Workshop em Ciências da Terra e do Espaço

Livro de Actas 2014

Programa Doutoral em Ciências da Terra e do Espaço

Universidade de Évora

UNIVERSIDADE
DE ÉVORA

Workshop em Ciências da Terra e do Espaço 2014

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Livro de Actas 2014

no âmbito da Unidade Curricular de Seminário do
Programa doutoral em Ciências da Terra e do Espaço
e
Mestrado em ciências da Terra, da atmosfera e do Espaço

Universidade de Évora
Instituto de Investigação e Formação avançada e Departamento de Física

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Indice

Prefácio

O Workshop em Ciências da Terra e do Espaço 2014 é um livro que reúne os artigos de investigação desenvolvidos pelos estudantes do programa Doutoral em Ciências da Terra e do Espaço e do mestrado em Ciências da Terra, da Atmosfera e do Espaço, no âmbito da Unidade curricular Seminário que faz parte dos seus planos de estudos. É uma unidade que apresenta os seguintes objetivos:

a) Permitir que os estudantes tomem contacto com trabalhos de investigação na área das Ciências da Terra, da Atmosfera e do Espaço.

b) Desenvolver capacidades para construção do conhecimento científico mediante a utilização de metodologias que promovam a pesquisa, discussão e debate de temas específicos.

c) Proporcionar a produção de elementos de divulgação (relatórios, artigos, comunicações) mediante a aplicação das regras aceites em meio académico.

d) Dar aplicação às metodologias científicas abordadas em diferentes domínios das Ciências da Terra, da Atmosfera e do Espaço.

Acreditamos que se podem atingir esses objetivos através do estudo de um assunto concreto. Nesse sentido procuramos conduzir o estudante ao conhecimento de um tema científico da sua escolha através de uma metodologia que inclua a investigação, discussão e o debate. Isto é, mediante a metodologia de seminário. Assim, para além do rigor científico com que os temas ecolhidos foram tratados, aspecto assegurado por investigadores da área que orientaram os trabalhos, pretendemos desenvolver no estudante a capacidade de comunicar de forma correta, inteligível, demonstrando um pensamento estruturado, plausível e convincente, e consequentemente levá-lo à formação de um juízo de valor crítico e coerente.

Nesse processo de construção do conhecimento fizeram-se várias discussões durante as sessões presenciais; proporcionou-se a apresentação pública dos trabalhos num encontro científico internacional: a 8ª Assembleia Luso Espanhola de Geodesia e Geofísica, em Évora entre 29 e 31 de Janeiro; e finalmente elaboraram-se os artigos científico que se publicam neste livro.

Évora, 15 de Outubro de 2014

Bento Caldeira e Maria João Costa
Docentes da unidade curricular Seminário

Agradecimentos

Os docentes das Unidades de Seminário do programa Doutoral em em Ciências da Terra e do Espaço e do mestrado em Ciências da Terra, da Atmosfera e do Espaço manifestam o seu reconhecimento aos autores dos trabalhos publicados. Um agradecimento especial ao Prof. Mourad Bezzegoud, diretor do Doutoramento em Ciências da Terra e do Espaço, por todo o apoio incentivo e conselhos, sem os quais este livro dificilmente existiria. Um profundo agradecimento aos orientadores que acompanharam os estudantes, ação que em muito fortaleceu a qualidade científica dos trabalhos aqui apresentados. Sem pretendermos diminuir todos os contributos dados por vários colegas para este trabalho, pretendemos demosntrar a nossa gratidão ao Dr. Domingos Romão (IIFA/UE) pela sua colaboração na concepção da capa e à Engª Cláudia Marques (IIFA/UE) pela sua permanente disponibilidade e pelo apoio na resolução dos problemas que surgiram para produzir o presente livro.

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AZORES SEISMOGENIC ZONES

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One condition to perform seismic hazard analysis is knowledge about seismogenic zones that is an invaluable source of information and play an important role because it is fundamental know the processes and properties that control the seismogenic zone. The aim of this work is distinguishing seismogenic zones in the Azores region applying different parameters such as the earthquake density, *b*-values, focal mechanism, historical seismicity and all of these conjugated within the geodynamic framework of the Azores. We identified 10 seismogenic zones plus the well known Mid Atlantic Ridge. The 10 zones we identified are over the major tectonic structures of the Archipelago, namely Terceira Rift and Linear Volcanic Ridges.

Introduction

Since the settlement in the XV century most of the Azores islands where struck by strong earthquakes that as caused severe damage. The seismicity records show that earthquakes occur in specific zones of the region, that correspond to the main tectonic structures associated to specific seismogenic zones, being a seismogenic zone where most earthquakes occur at the upper crust layer. It is important to know the role of earthquakes in the tectonics, namely the processes and the physic properties that control a seismogenic zone. The first model proposed by [1], is composed by 28 seismogenic zones taking into account the geotectonic setting of the Azores region, the space-time variations of the seismic activity and the geographical distribution of the seismic stations. [2] used previous work and reduced the number of the seismogenic zones to nine, being defined by their activity rate, the b-value and the maximum magnitude. Recently [3] proposed another model with seven zone using statistical methods, particularly goodness-of-fit tests.

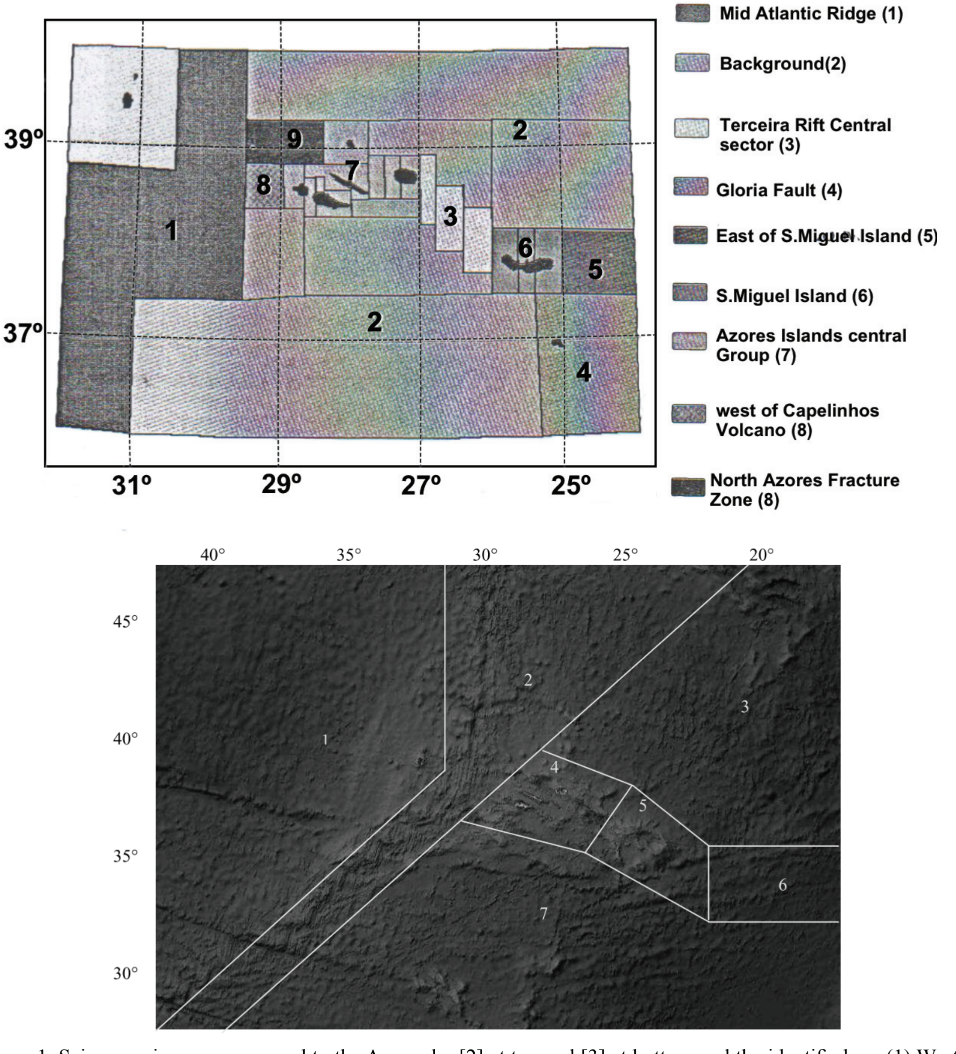

Figure 1. Seismogenic zones proposed to the Azores by [2] at top and [3] at bottom and the identified are (1) West of the Mid-Atlantic ridge, (2) Mid-Atlantic Ridge, (3) Northeast of Mid-Atlantic Ridge, (4) Azores Island Central Group, (5) Azores Island Eastern Group, (6) Gloria Fault, (7) South of Azores Islands.

1.1. The Geodynamic Framework of the Azores

The Azores islands rise from a platform (AP), based on the 2000 m bathymetric curve [4] that defines the Azores Triple Junction (ATJ) as the meeting point of the American, Eurasian and Nubian lithospheric plates (figure 2).

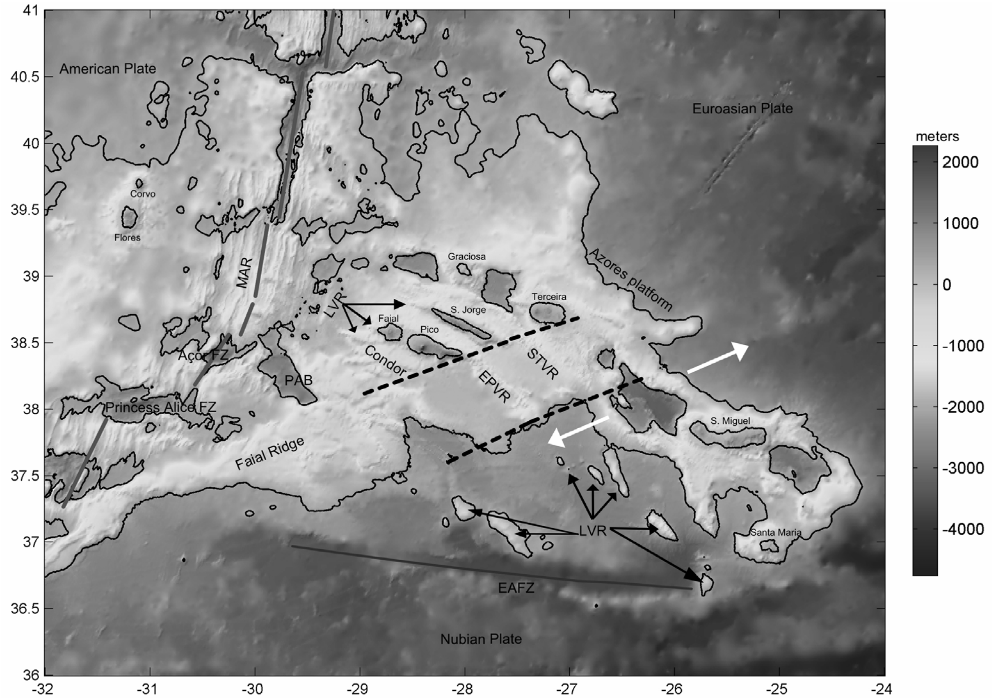

Figure 2. Major tectonic structures in the Azores (modified from [5]). STVR: South Terceira Volcanic Ridge, EPVR: East Pico Volcanic Ridge; LVR: Linear Volcanic Ridge; EAFZ: East Azores Fracture Zone, MAR: Mid-Atlantic Ridge. Black dotted lines separate different LVR sectors. The white vectors show the relative motion between Eurasian and African plates at around 7.56Ma [6]. In the background is shown the bathymetry from [7].

Due to its geodynamic setting various structures have a key role on the local tectonic. Some structures were seismically active in the past as West Azores Fracture Zone (WAFZ) [8] or even the East Azores Fracture Zone (EAFZ) that the lack of seismicity suggest that this structure is inactive or with low activity [9]. The major structures that entitle uncommon characteristics to the Archipelago are the Mid-Atlantic Ridge (MAR), the Terceira Rift (TR) and the Gloria Fault. The MAR is a pure extensional structure, seismically active, divided into several segments that give differential expansion rates. The expansion velocity of MAR, south of the Azores, is 1.3 cm/y, whilst to the north is 1.8 cm/y [10]. The earthquakes show leftward movements to the south and rightward movements to the north of the MAR [11]

The TR extends from the extreme west of the Gloria fault until the MAR and is characterized by a succession of volcanic massifs (islands) and basins. Most of the deformation of inter-plate deformation occurs in TR but not exclusively. The fractures zones defined by S.Jorge island and Pico-Faial islands are also responsible by a significant deformation. A morpho-structural analysis concludes that the Azores region is controlled by two sets of conjugated faults with N120º and N150º strikes that are the directions that establish the framework for the distribution of the volcanism [12],[13]. [12] and [13], have classified the linear volcanic ridges (LVR) into three categories. The first category includes S.Jorge, Faial and Pico islands and the "Condor" ridges showing an axial orientation of N120º, while the second category encompasses the East Pico Volcanic Ridge (EPVR), the South Terceira Volcanic Ridge (STVR) having axial orientations of ~N135º - N140º. The third category of LVR occurs to the south of S.Miguel island and the axial orientation range from N150º up to N-S orientations. From these three categories, the first LVR is the one that is more recent and active with evidence of ridge propagation westwards and earthquake activity located to the west of sector one [13]. Volcanism in sectors two and three of LVR are less robust [13]. This region is active in terms of seismicity and volcanism. The limits of plate boundaries are not well defined between Eurasian and Nubia [14][15], however, it is classified as a slow-spreading ('hyper-slow') plate boundary, with opening rates of 4 mm/y [16].

The segment to the east of Santa Maria is called Gloria fault, with 400 km of extension along an N85E direction and seismically active along almost all its extension [17]. The focal mechanism of the (8 May 1939, M_S7,1) earthquake shows a right lateral-slip fault [18].

Different authors have proposed models that try to accommodate the different structures working altogether. It is not the aim of this paper to describe all the models (for a revision see [8], [19], [10], [20], [21], [22] and [23]).

Despite the different opinions about the model that fits better to the Azores region and the evolution of ATJ [24] state that at 10 Ma Azores ago, the region were delimited by a microplate and the southern limit was the Princess Alice Fault Zone (PAFZ). Then, ATJ have jumped from the intersection of the MAR with the PAFZ to the intersection with the Açor Fracture Zone (AFZ), and then to Faial and Pico, that is a result of this migration [24].

1.2. Tectonic of the islands

The Azores islands represent a small expression of a wide and complex tectonic setting giving some indicators of the regional tectonic that is inaccessible, being the volcanism of the islands strongly constrained by the tectonics. To describe the tectonic of each island we gathered faults directions from geologic and volcano-tectonic maps using works of [9], [25], [26], [27], [28], [29], [30], [31], [32] to fill information lacks. We considered the identified faults, and inferred faults from volcanic cones alignments. Nevertheless, some authors drew probable faults or other tectonic structures that we do not take in consideration due to the subjectivity of each author. We also exclude tectonic of Corvo and Flores islands because they are settled in an intraplate environment and seismicity is almost null. Figure 3 show the tectonic patterns of the islands along Terceira Rift where it is possible identify four groups according with their tectonic pattern. The first group of islands (S. Jorge, Faial and Pico) the dominant orientation is N124º; the second group consists of Graciosa and Terceira islands and the dominant direction of tectonic structures is N146º. The third group comprises only S.Miguel island that exhibit a tectonic pattern more complex with two dominant directions, N124º and N169º although without neglecting the direction N146º. Finally, the fourth group also comprises only one island, Santa Maria with a tectonic general trend N169. S.Miguel island by accumulating the typical directions of the Central Group, and somehow S.Maria island, suggests it accumulates all type of tensions generated on the ATJ working as a proxy.

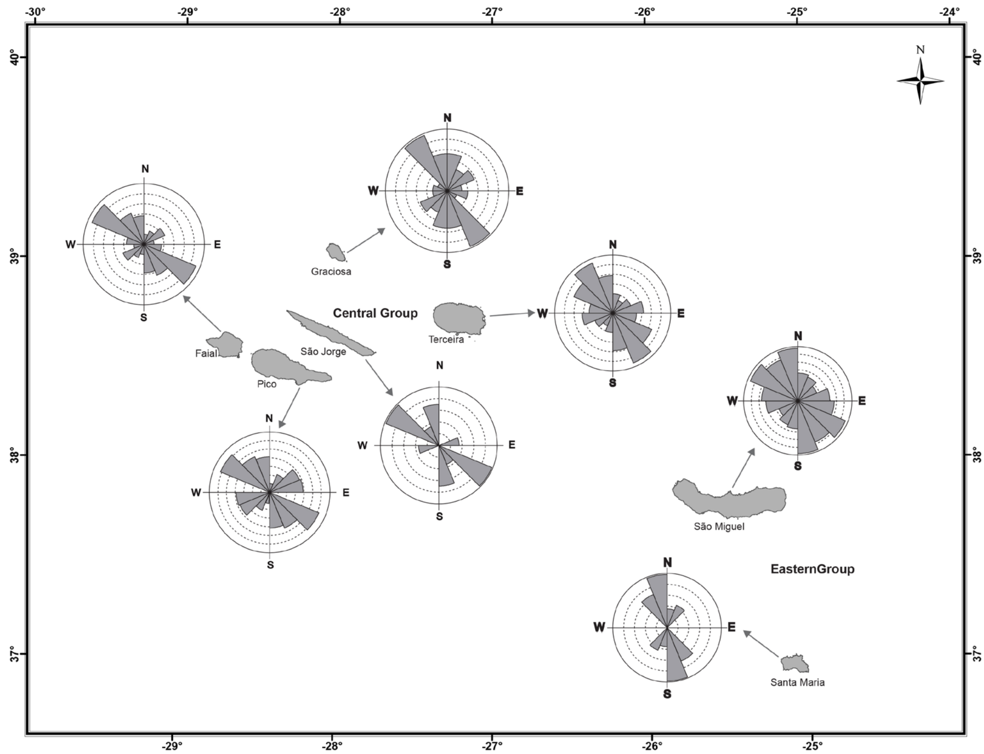

Figure 3. Average tectonic pattern of each island of the Central and Eastern groups of the Azores Archipelago. Each bar on the graphs has 11,25º and the nunber of tectonic structures in each bin is variable.

1.3. Seismicity and data set

The Earthquake Catalog in the Azores region is very limited on time, considering the settlement in the Azores islands was on century XV. First description of an earthquake refers to the one of 22 October 1522 that struck S.Miguel island and triggered a massive landslide that buried Vila Franco do Campo and killed around 5 000 people.A new era started in 1902 with the installation of the first seismometer in Ponta Delgada (S.Miguel island), and then in Terceira (1932) and Faial islands (1957). After the Terceira earthquake (1980, M7.2) the University of the Azores start operating a seismic network with 8 seismic stations in S.Miguel and 6 in Terceira island. Since them, seismic activity has been recorded consistently with minimum of quality.

The annual number of recorded earthquakes in Azores between 1915 up to mid 2012 (figure 4) is marked by a rapid rise after 1980 due probably to the increase of the seismic activity but also the improvements of the seismic network. Since 1980, four main episodes are distinguished: (i) in 1989 seismic swarm on the area of Fogo-Congro volcanoes in S.Miguel island; (ii) The Mw6,1 earthquake (Global Centroid Moment Tensor - GCMT) in 1998 and the following long aftershocks sequence; (iii) The 2005-2006 that occurred again in the area of the Fogo-Congro volcanoes and (iv) The Mw6.3 (GCMT) 2007 earthquake in the area of the Formigas isl

In fact figure 4 suggests how limited is the time span with minimum quality of the earthquake recorded in the Azores. Other problems arise such as the minimum magnitude completeness of the earthquake catalogue and non-homogeneity of the reported magnitude type. The entire earthquake catalog [33] of recorded event is used to assess the spatial distribution and for other analysis specific filters are applied. [33]. To evaluate *b*-values where we wish obtain stable results we cut off the earthquake catalogue to the last 12 years (mid 2000 - mid 2012), and we declustered method developed by [34]. Focal mechanism solutions, were selected from global databases such as GCMT ([35], [36]) or ISC ([37]) and in individual studies. The most recent reviewed and published focal mechanism is selected when duplicates were found. The number of focal mechanism solutions of database is 259 (table 1).

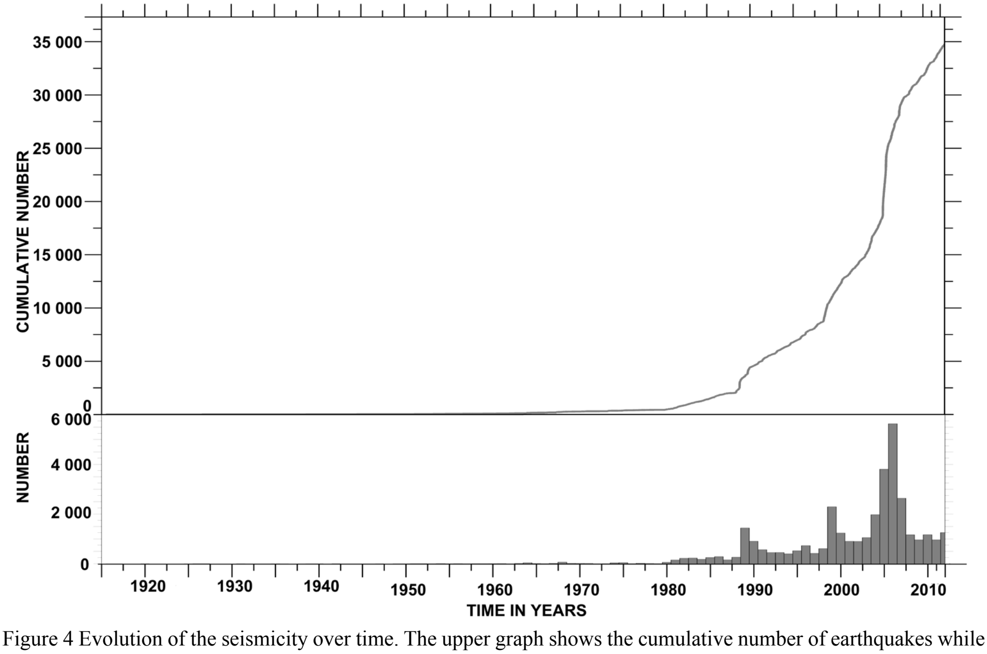

Figure 4 Evolution of the seismicity over time. The upper graph shows the cumulative number of earthquakes while the lower graph is the earthquake frequency.

Table 1. Number of focal mechanism solutions by source contributions

Source	N.º of focal mechanism solutions
[35] [36] [37]	179
[38]	26
[39]	20
[40]	18
[41]	13
[42]	2
[43]	1

2. Definition of seismogenic zones

To identify seismogenic zones, the earthquake density was evaluated with a tool provided in ZMAP software [44] for the entire earthquake catalog (1915 – 2012). The map of figure 5 depicts the earthquake density on the Azores region (cold colors indicate low seismic activity and warm colors high values) and give good indicators about earthquake distribution. Several seismogenic zones identified (red colored zones, figure 5) are associated with the major tectonic structures of the Archipelago. However, S.Jorge island, where occurred an MMI XI earthquake in 1757, it seems to be an exception since the earthquake density is low. In a stable geodynamic environment such as the Flores and Corvo Islands the seismicity is very low. One should notice that the earthquake density parameter does not discriminate volcanic or tectonic earthquake sources.

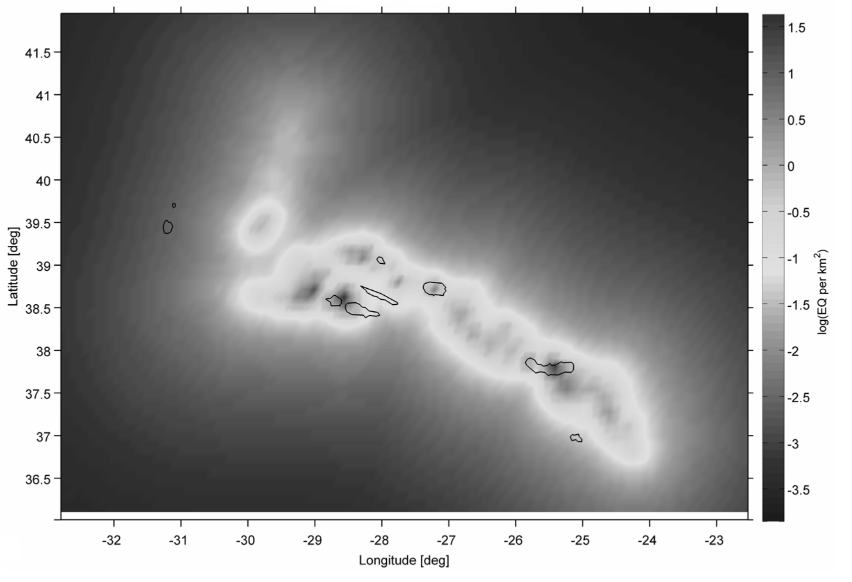

Figure 5. Earthquake density in the Azores region between 1915 - mid 2012. Cold colours mean that does not exist earthquakes (blues) while warm colours (orange - reddish) mean a strong earthquake density. Data time span 1915-2012 [33]

After we identified zones showing high earthquake density, one proceed with the study of *b*-value that is given by $\log_{10}N = a - bM$, where N is the number of events with magnitude greater or equal to M, *a* and *b* are constants related to the activity and earthquake size distribution [45]. The last 12 years (2000 - mid 2012) of the catalogue is selected for this analysis in order to avoid periods with low data quality, high minimum magnitude of completeness or heterogeneity of magnitude scales reported. Seismogenic zones are identified using the trial and error methodology and by testing testing different areas in the same zone. The process was repeated until stable b-values were obtained. 11 seismic zones are finally proposed as shown in the map of the figure 6. For each zone b and a values, number of earthquakes with $M \geq 5$ and maximum magnitude are given (Table 2)

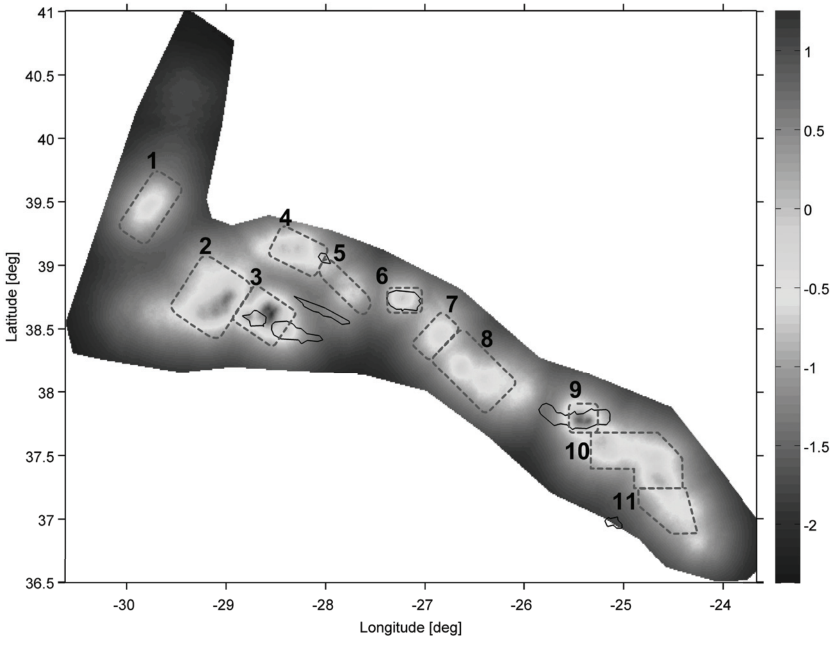

Figure 6. Seismogenic zones defined with methodology of trial and error until we get stable b-values. The values of each zone are in table 2. Background show earthquake density time span 2000 -mid 2012 [33]. Cold colours mean that does not exist earthquakes (blues) while warm colours (orange - reddish) mean strong earthquake density

The b-value can be high when perturbed by an increase of material heterogeneity ([46]), or thermal gradient ([47]) while, an increase in applied shear stress ([48]), or increase in effective stress ([49]) decreases the b value. The b-values range between 0,72 in the Terceira island up to 1,57 in the Mid Atlantic Ridge. The highest b-value found should be considered with some caution because the seismicity recorded is very distant of seismic sensors. Despite a-value only represent seismicity activity of the region, it demonstrates that each seismic zone has a different activity. If we take in consideration the *b*-value of the Central Group with the one of Eastern group, the difference is also evident. The values are 1,28±0,14 and 0,82±0,17, respectively that emphasise significant differences in strain between the MAR - Terceira and Terceira - Gloria Fault. These differences are also corroborate by the total seismic moment tensor [50] (figure 8).

Table 2. Characteristics of each seismogenic zone.

Seismog. zone	a-value	b-value	n.º EQ ≥5	Mag. max.
1	5,9	1,57	2	5,1
2	4,9	1,26	5	6
3	3,9	1,17	2	5,8
4	4,1	1,21	2	5,7
5	2,9	1,06	1	7,2
6	1,7	0,72	-	-
7	4,4	1,41	2	5,4
8	4	1,10	7	5,9
9	2,5	0,93	-	-
10	3,4	0,79	6	5,5
11	3,2	0,85	4	7

Then we correlate these areas with focal mechanisms, tectonic of the islands and historical seismicity. Figure 7 show the focal mechanism solutions between 36N-42N and 23W-34W latitude and longitude, respectively. Analyzing focal mechanism solutions of the Mid-Atlantic Ridge (MAR) in the area defined by the Azores Platform the events are of normal fault type except between 38,5N-39,5N, where the events are marked strike-slip. The seismicity generated in the area that comprises MAR up to the Terceira island are strike slip and in some cases strike-slip with normal component. The last two strong earthquakes occurred in this region - near Terceira island (1980/01/01, M7,2) and the other one by Faial island (1998/07/09, Mw6.2) - were pure strike-slip events with slip direction N150E and N153E, respectively. The region between Terceira and S.Miguel islands is characterized by normal mechanisms with strike-slip component and strike-slip mechanisms. The Formigas islet is located between S. Miguel and Santa Maria Islands and it is one of the most active tectonic structures of the Azores region. This region characterized by normal mechanisms, some of them with a component of strike-slip motion was struck by two strong earthquakes (2007/07/05, Mw 6,2, and 2013/04/30, Mw 5,7, NEIC). In the Central and Eastern group the total seismic moment tensor obtained by [50] show predominantly normal faulting. It is also notorious the rotation of pressure and tension axis from the Central group to the Eastern group [51]. Moreover, the values of slip velocity obtained from seismic strain in shallow seismicity highlight differences between the two groups, where Central Group is 6,7 (mm/yr) and in the Eastern Group is 3.1 (mm/yr) [50].

On the other hand, comparing the historical seismicity (figure 9) with the seismogenic zones, we can see a strong correlation between them. In general, most of the seismogenic zones determined in this study fit very well to the seismicity of the region (figure 9). Nevertheless, seismicity in S.Jorge island is almost null, despite that, in the past, the strongest earthquake of the Archipelago was recorded in this Island (1757, XI MMS [52]). However, the epicenter still unclear [52], [53],[9].

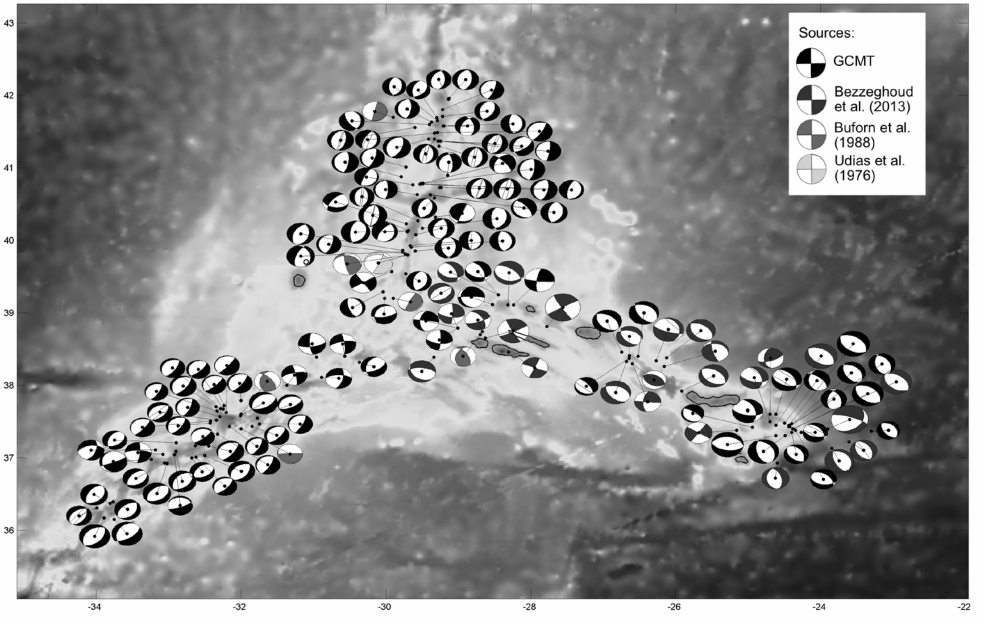

Figure 7. Focal mechanisms of the Azores Region. Data were limited to the following latitude and longitude 36N-42N and 23W-34W, respectively. Data covers period 1939 - 2013 and magnitude range 4.4 Mw - 7.1Ms. In the background is shown the bathymetry from[7].

3. Discussion and conclusions

Considering the geodynamic setting and the data available to the Azores is difficult to know all the seismogenic sources. The tectonic of the islands is constrained by the deformation of the internal structures of the Azores Plateau [5]. Geodetic data depicts Graciosa island followed the average movement of Eurasian plate, Santa Maria islands express the same vector of Nubian plate while the other islands show a behaviour of inter plate deformation[54]. The seismicity generated on the region is characterized by a high frequency of events with low energy radiate and is associated to the main tectonic structures of the region or active volcanoes.Although contiguous areas exhibit different *b*-values that express different stress fields, material heterogeneity and thermal gradient, but can not discriminate which one. Despite that, is a good technique to distinguish seismicity in contiguous areas. Focal mechanisms are another source of information of seismogenic sources, is possible identify rupture behavior and geometry. Crossing all this information allow us distinguish 10 seismogenic zones plus MAR (figure 10). We differentiate MAR from the others because it is well identified as a seismogenic source in his all extension while the other 10 zones, the sources are not all known. Some zones are well defined such as 3, 4, 6, 7, 8 9 and 10 and MAR. Zones 1 and 2 are the ones that are less clear if it is a single seismogenic zone or two. We separate in two zones because the first zone has significative number of a strong earthquake probably due to being near or in transition of the Terceira Rift to the Gloria Fault. The second zone presents less seismic activity and maximum magnitude are lower compared with previous zone. Zone 7 is another one whose definition could be controversial; however, the b-values are very clear despite this is one of the areas with hypocenters at abnormal deep ([55]). S. Jorge island constitutes a problem because seismicity is very low and close, however, on the past the strongest earthquake in the Azores Archipelago was in the island. S.Jorge is intercalated by two seismic zones, namely the 3, at south, and 5 at north. In these two seismic zones occurred two strong earthquakes in 1980 and 1998 (figure 9).

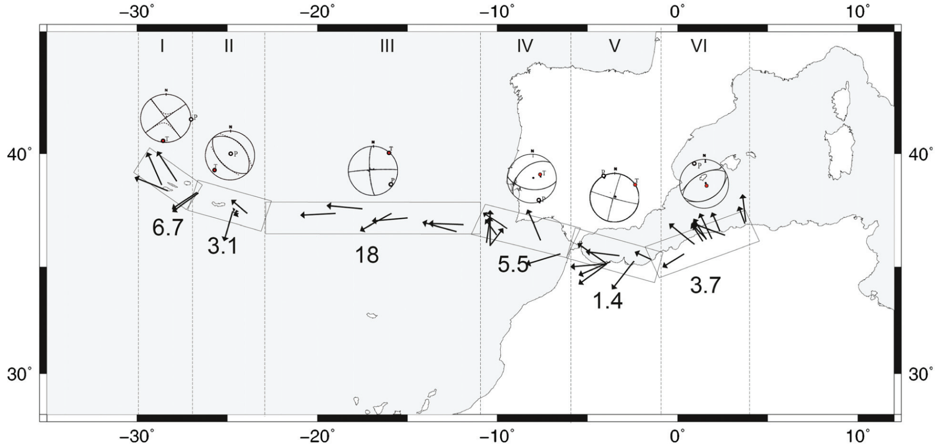

Figure 8. Total seismic moment tensors and horizontal projection of the slip vector for earthquakes between MAR up to North Algeria. The criterias to select earthquake are depth ≤40 Km; M≥5.5. (figure source:[50]).

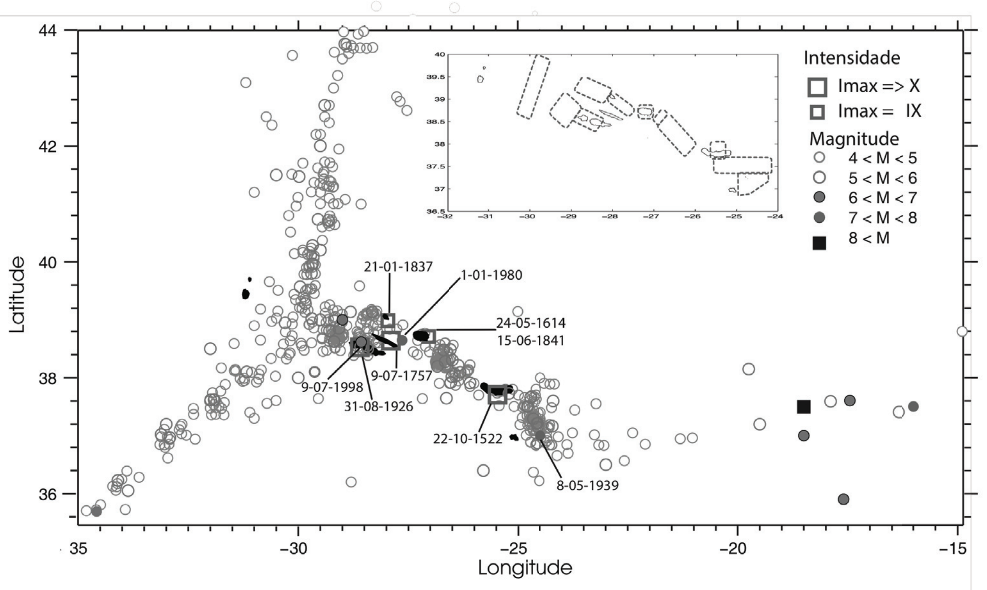

Figure 9. Seismicity in the Azores. The earthquakes are represented by circle and M ≥ 4, and the historical events (max. intensity ≥ IX) are the empty blue boxes. The inset are the seismogenic zones delimited.

The seismogenic zones proposed by [1] are very detailed, and include zones with low or absent seismicity and some of the zones that the authors consider different belong to the same zone. This high number is related with the criteria the authors used to define seismogenic zones. Some of the zones identified coincide with our work. Comparing seismic zones defined here with the ones proposed by [2] show some similarities. However [2] prefer distinguish big zones such as Azores Islands Central Group, Gloria Fault and S. Miguel. Some zones we do not understand the limits defined, where the seismicity is very low or absent such as the eastern part of S.Miguel and to the east, western and to the south of Santa Maria and to the north and south of the Azores Archipelago. The model proposed by [3] it is generic, overestimating the area of seismogenic zones identified and consider zones of stable tectonic environment, without seismicity as seismogenic zone . The results show that the methodology chosen is not adequate to define seismogenic zones in a complex area such as the Azores. In fact the three models do not consider seismotectonic models of the region.

During this work was notorious the differences of seismicity in contiguous areas, that represent different strain fields, material heterogeneity and that poses problems in the seismic hazard analysis. Our main concerns were defined seismogenic zones whose seismic origin were homogenous avoiding mixture volcanic seismicity with tectonic seismicity. Despite these origins are strongly related making it difficult to distinguish especially in the Azores geodynamic setting. We conclude that our approach to define seismogenic zones in the Azores fits well to the tectonic and considering data available. We distinguished 10 seismogenic zones plus the MAR seismogenic source. The zones we identified fits with the historical seismicity, almost of the important events fall in zones defined. However S.Jorge island does not fit in any seismogenic zone despite the major earthquake of 1757.

4. Acknowledgments

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