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EDICIONES COMPLUTENSE

Grandes terremotos en Azores

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Resumen. La historia del archipiélago de Azores, desde el descubrimiento y colonización en la primera mitad del siglo XV hasta ahora, está marcada por los impactos sociales y económicos producidos por los terremotos, principalmente los de alta intensidad. La información compilada nos lleva a concluir que en este periodo 33 terremotos han afectado las islas de Azores con una intensidad igual o superior a VII, causando unas 6.300 muertes y la destrucción generalizada en algunas Islas del Archipiélago, principalmente en S. Miguel, Terceira, Graciosa, Faial, S. Jorge y Pico. La acomodación de los movimientos diferenciales que se producen debido al límite entre las placas eurasiática (EA), africana (AF) y norteamericana (NA) y también al volcanismo que ocurre en la región, son los principales responsables de la intensa actividad sísmica que ocurre en este archipiélago. Este trabajo revisa los temas científicos de los terremotos conocidos que han interferido severamente con la vida del pueblo azoreano a lo largo de su historia, a esos terremotos llamamos grandes terremotos.
Palabras clave: Terremotos de Azores; Sismotectónica de Azores; Mecanismo focal de los terremotos de Azores.

[en] Large earthquakes in the Azores

Abstract. The history of the Azores archipelago, from its discovery and settlement in the first half of the 15th century through the present, is marked by the social and economic impacts produced by earthquakes, mainly the high-intensity ones. Information that has been compiled leads to the conclusion that in this period, 33 earthquakes with intensity equal to or greater than VII have affected the Azores, which caused approximately 6,300 deaths and widespread destruction on some islands of the archipelago, principally S. Miguel, Terceira, Graciosa, Faial, S. Jorge and Pico Islands. The accommodation of strain resulting from the dynamics of the Azores triple junction (ATJ) plate boundary and volcanism, which also occurs in the region, are the main factors responsible for the intense seismic activity in this archipelago. This work reviews the scientific issues of the known earthquakes that have severely interfered with the lives of the Azorean people throughout their history, which we call large earthquakes.
Key words: Azores earthquakes; historical earthquakes; seismotectonics of Azores; focal mechanisms.

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Summary: 1. Introduction, 2. Geodynamic and Seismotectonic setting of the Azores, 3. The large earthquakes in the framework of the Seismicity of the Azores, 4. Focal Mechanism of the Large earthquakes, 5. Final Remarks, 6. Acknowledgements, 7. References.

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1. Introduction

The historical information available, which describes the destructive effects caused by earthquakes, shows spatial and temporal gaps that are due in large part to the geographical distribution of the population. While for the Portuguese continental territory, there are historical reports of earthquakes back to the year 33 B.C. (Oliveira, 1986), in the Azores region, such information is not available before the beginning of the sixteenth century, when a sizable population began to occupy the islands. For these reasons, the entire oceanic region between the islands and the mainland lacks historical information that cannot be provided.

In 1932, in the celebrations of the V centenary of the Azores discovery, the Azorean writer Vitorino Nemésio claimed that…*the spirit of Azorean people does not include only the age of colonization: it is a reflex of a telluric past that geologists can convert in time if they wish,…our written memories include about fifty percent of reports of earthquakes and floods.* In fact, the effects of earthquakes and volcanoes have marked the lives of the Azorean people, as described the historical narratives of Frutuoso (1981), Chagas (1989), Montalverne (1961), Cordeiro (1981) and Maldonado (1711). Earthquakes mentioned in the records of significant memoir events of the Azores are also a recurrent issue (Bessone, 1932), found mainly in the archives of natural events such as Canto (1981 to 1986); Araújo (1801), Abranches (1877), and Mendonça (1758). After the middle of the 19th century, local newspapers such as "Açoriano Oriental", "Correio dos Açores" and "Diário dos Açores" become the main sources of information about earthquake effects.

Moreira de Mendonça (1758), in his book "Universal History of Earthquakes that have occurred around the world since its creation up to the current century", describes the catastrophic effects of tens of earthquakes in the Azores, such as the one in 1522 that destroyed Villa-Franca, at that time the capital of S. Miguel island, with estimated fatalities between 3000 and 5000 people: *On a Wednesday, October 22, the fourth day of the Moon, two hours before dawn, the weather being calm, and the Sky clear, without any cloud, when a horrible earthquake destroyed the mountain that was next to Villa-Franca, S. Miguel Island, and buried that capital, not being saved of her more than a small suburb of the West side, and two houses on the beach. Of these places there survived little more than seventy people…. in that day were repeated four more horrible earthquakes*. From the same author comes to us a description of another large earthquake in 1614: *On May 14, around three o'clock in the afternoon, Terceira Island was shaken by one horrible earthquake, which seemed to submerge the island. All the buildings were ruined: 28 Temples fell to the ground, where all the pulpits were maintained standing, respecting the truth that was* *announced in them. There were great ruins of lives, houses, and farms. In Praia town, no house remained standing.*

The *Observador* newspaper, in its edition of 8/8/2016, under the title *Earthquake of 1998 changed the island of Faial forever*, recalled that…*in the dawn of July 9, 1998, an earthquake with a magnitude of 5.9 on the Richter scale destroyed many houses in the municipality of Horta, the only one of Faial where houses traditionally built on stone and clay prevailed. In addition to the destruction of a large part of the housing stock in Faial and the eight deaths, the earthquake also damaged approximately 20% of the houses on the neighbouring island of Pico*. These are three descriptions of the many possible ones regarding the consequences of the earthquakes, sometimes with relatively low magnitudes, that throughout history have perturbed the stability of the Azoreans. In this work, we consider as large earthquakes the ones that affect the lives of people.

The catalogue of the International Seismological Centre (ISC) in the strip containing the Azores Islands (35º<LAT<42º; -35º<LONG<-22º) shows that the number of seismic events recorded between 1926 and 2017 with M>3 is 9420. Converting the magnitude of each earthquake to the seismic scalar moment (M0) and analysing the results, we find that 84.1% of the total seismic moment released in this area during the instrumental period was produced by only 7 of the earthquakes recorded. The conversion of magnitude into seismic moment was made using the empirical relations of Buforn et al. 2004, Kanamori (1977) and Borges (2003) for the events catalogued with the magnitudes Mb, Mw and Ms, respectively. These seven earthquakes, represented in Fig.1 are [1]- 8 May 1939 (Ms = 7.1 and 49.9% of the total M0); [2]- 1 January 1980 (Mw = 6.9 with 25.0% of M0); [3]- 5 April 2007 (Mw=6.3 with 3.2% of M0); [4]- 9 July 1998 (Mw=6.2 with 2.2% of M0); [5]- 7 April 2007 (Mw=6.1 with 1.6% of M0); [6]- 5 April 1926 (Ms=6 with 1.1% of M0); and [7]- 30 November 1992 (Mb=6 with 1.1% of M0).

The purpose of this study is to review the scientific issues of the known earthquakes with economic and social impacts in the Azores archipelago. Considering that the focal mechanisms of recent significant earthquakes are the information basis to understanding geodynamic and seismotectonic models of the Azores, this issue will be also addressed in the current study.

2. Geodynamic and Seismotectonic setting of the Azores

The epicentre map of instrumental seismicity (Fig. 1) shows the branches of the triple junction of the Azores region well defined to 24° W, along a sector that includes the Azores Plateau (AP) and extends from the Mid-Atlantic Ridge (MAR) to 24º W. The Azores Islands are located in this sector. Morphologically, the AP is a triangular structure with an area of approximately 400,000 km^2 that is roughly bounded by the 2,000-m bathymetric line. The AP stands out clearly from the abyssal plain, whose depths can exceed 3,500 m, and presents a strongly irregular topography consisting of peaks and volcanic ridges that reach the surface in seven places coincident with seven of the nine Azores islands (Corvo and Flores Islands lie within the North American (NA) plate).

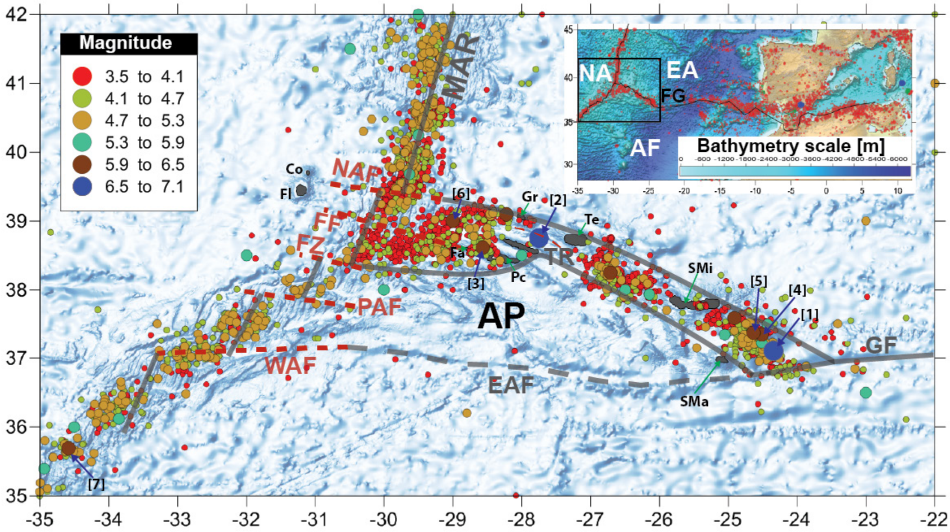

Figure 1. Top panel - Seismicity (M> 4.0) along the western part of the Eurasia-Africa plate boundary from 1926 to 2017 (from NEIC data files). Bathymetric data are from the GEBCO_2014 Grid. NA=North American plate, EA=Eurasian Plate, AF=African plate; the black rectangle corresponds to the Azores region area shown in the bottom panel. Bottom panel - Instrumental seismicity (M>3.5) for the Azores region from 1926 to 2017 and main tectonic accidents. The numbers between brackets correspond to the 7 earthquakes that represent 84.1% of the total seismic moment released in this area during the instrumental period (1926 - 2017): The island names are Co= Corvo; Fl= Flores; Fa= Faial; Pc= Pico; Gr= Graciosa; Te= Terceira; Smi= S-Miguel: SMa= Sta. Maria. MAR= Mid-Atlantic Ridge; TR=Terceira Ridge; NAF=North Azores Fracture Zone; FF= Faial Fracture; AF= Azores Fracture; PAF= Princess Alice Fracture; WAF=West Azores Fracture; EAF=East Azores Fracture; GF= Gloria Fault; AP= Azores Plateau.

The Azores Plateau is traversed in the N-S direction by the Mid-Atlantic Ridge (MAR), and its boundaries are: the North Azores Fracture Zone (NAF) with an E-W trend, which continues into the Terceira Rift (TR), trending SE and including the S. Miguel—Terceira—Graciosa, Faial—Pico and S. Jorge alignments, and the East Azores Fracture (EAF) striking E-W to the south, continuing to the Gloria Fault (GF) (Buforn et al., 1988; Luis et al., 1994).

The main tectonic feature of this region is the MAR, which intersects the approximate midpoint between Flores and Graciosa Islands. Its trend varies from N10°E to N20°E, and as it progresses south, it undergoes morphological changes: (i) MAR becomes less rugged, to the point where its median valley, well emphasized in other latitudes, essentially ceases to exist, possibly due to the influence of a mantle plume under the AP hotspot (Lourenço et al., 1998; Silveira et al., 2006), (ii) its thickness is sharply reduced (Luis et al., 1994).

The MAR is offset by five transform faults that have a general E-W trend (red dotted lines of Fig. 1). They are, from north to south: the North Azores

Fracture Zone (NAF), the Faial Fracture Zone (FF), the Azores Bank Fracture Zone (FZ), the Princess Alice Fracture Bank (PAF), and the West Azores Fracture Zone (WAF), which is also called the Azores Fracture. The EAF (grey dotted line of Fig. 1) extends to the east of the WAF to the GF, which defines the southern limit of the AP, where there are no records of any significant seismic events.

The Azores Plateau, which is formed by abnormally thick oceanic crust, may be related to the existence of a mantle plume. The arguments in favour of the existence of the mantle plume are based on observations of anomalous topography, gravitational distribution, crustal thickness, S- and P-wave velocities, and geochemical signatures (Silveira et al., 2006; Schilling, 1975; Zhang and Tanimoto, 1992; Montagner and Ritsema, 2001; Montelli et al., 2004). Reinforcing this hypothesis are the strong similarities between the types of lava found in the Azores and the lava types found in regions such as Iceland, whose origin is clearly associated with a hotspot, as shown by Madureira et al (2005). Global kinematic models based on geology (DeMets et al. 2010) or geodesy (Calais et al. 2003) provide similar spreading velocities for the Mid-Atlantic Ridge. From north to south, these velocities are as follows, in accordance with the Morvel model (DeMets et al., 2010): north of the platform, the expected velocity is approximately 1.7 cm/yr, and the average value to the south is 1.2 cm/yr (parallel to the transform faults). The same kinematic models suggest that in the third arm of the ATJ, there is relative motion between the EA and AF plates in the ENE-WSW direction in the Azores region, with a velocity of the AF plate relative to that of the EA of approximately 4.3 mm/yr in the WSW direction. The slip velocities derived from the total seismic moment of the significant earthquakes (Bezzeghoud et al. 2014) enable the identification of two distinct seismotectonic patterns in the Azores region: zone I, between MAR and Terceira Island (30°W to 27°W), and zone II, which corresponds to the oriental group of the Azores (27°W to 23°W). In zone I, the motions are compatible with left-lateral strike-slip faulting with horizontal pressure and tension axes in the E-W and N-S directions, respectively, and a slip velocity = 6.7 mm/yr in the SW direction. In zone II, the characteristic mechanism is normal faulting, with a horizontal tension axis trending NE-SW, normal to the TR, and an average slip velocity=3.1 mm/yr (Fig. 2). The verified rotation of the tension and pressure axes from zone I to zone II is interpreted by the authors as in agreement with the morphological features of the linear volcanic ridges.

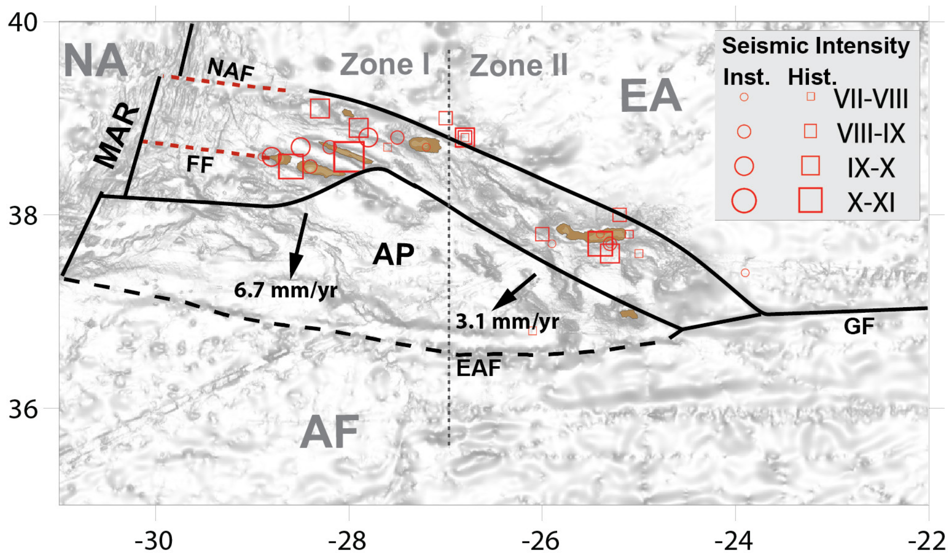

Figure 2. Epicentres of the 33 most destructive Azores earthquakes reported by Nunes et al., 2001. The squares represent historic earthquakes and the circles instrumental ones. The epicentre locations of the historic earthquakes were estimated from the distributions of the reported intensities. The black arrows represent the motion of the AF plate relative to the EA plate in the two considered seismotectonic zones of the Azores (zones I and II) (zones I and II) derived from the total seismic moment of the significant earthquakes

Different explanations have been proposed for the origin of the Terceira Rift. According to some authors, this ridge corresponds to an extensional zone normal to the MAR (Udías et al., 1976; Buforn et al., 1988; Udías 1980) or an oblique extension zone (McKenzie, 1972; Searle, 1980). Madeira and Ribeiro (1990) proposed a leaky transform model. Lourenço et al. (1998) postulated that a diffuse boundary simultaneously acts as an ultra-slow spreading centre and as a transfer zone between the MAR and the dextral Gloria Fault, because it accommodates the differential shear motion between the Eurasian and African plates. Vogt and Jung (2004) suggested that the Azores axis, with a length of 550 km, is the slowest spreading organized accreting plate boundary in the world, (seafloor spreading rates at the TR <1 cm/yr) with a typical mixture of faulting mechanisms that make difficult to understanding the dynamics of the ATJ. Nevertheless, the high level of seismicity along the MAR and the TR (Fig. 1) is strongly associated with seafloor spreading and the northeastward motion of the Eurasian plate with respect to the African plate (Luis et al., 1994).This argument was also supported by Fernandes et al. (2002), who proposed an elastic model with two possible locations of the Azores triple junction: along the extension of the TR at the same latitude as Graciosa Island or on the Faial fracture zone at the same latitude as Faial Island.

3. The large earthquakes in the framework of the seismicity of the Azores

In general, the seismicity of the Azores is dominated by a high number of earthquakes with low magnitudes and shallow focal depths (h<20 km). Nevertheless, earthquakes of moderate magnitude ($5 \leq M \leq 7$) have occurred in the archipelago, and some of them caused heavy damage and social losses. Since the settlement of the Azores, 33 earthquakes have occurred with MMI ≥ VII (Nunes et al., 2001), whose estimated epicentres are shown in Figure 2 and Table1. The most remarkable earthquakes according to the severity of caused losses were as follows:

— The October 22, 1522, earthquake of MMI X triggered a massive landslide that buried the first capital of São Miguel Island. Following the main shock, four strong aftershocks occurred, the first one very strong and arriving moments after the main shock. The death toll was approximately 5.000, and as a consequence, the main capital of the island was moved to the current one, Ponta Delgada. The epicentre was located on the south flank of Fogo volcano;
— On May 24, 1614, a strong earthquake with MMI X caused severe damage in the eastern part of Terceira Island and killed more than 200 people. According to the historical account of an anonymous source who witnessed the event, as related by Maldonado (1711), Lajes and Vila Nova were completely destroyed, and the ground cracks increased in depth and size from Vila Nova to Lajes, suggesting that the vertical peak ground acceleration was higher than the gravitational acceleration. The main shock was inserted into a seismic sequence that started on April 9, 1614, and lasted until November 20, 1614. The epicentre was located in the Lajes graben, a tectonic structure that lies in the northeastern part of Terceira Island with a general direction of NW-SE.
— On July 9, 1757, a strong earthquake of MMI XI struck São Jorge Island killing 1.046 people, one quarter of the population at that time. Machado (1949) estimated a magnitude of 7.4 through an empirical relation based on the area of perceptibility. According to Machado (1949) the epicentre was on a fault located in the channel between São Jorge and Pico Islands; however, Madeira (1998) states that the epicentre was by the north shore;
— On April 16, 1852, an earthquake of MMI VIII caused damage on Ribeira Grande - São Miguel Island. The death toll fell between 9 and 12. According to Nunes et al. (2001), the epicentre likely was located inland on Santana. The event caused severe damage not only in the parish of the north shore but also in Ponta Delgada city where some buildings collapsed.
— On August 31, 1926, Faial Island was struck by an earthquake of Ms 5.6 and MMI X, and the epicentre was located in the channel between Faial and Pico Islands. Horta city, as well as Flamengos and Praia do Almoxarife, suffered heavy damage that caused 9 deaths.
— On January 1, 1980, an earthquake of ML 7.2 and MMI IX caused heavy damage on Terceira Island, especially at Angra do Heroísmo but also at other settlements on the island. São Jorge and Graciosa Islands felt the devastating effects of this event. In total, the earthquake killed 61 people. Further details about the fault kinematics of this event are given in section 5 - Focal mechanisms of the large earthquakes.
— On July 9, 1998, another earthquake of Mw 6.2 hit Faial Island and caused heavy damage in the parish on the north side of the island and in other regions due to site effects, i.e., Flamengos and Lombega. In this event, 8 people were killed. Further details about the kinematics of the Faial earthquake are given in section 5 - Focal mechanism of the large earthquakes.

#	Year	Island and places more afected	Date	Max Intensity	Mag.	LAT	LONG	H0	N.° of deaths
1	1522	S. Miguel, V. Franca	22 October	X		37,7	-25,4	12	4000 to 5000
2	1547	Terceira, N zone	17 May	VII/VIII					> 3
3	1571	Terceira,		VII ?					
4	1591	S. Miguel, V. Franca	26 July	VIII/IX					unknow
5	1614	Terceira, Praia da Vitória, East	24 May	IX					> 200
6	1713	S. Miguel, Ginetes	08 December	VIII					
7	1730	Graciosa, Caldeira, Luz	13 June	VIII/IX?					
8	1757	S. Jorge, Calheta	09 July	XI	M=7.4	38,6	-28	10,7	1046
9	1800	Terceira, East island, Praia da Vitória	24 June	VII/VIII					
10	1801	Terceira, East Island, S. Sebastião	26 January	VIII					2
11	1837	Graciosa, Guadalupe and Sta Cruz	21 January	IX ?					3
12	1841	Terceira, Praia da Vitória, East	15 June	IX					
13	1852	S. Miguel, Rib. Grande	16 April	VIII					9 to 12
14	1881	S.Miguel, Povoação	09 February	VII ?					1
15	1912	Terceira, Angra do Heroísmo	26 January	VII					
16	1912	Terceira, Praia da Vitória	11 June	VII/VIII					
17	1926	Faial, Horta	31 August	X	Mb=5.3-5.9	38,5	-28,6	1.6-4.8	9
18	1932	S.Miguel, Povoação	05 August	VII		37,8	-25,1		
19	1935	S.Miguel, Povoação	04 March	VII					1
20	1937	Santa Maria, Sto Espírito	21 November	VII		36,8	-26,1		
21	1939	Santa Maria and S.Miguel, Sto Espírito and Rib. Quente	08 May	VII	Mb=7.0-7.1				
22	1945	Faial, Capelo	15 June	VII					
23	1946	Terceira, Serreta	27 December	VII/VIII					
24	1950	Terceira, Agualva	29 December	VII		38,7	-27,2		
25	1952	S.Miguel, Povoação and Rib.Quente	26 June	VII		37,7	-25,3		
26	1952	S.Miguel, Rib.Quente	26 June	VIII		37,7	-25,3		
27	1958	Faial, Praia do Norte and Rib.ª Funda	13 May	VIII/IX		38,6	-28,8	1	
28	1964	S.Jorge, Rosais	21 February	VIII	Mb= 5.5	38,7	-28,2	9	
29	1967	S. Miguel, M. Escuro	10 August	VII	M=4.6	37,8	-25,4		
30	1968	S. Miguel, Várzea	17 June	VII	M=4.6	37,7	-25,9		
31	1973	Pico, Bandeiras	23 November	VII/VIII	Mb=5.0	38,5	-28,4	16	
32	1980	Terceira, Doze Rib.ª	01 January	VIII/IX	M=7.2	38,8	-27,8	10	61
33	1998	Faial, Ribeirinha	09 July	VIII/IX	Mb=5.8	38,7	-28,5	1,2	8

Table 1. Epicentres of the 33 most destructive Azores earthquakes, adapted from Nunes et al., 2001

The map of maximum observable intensity (MOI) (Fontiela et al. 2017) shows that São Miguel, Terceira, Graciosa, São Jorge, Pico, and Faial have experienced at least one earthquake of MMI ≥ VIII in the last five centuries. According to the MOI maps, the south central part of São Miguel Island is the place where past strong ground shaking has been high (MMI X); on Terceira Island, the northeastern (MMI X) and western (MMI IX) parts are the ones with the highest strong ground shaking; the maximum ground shaking on the eastern part of Graciosa Island is equivalent to MMI IX; on Pico Island, the maximum intensity is VIII (MMI), and on Faial Island, the maximum ground shaking is X (MMI).

The seismicity on Flores and Corvo Islands is very low mostly due to their geodynamic framework because both islands lie on the North American plate. Notwithstanding, the first historical account goes back to July 1793 when an earthquake of undetermined intensity triggered a landslide (Nunes et al. 2001). According to the same authors, the following two earthquakes recorded on Corvo Island were in July 1968 with maximum intensity of III/IV and one on Flores Island on November 1981 with MMI III.

The instrumental period started in 1902 with the installation of the first seismic station on São Miguel Island, followed by a second instrument on Terceira Island in 1932 and a third one on Faial Island in 1957. The first earthquake reported in the earthquake catalogue of the International Seismological Centre is the one of July 18, 1923, whose epicentre was on the Mid-Atlantic Ridge (MAR). In a brief analysis of the ISC catalogue for the Azores region (Flinn Engdahl geographic region 405) during the period 1926-2016, we found 61 earthquakes of M≥5, and a maximum of 7.1 for the Terceira earthquake (January 1, 1980). The seismicity in the Flinn Engdahl geographic region 404 comprises 146 earthquakes of M≥5 mostly located on the MAR and to the west of São Miguel and Santa Maria Islands. The maximum magnitude recorded in this region is Ms~7 on May 8, 1939 (Fig. 1), with an epicentre east of Santa Maria Island.

On Figure 1, we observe that the seismicity is located on the MAR and along the Azores Islands, which comprise Pico, Faial, São Jorge, Graciosa, Terceira, São Miguel and Santa Maria Islands. These islands lie in a complex area classified as a diffuse boundary between the Eurasian and African lithospheric plates (Lourenço, 2007). The seismicity is organized in clusters. Based on the earthquake density and on the frequency magnitude distribution, Fontiela et al. (2014) identified 10 seismogenic zones around and on the Azores islands and one in the MAR. Later, Fontiela et al. (2017a) analysed the seismicity on a regular grid for the period 2000 - 2012 and found that the frequency magnitude distribution is extremely variable. Nevertheless, the authors recognized that the seismicity of the islands of Pico, Faial, São Jorge, and Graciosa and in the region between Terceira and São Miguel Islands is conditioned by a distinct buoyant upwelling as stated by Adam et al. (2013) and the crust is likely to be cracked as illustrated by the high number of small events. According to Fontiela et al. (2014), the low b-values in Terceira Island can be interpreted as an increase of shear stress or effective stress due to lateral compression (Navarro et al., 2003 and Miranda et al., 2012).

The seismicity on São Miguel Island is mostly located in the central part of the island, mainly between the Fogo and Furnas volcanoes. In between them exists another volcano called Congro. In addition, the region amongst these volcanoes is marked by intense geothermal activity as demonstrated by Dawson et al. (1985) using the

Vp/Vs ratio and by Zandomeneghi et al. (2008) through seismic tomography. The first seismic sequence recorded dates from 1922 and lasted two months with tens of earthquakes felt by the population; later on, between 1988 and mid-1989, another seismic sequence recorded more than 8.000 earthquakes (Nunes and Oliveira, 1999). In May 2005, a seismic sequence started, and lasted until late 2006, and thousands of earthquakes were recorded. Silva et al. (2012) analysed the focal mechanisms of several earthquakes located in different seismic clusters and concluded that on the Fogo Volcano, a normal regional stress field prevails, and at the contiguous volcano Congro, there is a highly heterogeneous stress field. The b-value in the central part of São Miguel Island is low (Fontiela et al., 2017a), which can be explained by the hypothesis that 75% of the displacement between the Eurasian and African plates is located on a narrow strip of 10-15 km in the central part of São Miguel (Jónsson et al., 1999).

The most active region of the Azores extends from south of São Miguel to eastern Santa Maria. The instrumental seismicity of the Azores since 1920 shows that several larger earthquakes (M>5.1) occurred as doublets (i.e., two events of similar magnitude separated by few hours). In the Formigas region, we have located the occurrence of the following doublets: in 1952 (May 26, at 13 h 06 m, Mb=5.5 and at 15 h 32 m, Mb=5.4), in 1966 (July 4, Mb=5.4 and 5 July, Mb=5.1) and in 2007 (April 5, Mw=6.3 and April 7, Mw=7).

From the analysis of the instrumental catalogues, the seismicity in the Azores is usually organized into seismic sequences, located mostly in the submarine areas. In general, the space-time distribution of seismicity follows two of the characteristic patterns of the earthquake sequences of the Mogi (1963) classification. The first, seismic swarms (type 3), is characterized by increased seismicity or earthquake swarms without any typical statistics or relationship with any major event; type 3 seismicity may be linked to an intensification of volcanic activity in the region. The second, type 2 seismicity, is associated with a main event followed by aftershocks whose rate decreases according to Omori's law (Matias et al., 2007). The main shock associated with type 2 seismicity sometimes occurs as an earthquake doublet. This behaviour is noted for both historical and instrumental seismicity across the whole region.

4. Focal mechanisms of the large earthquakes

The study of the focal mechanisms of Azores earthquakes is the basis of seismotectonic research that enables a characterization of its complex geodynamics. Since 1972, several studies of seismic sources have been performed in the Azores-Gibraltar region. Some of these studies were based on polarities, and some focused on modelling the form of the body waves.

Due to the moderate nature of the seismic activity in the Azores, together with the poor azimuthal coverage of the seismic area (unfavourable azimuthal distribution of stations regarding the epicentres), it is often a difficult task to obtain focal mechanisms for this area. Hence, the number of focal mechanisms currently available is relatively small in comparison with the data on the mainland of Portugal and other parts of the globe. Consequently, almost all of the currently available solutions calculated by global or regional institutions (NEIC - National

Earthquake Information Centre; USGS - U.S. Geological Survey; the seismology group at Harvard University; EMSC - European Mediterranean Seismological Centre) correspond to events of moderate to greater magnitudes (M>5.5) or were obtained by studies of regional and teleseismic data. It is important to highlight some of the studies that have significantly contributed to the understanding of the geodynamics of this region.

The first studies of focal mechanisms were performed by McKenzie (1972) and Udías and Arroyo (1972). Based on his results and previous knowledge of the region's seismicity, he established the first geodynamic model for the Azores-Gibraltar region. Arroyo and Udías (1972) studied the focal mechanism of the 1969 earthquake and its aftershock sequence, which allowed estimating the fault dimensions and the source parameters for this earthquake. From the focal mechanisms of four earthquakes that occurred near the MAR and the Azores region, the authors interpreted these results in the context of the Azores-Gibraltar seismotectonics. Udías et al. (1976) studied the seismicity and the focal mechanisms of the Azores-Alboran region using new data and proposed a new seismotectonic model for the entire region based on changes in the seismicity and focal mechanisms. As a consequence of the different character, both in seismicity and a focal mechanism, of the region (between the MAR in and Gibraltar), the authors suggested a division into four different subzones. Later, Grimison and Chen (1988), using the World Wide Standardized Seismograph Network's (WWSSN) long-period records, obtained the focal mechanism of the January 1, 1980, earthquake from body-wave modelling, bringing to light for the first time the complex nature of the rupture process that characterizes the earthquakes in this region.

The distribution of more than 400 aftershocks of the January 1, 1980, earthquake recorded by the telemetric seismic network installed on Terceira, S. Jorge, Graciosa, and Pico Islands shows a N150°E trend; this agrees with one of the fault planes estimated for the main shock and indicates pure left-lateral strike-slip motion along a vertical plane between 149° and 154° (Buforn et al., 1988; Grimison and Chen (1988); Hirn et al., 1980). Hirn et al. (1980) obtained a composite solution for the aftershocks that coincides with that for the main event using polarities recorded by a temporary network. A detailed analysis of the distribution of epicentres allowed for alignments with azimuths to be identified that agreed with the fault of the January 1, 1980, earthquake. During the recording period, there were two events of moderate magnitude (magnitudes 3.2 and 3.4) with epicentres located near of the epicentre of the main shock. The focal mechanism solution obtained describes strike-slip motion with nodal planes similar to those of the main event (Borges et al. 2007; Buforn et al., 1988). Buforn et al. (1988) analysed, among others, eight focal mechanisms for events located on the AP (where they found a diversity of mechanisms without any identifiable patterns) and eleven earthquakes on the MAR (where normal and strike-slip fault mechanisms are typically associated with spreading ridge). These results provided a more detailed outline of the geodynamic behaviour of the area and determined its seismic deformation rate. Fig. 3 shows the available earthquake mechanisms of the Azores region between longitudes 30°W and 24°W; from them, it is possible to deduce the mechanism pattern of the area.

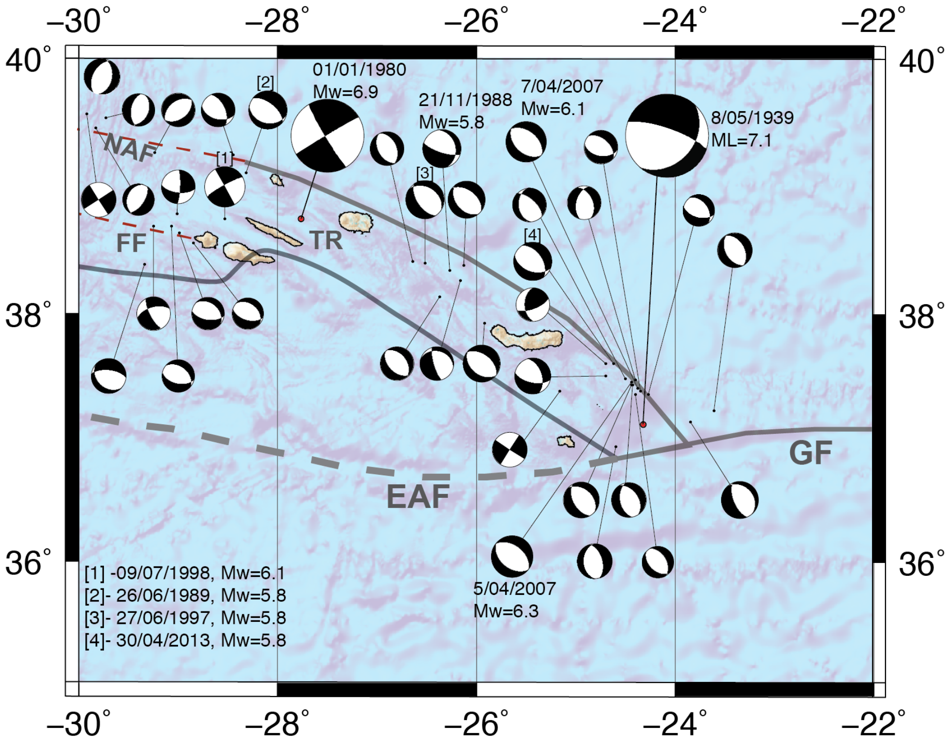

Figure 3. Available earthquake mechanisms from the occidental segment of the EA-AF boundary that corresponds to the Azores region.

After the 1998 Faial earthquake (event [1] in Fig. 3), a temporary seismic network composed of seven short-period stations was installed on Faial, Pico, and S. Jorge Islands. More than 1200 aftershocks were recorded, showing NNW-SSE to ENE-WSW alignments (Vales et al., 2001). The good azimuthal coverage offered by the temporary network and the dynamic ability of the stations provided the locations of the aftershocks of this earthquake with high accuracy. Unlike the January 1, 1980, earthquake, the alignments defined by the aftershocks of the 1998 earthquake occurred in two preferred directions, approximately coinciding with the nodal planes of the mechanism of the main event, thus making it impossible to identify the fault plane responsible for the main shock. Given the large number of aftershocks, it was still possible to calculate 18 focal mechanisms in which strike-slip motions clearly dominated (Dias, 2005).

The first study of Azorean earthquakes using extensive source models was performed by Borges et al. (2007). This work was made possible by the existence of digital records of the long period of the 1980 earthquake (Mw = 6.8), obtained by the GDSN network, and the broadband data of the July 27, 1997 (Mw = 5.9), and July 9, 1998 (Mw = 6.0), earthquakes, obtained by worldwide networks (IRIS-Incorporated Research Institutions for Seismology). Two important results of this study are (i) the determination of the fault plane using the directivity effect and (ii) a description of the rupture using an extended source model. From the directivity study, these authors obtained NNE-SSW fault planes with left-lateral motion for the 1980 and 1998 shocks. The focal mechanisms defined the seismotectonic regime of each region, providing correlations between the geophysical information and the geological data. The three events studied in detail allowed analysis of the rupture process, which helps to identify the heterogeneities in the focal area. The main directions of the stress pattern obtained from the focal mechanisms (the directions of the P and T axes of the mechanisms) permit us to define an average orientation of extension in the region. Then, from the Fig. 3, it can be perceived that in the Terceira Ridge region the tension axis is horizontal and oriented in the NW-SW direction.

5. Final Remarks

The proximity of the Azores archipelago of the active triple junction confers to this region the moderate seismic activity noted. However, despite this characteristic, since settlement in 1432, 33 major earthquakes have occurred that caused great destruction in the islands of the central and eastern groups, mainly on Terceira and S. Miguel Islands, and thousands of deaths. The estimation of the released seismic moment in the Azores area during the last 90 years, based on data from the ISC catalogue between 1926 and 2016, shows that only 7 events with magnitudes between 6 and 7.1 account for 84.1% of the total seismic moment produced by thousands of earthquakes with M>3.

Understanding the seismic phenomena of the Azores requires a geodynamic model that describes observations on different spatial and time scales, whether the phenomena are of a seismic, magmatic, geomorphologic, geodetic, or geomagnetic nature. Seismic source studies appear to be the most direct way to achieve this objective due to the following: i) identification and qualification of faults, ii) characterization of the stress field, and consequently, iii) estimates of the deformation rates. Although the importance of this problem has been recognized and although there has been quality work on this subject over the past 36 years, the number of focal mechanisms existing in the region is small compared with those of other regions of the world with similar characteristics. The main reason for this scarcity of focal mechanisms is the poor azimuthal distribution of seismic stations. The solutions currently available correspond almost exclusively to events of greater magnitude that are capable of producing data on a global scale.

Because this seismic knowledge is important for reducing various types of risks in this region, efforts must be made at different levels. First, more detailed data need to be compiled, and the capacity for seismic observation in the Azores should be increased. Furthermore, there should be studies for the improvement of seismotectonic and geodynamic models and the development of the ability to simulate scenarios with the goal of forecasting strong ground motions and their consequences on the associated building stock.

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