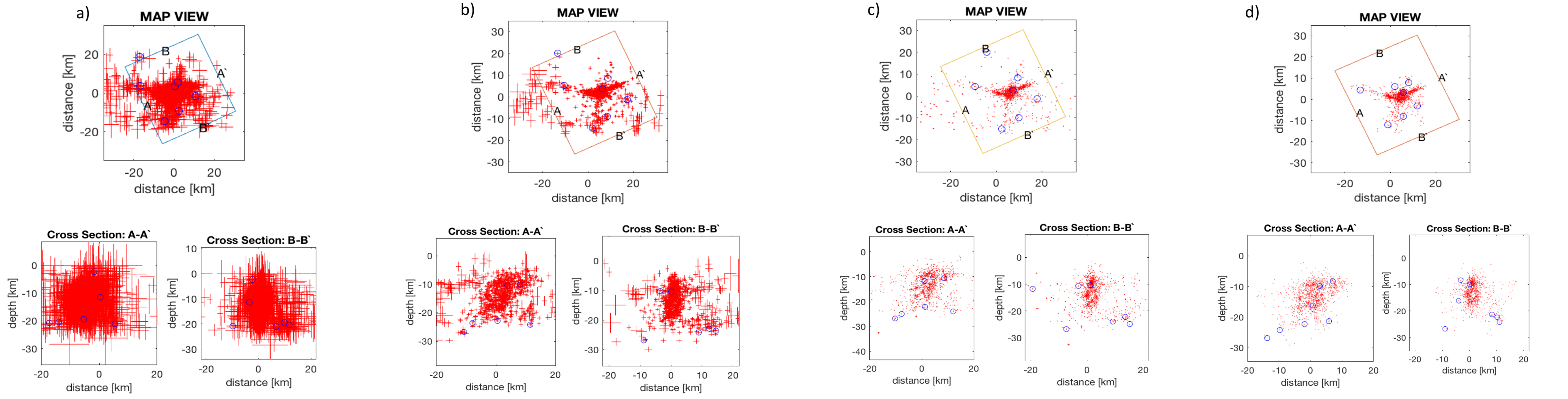


Figure 9 –Dendogram (left) and cross-correlation matrix resulted from the clustering procedure (middle). Epicenter map of events the cluster founded (example of the sequence with more correlated events – 14 events with the coefficient of correlation larger that 0.75) (right). The cluster here presented are on top of the Monchique igneous complex. With only 3 identified earthquake families with 10 or more events, we can conclude that, for the P wave, there is no significant results for waveform similarity in this region, that is, there is no identified sequence that can be related to any catalogued geological feature/fault.

2. Earthquake Location with HypoDD

Earthquake Location - HypoDD

※ For the relative earthquake location we use the HypoDD software and the IGN reference 1D model. From the several tests that we performed (using only catalog information and adding the waveform cross correlation results) it was selected the tree of the considered "best" results.



(a) N events	1487
N stations	113
mean ex (km)	2.696
mean ey (km)	3.076
mean ez (km)	4.291

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N stations	113
mean ex (km)	2.696
mean ey (km)	3.076
mean ez (km)	4.291

(c) N events	1326
N stations	39
mean ex (km)	0.0704
mean ey (km)	0.0524
mean ez (km)	0.0928

(c) N events	1189
N stations	29
mean ex (km)	0.0027
mean ey (km)	0.0029
mean ez (km)	0.0040

Figure 10 – Relative locations using hypoDD software: Map view and cross sections delineated by the square inside the map view plot. a) IPMA catalog locations, b) test using only catalog data, c) test using catalog and cross-correlation calculated in 2 steps of 8 iterations, d) relative location using catalog, cross-correlation data and adapted hypoDD example approach calculated in 0.5 in 5 steps of 5 iterations. Events are represented by red dots, horizontal error by red line. Blue circles are events with magnitude > 3. Note that adding the cross-correlation results improve the relative location mean uncertainties (ex, ey, ez) and we can distinguish a clearer pattern of the earthquake distribution.

```
*--- data weighting and re-weighting:
* NITER:         last iteration to used the following weights
* WTCCP, WTCCS:     weight cross P, S
* WTCTP, WTCTS:     weight catalog P, S
* WRCC, WRCT:       residual threshold in sec for cross, catalog data
* WDCC, WDCT:       max dist [km] between cross, catalog linked pairs
* DAMP:          damping (for lsqr only)
*       ---  CROSS DATA ----- ----CATALOG DATA ----
* NITER WTCCP WTCCS WRCC WDCC WTCTP WTCTS WRCT WDCT DAMP
  8     -9     -9   -9   -9    1     1    -9    -9   80
  8     -9     -9   -9   -9    1     1     6     9   80
```

```
*--- data weighting and re-weighting:
* NITER:         last iteration to used the following weights
* WTCCP, WTCCS:     weight cross P, S
* WTCTP, WTCTS:     weight catalog P, S
* WRCC, WRCT:       residual threshold in sec for cross, catalog data
* WDCC, WDCT:       max dist [km] between cross, catalog linked pairs
* DAMP:          damping (for lsqr only)
*       ---  CROSS DATA ----- ----CATALOG DATA ----
* NITER WTCCP WTCCS WRCC WDCC WTCTP WTCTS WRCT WDCT DAMP
  8      0.1   0.05   -9   -9   1.0   0.5   -9   -9   80
  8      1.0   0.5     6    3   0.1   0.05   6    9   80
```

```
*--- data weighting and re-weighting:
* NITER:         last iteration to used the following weights
* WTCCP, WTCCS:     weight cross P, S
* WTCTP, WTCTS:     weight catalog P, S
* WRCC, WRCT:       residual threshold in sec for cross, catalog data
* WDCC, WDCT:       max dist [km] between cross, catalog linked pairs
* DAMP:          damping (for lsqr only)
*       ---  CROSS DATA ----- ----CATALOG DATA ----
* NITER WTCCP WTCCS WRCC WDCC WTCTP WTCTS WRCT WDCT DAMP
  5     0.01  0.01  -9   -9    1.0   0.5    -9   -9   80
  5     0.01  0.01  -9   -9    1.0   0.5     6    4   80
  5     1.0   0.5   -9    2    0.01  0.005   6    4   90
  5     1.0   0.5    6    2    0.01  0.005   6    4   90
  5     1.0   0.5    6    0.3  0.01  0.005   6    4   90
```

Figure 10.1 – Weighing scheme for the tests b) on the 1st raw, c) on the middle raw and d) on the 3rd raw.

4. Focal Mechanism

Focal Mechanisms

※ We computed the focal mechanisms for tree earthquakes of the Monchique region using the ISOLA software: 2015-07-22, 2017-09-11 and 2019-01-31. Down below is represented the result for the 2015-07-22 earthquake.

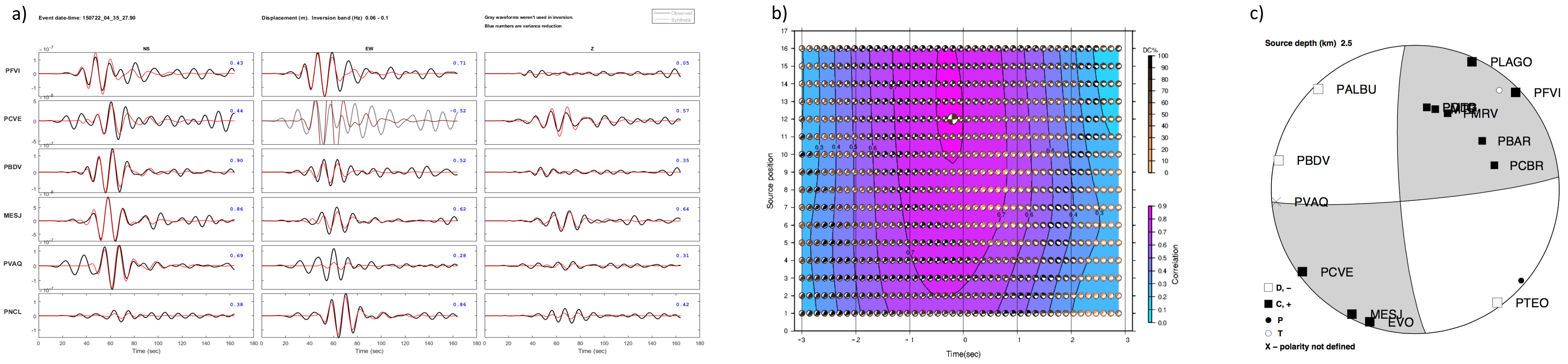

Figure 11 – Centroid moment tensor solution of the 22-07-2015 event using ISOLA. a) Waveform fit between observed and synthetic displacements. b) and c) Source mechanism fit: left strike-slip solution with correlation=0.9.

Focal mechanisms

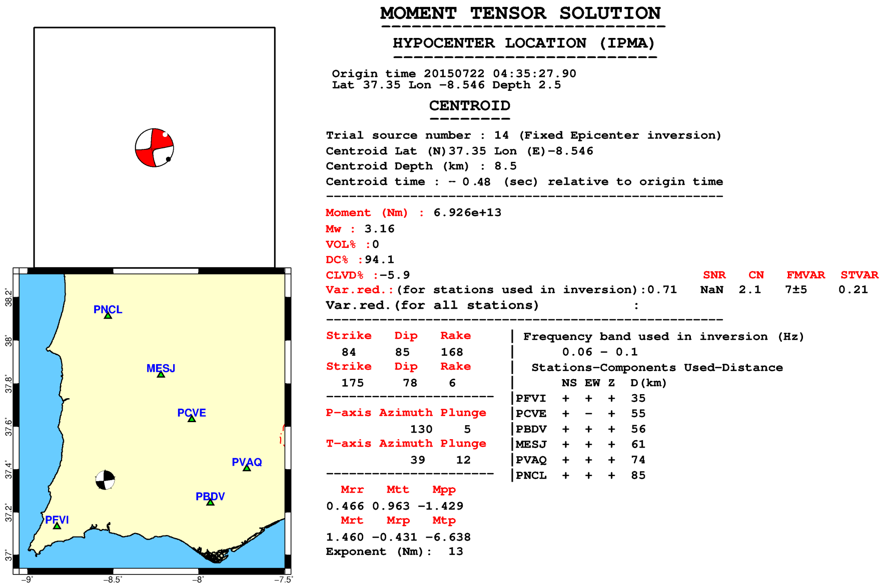

Figure 12 – Moment tensor solution for the 2015-07-22 using ISOLA software.

Table 1 – Focal mechanisms solution of 3 events, using the polarity of the P-wave (01-31-2019) and adding the solution by inversion of the waveform or joint inversion (07-22-2015 and 09-11-2017 events). We observed that all 3 events analyzed resulted on strike-slip faulting. The example presented on Figure12 shows a shallow earthquake (depth = 2.5 km) with strike-slip solution that coincide with the surface orientation of the massif (elongated on the E-W direction).

Fault Plane Solutions							
Event_id	ML	Nº Polarities	Strike (º)	Dip (º)	Rake (º)	Fault Mechanism Solutions (EXAUST)	Fault Mechanism Solutions (CSPS/Deviatoric Inversion)
2015-07-22	3.4	24	250	65	175		
2017-09-11	3.6	25	95	40	175		
2019-01-31	3.3	14	270	80	-20		

Earth structure

Earth structure

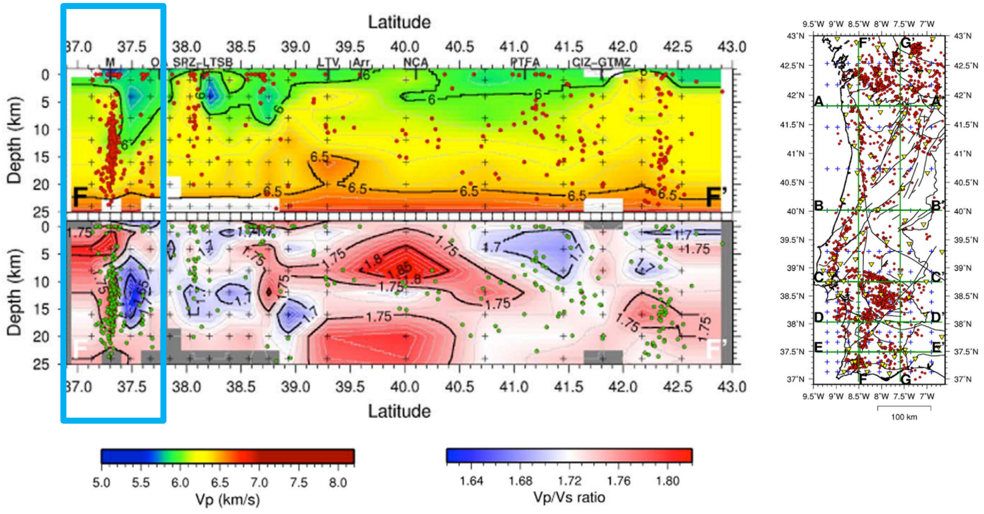

Figure 13 – Vertical profiles of Vp and Vp/Vs 3D crustal tomographic models based on local earthquakes (Veludo et al, 2017). a) Upper left: relocated hypocenters, crustal structure and stations. Upper right: position of cross-sections. Vertical exaggeration 5:1. [Adapted from Veludo et al., 2017]. The earthquakes are located along a low-velocity anomaly, directly south of a fast anomaly, which possibly corresponds to the igneous Cretaceous intrusion.

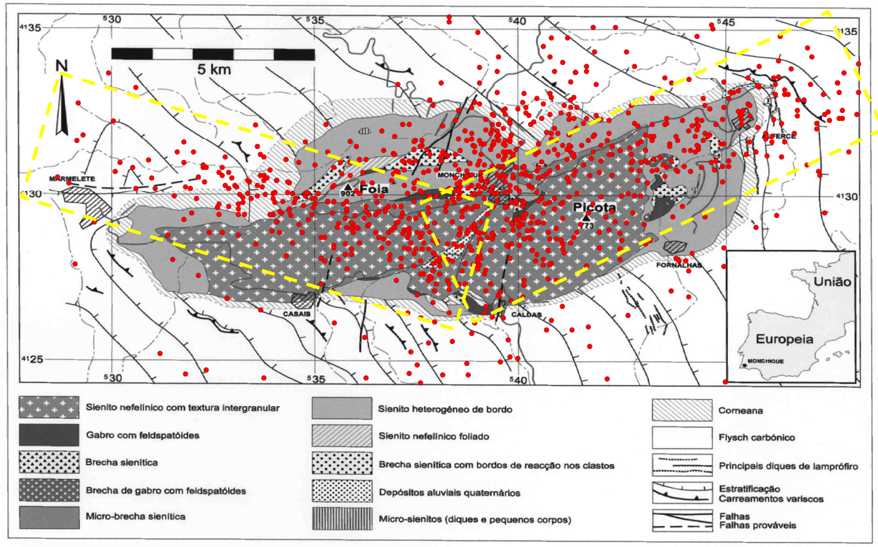

Figure 14 – Epicenters, re-located using the 1D IGN reference velocity model, and geologic map from González-Clavijo and Valadares (2003). The surface expression of the igneous intrusion is little affected by faulting. Natural thermal springs exist on the southern border of the intrusion.

※ Note that the epicenters are concentrated on the north section of the massif and its distribution coincide with the surface orientation of the magmatic intrusion.

Conclusions

- ※ The *b-value* > 1 indicates that there is a significant abundance of small-magnitude earthquakes, that can possibly suggest a hydrothermal control. However, the linear fit only adjusts the small earthquakes, and the number of moderate magnitude earthquakes is larger than expected from the GR law.

- ※ The GR analysis may suggest that small earthquakes are controlled by fluids movement and the larger events are associated with tectonic deformation.

- ※ The moderate magnitude earthquakes occur on the edges of the Monchique cluster that nucleate at 10-15 km depth.

- ※ From the absolute relocations results, we can conclude that independently of velocity model used, earthquakes in Monchique align mostly along two main directions, E-W and NNE-SSW, coinciding with the surface orientation of the magmatic intrusion.

Conclusions

※ Observing the relative locations results we can see that in this region,

i. The E-W alignment reveal to be dominant and appears to be to fragmented in two segments: one with ENE-WSW direction and other orientated WNW-ESE.

ii. The NNE-SSW alignment became diffuse and its north section disappeared.

※ Up to now, the waveform similarity analysis has not yet yielded significant results. This could imply that earthquakes in Monchique occur in small fractures indicating the possible presence of a zone of fracture (shear zone).

※ Focal mechanisms indicate dominantly strike-slip faulting. Fault planes coincide with the favored directions of the earthquake lineations, but also with the regional tectonic and faulting directions.

The results suggest that the Monchique igneous intrusion is little deformed (a hypothesis is that it acts as a barrier to tectonic deformation), with seismic and hydrothermal activity concentrating on its northern border.

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