# "TWO DECADES OF EARTH SCIENCE RESEARCH"

CGE
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Celebration of 20 Years

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# TWO DECADES OF EARTH SCIENCE RESEARCH

*On the occasion of the 20th anniversary of the CGE*

Edited by

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# Foreword

In 2012, the Évora Geophysics Centre (CGE) celebrates 20 years of activity. In these two decades, the national scientific system underwent a profound transformation, new organizational structures appeared, and participation in structures and international networks, and scientific integration reached very high levels. The national scientific environment is now more qualified and competitive; however the available funding per researcher became scarcer.

Currently the CGE team includes 67 full members, and is organized in two main Lines of Research: (1) *Atmosphere and Hydrosphere*, (ii) *Solid Earth*. The first one comprises the centers of activity: *Meteorology* & *Climate*, *Water, Environment,* & *Surface Processes*, and *Energy* & *Flow Structures*, while the latter is composed of the centers of activity: *Active Tectonics & Risks*, *Lithosphere, Mantle & Geological Resources*, and Heritage & Archeometry.

The time of maturity has come for GCE as a research unit, with a growth trajectory that was not always linear; however it has been progressive with respect to scientific quality, organizational structure, and the scientific and training outputs that were made available to the community.

It is also the time to reflect on the past and to define future strategies. This debate is carried out within the evolving framework in which the CGE develops its activity. Actually, CGE faces new challenges on the times ahead. At the national level new rules of public funding have been announced, which are expected to increase competition for national funding, together with a strong pressure to make networking among the teams for the use of the available facilities. At the international level, CGE is challenged to collaborate with national and international teams to get access to the new European funding program HORIZON 2020.

The workshop "Two Decades of Earth Science Research" was held at the University of Évora, on 23 November 2012, as the closure of the Program of Celebrations, which spanned over the year of 2012. For this workshop we invited national and international key figures as "keynote speakers", and other colleagues, which with us will reflect on the evolution of Earth Sciences, Atmosphere and Hydrosphere, and the national and European science on these two decades. With this initiative we will also make our contribution to the community for the analysis of this framework and define new directions for the scientific activity.

Finally, we wish to thank the keynote speakers, Professors Agustin Udías, Hervé Le Treut, and Maria da Graça Carvalho for their kind collaboration by delivering timely and important speeches, as well all colleagues who contributed to this workshop with their papers, and also all the other people that somehow contributed to the success of the workshop "Two Decades of Earth Science Research".

Évora, 23 November, 2012,

The Organizing Committee,
The Book Editors,

*Ana Maria Silva*,
*António Alexandre Araújo*,
*António Heitor Reis*,
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# SEISMICITY OF AZORES AND GEODYNAMIC IMPLICATIONS

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Over the past thirty years, several seismological studies have been carried out in the Azores region in order to characterize the geodynamic complexity of this region. In this work, we summarize these studies and highlight their main conclusions. The analysis of the focal mechanisms of large earthquakes reveals that there are two zones in the Azores, namely, zones I and II, with different stress pattern and strain rates. In zone I, which is located between 30º W and 27º W, faulting motion corresponds to a left-lateral strike slip with horizontal E-W compression and N-S extension and a strain rate of 6.7 mm/yr. In zone II, which is located between 27º W and 23º W, the seismic moment tensor indicates normal faulting with horizontal NE-SW extension and a strain rate of 3.1 mm/yr..

## 1 Introduction

Throughout history, the lives of the Azorean people have been marked by earthquakes that have had different effects depending on their proximity and magnitude. This seismic activity, which may have volcanic or tectonic origins, has affected the population of these islands by destroying infrastructure and claiming lives. The social and economic impacts of these phenomena are great—note the consequences of the recent 1980 Terceira and 1998 Faial earthquakes. Therefore, the following measures are necessary to minimize the risks associated with this seismic activity: **(i) Increase the capacity to monitor seismic phenomena on different space-time scales**: It is true that, in recent decades, there has been a substantial improvement in seismic activity monitoring in the Azorean region. However, in some areas, more work needs to be done to improve this type of monitoring. Such work includes improving the compatibility of data and sensors, providing data in real time, reducing azimuthal gaps in the network by installation of OBS, monitoring intense seismic motions and establishing the capability of seismic monitoring by installing mobile networks and homogeneously upgrading seismic catalogues.

**(ii) Improve seismotectonic and geodynamic models**: There is still no established consensus on the type of geodynamic model that would be able to provide a full explanation of the observed phenomena, especially the focal mechanisms of the more energetic earthquakes [1], their morphology [2] and geodetic observations [3]

**(iii) Develop simulation tools for predicting the ground's motion and its consequences on the level of built stock**: Simulations are mainly based on source characteristics and are heavily dependent on the medium, which is still poorly understood [4,5,6].

On the basis of these considerations, we conclude that the characterization of the seismic source of earthquakes in this region is an essential contribution. In this paper, we present a brief seismotectonic characterization of the Azores region in the context of the Azores-Gibraltar plate boundary using the results of works from the past 36 years. We include some results of the recent seismic activity to define the current state of the seismic stress pattern and the seismological cortical deformation in the region.

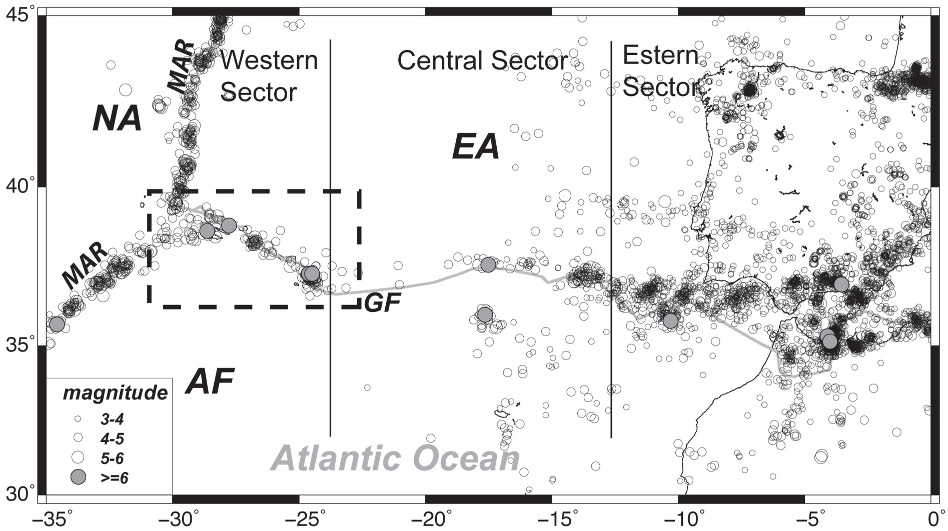

Figure 1 - Seismicity of the Azores–Gibraltar region during the period of 1973–2012 for a magnitude of M≥4.3 (NEIC Data File, USGS); GF=Gloria Fault; MAR=Mid-Atlantic Ridge; NA=North American plate; EA=Eurasian plate; AF=African plate.

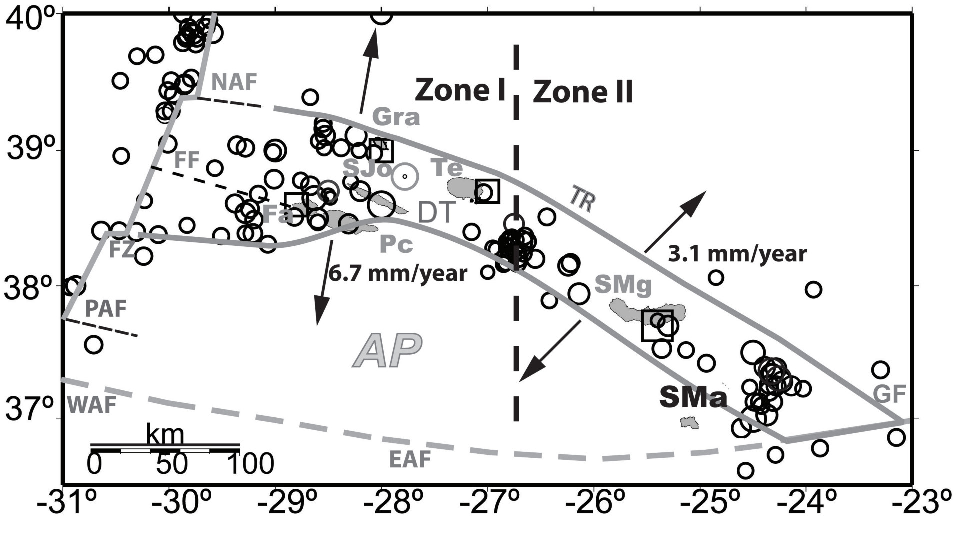

Figure 2 - Instrumentally (circles) and historically (squares) determined seismicity for the Azores region. The island names are Fa=Faial, Pc=Pico, SJo=San Jorge, Gra=Graciosa, Te=Terceira, SMg=San Miguel, SMa=Santa María. The grey stars show the epicentres of the three earthquakes studied. MAR=Mid-Atlantic 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. Arrows shows the direction of the T Axis (traction) for and the strain rate for both zones.

## 2 Seismotectonics and geodynamics of the Azores-Gibraltar region

The study of seismic activity in the Azores-Gibraltar region (Figure 1) includes instrumental data recorded by local and regional networks. For the larger earthquakes, data from global networks were also used. The hypocentre determinations and magnitudes of earthquakes give us an image, even if incomplete, of the activity associated with the main active tectonic features, plate boundaries, and fracture zones.

The historical record of the region's seismicity, a supplement to the instrumental seismicity, is of crucial importance for the characterization of its seismic activity. The historical seismicity is often the only source of information of major earthquakes with recurrence periods larger than the period of the first instrumental records. The historical information available, which describes the destructive effects caused by the earthquakes, shows spatial and temporal gaps that are due, in large part, to the geographical distribution of the population. Thus, for the Portuguese Continental territory, there are historical reports of earthquakes dating back to the year 33 B.C., but 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 shows a lack of historical information that cannot be provided. The epicentre map (Figure 1) shows that the three branches of the triple junction of the Azores region are well defined up until 24° W, after which a lack of seismicity is observed (seismic gap) that extends to 18º W. To the east of this meridian, epicentres are scattered over a wide area, setting a track of intense seismic activity up to the Gibraltar region.

Based on the historical and instrumental seismicity, the Azores-Gibraltar region has been divided into three sectors [7]: the West Sector, which includes the Azores plateau (AP) and extends from the Mid-Atlantic Ridge (MAR) to 24º W; the Central Sector, which begins at the GLORIA Fault (GF) and extends up to 13º W; and the Eastern Sector, which extends from the Tore-Madeira Ridge (at approximately 13º W) to Gibraltar.

The Azores Islands are located in the West Sector. The area located the furthest to the west is the AP. Morphologically, the AP is a triangular shaped structure with an area of approximately 400,000 $km^2$ that is roughly bounded by a 2,000 m bathymetric line (Figure 2). The AP clearly stands out 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 that are coincident with seven of the nine Azores islands (the Corvo and Flores islands are within the NA plate).

The Azores plateau is traversed in a NS direction by the Mid-Atlantic Ridge (MAR) and its boundaries are: the magnetic anomaly 6 (20 Ma) in the west; the North Azores Fracture Zone (NAF) with an EW trend, which continues into the Terceira Ridge (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) [7,8].

The main tectonic accident of this region is the MAR, which approximately intersects the midpoint between the Flores and Graciosa Islands. Its trend (Figure 2) varies from N10º E to N20º E and as it progresses south it undergoes morphological changes: (i) it 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 basis of the AP hot-spot [2,9], (ii) its thickness is sharply reduced [8], and (iii) the median valley, which characterizes this feature in other latitudes, is largely absent here.

The MAR is offseted by five transform faults that have a general E–W trend (Figure 2). 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 WAF extends to the east of the EAF (dotted line, Figure 2), up 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 an 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 an anomalous topography, gravitational distribution, crustal thickness, S and P wave velocities, and geochemical signatures [9,10,11,12,13] Reinforcing this hypothesis is the fact that there are strong similarities between the type of lava found in the Azores and the lava types found in regions such as Iceland, whose origin is clearly associated with a *hot-spot* [14].

Azimov et al., [15] proposed an alternative model: the *wet-spot model*. According to this model, the so-called *Azores hot-spot* could be explained by a melting anomaly that is not due to a thermal anomaly, but is a result of the presence of water in the mantle. The authors argued that the proposed model would be able to simultaneously explain the anomaly of the crustal thickness and the presence of certain chemical elements observed along the MAR in the vicinity of the Azores plateau, whose origin is usually associated with a hot-spot. In contrast, [16] argued that negative anomalies in the propagation velocity of seismic waves do not necessarily indicate the existence of a hot mantle. The chemical composition, the mineralogy, the presence of volatile activity, the inelasticity, and the anisotropy can also cause this low velocity. Mantle plumes have been the focus of intense debate, and the controversy concerning their origin continues today [16].

Global kinematic models provide expansion velocities for the Mid-Atlantic Ridge. From north to south, these velocities are as follows: (i) in accordance with the Nuvel-1A model [17]: north of the platform, the expected velocity is about 1.7 cm/yr, and the average value to the south is 1.2 cm/yr (parallel to the transforming faults); (ii) Luis et al. (1994) proposed a model in which the relative plate motion at the MAR in the Azores region decreased from 4 cm/yr to 1.4 cm/yr, in the interval from 10 to 3.85 Ma, and then increasing then to a value of 2.5 cm/yr according to the N100° W azimuth. The same models [8,17] suggest that in the third arm of the ATJ, there is a relative motion between the EA and AF plates of the right disconnection of the trans-tension type with a length component of 3 mm/yr. This is a considerably lower rate of expansion, which indicates this border has ultra-slow expansion characteristics (<10 mm/yr).

Different explanations have been proposed for the origin of the Terceira Ridge. According to some authors, this ridge corresponds to an extensional zone normal to the MAR [7,18] or an oblique extension [19,20]. Madeira and Ribeiro [21] proposed a leaky transform model. Lourenço et al. [2] proposed 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. Recently, Vogt and Jung (2004) suggested that the Azores axis, with a length of 550 km, is the slowest spreading organised accreting plate boundary in the world, with a typical mixture of faulting mechanisms. Understanding the dynamics of the Azores triple junction due to the very slow seafloor spreading rates at the Terceira Ridge (<1 cm/yr). Nevertheless, the high level of seismicity along the MAR and the Terceira Ridge (Fig. 1 and 2) is strongly associated with seafloor spreading and the northeastward motion of the Eurasian plate with respect to the African plate [8] (Fig. 1). This argument was also supported by [22], who proposed an elastic model with two possible locations of the Azores triple junction: along the extension of the Terceira Ridge at the same latitude as Graciosa Island or on the Faial fracture zone at the same latitude as Faial Island (Fig. 1).

## 3 Seismotectonics and geodynamics of the Azores-Gibraltar region

The seismicity of the Azores region is associated the plate boundary between the Eurasian (EA), African (AF), and North American (NA). In general, the seismicity is of low (M <5) and moderate ($5 \leq M \leq 6$) magnitude and is located at shallow depths (h<20 km). Since 1920, only two earthquakes have had Ms~7: one on 8 May 1939, with an epicentre east of Santa Maria Island, and the other on 1 January 1980, with an epicentre between the Terceira and Graciosa Islands. Most of the seismic activity is located on the MAR; a second zone with important seismic activity is located along the NE–SW direction from the ridge to Graciosa Island, through Pico and the Faial islands and continuing into the Terceira Ridge (Fig. 2); the East Azores fracture zone is practically inactive. From the historical seismicity, we know that large shocks occurred in the Azores with maximum intensities of X (modified Mercalli — MM) [23]. The data compiled by [23] since the beginning of the settlement lead us to conclude that the Azores region has been affected by 13 earthquakes with intensities equal to or greater than VII (Table I); these earthquakes caused about 6,000 deaths and the destruction of some islands in the archipelago. Table 1 and Fig. 2 show historical earthquakes with a maximum intensity of VII or larger and earthquakes with magnitudes greater than 4.0 for the period of 1973–2012 (National Earthquake Information Centre Data File — NEIC). Figure 2 shows that the historical and instrumental seismicity follow the same trend as the islands: approximately ENE from the MAR

Table I. Historically and instrumentally determined epicentres reported in the studied area, based on Nunes and Ribeiro (2001). $I_o$ = maximum intensity, MM = Modified Mercalli, mb = body wave magnitude, Ms = surface wave magnitude, Mw = moment magnitude.

| Date (d/m/y) | Latitude | Longitude | $I_o$ (MM) | Magnitude | Location |
|---|---|---|---|---|---|
| 22/10/1522 | 37.7°N | 25.4°W | X | - | S. Miguel |
| 24/05/1614 | - | - | IX | - | Terceira |
| 09/07/1757 | 38.6°N | 28.0°W | XI? | - | S. Jorge |
| 21/01/1837 | - | - | IX? | - | Graciosa |
| 15/06/1841 | - | - | IX | - | Terceira |
| 31/08/1926 | 38.5°N | 28.6°W | X | - | Faial |
| 08/05/1939 | 37.0°N | 24.5°W | VII | 7.0-7.1 | S. Maria |
| 26/06/1952 | 37.7°N | 25.3°W | VII | - | S. Miguel |
| 26/06/1952 | 38.7°N | 28.2°W | VIII | 5.5 mb | S. Miguel |
| 13/05/1958 | 38.6°N | 28.8°W | VIII/IX | - | Faial |
| 21/02/1964 | 38.7°N | 28.2°W | VIII | 5.5 mb | S. Jorge |
| 01/01/1980 | 38.8°N | 27.8°W | VIII/IX | 7.2 Ms | Terceira |
| 09/07/1998 | 38.7°N | 28:5°W | VIII/IX | 6.2 Mw | Faial |

(30$^o$ W) to Terceira Island (where the 1980 and 1998 shocks were located) and SE from Terceira Island to San Miguel Island (the 1997 earthquake was located SE of Terceira Island). The seismicity stops at 24° W, where the Terceira Ridge joins with the Gloria Fault, which is considered seismically inactive (Figure 1).

Despite the fact that instrumental seismic information has been recorded in the Azores since the beginning of the twentieth century, the regional network was not reformulated until the earthquake on 1 January 1980; there have increases in both the number of stations and their capacities, enabling a considerable improvement in the accuracy of locations and the network's detection sensitivity.

## 4 Focal mechanisms

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 carried out in the Azores-Gibraltar region. Some of these studies were based on polarities, and some focused on modelling the form of the body waves.

Table II. Focal parameters of the Azores area used to plot the focal mechanisms and the seismic moment tensor shown in Figs. 3 and 4. CMT = centroid-moment tensor (Harvard); BUF=Buforn et al., 1988; BOR = Borges et al., 2007. For the magnitudes of w and s, we write Mw and Ms, respectively.

| Nº | Date (d/m/y) | Lat (°N) | Lon (°E) | Depth (km) | M | Mo (x$10^{17}$ Nm) | Strike | Dip | Rake | PF | PQ | TF | TQ | REF. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 20/01/1993 | 38.39 | -29.34 | 15 | 5.4w | 1.20 | 132 | 33 | -59 | 151 | 67 | 20 | 16 | CMT |
| 2 | 11/12/1973 | 38.74 | -28.67 | 15 | 5.0w | 0.34 | 329 | 58 | -20 | 294 | 35 | 197 | 10 | BUF |
| 3 | 09/07/1998 | 38.65 | -28.63 | 7 | 6.0w | 14 | 153 | 85 | 6 | 288 | 1 | 18 | 8 | BOR |
| 4 | 23/11/1973 | 38.46 | -28.31 | 15 | 5.1s | 2.0 | 23 | 90 | -179 | 247 | 1 | 157 | 1 | BUF |
| 5 | 01/01/1980 | 38.81 | -27.78 | 7 | 6.8w | 190 | 149 | 85 | -2 | 104 | 5 | 14 | 2 | BOR |
| 6 | 28/06/1997 | 38.41 | -26.64 | 15 | 5.1w | 0.58 | 290 | 44 | -114 | 1 | 88 | 243 | 1 | CMT |
| 8 | 20/04/1968 | 38.30 | -26.60 | 15 | 4.6w | 0.09 | 117 | 42 | 89 | 28 | 3 | 220 | 87 | BUF |
| 7 | 06/09/1964 | 38.30 | -26.60 | 15 | 5.1w | 0.54 | 185 | 62 | 3 | 142 | 17 | 46 | 21 | BUF |
| 9 | 27/06/1997 | 38.33 | -26.68 | 7 | 5.8w | 7.0 | 290 | 44 | -114 | 115 | 73 | 216 | 3 | BOR |
| 10 | 21/11/1988 | 38.34 | -26.27 | 15 | 5.9w | 7.10 | 345 | 29 | -37 | 348 | 55 | 217 | 25 | CMT |
| 11 | 27/06/1997 | 38.26 | -26.16 | 15 | 5.2w | 0.62 | 284 | 27 | -147 | 102 | 54 | 236 | 27 | CMT |
| 12 | 02/12/1981 | 38.38 | -26.13 | 15 | 5.6w | 3.20 | 141 | 42 | -80 | 162 | 82 | 43 | 3 | CMT |
| 13 | 21/01/1989 | 37.92 | -25.92 | 15 | 5.7w | 3.40 | 131 | 41 | -87 | 195 | 85 | 39 | 5 | CMT |
| 14 | 16/10/1988 | 37.38 | -25.16 | 15 | 5.3w | 0.89 | 303 | 90 | 180 | 168 | 0 | 258 | 0 | CMT |
| 15 | 05/07/1966 | 37.60 | -24.70 | 18 | 5.0w | 0.41 | 180 | 48 | 30 | 129 | 12 | 24 | 48 | BUF |
| 16 | 04/07/1966 | 37.50 | -24.70 | 10 | 5.5w | 1.90 | 341 | 49 | -42 | 318 | 55 | 219 | 6 | BUF |
| 17 | 08/05/1939 | 37.40 | -23.90 | 15 | 7.1s | 199 | 41 | 35 | -154 | 234 | 49 | 355 | 24 | BUF |
| 18 | 09/03/1996 | 37.13 | -23.85 | 15 | 5.7w | 3.80 | 319 | 28 | -106 | 85 | 71 | 241 | 18 | CMT |
| 19 | 09/12/1991 | 37.22 | -23.61 | 15 | 5.2w | 0.82 | 330 | 45 | -90 | 180 | 90 | 240 | 0 | CMT |
| 20 | 09/09/1984 | 36.93 | -24.60 | 12 | 5.3w | 0.95 | 178 | 37 | -79 | 221 | 79 | 81 | 8 | CMT |
| 21 | 26/06/1989 | 39.11 | -28.32 | 15 | 5.8w | 5.40 | 105 | 32 | -110 | 248 | 72 | 29 | 14 | CMT |
| 22 | 23/09/1989 | 39.27 | -29.24 | 15 | 5.1w | 0.44 | 233 | 45 | -90 | 180 | 90 | 143 | 0 | CMT |
| 23 | 01/08/2000 | 38.79 | -29.01 | 15 | 5.1w | 0.51 | 97 | 62 | -170 | 316 | 26 | 53 | 13 | CMT |
| 24 | 30/11/2002 | 39.25 | -28.45 | 15 | 5.1w | 0.52 | 106 | 45 | -129 | 300 | 63 | 42 | 6 | CMT |
| 25 | 05/04/2007 | 37.45 | -24.62 | 12 | 6.2w | 41 | 129 | 44 | -89 | 0. | 90 | 38 | 1 | CMT |
| 26 | 04/11/2007 | 37.40 | -24.39 | 12 | 6.0w | 11 | 133 | 44 | -87 | 0 | 90 | 41 | 1 | CMT |

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 epicenters), it is often a difficult task to obtain the focal mechanisms for this area. Hence, the number of focal mechanisms currently available is relatively small in comparison with the data in Portugal Mainland 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 in this region.

The first studies of focal mechanisms were performed by [19] . Based on their results and previous knowledge of the region's seismicity, they established the first geodynamic model for the Azores-Gibraltar region. Arroyo and Udías [24] studied the focal mechanism of the 1969 earthquake (Table II) and its aftershocks. They estimated the fault dimensions and the source parameters for this earthquake and, using the focal mechanisms of four earthquakes that occurred near the Mid-Atlantic Ridge and the Azores region, they interpreted these results in the context of the Azores-Gibraltar seismotectonics. Udías et al. [25] studied the seismicity and the focal mechanisms of the Azores-Alboran region using new data, and they proposed a new seismotectonic model for the whole region based on changes in the seismicity and focal mechanisms. They suggested a division into four different parts, along the boundary from the MAR in the west to Gibraltar in the east. Later, Grimison and Chen [26], using the World Wide Standardized Seismograph Network's (WWSSN) long-period records, obtained the focal mechanism of the January 1st 1980 earthquake from body-wave modelling, bringing to light, for the first time, the complex nature of the rupture process that characterises the earthquakes in this region.

The distribution of more than 400 aftershocks of the 1 January 1980 earthquake recorded at the telemetric seismic network installed on the Terceira, S. Jorge, Graciosa, and Pico Islands showed a N150° E trend; this agrees with one of the fault planes estimated for the main shock and indicates a pure left-lateral strike–slip motion with a vertical plane between 149° and 154° [7, 26, 27]. Hirn et al. [27] obtained a composite solution for the aftershocks that coincides with the main event using polarities recorded by a temporary network. Buforn et al. [7] analysed, among others, eight focal mechanisms for the events located on the Azores Plateau (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 an expanding dorsal). These results provided a more detailed outline of the geodynamic behaviour of the area and determined its seismic deformation rate.

An ocean bottom seismometer survey was carried out for 27 days in the Azores region in 1992. This survey showed a concentration of hypocentres along the islands themselves, with a maximum depth of 15 km. The distribution of epicentres confirmed that the seismicity is distributed along the strip corresponding to the Terceira axis [28]. A more detailed analysis of the distribution of epicentres allowed for the identification of alignments with azimuths that agree with the fault of the January 1st 1980 earthquake. During the recording period, there were two events of moderate magnitude (magnitudes 3.2 and 3.4), with epicentres located near that of the January 1st 1980 earthquake. The focal mechanism solution obtained describes a strike-slip motion with nodal planes similar to those of the January 1st 1980 earthquake [1,7].

After the 1998 earthquake, a temporary seismic network composed of seven short-period stations was installed on the Faial, Pico, and S. Jorge Islands. More than 1200 aftershocks were recorded, showing NNW–SSE to ENE–WSW alignments [29]. The good azimuthal coverage offered by this network and the dynamic ability of the stations provided the locations of the aftershocks of this earthquake with high accuracy. Unlike the January 1st 1980 earthquake, the alignments defined by the aftershocks of the 1998 earthquake occurred in two preferred directions, roughly 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 quake [29]. Given the large number of aftershocks of this earthquake, it was still possible to calculate 18 focal mechanisms in which strike-slip motions clearly dominated [30,31].

The first study of Azorean earthquakes using extensive source models was carried out by [1,2]. 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 27th 1997 (Mw = 5.9) and July 9th 1998 (Mw = 6.0) earthquakes, obtained by worldwide networks (IRIS – Incorporated Research Institutions for Seismology).

Two important results of this study [1] 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 a NNE-SSW fault plane 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. In some cases—in particular, the three events in the studied Azores region—it was possible to analyse the rupture process [1], which helps to identify the heterogeneities in the focal area. The main directions of the stress pattern can be obtained from the focal mechanisms (the directions of the P and T axes of the mechanisms) and allow us to define an average extension orientation in the region.

## 5 Seismic deformation

In Table II and Figure 3, the focal mechanisms (magnitude ≥ 5) of the Azores region are given. These mechanisms were obtained from waveform inversion, centroid-moment tensor inversion, and body-wave polarities. Note that most of the mechanisms from the triple junction to Terceira Island correspond to strike–slip solutions with planes along the NNW–SSE and NNE–SSW directions (Zone I, Fig. 2). Events are mostly located between the Terceira Ridge and the Gloria fault (Zone II, Fig. 2). The 1980 earthquake is the largest in the studied area (with the exception of the earthquake located SW of the Azores Islands), with a magnitude Mw=6.8. One problem for this region is the selection of the fault plane for the 1980 and 1998 shocks. The aftershock distribution obtained for the 1980 event by [27] suggests a NNW–SSE fault plane. For the 1998 shock, Vales et al. [29] obtained two alignments for the aftershocks, both with the same trend as the two planes obtained from the focal mechanism study. In this study, the directivity function indicates that the NNW–SSE plane was the fault plane for both events, with the rupture propagating to the SSE.

The 1939 and 1980 shocks had magnitudes of Ms~7; because the other earthquakes had magnitudes between 5.0 and 6.0, it is difficult to quantify the stress regime in this area (Table II and Fig. 2). One approach is to use the total seismic moment for the area, which is defined as the sum of the moment tensors calculated from individual solutions:

$$M_{ij}^{total} = \sum_{k=1}^{N} M_0^k m_{ij}^k \qquad (1)$$

where N is the number of earthquakes, $M_0$ is the scalar seismic moment of each event, and mij represents the seismic moment tensor components. Larger earthquakes with high values of Mo make larger contributions to the estimation of the total seismic moment tensor. Using the solutions given in Table 2 and Eq. (1) we estimated the components of Mij for the two regions represented in Figure 2: in Zone I, the total seismic moment tensor corresponds to strike–slip faulting with horizontal pressure and tension axes along the E–W and N–S directions, respectively. The compensated linear vector dipole component (CLVD, which is the amount of non-DC) is 8%, which confirms that the focal mechanism presented in Figure 3 is representative of the faulting type in Zone I. For Zone II, the total moment tensor corresponds to normal faulting with a horizontal tension axis along the NE–SW direction, normal to the Terceira Ridge, with a CLVD of 14%. The low amount of CLVD obtained for both zones confirms that both dominant mechanisms are representative of the stress regimes and, consequently, of the changes between the two zones.

Table III - The rate of deformation calculated from relation (2) (in the text) for the two zones (I and II) based on the data listed in Table II: T=84 years, $\mu$=3.3x1011 dyne cm-2, the value of W is chosen based on the slope of the fault plane, assuming that this plane covers the entire seismogenic layer (height of 10 km).

| Zones | L(km) | W(km) | $M_o$ | Dip (°) | Rate of deformation (mm/yr) |
|---|---|---|---|---|---|
| Zone I | 172 | 10 | 22 | 90 | 6.7 |
| Zone II | 250 | 14 | 30 | 45 | 3.1 |

The rotation of the tension and pressure axis from Zone I to Zone II is in agreement with the results obtained by Lourenço et al. (1998), who used the morphological characteristics of the ocean floor based on the linear volcanic ridge orientations.

From the seismicity and focal mechanisms, we estimated the average slip velocity for Zones I and II, using data from earthquakes with a magnitude of Ms≥4.0 that occurred between 1923 and 2007 and the following expression [1,7,33]:

$$\Delta \dot{u} = \frac{\sum M_0^i}{\mu L W T} \qquad (2)$$

where $M_0$ is the total scalar seismic moment, $\mu$ is the rigidity coefficient, LW is the fault area, and T is the period. For earthquakes without an estimation of the seismic moment Mo, an empirical relation between Mo and Ms was derived for Azores earthquakes with magnitudes greater than Ms=4.4 [32] for the period of 1973–1997 (ISC catalogue). Table III presents the parameters used to calculate the rate of seismic deformation for the two areas, as given by equation (2).

From these results and the seismic moment tensor we can conclude that the average rates of slip for Zone I and Zone II are 6.7 mm/yr and 3.1 mm/yr, respectively, which corresponds to a horizontal extensional rate of 2.3 mm/yr in Zone II in a N46° E direction, as deduced from the total seismic moment tensor (Fig. 10). In Zone I, the relation between the strain rate and the relative plate movement is more complex because the strain release essentially occurs by strike–slip motion. Nevertheless, if we assume that Zone I is a large area of deformation confined by the EA and AF plates, where their relative movement is accommodated by block rotation McKenzie and Jackson [34], we could conclude that, for this zone, the deformation is accommodated by seismic strain with an extensional component of movement in the N53° E direction, as deduced from the total seismic moment tensor. The value of the horizontal extensional rate for Zone I depends on the choice of the distributed deformation model [34], a problem that is not the focus of this work.

The average seafloor spreading rate for Zones I and II is 4.2 mm/yr, similar to the value (~4.2 mm/yr) obtained from GPS data [35,36]. This value is supported by the relative rate of motion (~4.5 mm/yr) predicted by the Nuvel-1A model [27] in the central and eastern islands of Azores. One difference between the direction of extension obtained in this work (toward N53° E and N46° E in Zones I and II, respectively) and that predicted by Nuvel-1A (toward N71°E) has been found. Some displacement is caused by a seismic process, which takes the form of folding, thickening, plastic deformation, or slow slip—these are not included in our estimation, suggesting that our seismic strain analyses may underestimate the geological deformation. Due to the uncertainty surrounding large historical earthquakes (Table 1), we have used only the instrumental period in this estimation. Discrepancies between the seismic deformation rates and geodetic values may be explained in terms of other types of deformation that were caused by seismic processes (folding, thickening, plastic deformation, or slow slip) that occur on the Azores Plateau but that were not considered. As a result, the seismic strain analyses may underestimate the geological deformation. Moreover, the seismic catalogue used for the calculations presented here may not be able to take into account the events of the high recurrence period. Given the shortness of the catalogue duration used in this study and the variability in the absolute rate, we do not necessarily expect spatial similarity between the geodetic deformation and the seismicity.

## 6 Current and future seismologic developments in the Azores Area

Prediction of ground motion in future earthquakes is the central challenge of seismology. Whoever, due to multiple spatial and temporal scales characterize earth response and due highly heterogeneous material properties and uncertainty in their geologic, this can be a complex task. Large limitations could be found when current methodologies for estimation of ground motion are applied to regions like the Azores Area for different kind of reasons: i) seismological data are sparse and do not cover sites were site effects could occur; ii) spatio–temporal description of the rupture and directivity is not known and they strongly influence the generation of near–field seismic motion; iii) Simple Peak Ground acceleration (PGA) and Peak Ground Velocity (PGV) description of the seismic motion does not satisfactorily response to the actual needs.

In the last years, due to 3D structural model improvement in SW Iberia and Lower Tagus Valley area several studies have successful obtained strong-ground motion synthesis for a rage of frequencies up to 1 Hz [4, 6,37]. However, due to the existence of small-scale heterogeneities in the earthquake source process and crustal properties, matches the high-frequency. We can say that observed high-frequency motions (T≥1s) behave stochastically and on this base many authors have developed stochastic models [38]. A current project for the Azores Region (SIGMA project, funded by FCT) are focused on broadband strong motion simulation by combining deterministic low-frequency waveforms with stochastic high-frequency synthetics seismograms. The merge of the two models will allow a broad band and a credible model for computing strong ground motion and it will contribute to a significant progress in strong ground motion modeling of earthquakes for the Azores Area.

## 7 Conclusions

Two types of seismic behavior in the Azores region divide the region into two zones: Zone I (from 30° W to 27° W) and Zone II (from 27° W to 23° W). The seismicity is along the ENE-WSW direction in Zone I and the NW-SE direction in Zone II. Earthquakes located in Zone I reveal a predominant strike-slip motion with horizontal extension along the N-S to NNE-SSW direction and horizontal compression in the E-W direction. The change in the stress direction in the Azores region is based on all the available seismological data and shows the complexity of the region. This difference in the stress pattern for regions I and II is also present in the velocities estimated from the seismic data, because the velocity is higher in region I with strike–slip movement, 6.7 mm/yr, compared with 3.1 mm/yr for region II with normal faulting. The overall regional stress pattern for both zones corresponds to a horizontal extension with an average velocity of 2.3 mm/yr for the whole region. The deformation of the Azores region is accommodated by an average seismic strain rate of about 4.4 mm/yr along the NW direction.

The Azores archipelago can be considered a moderate seismic region. Its location near the triple junction, which is associated with a slow rift, gives it this characteristic. Understanding the seismic phenomenon of the Azores requires a geodynamic model that describes the observable phenomena on different space 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 that 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 need to be made at various levels. First, better data needs to be compiled, and the capacity of seismic observation in the Azores should be increased. Furthermore, there should be studies of the improvement of seismotectonic and geodynamic models and a 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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