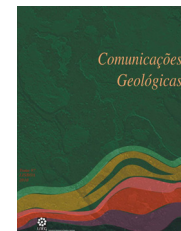# Azores seismogenic zones

Zonas sismogénicas dos Açores

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Artigo Curto
Short Article

Abstract: 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.

Keywords: Seismogenic zones, b-values, Focal mechanisms, Seismic hazard, Azores.

Resumo: As zonas sismogénicas constituem uma fonte de informação dos processos e propriedades físicas que controlam a zona. O objetivo deste trabalho é identificar zonas sismogénicas na região dos Açores, aplicando diferentes tipos de informação, nomeadamente, densidade sísmica, valores de b e a, mecanismo focal, sismicidade histórica. Identificamos 10 zonas sísmicas mais a Crista Média Atlântica. As 10 zonas que identificamos estão directamente relacionadas com as principais estruturas tectónicas do Arquipélago, nomeadamente o Rift da Terceira e as cristas vulcânicas formadas por Faial-Pico e São Jorge.

Palavras-chave: Zonas sismogénicas, Valor-b, Mecanismo focal, Perigosidade sísmica, Açores.

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1. Introduction

One could define seismogenic zone as the upper crust layer where most earthquakes happen. It is important know the role of earthquakes in the tectonics, namely the processes and the physic properties that control a seismogenic zone. For Azores, several authors did this work as if detailed tectonic studies of the Azores are limited to the islands. The first model proposed by Nunes *et al.* (2000) 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. Carvalho *et al.* (2001) used the previous work and reduced the number of the seismogenic zones to nine, defined by their activity rate, b-value and the maximum magnitude. Recently Rodrigues & Oliveira (2013) proposed another model with seven zone using statistical methods, particularly goodness-of-fit tests.

1.1. Seismicity and data set

The annual number of recorded earthquakes in Azores between 1915 up to mid 2012 (Fig. 1) is marked by an increase after 1980 due to increase of the seismic activity but also the improvement of the seismic network. Since 1980, 4 main episodes are distinguished: (i) in 1989 seismic swarm on the area of Fogo-Congro volcanoes in S. Miguel island; (ii) The Mw 6.1 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 Mw 6.3 (GCMT) 2007 earthquake in the area of the Formigas Islet.

The entire earthquake catalog (Fontiela *et al.*, in preparation, a) is used to assess spatial variability. Focal mechanism solutions were selected from global databases such as GCMT (Dziewonski *et al.*, 1981; Ekström *et al.*, 2012) or ISC (2011) 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.

2. Definition of the seismogenic zones

Seismogenic zones are defined by evaluating the earthquake density (average number or earthquakes by square kilometer) using the ZMAP software (Wiemer, 2001) for the entire earthquake catalog (1915-2012). The map of the figure 2a depicts the earthquake density on the Azores region (cold colors indicate low seismic activity and warm colors high values) and give a good clues about

earthquake distribution. Several seismogenic zones (red colored zones, Fig. 2a) identified are associated with the major tectonic structures of the Archipelago. However, S. Jorge Island, where an MMI XI earthquake occurred in 1757, is 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.

For each zone showing a 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 (Gutenberg & Richter, 1944). 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 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 2a. For each zone b and a values, number of earthquakes with M ≥ 5 and maximum magnitude are given in the table in the figure 2a. The b-values range between 0.72 in the Terceira Island up to 1.57 in the Mid Atlantic Ridge (MAR). The b-value can be higher than 1 zones with an increase of material heterogeneity (Mogi, 1962), or thermal gradient (Warren & Latham, 1970) and bellow 1 in zones of high applied shear stress (Scholz, 1968), or increase in effective stress (Wyss, 1973). The highest b-value corresponds to zones where the closest seismic stations are very distant (hundreds of kilometers). The a-value, that represents the seismicity rate of the region, varies between 1.7 and 5.9, showing the difference of activity of each seismic zone. The b-value of the Central Group (zones 2, 3, 4, 5 and 6, Fig. 2a) and the Eastern Group (zones 7, 8, 9, 10 and 11) are 1.28±0.14 and 0.82±0.17, respectively, emphasizing significant differences in strain between the MAR-Terceira and Terceira-Gloria Fault. These differences recently corroborated by Bezzeghoud *et al*. (2014) using the total seismic moment tensor.

Then, we correlate these areas with focal mechanisms, tectonic of the islands and historical seismicity. The focal mechanism solutions of the MAR show mainly normal fault type except between 38.5ºN – 39.5ºN, where the events are due to 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, Mw 7.2) and the other one by Faial Island (1998/07/09, Mw 6.2) - were pure strike-slip events with slip direction N150ºE and N153ºE, 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 the Eastern Group, the total seismic moment tensor obtained by Bezzeghoud *et al*. (2014) show predominantly normal faulting. Borges *et al*. (2007) show a rotation of the pressure and tension axis from the Central group to the Eastern group as Bezzeghoud *et al*. (2014) measure a slip velocity, obtained from seismic strain, of 6.7 mm/yr and 3.1 mm/yr respectively for these two groups.

On the other hand, comparing the historical seismicity 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 (Fig. 2a). 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).
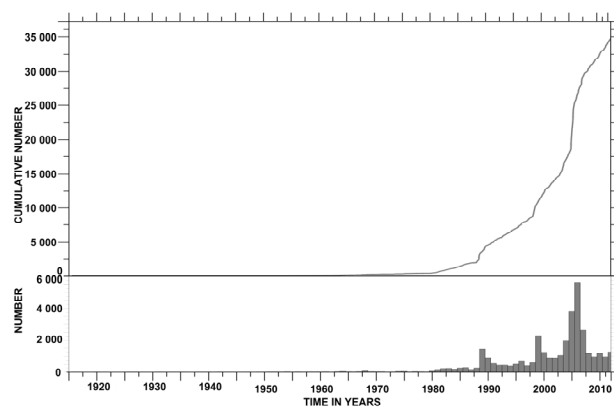

Fig. 1. Distribution of the recorded seismicity since 1915. The upper graph shows the cumulative number of earthquakes while the lower graph is the annual earthquake frequency.

Fig. 1. Evolução da sismicidade desde 1915. O gráfico superior mostra o número cumulativo de sismos enquanto que o inferior mostra a frequência dos sismos.

3. Discussion and conclusions

The tectonic of the islands is constrained by the deformation of the internal structures of the Azores Plateau (Neves *et al*., 2013). Geodetic data depicts that Graciosa Island follows the average movement of the Eurasian plate, the Santa Maria Island express the same vector as the Nubian plate while the other islands show a behavior of inter plate deformation (Fernandes *et al*., 2006). The seismicity of the region is characterized by a high frequency of events with low energy radiate and is associated with the main tectonic structures of the region or active volcanoes. Contiguous areas exhibit different b-values that could express different stress fields, material heterogeneity or thermal gradient. The complementary uses of different sources of information allow to distinguish 10 seismogenic zones plus MAR (Fig. 2a,b).

The zones 3, 4, 6, 8, 9, 10 and MAR are clearly identified by the earthquakes density, b-values and focal mechanism. Zones 1 and 2 could be grouped into one, nevertheless the first one has a significative number of strong earthquakes probably located in the transition of the Terceira Rift to the Gloria Fault as the second zone presents a lower seismic activity of lower magnitude. The limits of zone 7 could be also controversial but the estimate of b-values is very stable despite the hypocenters depths are abnormally high (Fontiela *et al.*,

in preparation, b). The low seismic rate of the S. Jorge Island constitutes a problem because the strongest earthquake (intensity XI in 1757) in the Azores Archipelago occurred in this island. But, southward, in zone 3, occurred the M7.2 earthquake in 1980 and northward, in zone 5, the Mw 6.2 event in 1998 as shown in the map of Figure 2b.

The proposed approach to define seismogenic zones in the Azores fits well with the tectonic seismic data.

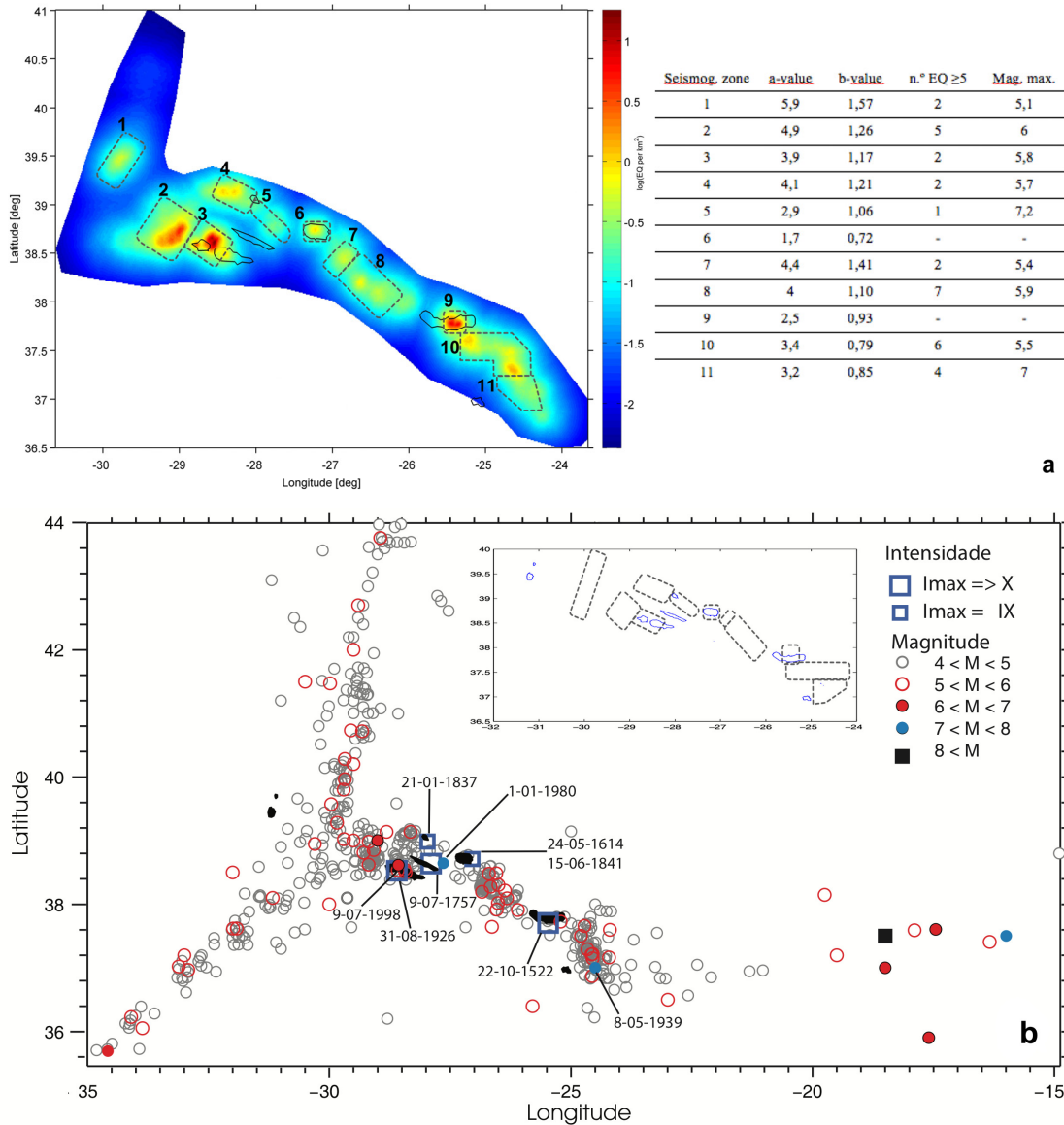| Seismog. zone	a-value	b-value	n.º EQ ≥5	Mag. max.
1	5,9	1,57	2	5,1
2	4,9	1,26	5	6
3	3,9	1,17	2	5,8
4	4,1	1,21	2	5,7
5	2,9	1,06	1	7,2
6	1,7	0,72	-	-
7	4,4	1,41	2	5,4
8	4	1,10	7	5,9
9	2,5	0,93	-	-
10	3,4	0,79	6	5,5
11	3,2	0,85	4	7

Fig. 2. a) Definition of seismogenic sources. The colored background expresses the earthquake density calculated for the time span 2000 -mid 2012; cold colors mean low rate of earthquakes (blues) while warm colors (orange - reddish) mean high density. Each seismogenic source (dashed line) is defined by its *b* and *a* values, number of earthquakes M≥5 and maximum magnitude of each zone as given in the Table at right. b) Historical and instrumental seismicity in the Azores. Instrumental earthquakes of M ≥ 4 and historical events of intensity ≥ IX are represented with color and shape codes. The inset map shows the different seismogenic zones.

Fig. 2. a) Zonas sismogénicas definidas através da metodologia de tentativa e erro até obtermos valores de *b* estáveis. A tabela, à direita, contém os valores de *b* e *a*, o número de sismos M≥5 e magnitude máxima registada em cada zona sismogénica. O fundo da imagem mostra a densidade sísmica no período compreendido entre 2000 até Junho 2012. As cores frias (azuis) significam que não existem sismos enquanto que as cores quentes (laranja-vermelho) significam que existe uma elevada densidade sísmica. b) Sismicidade histórica representada por quadrados vazios com intensidade ≥ IX; os círculos representam a sismicidade instrumental com M ≥ 4.

Acknowledgments

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