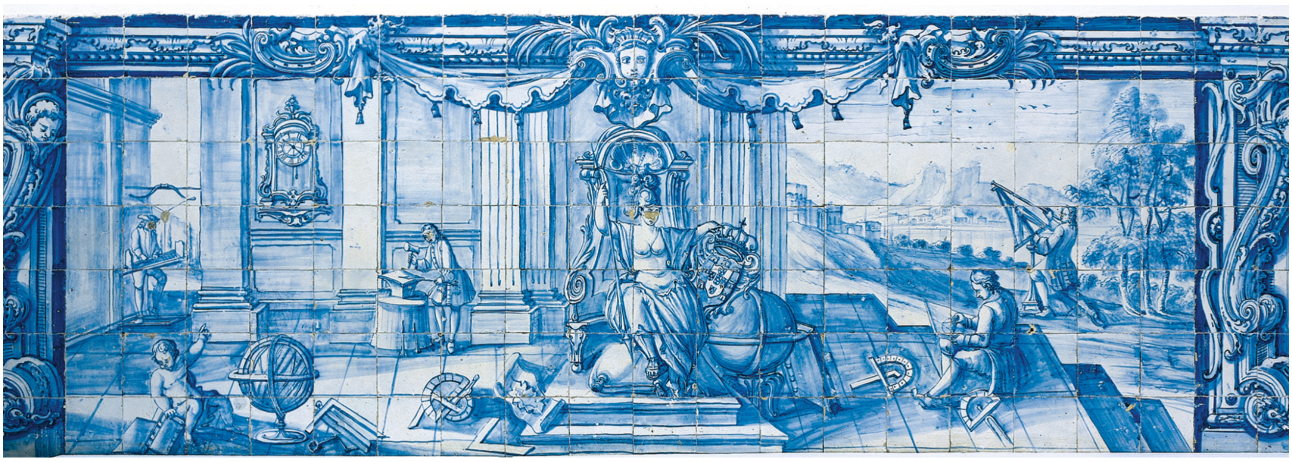
SEISMICITY AND SEISMIC HAZARD ASSESSMENT IN THE AZORES

João Fontiela

Tese apresentada à Universidade de Évora
para obtenção do Grau de Doutor em Ciências da Terra e do Espaço
Especialidade: Geofísica

ORIENTADORES: *Mourad Bezzeghoud*
Francisco Cota Rodrigues
Philippe Rosset

ÉVORA, SETEMBRO DE 2018



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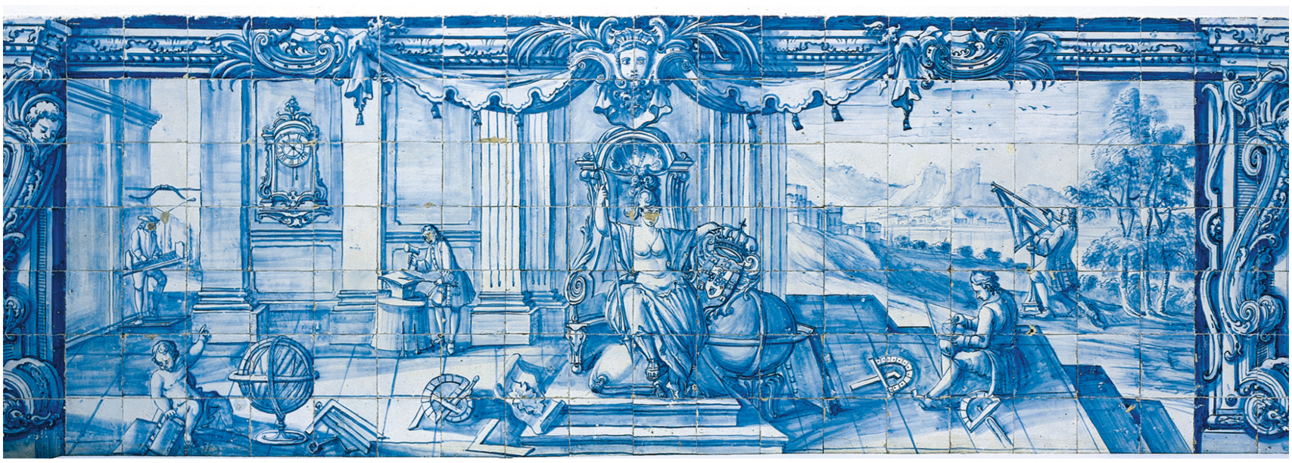

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"Under normal conditions the research scientist is not an innovator but a solver of puzzles, and the puzzles upon which he concentrates are just those which he believes can be both stated and solved within the existing scientific tradition"

Thomas Kuhn

À memória do meu pai
In memory of my father
Eduardo Figueiredo

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ACRONYM LIST

CMT	Centroid Moment Tensor
CSRA	Catálogo Sísmico Região Açores
CTBTO	Comprehensive Nuclear-Test Ban Treaty
DSHA	Deterministic seismic hazard assessment
EC2012	Earthquake Catalogue 2012
EFZ	East Fracture Zone
EMS-98	European Macroseismic Scale 1998
EMMVA	European macroseismic method for vulnerability analysis
FFZ	Faial Fracture Zone
FMD	Frequency Magnitude Distribution
GCMT	Global Centroid Moment Tensor
GMPE	Ground Motion Prediction Equation
ICM	Initial casualty matrix
IDC	International Data Centre, CTBTO
IM	Instituto de Meteorologia
Imax	Maximum Intensity
IMO	Intensidades Máximas Observadas
IPMA	Instituto Português do Mar e Atmosfera
IRIS	Incorporated Research Institutions for Seismology
ISC	International Seismological Centre
M	Magnitude
MAR	Middle Atlantic Ridge
MB	Magnitude of Body Waves
MC	Minimum Magnitude of Completness
MCS	Mercalli–Cancani–Sieberg scale
MD	Magnitude of Duration
M_D	Mean damage (appears on chapter 5, section 3, page 87)
ML	Local Magnitude
MOI	Maximum Observable Intensity Map
MMI or MM	Modified Mercalli Intensity scale
MMI 56	Modified Mercalli Intensity scale 1956[1]
MS	Magnitude of Surface Waves
MSK	Medvedev–Sponheuer–Karnik intensity scale
MW	Moment magnitude
NAFZ	North Azores Fracture Zone
NEIC	National Earthquake Information Center

OK	Ordinary Kriging
PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Assessment
QLARM	Quake Loss Assessment for Response and Mitigation
RC	Reinforced Concrete
SIVISA	Sistema de Vigilância Sismológica dos Açores
SRL	Seismological Research Letters
SS	Seismic source
SZ	Seismic zone
TR	Terceira Rift
TSMT	Total seismic moment tensor
UAz	Universidade dos Açores
USGS	United States Geological Survey
Vp	Velocity of P-wave
Vs	Velocity of S-wave

Seismicity and Seismic Hazard Assessment in the Azores

Abstract

The peculiar geodynamic framework of the Azores is responsible by the high number of events of low magnitude, despite several earthquakes of M≥5 or maximum intensity ≥VII that in the past affected the islands of the Central and Eastern groups. Thus, the seismic hazard is considerable and the study of the seismicity is a challenge to the scientific community.

This thesis, which comprises four papers published and one submitted, is a comprehensive study of the seismicity and seismic hazard in the Azores.

The analysis of the seismicity using b-value of frequency-magnitude distribution reveals a general decrease trend from west to east. The high b-values could be within the volcanic activity, thermal anomalies or hydrothermal activity while the low b-values are certainly related with the increase of effective stress. In the scope of the seismic hazard assessment we identify 11 seismogenic zones where the b-values ranges from 1.57 in the Middle Atlantic Ridge to 0.72 in the seismogenic zone of Terceira Island. We select maximum observed intensity (MOI) maps to assess the maximum ground shaking using historical and instrumental seismicity since this analysis is performed with MOI. Still, in the seismic hazard, we estimate human losses caused by possible earthquakes in the future on a volcanic island, although the difficulties inherent to the geological heterogeneities. The last two topics (MOI maps and human losses) were a pioneer work since they were applied for the first time in the Azores, therefore contributing to mitigate the seismic hazard in the Azores region.

Keywords: Seismicity, Seismic hazard, Seismogenic zones, Maximum observed intensity, Human losses estimation

Sismicidade e avaliação da perigosidade sísmica nos Açores

Resumo

Devido ao peculiar contexto geodinâmico dos Açores a sismicidade é elevada, apesar da baixa magnitude dos eventos. Vários sismos de M≥5 ou intensidade máxima ≥VII afectaram as ilhas dos grupos Central e Oriental no passado. Assim, a perigosidade sísmica é considerável e o estudo da sismicidade é um desafio para a comunidade científica.

Esta tese compreende quatro artigos publicados e um outro submetido é um estudo abrangente sobre a sismicidade e a perigosidade sísmica nos Açores.

A análise da sismicidade, usando o valor-*b* da distribuição da frequência-magnitude, revela uma tendência geral de diminuição de oeste para o leste. Os valores elevados do *b* podem ser devido à actividade vulcânica, à presença de anomalias térmicas ou à actividade hidrotermal, enquanto os valores baixos estão relacionados com o aumento das tensões efectivas. No âmbito da avaliação da perigosidade sísmica, identificamos 11 zonas sismogénicas cujos valores-*b* variam entre 1,57 na Crista Média Atlântica e 0,72 na zona sismogénica que referente à ilha Terceira. Utilizamos os mapas de máxima intensidade observada (IMO) para avaliar os movimentos fortes do solo, recorrendo à IMO quer para o período de sismicidade histórica quer instrumental. Ainda no domínio da perigosidade sísmica, apesar das dificuldades inerentes às heterogeneidades geológicas, estimamos as perdas humanas causadas por futuros sismos numa ilha vulcânica. De referir que os dois últimos tópicos (mapas IMO e estimativa das perdas humanas) são uma novidade, uma vez que foram aplicados pela primeira vez nos Açores, contribuindo para mitigar a perigosidade sísmica na região.

Palavras chave: Seismicidade, Perigosidade sísmica, Zonas sismogénicas, Intensidade máximas observadas, Estimativa de perdas humanas

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1

Introduction

1.1. Preliminary words

Since the 15th century the Azores Archipelago has been struck by several earthquakes, some with catastrophic effects, along with tens of thousands of micro-earthquakes unfelt by the population. Seismicity in the Azores is high but of low magnitude, indeed it is associated with volcanic activity. Additionally, the location of the Azores islands in the boundary of the American, Eurasia and Nubian lithospheric plates gives a particular status to the region. On the other hand, integrated seismological studies are limited by the geographical disposition of the islands in a narrow band of NW-SE general trend. Undoubtedly, the vast submarine territory of the Azores is wealthy in unknown tectonic structures as well as in volcanoes.

The study of the seismic hazard is never outdated due to earthquake unpredictability, by the social impacts and disruption caused to human activity. Fulfilling the seismic hazard study is needed to gather a wide variety and quantity of data such as seismotectonics, historical seismicity, ground motion prediction equation that fits the geological conditions, and evaluation of soil conditions. Despite the historical seismicity in the earthquake catalogues is well established, the knowledge of the remaining mentioned subjects is not known entirely or totally. It needs a systemic approach to fill these knowledge gaps. Such gaps can result in limited financial support given to seismic hazard assessment, the absence of cooperation between research institutions or natural limitations such as the ones of the Azores. Some recent studies were conducted to clarify the complexity of site conditions and contribute to mitigating the seismic hazard. The works of Teves-Costa and Veludo (2013), Lopes et al. (2013) and Santos et al. (2011) are examples of assessment of the local site conditions in Angra do Heroismo, and in São Sebastião, both in Terceira Island. In both sites, the authors were faced with the complexity of volcanic geology. Concerning seismotectonics, it is worth noting the extensive works of Madeira (1998) of the neotectonics of São Jorge, Pico and Faial Islands, and the one of Carmo (2013) of São Miguel Island. Hipólito et al. (2013) studied the neotectonics of Graciosa Island. The neotectonics of Terceira and Santa Maria Islands are in the work of Madeira et al. (2015). In all studies mentioned, the authors calculated parameters such as fault length, slip, recurrence periods and earthquake magnitude. The probabilistic seismic hazard assessment using the methodology proposed by Cornel (1968) was applied to São Miguel by Oliveira et al. (1990) and to the islands of the Central Group by Carvalho et al. (2001). To celebrate ten years of the 1980 and 1998 earthquakes two books (Oliveira et al., 1990; Oliveira et al. 2008) were published to preserve the memory of the happenings and studies developed at the time of the two events. Both books had the support of the Regional Government of the Azores with the collaboration of the professor Sousa Oliveira (Instituto Superior Técnico, Lisboa). Moreover, some research projects have not yet published their results, which will contribute to increasing the knowledge of the Azores region.

The study of the seismicity in the Islands of the Central Group deserves special attention in future because, from the 33 earthquakes recorded in the Azores with intensity ≥VII, 20 were in the islands of the Central Group. Some earthquakes struck the eastern part of Terceira Island (comprising the region in between Praia da Vitória up to São Sebastião) in 1614, 1800, 1801, 1841, and in the western part in 1980 (Ms7.2). Beyond these events, some seismic swarms occurred on the island like the ones of 1946 and 1950 in Serreta and Agualva respectively; nevertheless, their location is unknown. ISC earthquake catalogue (ISC, 2015) shows that since 1926, there has been only one earthquake (M≥4) near those settlements, beyond the seismic sequence of the 1980 earthquake. Earthquake number in the fault of the 1980 earthquake is low, meaning that most of the energy was released in the mainshock and aftershock sequence. The earthquakes of 1730 and 1837 struck Graciosa Island causing damage in the building stock. Analysing the instrumental seismicity in Graciosa, most of the epicentres of M ≥4 (ISC, 2015) are in the SW offshore sector. The major earthquake that occurred in the Central group was the one that struck São Jorge Island in July 1755 with M7.4 (estimated by Machado, 1949). The instrumental background seismicity is low, which leads us to believe that São Jorge is a seismic gap. The relevant earthquake in Pico Island was in 1973 (Mb 5). Based on the seismicity, Pico can be separated into two parts: the eastern one with low background seismicity and the western one with high background seismicity. Faial Island was struck by the earthquakes of 1926 (Mb ~5.6) 1958 (Imax X) and 1998 (Mw6.2).

The historical seismicity in the Eastern group is pointed out by the earthquake at Vila Franca (Imax X) in 1522 that triggered a massive landslide that buried the settlement. The death toll of this sequence of events was around 5.000. In 1591 another event affected Vila Franca do Campo however, the historical accounts do not have enough detail to characterize the event. In 1852 an earthquake with Imax VIII located in the north part of the island caused severe damage, and the number of deaths was around 9 - 12. Since then, four moderate earthquakes (Imax VII up to VIII) hit the southwest part of São Miguel between Ribeira Quente - Povoação in the period 1932 - 1952. In 1939 an earthquake of

Ms 7.1 in the western end of Gloria fault caused severe damage on Santa Maria Island. Besides these earthquakes, in São Miguel Island several earthquake swarms occurred associated with the volcanoes of Sete Cidades, Fogo, Congro and Furnas. The duration of these swarms varies between a few hours up to several months, and the number of earthquakes ranges from tens up to thousands of events.

Several volcanic eruptions took place in the Azores region, 14 inland and 13 offshore. The distribution of volcanic eruptions by island is the following: São Miguel (6), Terceira (1), São Jorge (2), Pico (3) and Faial (2). These eruptions were accompanied by earthquakes, but the historical accounts do not have enough detail to follow the evolution of the volcano, except for recent ones of Capelinhos 1957/58 and Rosais 1964.

The high number of earthquakes on the Central group is well correlated with the slip velocity estimated by Bezzeghoud et al. (2014) and Borges et al. (2007). The few earthquakes that struck Graciosa Island are linked with the kinematics of the island that behaves like Eurasia plate (Fernandes et al., 2006) while remaining islands of the Central group don't exhibit an explicit behaviour of Nubia plate neither does Eurasia. Slip velocity is much slower in the eastern islands compared with the ones of the Central Group. Nevertheless, according to Fernandes et al. (2006), Santa Maria kinematic is similar to the one of the Nubia plate.

All these earthquakes show that the islands of Central Group have a high seismic hazard and seismic risk. The risk is high taking into consideration that the lives of 99,100 people, and building stock comprising 45,164 buildings (INE, 2013) without considering vital structures like hospitals, airports, lifelines and other structures essential to the human activity. The population at risk increases in the case of the interaction between earthquakes and volcanic eruptions, where events with moment magnitude 5 - 6 are activated up to 50 km from the volcano for 0.3 years after the beginning of an eruption

(Nishimura, 2018).

This thesis contributes to reducing the knowledge gap of the seismic hazard on the Azores Archipelago. With this work, I intend to do a consistent transition from seismic hazard to seismic risk. Hence, the purpose of the second chapter is the assessment of the seismicity of the Archipelago and the earthquake catalogue. Moreover, through b-values of frequency magnitude distribution, I distinguished the seismicity behaviour along the Azores region relating b-values to physical properties such as stress, and material homogeneity. The second part of the chapter is about the large earthquakes in the Azores. Then, with the data from the second chapter, I established a new seismogenic zone model to the Azores using b-values associated to a methodology based on a trial and error earthquake selection up to reach a stable b-value (chapter 3). The main asset of the seismogenic zones is essentially one of the inputs to perform a probabilistic seismic hazard assessment (PSHA). Instead of the study of PSHA, I preferred the study of maximum observed intensity (MOI) map (chapter 4), never done on the Azores using a systematic approach. These maps allow identification of regions that in historical times experienced maximum peak ground acceleration. Additionally, these map are a simplistic approach to the deterministic seismic hazard assessment. Chapter 5 is the transition from the seismic hazard to the seismic risk where I estimate human losses in Faial Island since last moderate earthquake (Mw6.2) that caused injuries in the Azores was in Faial. Therefore, the quality of data available concerning damage buildings, population distribution is very good. In the last chapter (6), I do the conclusions of the previous chapters.

1.2. Objectives

With this thesis the objectives proposed were:

- Contribute to the knowledge of the seismic hazard and risk assessment in the Azores;
- Analysis of temporal and spatial heterogeneities assessed through the variations of the frequency magnitude distribution in the upper crustal seismicity of the Azores region;
- Propose new seismogenic zones based on the frequency magnitude distribution;
- Appraise seismic hazard assessment employing deterministic approach;
- Interpret maximum observed intensity maps as a contribution to seismic hazard assessment;
- Demonstrate the importance of seismic hazard into the seismic risk analysis;
- Assess the population and building seismic risk in likely future earthquakes in Faial Island;

All these objectives were attained with success depicted by the papers published and submitted.

1.3 Personal motivation

Behind a Ph.D. thesis, it is the personal motivation of the graduate student combined with the strategy of a research group or centre. My desire to join University of Évora and Institute for Earth Sciences (former Centre for Geophysics of Évora) is related to the strategy for the study of the seismicity in the vast area that comprises the Azores and extends up to Ibero Maghrebian region (Bezzeghoud et al. 2017), besides the number of seismic instruments and conditions available. With my Ph.D., ICT understood the need to develop seismic hazard assessments as one of the research interests' areas of the centre. Looking back, I felt that was a safe bet move to Évora by the different opportunities I had. Amongst these opportunities, I highlight tutoring a Ph.D. student, transferring to him the knowledge and work methodologies that I received from my tutors, and the result was the publication of a paper (Belayadi et al. 2017). Another valuable opportunity was the deployment and management of a temporary seismic network to survey the seismic sequence of the Arraiolos earthquake (Ml4.9) on 15 January 2018. The chance of fieldwork abroad in a different culture and geological environment arose through the bilateral project between Portugal and Algeria. Nevertheless, all of these achievements weren't possible without the financial support of the Regional Directorate for Science and Technology of the Regional Government of Azores.

1.4. Structure of the thesis and resulting publications

The presented thesis is divided into six chapters with a relationship between them except for the introduction and conclusion chapters. Thus, the second chapter analysis in detail the seismicity in the Azores while the third one takes the results of the previous chapter into consideration to propose new seismogenic zones, a contribution to the seismic hazard assessment. The fourth chapter, relates to the previous ones through the seismic hazard assessment using a deterministic approach. The fifth chapter makes the transition from the seismic hazard to the seismic risk.

All chapters are divided into two sections except for the introduction (first chapter) and conclusions and outlook (last one). The first section of each chapter contains the summary where the background is presented and the main ideas underlying the publication and the references cited in this section. The second section consists of the following content:

Chapter 1: The first chapter gives the general motivation of this study. Subsequently there is an overview of the seismic hazard in the Azores.

Chapter 2: This chapter is based on two papers. The first paper ***Caldeira, B., Fontiela, J., Borges, J., and Bezzeghoud, M. (2017). Large earthquakes in the Azores. Física de la Tierra, 29, 29-45*** focus on the large earthquakes in the Azores and their relationship with the geodynamic of the Archipelago. The second one published in the book Volcanoes of the Azores: ***Fontiela, J., Sousa Oliveira, C., and Rosset, P. (2018). Characterisation of Seismicity of the Azores Archipelago: An Overview of Historical Events and a Detailed Analysis for the Period 2000–2012. In U. Kueppers. and C. Beier (Eds.), Volcanoes of the Azores (pp. 127-153). Berlin, Heidelberg: Springer Berlin.*** These publications give a first introduction to the seismicity in the Azores. Subsequently, there is an overview of the historical seismicity, an evolution of compilation of earthquake catalogues and seismic networks operating in the region, and finally there is an assessment of the frequency magnitude through b-value in the period 2000 - 2012 based on a regular grid of 2º x 2º highlighting the different stress regimes in the Archipelago.

Chapter 3: This chapter is based on the paper published in Comunicações Geológicas : ***Fontiela, J., Bezzeghoud, M., Rosset, P., Borges, J. F., and Cota Rodrigues, F. (2014). Azores seismogenic zones. Comunicações Geológicas, 101(Especial 1), 351-354.*** In the publication is proposed a new approach to define seismogenic zones based on the frequency magnitude and earthquake density and presented the seismogenic zones identified.

Chapter 4: It is based on a manuscript published in Seismological Research Letters:

Fontiela, J., Bezzeghoud, M., Rosset, P., and Rodrigues, F. C. (2017). Maximum Observed Intensity Map for the Azores Archipelago (Portugal) from 1522 to 2012 Seismic Catalog. Seismological Research Letters, 88(4), 1178-1184. Describe the validation of the methodology used to calculate the maximum intensities observed in each settlement since the 15th century as well as the settlements and inland regions with high seismic hazard.

Chapter 5: This chapter is based on a manuscript submitted to Georisk: ***Fontiela, J., Rosset, P., Wyss, M., Bezzeghoud, M., Borges, J., and Rodrigues, F. C. (2018) Human losses and damage expected in future earthquakes in Faial Island - Azores.*** Detailed statistical information of population and building stock distribution, and ground motion prediction equation suitable to the Azores were validated based on past earthquakes. Then, two scenarios were prepared to estimate human losses in Faial Island based on a rupture inland and one offshore.

Chapter 6: The last chapter concerns the overall conclusions obtained throughout the different chapters and outlook, or ongoing work is outlined.

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2

Characterization of seismicity of the Azores archipelago

2.1. Summary

This chapter comprises two papers. The first one *Large earthquakes in the Azores* was published in Fisica de la Tierra, and the other one *Characterization of seismicity of the Azores archipelago: An Overview of Historical and a Detailed Analysis of the Period 2000-2012* is the chapter 8 of the book Volcanoes of the Azores, Active volcanoes of the world,

Geographical constraints and time, amongst other factors such as politics or religion, could limit the seismological knowledge. The Azores region belongs to the group where the geographical constraints and time limit the comprehension of the seismicity. A considerable amount of seismogenic sources are in the ocean bottom. Additionally, the historical seismicity record is not long enough nor detailed enough to extrapolate recurrence periods of great earthquakes that took place in the Archipelago.

The peculiar location of the Azores region at the Triple Junction of the American, Eurasian and Nubian lithospheric plates (figure S1), is pointed out by a high number of earthquakes of low magnitude, and some events of M≥ 5. Despite the temporal limitations, there were felt or recorded 33 earthquakes of intensity ≥VII (Nunes et al. 2001) since the 15th century in the Azores. Some of these events caused an extent social damage and heavy damage in the building stock. The volcanic activity is also responsible for several earthquakes and seismic swarms in the region.

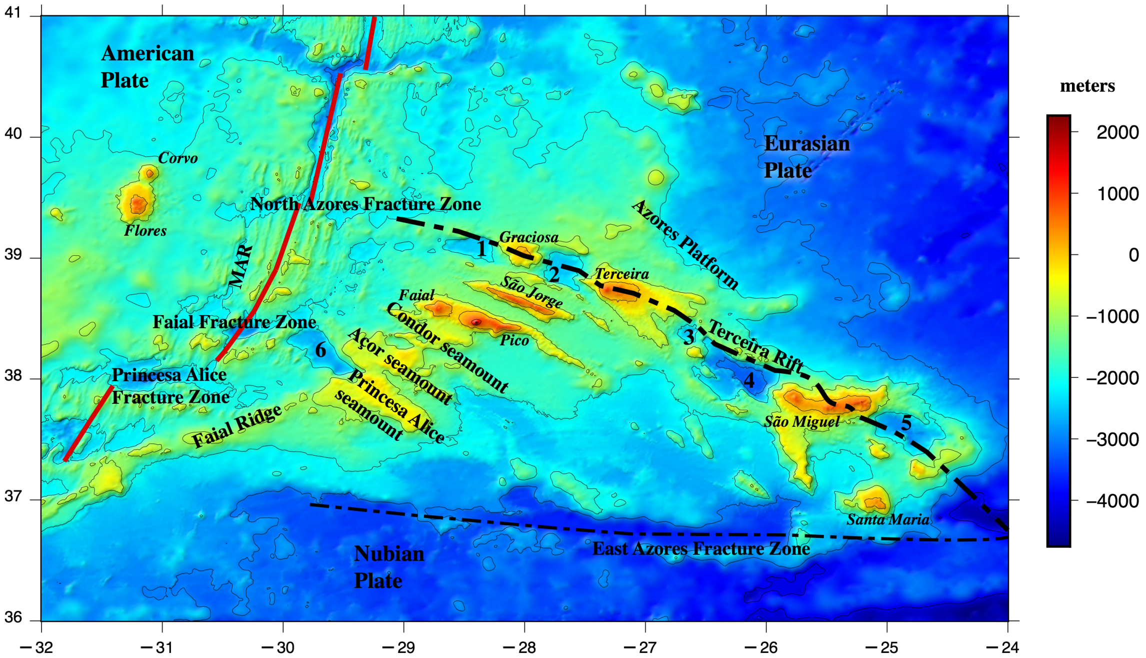

Figure S1: Morphologic and bathymetric map of the Azores region. 1 – Graciosa western basin; 2 – Graciosa eastern basin; 3 – North Hirondelle basin; 4 – South Hirondelle basin; 5 – São Miguel basin; 6 – Princesa Alice basin. The bathymetry is shown as background from Smith and Sandwell (1997).

This chapter has a "typical" organization. The first section is the introduction where I make a general presentation of the geodynamics framework of the region. Then, in the second section, I will address subjects like the historical seismicity, the evolution of earthquake catalogues, seismic networks operating in the Azores, and a brief analysis of the seismicity in the period 1915 mid-2012 (section 2). Section 3 is dedicated to the characterization of the seismicity, based on the frequency magnitude relation of Gutenberg and Richter (1944) between 2000 up to mid-2012 in a regular grid of 2º by 2º (latitude and longitude, respectively) with variable superimposition. In the Mid Atlantic Ridge, the windows superimpose 1º in latitude and longitude, while in Terceira Rift is 1.5º by 1º. Nevertheless, this approach has limitations since the Azores are located at the boundary of three lithospheric plates, controlled by a set of tectonic structures. It means that the seismicity occurs in different tectonic structures instead of different segments. Besides, the seismicity associated to the volcanic activity play a major role in the Archipelago. Thus, our approach catches the main seismic features of the region. Hence, *b*-value is discussed taking into consideration that, it is inversely proportional to the mean magnitude as Aki (1965) proposed. In accordance with this relationship, volumes of low *b*-value produce more moderate magnitude earthquakes and increase the likelihood of a mainshock. In the same section (3) we characterize the magnitude of completeness (minimum earthquake magnitude threshold detected by a seismic network (Wiemer and Wyss, 2000). I finish the chapter with the discussion and the conclusions.

Magnitude of completeness is a quality measure essential to examine the spatial and temporal homogeneity of the earthquake catalogue. Thus, we assess the quality of the catalogue and decide the analysis should be restrained to the period 2000-2012. Previously, the magnitude reported in the seismic bulletins were heterogeneous and it is not desirable analyse *b*-values using different magnitudes since it introduces bias (Wiemer and Wyss, 2002). Magnitude of completeness is variable on our analysis due to two factors. The first one is related to poor azimuthal coverage of some seismogenic zones contrasting with others where it's very good. The other factor that affected the minimum magnitude of completeness is related to the end of the SIVISA[1] consortium and the consequent reduction of sensors network available. Despite all these limitations the minimum magnitude of completeness in the Central group is 2.4 and 2.2 in the Eastern group. The observed high values in the Mid-Atlantic Ridge (MAR) and in the Central group are in regions with poor azimuthal coverage.

The analysis of *b*-values shows a gradual decrease from west to east (for further details see table 3 of this chapter), persistence of high *b*-values (≥ 1.2) in the region that comprises the MAR and the islands of the Central Group (Graciosa, São Jorge, Faial, Pico and Terceira). I link these high *b*-values with the presence of two distinct buoyant mantle upwelling's that could mean an increase of heterogeneity or lower stress; it is likely that the crust is also cracked as depicted by low mean magnitude. Moreover, hydrothermal systems can increase the *b*-values due to an increase of pore pressure (Warren and Latham, 1970). Nevertheless, some regions have a poor azimuthal coverture of the seismic network, which could lead to bias in the *b*-values; especially to the west of the islands of the central group. The eastern tip of the Eastern Group (São Miguel and Santa Maria Islands) is pointed out by the transition of the Terceira Rift to the Gloria Fault. The seismicity, in between longitude 28.85 W (western tip of São Miguel Island) up to 24.5 W (western end of Gloria Fault) show two regions of high seismicity: 1) the central part of São Miguel Island, and 2) the one that extends from south of São Miguel and it goes through the Formigas Islets and finishes in the transition to the Gloria Fault. The central part of São Miguel Island is complex since it may accommodate the deformation of the Terceira Rift, associated with a hydrothermal system and, less evident, a volcanic

[1] Sistema de Vigilância Sismológica dos Açores

plumbing system. In the other mentioned region, the low *b*-values (0.8) may be related to the volcanism extinction in this part of the Archipelago (Hübscher et al. 2016).

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2.2. Paper: *Large earthquakes in the Azores*

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EDICIONES COMPLUTENSE

Grandes terremotos en Azores

Bento Caldeira[1]; João Fontiela[2]; José F. Borges[3]; Mourad Bezzeghoud[4]

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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).

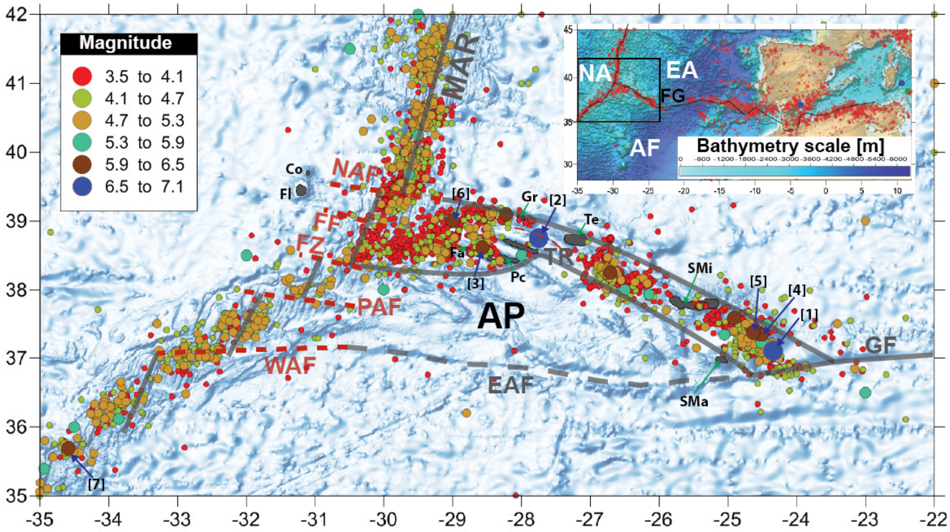

Figure 1. Top panel - Seismicity (M> 4.0) along the western part of the Eurasia-Africa plate boundary from 1926 to 2017 (from NEIC data files). Bathymetric data are from the GEBCO_2014 Grid. NA=North American plate, EA=Eurasian Plate, AF=African plate; the black rectangle corresponds to the Azores region 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.

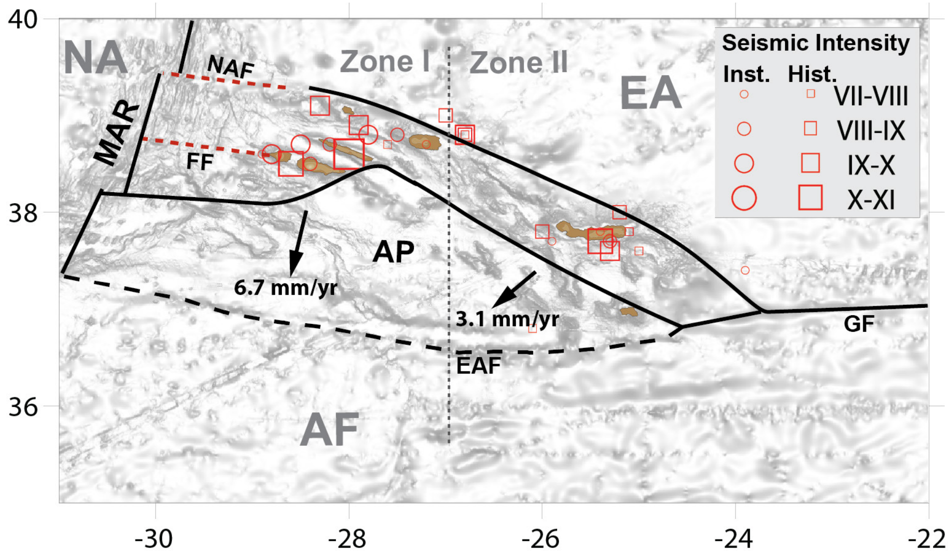

Figure 2. Epicentres of the 33 most destructive Azores earthquakes reported by Nunes et al., 2001. The squares represent historic earthquakes and the circles instrumental ones. The epicentre locations of the historic earthquakes were estimated from the distributions of the reported intensities. The black 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 ≤ M ≤ 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, Places more affected	Date	Max. Intensity	Mag.	Lat (deg)	Long (deg)	H 0 (km)	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	St Maria, 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.

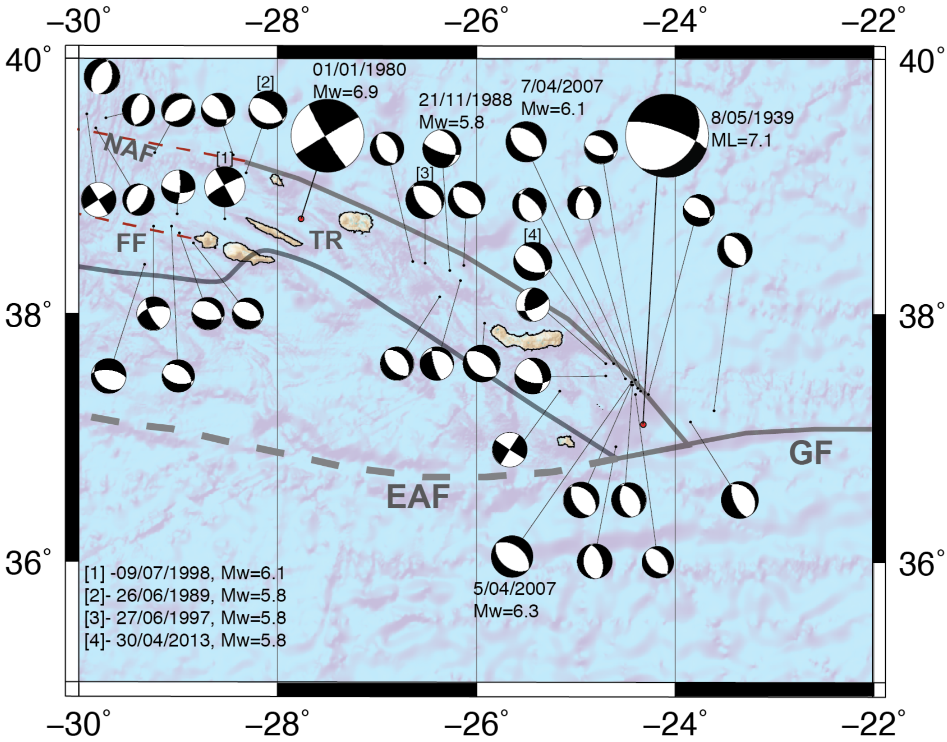

Figure 3. Available earthquake mechanisms from the occidental segment of the EA-AF boundary that corresponds to the Azores region.

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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2.3. Paper: *Characterization of seismicity of the Azores archipelago: An overview of historical and a detailed analysis of the period 2000 – 2012*

Characterisation of Seismicity of the Azores Archipelago: An Overview of Historical Events and a Detailed Analysis for the Period 2000–2012

João Fontiela, Carlos Sousa Oliveira and Philippe Rosset

Abstract

The Azores Archipelago is located in the Middle Atlantic Ridge, at the Triple Junction formed by the contact of the Euro-Asiatic, the Nubia (African) and the American plates (see also Vogt and Jung, Chapter "The "Azores Geosyndrome" and Plate Tectonics: Research History, Synthesis, and Unsolved Puzzles"). Its seismicity rate is very high with earthquakes with relatively low magnitude, defining quite well the contact regions. This chapter gives an overview of the existing historical and instrumental catalogues, describes the seismicity of the region essentially since early 1915, and analyses in more detail the characteristics of the recorded data in the period 2000–2012. The spatial variations of the minimum magnitude of completeness (Mc) as well as the b-value is studied for this period within the stripe of observed seismicity which contains the alignment of the Archipelago islands. A preliminary interpretation of the Mc and b-values is made keeping in mind the geological transition between the Gloria fault to the East and the Mid-Atlantic Region to the West.

Keywords

Azores tectonic structures · Earthquake catalogue · Seismic zoning · Minimum magnitude of completeness · b-value

Electronic supplementary material
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1 Introduction

The Azores Archipelago is composed of nine islands divided into three groups; from west to east, the Western group includes Flores and

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Corvo, the Central group is composed of Graciosa, Faial, Pico, São Jorge and Terceira and the Eastern group comprises São Miguel and Santa Maria. The Archipelago is located at the Triple Junction of the Eurasia, Nubia and, the North America lithospheric plates. The Central and Eastern groups are eastward of the Middle Atlantic Ridge (MAR) and at the boundary of the Eurasian and Nubian plates. The Western group is located to the west of MAR and lies on the American plate. The Azores Islands lie on a plateau formed by tectonic and/or magmatic activity. Various theories have been proposed (e.g., a melting anomaly, Schilling 1975); Vogt and Jung (Chapter "The "Azores Geosyndrome" and Plate Tectonics: Research History, Synthesis, and Unsolved Puzzles") have compiled an overview of the models explaining the presence of the volcanic islands of the Azores. The eastern side of the Azores region has a roughly triangular shape delimited by three tectonic discontinuities: the East Fracture Zone (EFZ) in the south, the MAR in the west and the Terceira Rift (TR) in the north. The EFZ is oriented E-W with a seismic activity decreasing to the East, and jumped from the EFZ to a point further north (Luís et al. 1994). MAR is a pure extensional structure, seismically active and, divided into several segments. At the 38°50′ latitude North, the direction is N10°E with a low inflection to the south around N20°E. While the origin, morphology and geodynamic features of these two tectonics limits are consensual, it is not the case for the Terceira Rift which is still debated. TR has a general WNW-ESE orientation and is characterised by a sequence of basins, seamounts, and Islands. According to Udías (1980) and Buforn et al. (1988), it is an extensional zone normal to the MAR or an oblique extension for Searle (1980). Madeira and Ribeiro (1990) state that TR is a leaky transform. According to them, the compressive stress axis (σ_1) is horizontally rotating from N-S out of the boundaries limit to NW-SE in the boundary limits. The maximum tensional stress (σ_3) is horizontal with a NE-SW orientation. Due to the stress deviation near the boundary, the dextral faults change from NNW-SSE to WNW-ESE and sinistral faults from NNE-SSW to NNW-SSE. Nevertheless, the wideness of the disturbed zone given by the direction of the maximum and minimum compression and by the morphological features indicates that Azores domain is a diffuse plate boundary with an oblique ultra-slow spreading centre that accommodates the shear movements between the Nubia and Eurasia plate (Lourenço et al. 1998). According to Vogt and Jung (2004), the TR is an ultra-slow ridge that comprises the segment formed by the Graciosa, Terceira and São Miguel Islands.

Seismicity encompasses a stripe formed by the Graciosa, São Jorge, Faial, Pico, Terceira, São Miguel and Santa Maria Islands and goes to east along the Gloria Fault. Figure 1 depicts instrumental seismicity between 1915 and 2012. Most of the seismicity in this period has $M \leq 4$ and the maximum magnitude recorded in the instrumental period is M_S 7.1. Focal mechanisms of the Azores region calculated and revised by several authors are compiled in the Fig. 2 (McKenzie 1972; Arroyo and Udías 1972; Udías et al. 1976; Grimison and Chen 1986, Buforn et al. 1988; Borges et al. 2007; Bezzeghoud et al. 2014). The deformation process in TR is dominated by earthquakes with right-lateral strike-slip faults or normal faults oriented N120°E or N150°E (Grimison and Chen 1986; Buforn et al. 1988). Both faulting systems are under horizontal tensions with mean direction N25°E normal to TR (Buforn et al. 1988).

Several authors divide TR into two zones with distinct seismicity. Borges et al. (2007) and Bezzeghoud et al. (2014) distinguish them from the total seismic moment tensor whereas Fontiela et al. (2014) consider the frequency magnitude relation. The first seismic zone comprises the area between the MAR up to the Terceira Island and the second one, from the Terceira Island up to the transition of the Azores domain to the western end of the Gloria fault.

Testimonies of the seismicity of the Archipelago begin in the middle of the 15th century with the first Portuguese settlements in the Archipelago. One of the largest events ever known in the Azores occurred in 1522 causing heavy damage in Vila Franca do Campo, the first capital city of São Miguel Island.

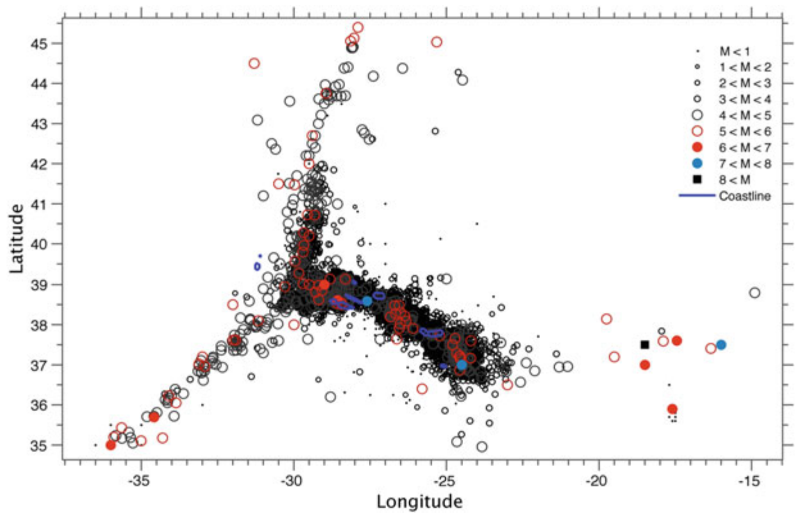


Fig. 1 Earthquake catalogue for the period 1915–2012 (EC2012). EC2012 includes 34.874 events

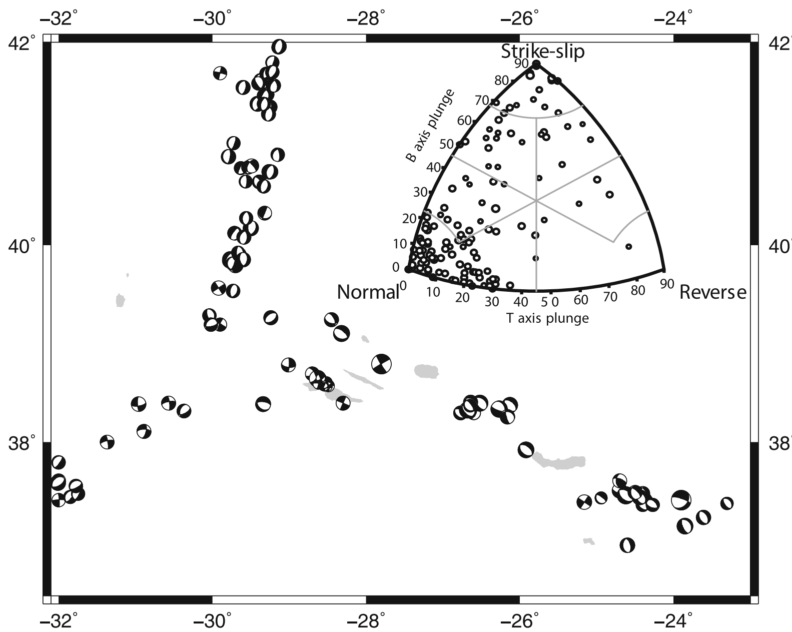


Fig. 2 Focal mechanisms map of the Azores region and triangle diagram to classify focal mechanism (Álvarez-Gómez 2014). Data represents time span 1939–2012 (data sources: Grimison and Chen 1986; Buforn et al. 1988; Borges et al. 2001; Dias 2005; Borges et al. 2007; Matias et al. 2007; Bezzeghoud et al. 2014; ISC—International Seismological Centre)

Among the several authors publishing on the historical seismicity of the Azores, Costa Nunes (1986) is the one who edited the first earthquake catalogue for the period 1444–1980. Later, another catalogue covering the period 1850–1998 was published by Nunes et al. (2004), correcting several events and adding new ones.

The present chapter gives an overview of the main sources of information and data used in these catalogues. It analyses the main characteristics of the evolution of seismicity in the period 1915–2012. For the period 2000–2012, a detailed analysis of the data completeness (i.e. minimum magnitude of completeness, Mc) and of a- and b-values of the Gutenberg-Richter magnitude law is made. Then, the variability of these values for the different zones is discussed.

2 Earthquake Catalogue

As in many other seismic areas of the world, the seismicity in the Azores is described in two periods: the historical and instrumental ones. The historical period concerns data reported by witnesses, its uncertainties depending on the perception and capabilities of the observers to describe the effects (see also Beier and Kramer, Chapter "A Portrait of the Azores: From Natural Forces to Cultural Identity"). For the instrumental period, data are collected on paper or digitally. The increasing number of operating seismic stations associated with an increasing quality of the seismological observatory practices have permitted rapid progress in the detection of small events. As a consequence, the number of events recorded and the quality of the determination of seismic source parameters have increased quite significantly in the last decades.

The 1522 earthquake was the first historical event referred in the Azores. Gaspar Frutuoso (*1522, †1591) described in detail the effects of this earthquake that triggered a massive landslide burying the city of Vila Franca do Campo. Other authors contributed with earthquake reports such as Drumond (1859), Macedo (1871), Junior et al. (1983), and Bessone (1932). Agostinho (*1888, †1978) and Machado (*1918, †2000) also actively contributed to a better understanding of the earthquake phenomena in the Azores. They studied the most severe earthquakes that struck the Islands. For further readings, one could refer to Machado (1948, 1949, 1966) and Agostinho (1927a, b, 1955a, b). Other valuable sources of historical seismicity are the Arquivo dos Açores (1981–1986) and local newspapers.

The first seismometer was installed in São Miguel Island in 1902, followed by the installation of a second station in Terceira in 1932 and a third one in Faial in 1957. Until 1980, the Azores seismic network was composed by these three stations only. Due to the small number of sensors during the period 1957–1980, the minimum magnitude threshold was very high, restraining the detection of events of small magnitude. The Terceira earthquake of the 1st January 1980 is a milestone in the seismology studies of the Azores. Few days after the main shock, the Universidade dos Açores (UAz) deployed a temporary seismic network that was operating on the geothermal project in São Miguel Island. Few months later, the seismic network operated by the UAz had six seismic stations in Terceira Island and eight in São Miguel Island. This network was able to detect tens of micro-earthquakes (Nunes 1991). After Terceira earthquake, and during many others seismic swarms, temporary seismic networks were deployed, but considering the aims and specificity of temporary seismic networks, they will not be referred herein. In 1996, IRIS, within the Global Seismic Network Project (IRIS/IDA), installed one surface and one borehole seismometer in São Miguel Island. Before 1997, two seismic networks operated independently of each other; one operated by the UAz and the other one by the Instituto de Meteorologia (IM). In 1997, these two institutions created the SIVISA (*Sistema de Vigilância Sismológica dos Açores*) Consortium which joins the two networks in a single one (Fig. 3a, b). With the Consortium creation, the number of seismic stations increased producing a decrease in the inland network gaps and improving the determination of the focal parameters. Ten years later, in March 2007, the SIVISA Consortium ended, splitting the network in two separate networks as it was prior to 1997. The seismic network operated by IM with 21 stations was updated with two broadband seismometers installed in Corvo and Flores Islands under the CTBTO (Comprehensive Nuclear-Test-Ban Treaty) framework (Fig. 3a, b). Figure 3a shows the spatial distribution of the SIVISA stations and later IPMA (former IM) while Fig. 3b shows the seismic network evolution as well as the seismic stations operating in the Azores between 2001 and 2012.

As referred previously, Costa Nunes (1986) edited the first earthquake catalogue of the Azores for the period 1444–1980. For this period, earthquake dataset was divided into three groups according to the data quality. The first group includes data collected before 1900. The number of events is small and concerned mainly strong earthquakes. The second group covers the

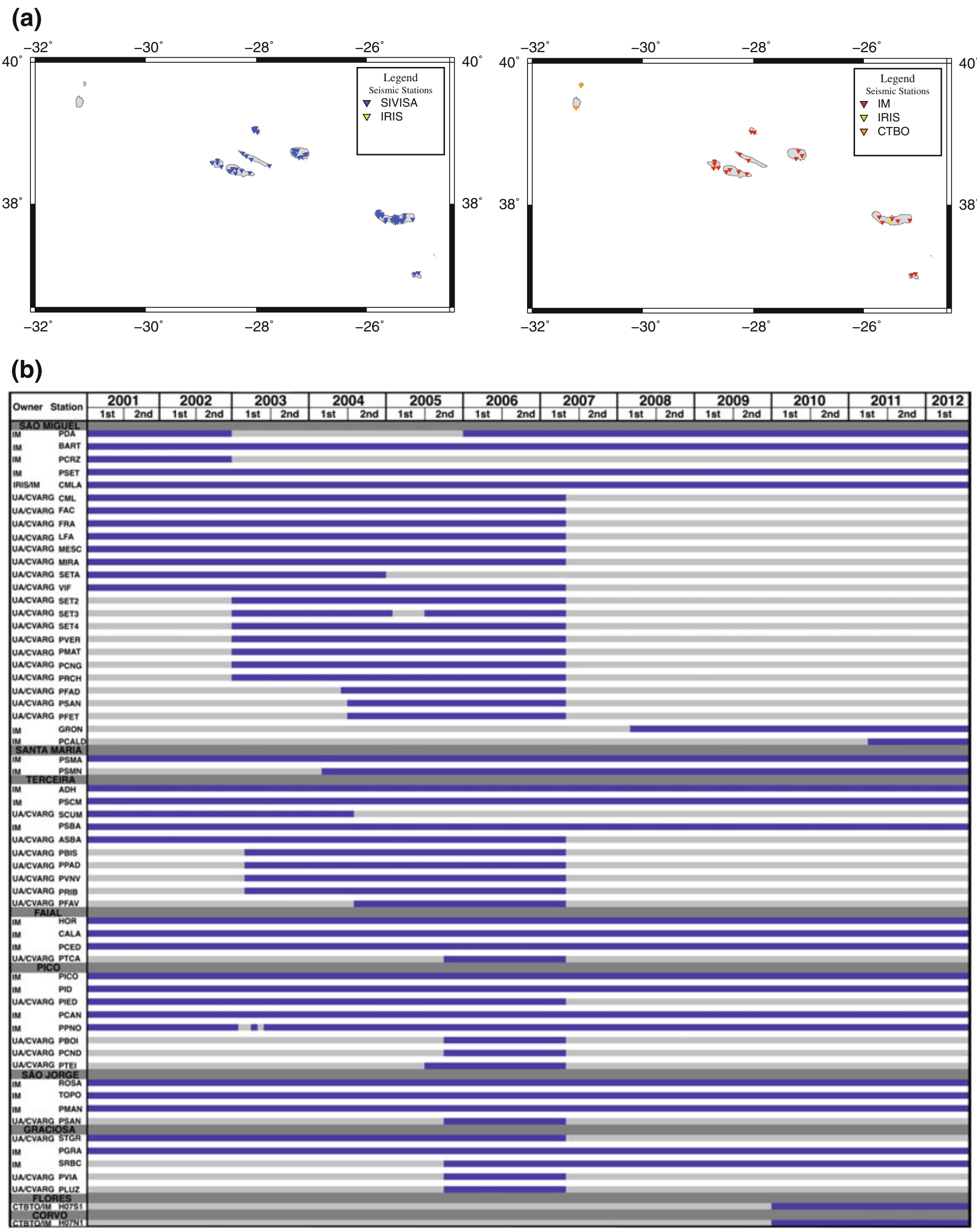


Fig. 3 Evolution of the seismic network in Azores for 2001–2012. **a** the left and right Figures show the seismic network operated by SIVISA and IPMA (former IM), respectively up to the end of 2014. **b** Depicts the seismic stations operating by SIVISA Consortium and after the end in April 2007. The time scale is in semesters. Operating stations are in blue, unknown or not-operating stations are in light grey and unknown status is marked in dark (*Source* Boletim Sismológico Preliminar dos Açores, published by SIVISA in monthly basis between 2001 and 2012. In the period 2007–2012 published by IM)

period 1900–1975 with more detailed and quality improved data. The number of events still remains relatively small. The third group, in the period 1975–1980, concerns mainly instrumental data provided by the seismic stations in the region.

The Earthquake Catalogue for the Azores Region (CSRA) published by Nunes et al. (2004) comprises the period 1850–1998. The CSRA combines the Azores Earthquake Database (BDSA) from Nunes (1991), the earthquake catalogue of Costa Nunes (1986) and data from worldwide earthquake catalogues. Nunes et al. (2004) reviewed the events reported in Costa Nunes (1986) and Nunes (1991) and added new information whenever available. After 1947, the primary earthquake data sources were Anuário Sismológico Nacional and the bulletins published by Instituto de Meteorologia (IM), now replaced by the Instituto Português do Mar e da Atmosfera (IPMA). From 1980 to 1998, data was provided by the seismological networks operated by the UAz and later by SIVISA. For the period 1970–1998, it can be noticed that the CSRA has some periods without records.

Nunes et al. (2004) claim about 900 earthquakes felt between 1850 and 1946, 6,460 recorded earthquakes for the period 1947–1979, and 2,600 recorded earthquakes for the period 1980–1998. The present study concerns data for the period January 2000–July 2012, compiling the data provided by the International Seismological Centre (ISC) for the period 1998–2002 and the data from the Seismological Preliminary Bulletin of Azores published by SIVISA and, since 2007, by the Meteorological Institute for the period 2003–2012. The newly created dataset, called the Earthquake Catalogue 2012 (EC2012) comprises the period 1915–2012. The EC2012 includes 34,874 entries, 75% of them recorded during the period 1998–July 2012. Magnitude scale reported on EC2012 are M_L, M_d, M_b and M_S. M_L and M_d scales are the most common ones with 60 and 23% of the cases, respectively. About 10% of the data have no reported magnitude.

The map locating the epicentres of the EC2012 (Fig. 1) shows seismicity distribution along a stripe that accommodates a complex system of tectonic structures, reinforcing that the Azores domain is a complex area. One could distinguish clusters of events with magnitude greater than five such as the one in the southeast of São Miguel Island, between São Miguel-Terceira, Faial-Pico Islands, west of Faial and Graciosa Islands, and on the MAR. The strongest earthquakes ($M \geq 6$) are located directly on the MAR, in the Central Group (Terceira, Graciosa, São Jorge, Pico, and Faial) and to NW and SE of São Miguel Island. The strongest earthquake ever felt in the Azores struck São Jorge Island on July 9th, 1757 with an estimated magnitude M of 7.4 (Machado 1949).

Figure 4 shows the annual frequency and cumulative number of earthquakes of the EC2012. Prior the improvement of the seismic network, in 1980, the number of earthquakes recorded is low and, after 1980, the annual number of recorded earthquakes increases. Several seismic crises (swarms) are clearly shown in the bottom graph of Fig. 4: in 1964 in S. Jorge, in 1973–1974 in Pico, in 1992–1993 and 1998 crises around Faial Island, and in 1989 and 2005–2006 seismic crisis that occurred in Fogo-Congro region of São Miguel Island. For the latter, no consensus was found on the number of earthquakes recorded during this period. Marques et al. (2007) report that 46,000 events were recorded between May 2005 and December 2005 while Silva et al. (2012) state that only 15,000 events were recorded between 2002–2010. Nevertheless, the number of events reported in Seismological Bulletins between May and December 2005, is lower than 7,500.

Figure 5 depicts the magnitude distribution of the events for the period 1915–2012. The magnitude ranges from 0.7 to 8.1 with three remarkable peaks; the first peak is between 0.8–1.2 and associated to seismic swarms characterised by a high number of events with smaller magnitudes. The second peak referring to magnitudes range between 1.5 and 2.3 corresponds to the largest number of recorded earthquakes in the Azores. The last peak, in the interval 2.5–2.8, is associated with seismic sequences like the one of the Faial in 1998. In general, the Azores

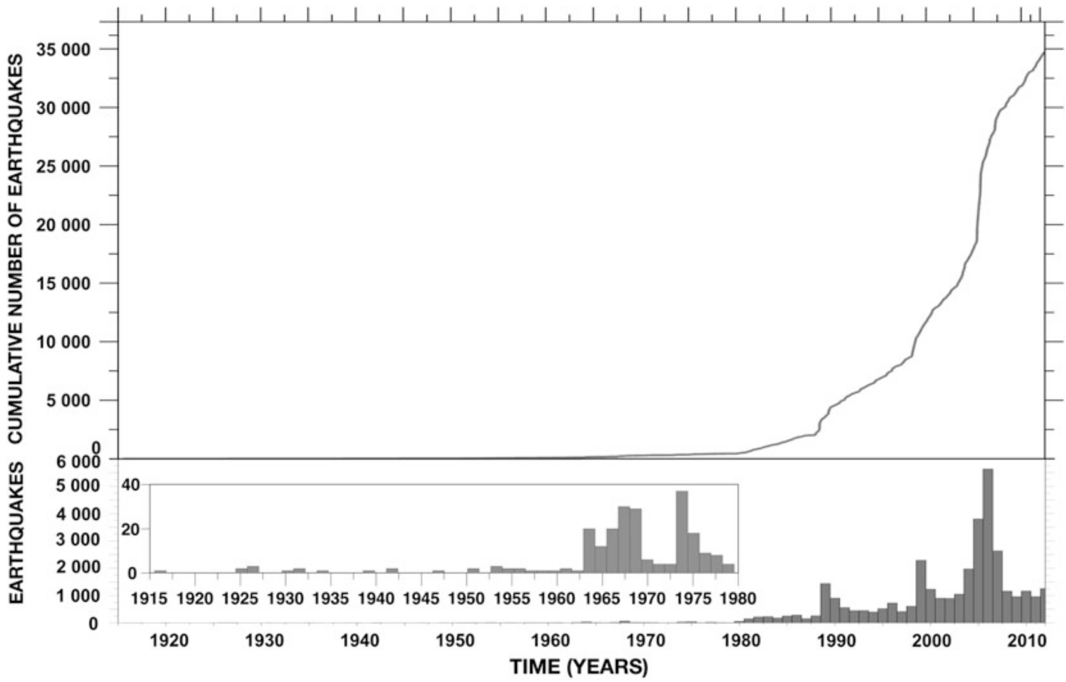


Fig. 4 Annual distribution of earthquake in the EC2012 (1915–mid2012). The cumulative number of earthquakes (above) and the annual number of events (below). The inset shows in detail the annual distribution between 1915 and 1979

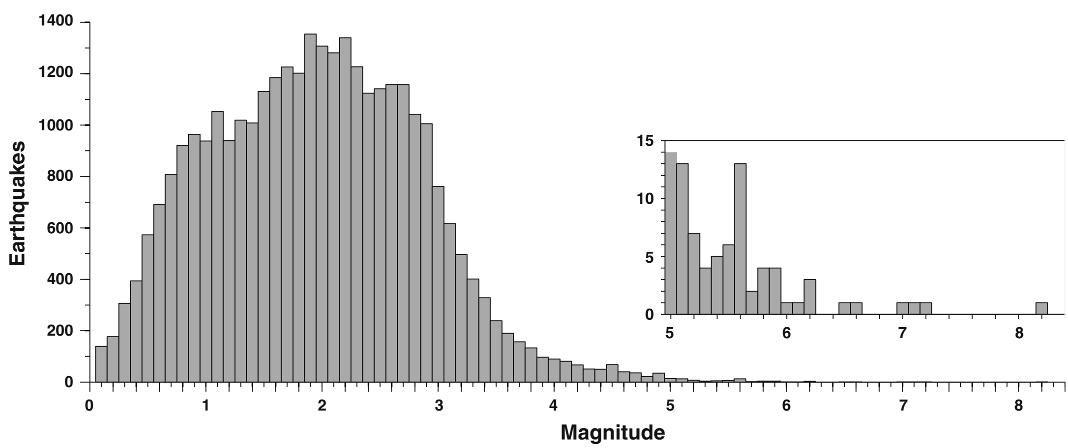


Fig. 5 Frequency magnitude distribution of the EC2012 data. The inset shows in detail the frequency magnitude distribution for magnitude higher or equal than 5. In both cases, bins have 0.1 unit of magnitude

seismicity is characterised by a high number of events of relatively small magnitude.

Most of the earthquakes in the Azores have a shallow depth, less than 10 km, as illustrated by the hypocentres distribution of Fig. 6. According to Kearey et al. (2009), the thickness of continental crust is around 40 km while the oceanic one is around 7 km. Nevertheless, the crust in the Azores is not a typical one. Searle (1976) estimated the thickness of oceanic crust around 8 km

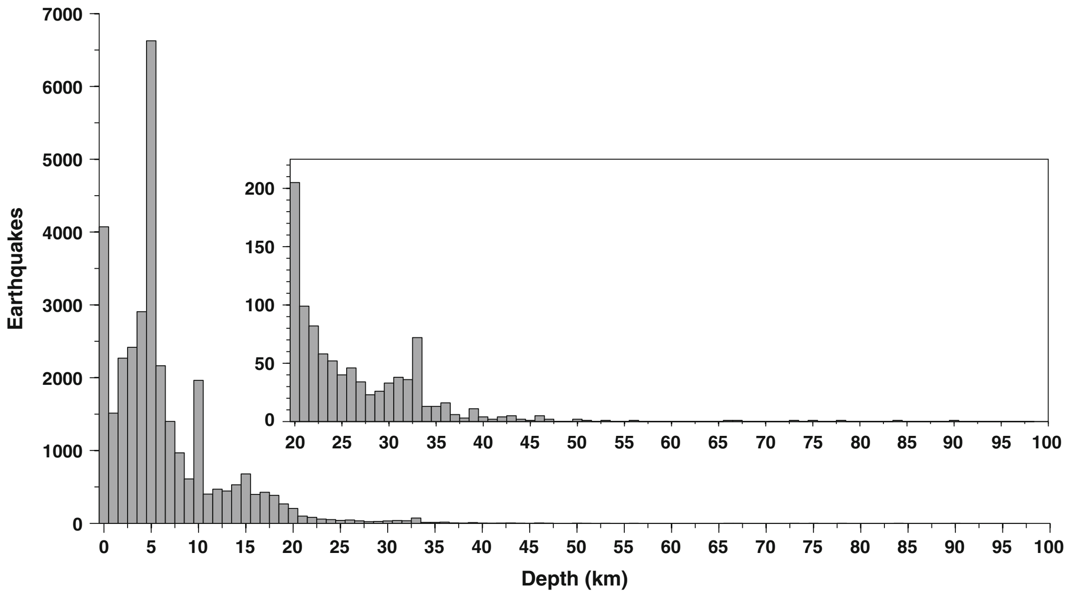


Fig. 6 Depth distribution of events in the of EC2012. 0, 5, 10 and 15 km depths corresponds to the automatic determination. The inset show in detail the seismicity for depths equal or higher than 30 km. In both cases, bins have 1 km depth interval

using the Rayleigh-Wave dispersion method; Steinmetz et al. (1977) in the MAR identified two reflectors at 9 and 30 km depth; Luís et al. (1998) estimated an elastic plate with 7–8 km thickness while Luís and Neves (2006) estimated in 4 km. Later, Matias et al. (2007) estimated the oceanic crust in 14 km in the area that comprises Faial, Pico and São Jorge Islands. Silveira et al. (2010) established a thick crust around 20–30 km. Figure 7 shows hypocentres in two cross-sections along the major tectonic structures of Azores. Three main earthquake clusters at a depth greater than 10 km are identified on cross-section A–B (Fig. 7b) beneath Graciosa Island, to the east of Terceira and beneath the central part of São Miguel Island which comprises the region beneath Fogo-Furnas volcanoes. Concerning cross-section C–D (Fig. 7c) is identifiable a seismic cluster that is related to the Faial earthquake (1998), where the foci are deeper than 25 km. Dias (2005) studied in detail the aftershocks sequence of Faial earthquake and calculated using inversion models that the Moho discontinuity is around 11–14 km. Another cluster is West of the Graciosa Island where earthquake depth reaches 40 km. The last cluster concerns the SE of the Terceira Island on a small area of a submarine section of the Lajes fault where deepest events attain 50 km depth (Lourenço et al. 1998).

3 Characterization of Seismic Activity

Earthquake catalogues are the primary source of information to study seismo-tectonics, seismicity, and hazard. Seismic data quality is the main criteria to obtain reliable and accurate results and provide pertinent statistical analysis. Unfortunately, data is not homogeneous since they come from the analysis of seismic waves recorded by different instruments with different operational practices and procedures, varying in space and time. Several authors (e.g. Habermann 1987, 1991; Habermann and Creamer 1994; Zuniga and Wiemer 1999) gave special attention to the heterogeneities in earthquake catalogues, introduced by network's limitations and man made changes. These heterogeneities in space and time

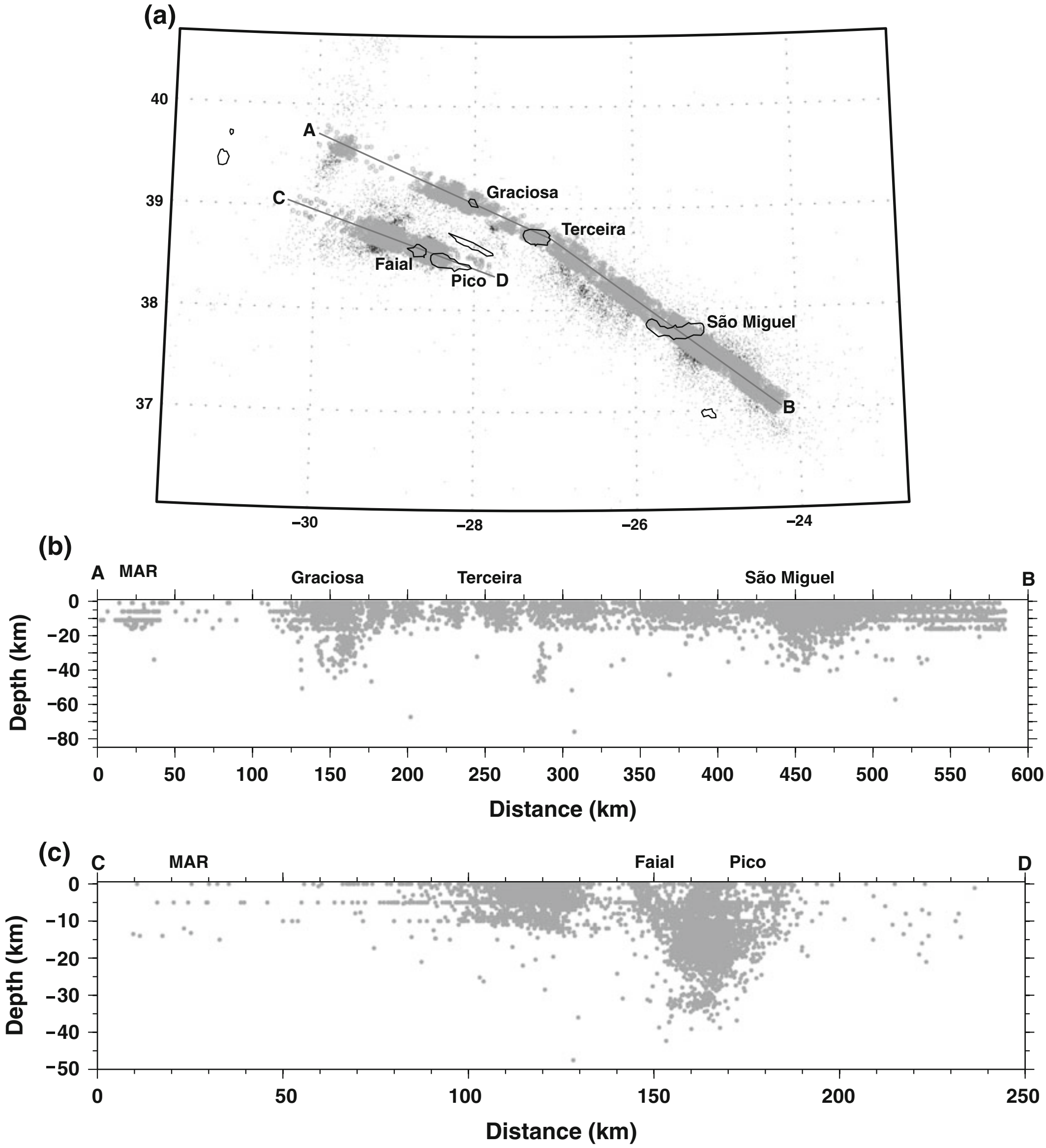


Fig. 7 **a** Location of cross sections along the major tectonic structures of Azores. The empty grey circles are earthquakes selected to draw the cross sections and black dots are earthquakes which are not represented on cross-sections. **b** Cross section A–B starts in the Middle Atlantic Ridge and crosses Terceira Rift until Gloria fault. **c** Cross section C–D starts in the Middle Atlantic Ridge and crosses Faial-Pico volcanic ridge

affect the completeness of the catalogue, and they need to be avoided. A parameter useful to verify the quality of an earthquake catalogue is the minimum magnitude of completeness (*Mc*). *Mc* is the lowest magnitude for which all earthquakes in a space volume and time period can be detected (Rydelek and Sacks 1989; Taylor et al. 1990; Wiemer and Wyss 2000, 2002). To estimate the minimum magnitude of completeness, a simple power-law can approximate the frequency magnitude distribution (FMD) for a given volume. The relationship between frequency of occurrence and earthquakes magnitude (Ishimoto and Iida 1939; Gutenberg and Richter 1944) is as followed:

$$\log_{10} N(M) = a - b\mathrm{M} \tag{1}$$

where N is the number of earthquakes having a magnitude larger than M, a and b are constants. The a-value describes seismic activity while b-value relates to tectonic stress (Mogi 1967; Scholz 1968). The b-value is near 1 in most seismically active regions on Earth (Frohlich and Davis 1993). However, b-value can be disrupted by an increase of material heterogeneity that produces high values (Mogi 1962) or by an increase of shear stress (Scholz 1968), and effective stress (Wyss 1973) that produces lower values. It is common in volcanic areas to have high b-values, up to 2, due to the high temperature gradient (Warren and Latham 1970) or during swarms. Several authors (e.g. Wyss et al. 1997; Wiemer and McNutt 1997; Wiemer et al. 1998; Murru et al. 1999) found high b-values limited to small volumes corresponding to active magma chambers and conduits.

To estimate *Mc*, we choose events with M_L due to their higher number of events in EC2012 for the period 2000–2012 (20,880 events). On the same time span, only 7,970 events were reported with duration magnitude (M_d). We reject M_d due to the dependence of signal-to-noise ratio of this magnitude scale and to the low number of events reported. The choice of having a single magnitude scale reduces the errors in the estimation of b-value (Wyss 1991; Zuniga and Wiemer 1999). Wiemer and Wyss (2000) proposed to combine Mc95 with Mc90 estimates and the maximum curvature method to estimate *Mc*. The Mc90 and Mc95 are the magnitudes at which 90 or 95% of the observed data are modelled by power law fit, respectively. The maximum curvature method estimates *Mc* using the point of maximum curvature of the FMD.

Large earthquakes produce hundreds to thousands of aftershocks that can reduce the statistical significance or introduce bias on seismicity rate. To remove aftershocks clusters, we apply the Reasenberg (1985) method to the earthquake catalogue. From 20,880 earthquakes, 9,625 were in clusters, representing 54% of the dataset (Fig. 8). Minimum magnitude of completeness Mc and b-value are determined using the ZMAP software (Wiemer 2001).

Figure 9 shows the frequency magnitude distribution and the power law fitting for all events declustered in the span 2000–2012. The best fit of the Eq. (1) is found with Mc = 2.5 and $\boldsymbol{b}$ = 0.9. Estimated error on Mc and b-value is ±0.4 and ±0.12, respectively.

To qualify the earthquake catalogue regarding *Mc*, b-value (for the period 2000–2012), and identify heterogeneities and spatial variations we create a regular grid of 2 by 2 degree. We obtained ten rectangular regions (Fig. 10), called cells. The grid has a superimposition window of 1° in latitude and longitude in the region of the Middle Atlantic Ridge (MAR) (cells 1, 2 and 4), and 1.5° by 1° in the Terceira Rift (TR) (cells 3, 5, 6, 7, 8, 9, and 10). The review of the seismological studies developed in the Azores Islands as well as the historical seismicity, with consequences in the islands, are mentioned in cells 6 and 9 to give a general view of seismicity of both regions. The following gives an overview of the seismic activity per cell. For all cells (but CELLs 6 and 8), the electronic supplement (S1–S9) show the cumulative annual distribution, the annual number of events and the frequency magnitude distribution.

CELL 1 includes the Northern part of the Azores plateau and a segment of the Middle Atlantic Ridge (MAR). Its seismic activity is scattered and irregular on time. Before 2003, no events were reported in this section of the MAR. Largest event is ML4.6, however most of the events have M_L between 2.8 and 3.8. The FMD fits very well all events above Mc 3.1 with an estimated error for Mc of ±0.2. The a- and b-value are 5.2 and 1.0 ± 0.2, respectively.

CELL 2 shows a cluster of earthquakes centres along a NE-SW trend that coincides with the intersection of MAR and North Azores Fracture Zone (NAFZ). The number of events is much higher than in the other sections of MAR. Around 700 earthquakes were recorded between 2000 and 2012, half of them belonging to the mentioned cluster. Most of the events reported

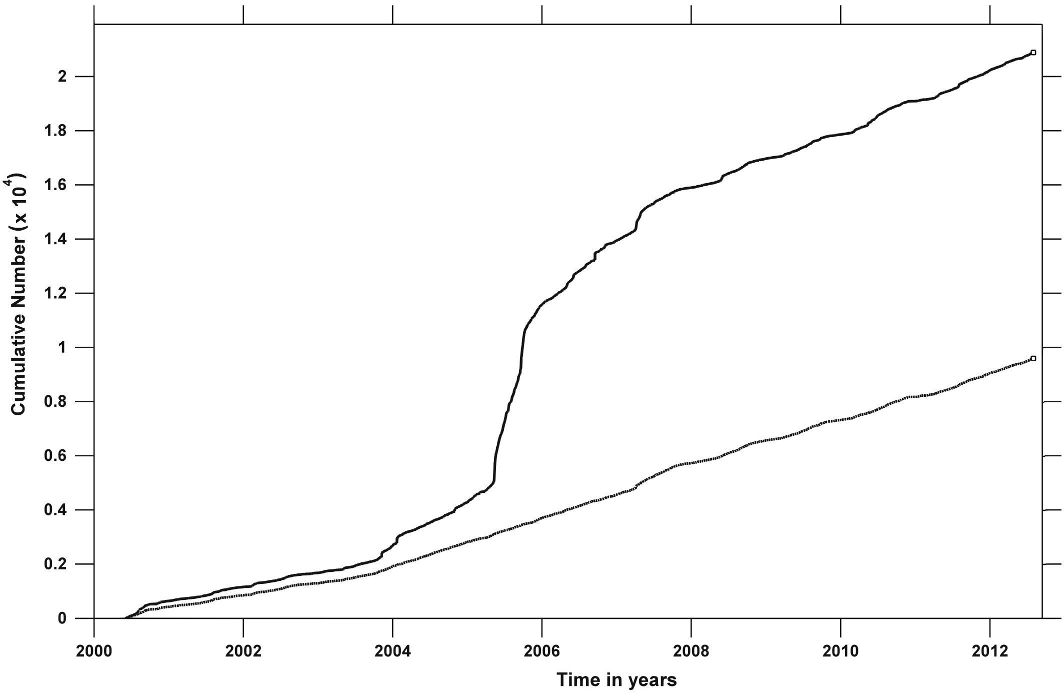
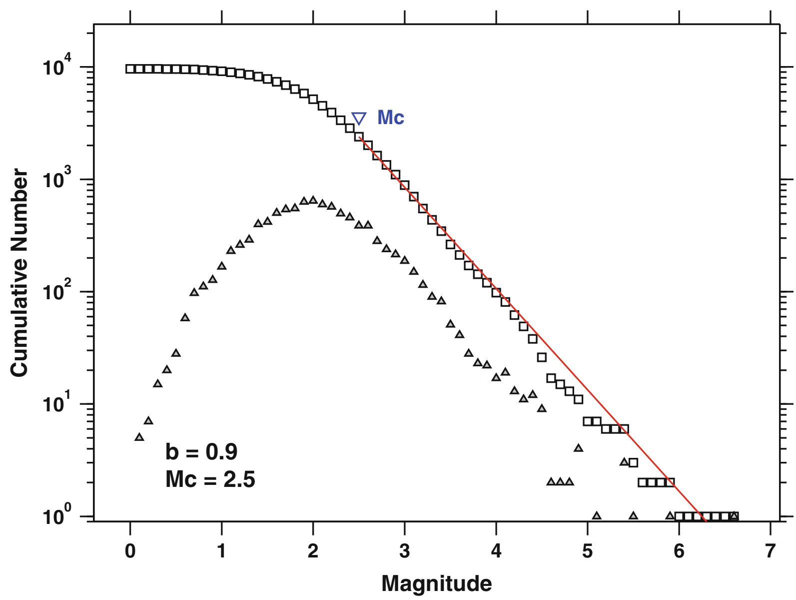


Fig. 8 Temporal distribution of earthquakes in the EC2012 catalogue. Cumulative number is in dark grey and declustered catalogue in light grey. Around 54% of the events on earthquake catalogue were located in clusters

Fig. 9 Frequency magnitude distribution of the EC2012. The error in magnitude completeness is ±0.04 and b-value ±0.12. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle)



have a magnitude between 2 and 4.5. Since 2005, the number of recorded earthquakes have increased partly (or wholly) due to the decrease of the magnitude threshold to 1.5. Mc is 3.2 ± 0.2 while a is 6.7 and b is 1.4 ± 0.3. The relatively high value of Mc in the cells 1 and 2 is due to the difficulty for seismic networks to record low magnitude offshore earthquakes.

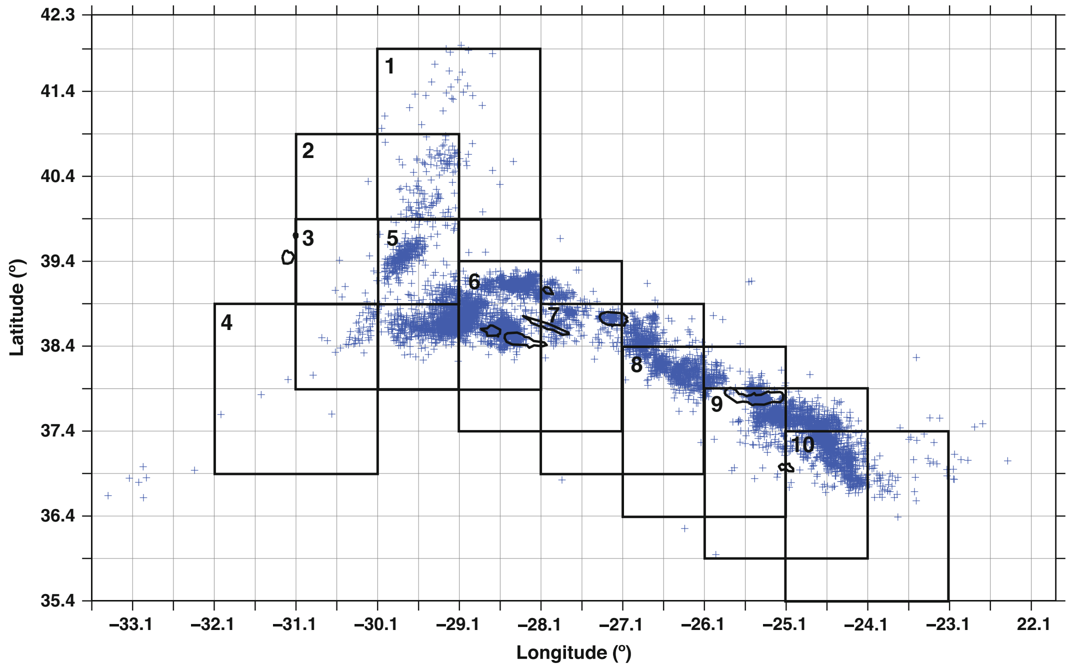


Fig. 10 Declustered earthquake catalogue EC2012 in a regular grid of 2° by 2°. The grid in the Mid Atlantic Ridge has superimposed windows of 1° in latitude and longitude (cells 1, 2 and 4) while in Terceira Rift, the superimposition is 1.5° × 1° (cells 3, 5, 6, 7, 8, 9 and 10)

CELL 3 includes a part of MAR and the west of Terceira Rift. The distribution of the seismic activity shows quiescence periods alternating with intense seismic activity. The seismogenic sources of the cell 3 produce more earthquakes (∼2,000) than in cells 1 and 2. The cumulative number of earthquakes softly increase until 2006, then sharply increase up to 2012. Two peaks at magnitudes $M_L = 2.2$ and 2.6 are identified which are related to the seismic activity to the West of Faial Island and with the activity in the MAR, respectively. Before 2005, the magnitude range is 2–3.5 (M_L) with few events of magnitude higher than 3.5. After 2005, the range of magnitude is 1.5–4. The magnitude-frequency distribution follows the power law model from *Mc* to M_L 4.1. In this case, Mc = 2.8 ± 0.2 whilst a = 5.9 and b = 1.2 ± 0.2.

CELL 4 is fairly aseismic. Most of the seismicity is limited to an area of 0.5° × 0.5°. In this area only 55 earthquakes were recorded, and magnitude range was 2.2 to 4.4. Due to the small number of events, the power law does not fit well the FMD. In this case, Mc = 2.8 ± 0.2, a = 4.1 and b = 0.9 ± 0.3.

CELL 5 covers the MAR and extends over the Islands of Faial, Pico and partially over São Jorge. Seismic activity occurs in a broad area between the Islands of Faial-Pico and the W of Graciosa Island. This cell shows a cluster with a general NE-SW trend and rough elliptical shape of 24 × 12 km at 23 km of the western Faial. Several authors (Luís et al. 1994; Miranda et al. 1998; Lourenço 2007) relate this seismic activity to the extension of the Faial Fracture Zone (FFZ).

In this cell, we notice two periods where seismicity increases; the first one on April–May 2007 when 550 earthquakes occurred with a maximum magnitude (M_L) of 4. Fourteen of them were felt by the population with the highest intensity IV (MM) in Faial Island. The second one in March–June 2010 with more than 400 earthquakes recorded. The maximum magnitude (M_L) was 4.5 and intensity reached V (MM) in Faial. Most of the events have a magnitude in the range 1.2–2.4 with a maximum at 4.5. At this stage, the seismic network can detect small events with M_L lower than 0.5. For this cell, the Mc = 2.8 ± 0.16; a = 6.5 and b = 1.3 ± 0.22.

CELL 6 includes the islands of the Central Group, namely Graciosa, São Jorge, Faial, Pico and the western part of Terceira. A high value of seismic activity can be seen, except in São Jorge Island. It could be explained by the release of energy which occurred with the 1757 earthquake (M7.4, Machado 1949). All the Islands in this cell felt the effects of strong earthquakes at least once on the historical period (Table 1).

Since 1900, Faial Island had to handle two earthquakes that caused heavy damage and deaths and a volcanic eruption. In chronological order the first one was:

- The earthquake of August 31st, 1926 is inserted in a seismic sequence started at 5 April 1926 and lasted up the end of September. Agostinho (1927a, b) estimated the epicentre near Faial Island at the channel between Faial-Pico Islands. The maximum intensity X (MSK) and estimated magnitude (M_b) 5.3–5.6 (Nunes et al. 2001). The main event caused severe damage in the main town of the Island and on nearby villages.
- The second one is the Capelinhos volcanic eruption which begun in September 1957 and finished in October 1958. Initially, the eruption was of surtseyan type and in April 58 decrease gradually to give place to strombolian and hawaiian eruption types. Suddenly, during the early evening of May 12th, 1958 a seismic crisis started and continued through next day. During the first night, the population felt around 450 earthquakes, two of them with maximum intensity X (MMI) and one of VIII (Machado et al. 1962). One maximum intensity was located in southwest of the caldeira and the other one in northwest at half-distance between the caldeira and the active crater whilst. The intensity VIII was in the northeast side of the Island at a focal depth of 1 km.
- On 9 July 1998 Faial Island was hit by a strong earthquake (Mw6.2), 10 km NE of Faial which affected mostly Faial and Pico Islands. The result was eight deaths, more than one hundred injuries and heavy damage on building stock. According to Senos et al. (2008),

Table 1 Historical earthquakes in cell 6 with Imax > VII (modified from Nunes et al. 2001)

Date	Intensity	Death toll	Region most affected
17/05/1547	VII/VIII (MMI)	>3	North zone of Terceira Island
24/05/1614	IX (MMI)	>200	Praia da Vitória, Terceira Island
13/06/1730	VIII/IX (MMI)		Luz, Graciosa Island
09/07/1757	XI (MMI)	1,046	Calheta, São Jorge Island
24/06/1800	VII/VIII (MMI)		Praia da Vitória, Terceira Island
26/01/1801	VIII (MMI)	2	São Sebastião, Terceira Island
21/01/1837	IX (MMI)	3	Guadalupe e Santa Cruz, Graciosa Island
15/06/1841	IX (MMI)		Praia da Vitória, Terceira Island
11/06/1912	VII/VIII (MMI)		Praia da Vitória, Terceira Island
31/08/1926	X (MMI)	9	Horta, Faial Island
27/12/1946	VII/VIII (MMI)		Serreta, Terceira Island
13/05/1958	VIII/IX (MMI)		Praia do Norte, Faial Island
21/02/1964	VIII (MMI)		Rosais, São Jorge Island
23/11/1973	VII/VIII (MMI)		Bandeiras, Pico Island
01/01/1980	VIII/IX (MMI)	61	Doze Ribeiras, Terceira Island
09/07/1998	VIII/IX (MMI)	8	Ribeirinha, Faial Island

around 7,600 aftershocks were recorded during the first month and more than 15,000 up the end of 2003, extending the seismic annual rate up to early 2005 (Dias 2005).

The study of the seismic sequence of Faial 98 earthquake by Matias et al. (2007) reveals an unusual high *p*-value of 1.40 using the Omori modified law, a value typical of mid-oceanic ridges. The authors calculated a 1D seismic velocity model fitted to the local conditions where the Vp/Vs ratio range between 1.77 and 1.91. The hypocentre relocation disclose two alignments. One with direction NNW-SSE and the other one with a rough orientation ENE–WSW. The analysis of the focal mechanisms of the mainshock and aftershocks indicate that the rupture is compatible with strike-slip mechanism; and few events with normal/reverse mechanism. From the epicentres and focal mechanism, the authors deduced that the alignment NNW-SSE are associated to left-lateral strike-slip fault solution and the WSW-ENE exhibit right-lateral component.

The tomographic study conducted by Dias et al. (2007) in the area of Faial, São Jorge, and Pico Islands with data recorded after the Faial 98 earthquake reveal that the shallow layers are consistent with tomographic signal on Faial Island; probably the plumbing system or even a magma chamber beneath Caldeira with low Vp (<6.0 km/s); a region of high Vp (>6.0 km/s) beneath NE Faial; the NE slopes of Faial – Pico ridge reveal a gradient in Vp and Vp/Vs models, and a tectonic segmentation of Faial Island.

Borges et al. (2007) conducted a study on the seismic source of the 1998 earthquake using the inversion of seismic body waves. They found that the rupture with the sub events was similar to the one of Terceira 1980 earthquake. Most of the energy was released on the first sub-event at 8 km depth with left-lateral strike-slip rupture. The location of the second sub-event was at the same horizontal position but at 7 km depth and less energetic than the first one. The scalar seismic moment of the first sub-event was 1.1×10^{18} Nm and second one 0.3×10^{18} Nm; the duration of the source time function was 2.5 s.

In Pico Island, earthquakes are located in the western part of the island around the volcanic edifice named Pico Mountain (Nunes et al. 1997). From October 1973 to March 1974, 802 earthquakes were recorded, 490 of them were felt by the population (Nunes et al. 1997). On November 23, and December 11, 1973 two moderate earthquakes occurred with M_d 5.8 and 5.6 and intensity VII–VIII and VI (MMI), respectively.

On the 9 July of 1757, a great earthquake struck São Jorge Island collapsing all buildings of the eastern region and causing more than 1,000 fatalities. The historical accounts refer that cracks were formed, some of them with more than 2.2 m depth, and changes on the topography of the island were observed. Machado (1949) assigned maximum intensity XI (MI 31) and estimated magnitude 7.4 for the event. From paleoseismological studies, Madeira (1998) estimated that the magnitude ranges from 6.4 to 6.8.

Concerning the volcanic eruption of 1963/64 near São Jorge, the first signs started towards the end of 1963 with the Horta seismic station recording continuous seismic tremor that lasted up to January of 1964 (Zbyszewski et al. 1977). Early in the morning of February 15th, 1964 a seismic crisis started and, up to midnight, 179 earthquakes were recorded; and 125 the next day. On the first days, the epicentres were located near the historical eruptions of Manadas in 1580 and Urzelina in 1808. According to the authors, the seismic tremor started around noon the 15th of February and ended the 22nd of February and were felt strongly in Manadas and Urzelina settlements. The strongest events, with maximum intensity VIII, occurred the following days, the 18th, 20th and 21st of February. The seismic crisis due to the eruption ended in September 1964 and more than 500 earthquakes were felt by the population.

In Graciosa Island, many old chronicles referred to damaging events without accurate details on the date and damage level. In 1730 and 1837, two earthquakes of maximum estimated intensity of VIII–IX and IX, respectively, destroyed most of the dwellings located in the southern part of the Island (Nunes et al. 2001).

In the past, strong earthquakes (intensity ≥ VII) inflicted economic and social losses to the inhabitants of Terceira Island (Table 1). According to this table, the island suffered the effects of seven earthquakes with maximum intensity ≥ VII/VIII MMI. The eastern and south-eastern areas were most severely affected. The largest events occurred in 1614, 1800, 1801 and 1841. With the exception of 1801, the other earthquakes occurred in the eastern part, more precisely in the Lajes Graben which extends to the seafloor, SE of Terceira (Nunes et al. 2001).

On January 1st, 1980 Terceira Island was affected by a strong earthquake Ms7.2 (Hirn et al. 1980) and maximum intensity IX MMI. The islands of São Jorge and Graciosa felt the earthquake with maximum intensity VII/VIII and VI/VII, respectively. The earthquake caused heavy damage in some areas of Terceira, especially in the city of Angra do Heroísmo where around 30% of the building stock collapsed, and caused a death toll of 61. The data referring to seven days of aftershocks made it possible to locate the epicentres within a ribbon of 40 km long by 6 km wide, and the strike N150°E (Hirn et al. 1980). These authors inferred from the aftershock sequence that the mainshock fault mechanism was pure sinistral shear along a N150°E fault plane, the same plane being found by the composite solution for aftershocks. The body wave inversion suggests the source time function had two peaks separated by 10 s (Grimison and Chen 1988). The authors state that the first sub-event is consistent with a pure strike-slip mechanism, while the second sub-event exhibits a large component of thrust faulting at depths of 12 and 20 km. These depths are not in agreement with the ones constrained by Hirn et al. (1980) nor consistent with an oceanic type of crust. Borges et al. (2007) obtained two sub-events with left-lateral strike-slip mechanisms. The second sub-event was located 25 km NNE of the main rupture plane, and was 12 s later than the first. The total scalar seismic moment obtained by Buforn et al. (1988) (2.0×10^{19} Nm) from long-period Rayleigh-wave inversion, is similar to the one obtained by Borges et al. (2007) (1.9×10^{19} Nm) from body wave inversion; nevertheless, Grimison and Chen (1988) obtained a higher value (3×10^{19} Nm).

The last volcanic eruption in the Azores was between 1998 and 2001, and took place at sea about 10 km west of Serreta (Terceira Island, Gaspar et al. (2003), Kueppers et al. (2012)). According to Gaspar et al. (2003) the number of earthquakes increased above background values on November 23rd, 1998. On November 27th, the number of earthquakes rose to 200, and two days later reached 400. Then the seismic swarm decreased to background values. On December 18th, the first sign of an ongoing eruption was observed.

Seismic hazard analysis by Carvalho et al. (2001) estimates a PGA value of around 2.5–2.75 m/s^2 (exceedance probability of 10% in 50 years) for this cell mainly in the west of Faial and in the Terceira Rift segment between the islands of Terceira and São Miguel.

The seismic temporal evolution is like cell 5, with magnitudes ranging from 0.2 to 4.5 (Fig. 11a, b). Earthquakes with magnitude (M_L) larger than 3.5 are isolated (e.g. in 2003 to the first quarter of 2004, and in 2010). Periods with low radiated energy (2005–2007 and 2008–2009) are followed by periods of increasing radiated energy (2000–2004, 2007 and 2010).

The FMD in cell 6 is well constrained by the power law for events larger than 2.4 (M_L). Mc is fixed at 2.4 ± 0.2; a = 5.9 and b = 1.2 ± 0.1 (Fig. 11c). Despite the generally improved azimuthal coverage along the Archipelago, some seismicity has been analysed in regions with poor azimuthal coverage, such as those to the west of both Graciosa and Faial Islands.

CELL 7 lies in a section of the Terceira Rift that includes Terceira Island, half of São Jorge Island and a small western section of Pico Island. Temporal evolution of seismicity shows a low annual rate from 2000 to 2003, a slight increase until 2007 and then an average rate. Several periods have reduced or no recorded earthquakes (e.g. 2000–2002, 2007 and 2009). Magnitudes (M_L) range between 0.2 and 4.4, with few events with a magnitude higher than 3. The

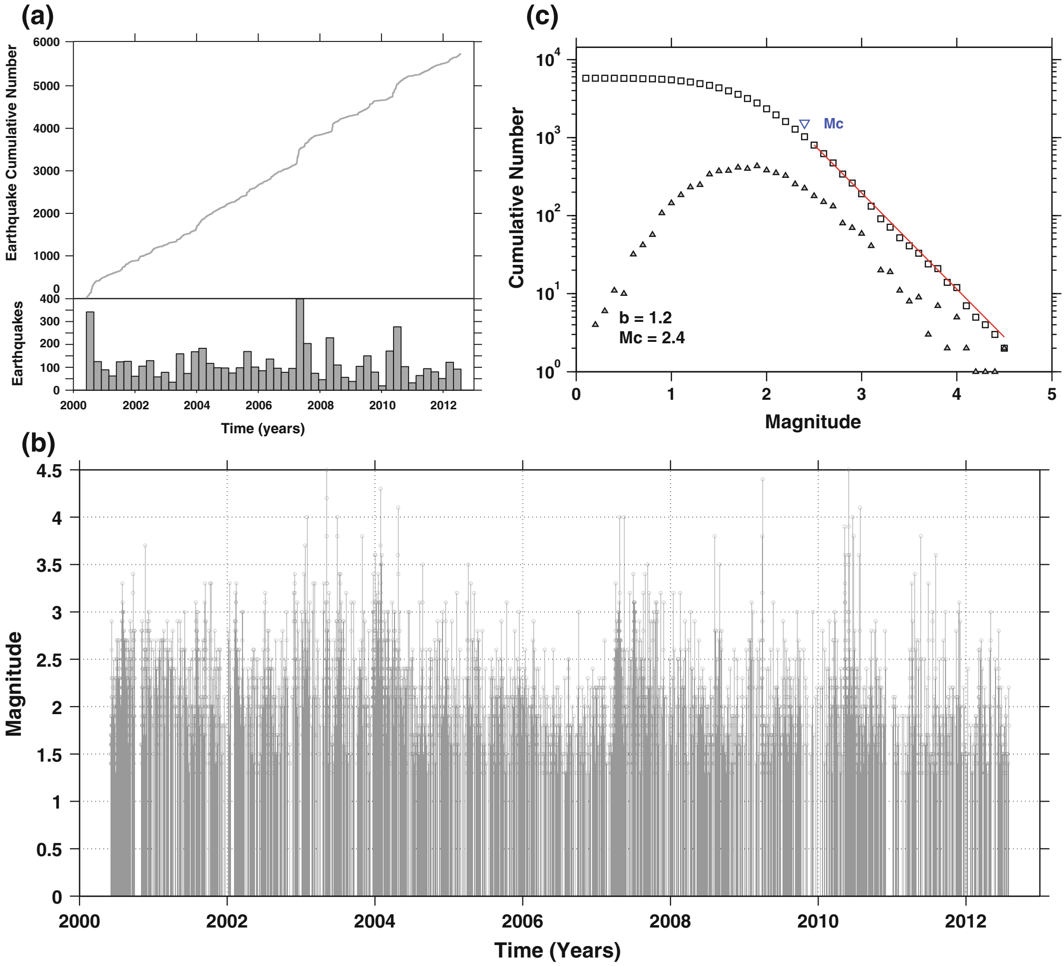


Fig. 11 Temporal distribution of earthquake in cell 6. **a** cumulative earthquake number (top) and annual distribution (bottom). **b** Annual number of event. The lack of seismicity for the first semester 2000 is due to the shift on reported magnitude. In December 2010, data are not available. **c** Frequency magnitude distribution. Triangles are noncumulative frequency magnitude distribution and empty squares are cumulative frequency magnitude distribution. The error in magnitude completeness is ±0.2 and b-value ±0.1. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle)

corresponding values of the Gutenberg-Richter law are: Mc = 2.5 ± 0.25: a = 5.8 and b = 1.3 ± 0.24.

CELL 8 covers the North and South Hirondelle basins, Dom João de Castro Bank located between these two basins, São Miguel Island and Povoação Basin to the west of São Miguel Basin.

Dom João de Castro Bank is an active volcano located in a segment of the Terceira Rift. The single known eruption was in December 1720. The population of the islands of Terceira and São Miguel felt some earthquakes associated to the eruption. Since 1933, several moderate earthquakes have been reported around the volcano (electronic supplement S7, earthquakes marked with ✳). Some seismic swarms (e.g. in October 1988 and in June 1997) had more than 2,000 earthquakes in the first month, and 45 of them had a magnitude higher than 4 (Gaspar 1997).

Based on the focal mechanism of Azores earthquakes, Borges et al. (2007) established a seismotectonic model to the west of Terceira

Island. In this area, the seismicity is oriented NW-SE, with a normal type of faulting system with a horizontal tension axis trending NE-SW, normal to the Terceira Rift. Study of the focal mechanism of the 28 June 1997 earthquake shows a normal fault with a rupture process divided into three sub-events at focal depths ranging from 5 to 7 km (Borges et al. 2007). The total scalar seismic moment is 7.0×10^{17} Nm with source duration around 5 s.

São Miguel Island is seismically the most active. In the following, seismicity in different parts of the island is presented: On 22 October 1522, a massive landslide triggered by an earthquake buried the first capital of São Miguel Island—Vila Franca do Campo. The event caused heavy destruction on building stock and around 5,000 deaths, the deadliest event in the archipelago (Frutuoso 1998). Maximum intensity assigned was X on both intensity scales McS-17 and MM-31 (Dias 1945; Machado 1966) respectively, while Nunes et al. (2001) and Silveira et al. (2003) assign the same intensity value, applying MMI and EMS-98 scales, respectively. The epicentre was inland, to the north of Vila Franca do Campo, and the focal depth was at 12 km (Machado 1966). Table 2 lists the earthquakes that occurred in São Miguel after 1522. Some of them (1522, 1591 and 1852) could be related to the volcanic activity of the Fogo-Congro region.

Nine volcanic eruptions have been reported since the settlement of São Miguel Island in the 15th century, most of them preceded or followed by earthquakes (França et al. 2003). Around the Sete Cidades volcano in the west of the island, seismic swarms of more than 150 events are common, while on the Fogo-Congro volcano in the central region they are counted in the thousands.

During a seismic crisis near Sete Cidades volcano in September 1996, a total of 180 earthquakes were recorded in seven hours. All earthquakes were associated with the Mosteiros Graben, a tectonic element NW of the volcano. The epicentres were located at a depth of between 2 and 4 km (Forjaz et al. 1996). In August 1998, another seismic swarm manifested by 120 earthquakes recorded in three hours; five of them felt by the population with a maximum magnitude of 3.1 and MMI of V (Gaspar and Wallenstein 1998). One month later, a new swarm of about 120 earthquakes in four hours occurred; five of them were felt by the population and one had an MMI of V.

The Fogo volcano includes a complex system of faults that accommodates a tectonic structure in a graben known as the Congro Fracture Zone. The first recorded swarm in this region was in 1922, and lasted two months, with tens of earthquakes felt by the population (Nunes and Oliveira 1999). In 1967, a second swarm occurred and lasted for four days. For both of them, the maximum intensity was VII (Nunes and Oliveira 1999). From 1988 until July–September 1989, more than 8,000 events were recorded with magnitude (M_d) up to 3.8 (Nunes and Oliveira 1999). From May 2005 to late 2006, thousands of earthquakes were again recorded.

The Fogo volcano includes a geothermal reservoir where two geothermal power plants

Table 2 Historical earthquakes in São Miguel Island since 1522 (modified from Nunes et al. 2001; Silveira et al. 2003)

Date	Intensity	Human toll	Region most affected
22/10/1522	X (MMI and EMS)	~5,000	Vila Franca do Campo, São Miguel Island
26/07/1591	VIII/IX (MMI and EMS)	Unknown	Vila Franca do Campo and Água de Pau, São Miguel Island
16/04/1852	VIII (MMI and EMS)	9	Ribeira Grande, São Miguel Island
05/08/1932	VIII (EMS); VII (MMI)	3,000 homeless	Povoação, São Miguel Island
27/04/1935	IX (EMS); VII (MMI)	1	Povoação São Miguel Island
26/06/1952	VIII (MMI and EMS)	600 homeless	Ribeira Quente and Povoação, São Miguel Island

have been installed. Due to the economic importance of this renewable energy, several studies were developed in this region. Dawson et al. (1985) searched for anomalies in seismic velocity that may reflect the presence of a magma chamber or hydrothermal system beneath the volcano. They found a low-velocity area in 5 km depth, 10 km long in E-W direction and 5 km in N-S direction. This region might be a hydrothermal reservoir or a body of partial melt, or a combination of both.

Zandomeneghi et al. (2008) found anomalies in P-wave velocity model and P- and S- wave velocity ratio (Vp/Vs) in the central part of São Miguel known as Congro. In the region Fogo-Congro, they found low velocity (Vp) and Vp/Vs ratio in the NW and NNE of Fogo volcano. Areas of high velocity and Vp/Vs ratio are found in the south of Fogo and the central region. However, the authors did not find shallow bodies of partial melt in the Fogo area as described by Dawson et al. (1985).

Using data from 2003–2007, Fontiela and Nunes (2008) identified sub-volumes with high *b*-values (1.6–1.7) at depths around 8–9 km, compared to surrounding zones with lower *b*-values around 0.6. These high *b*-values could be explained by the presence of hydrothermal systems or dyke intrusions. A seasonal correlation between rainfall and velocity patterns is found by Martini et al. (2009). It is related to local pressure changes at depth in response to surface rainfall, when the system is critically stressed and/or interacts with the geothermal system. Fogo Volcano is dominated by a normal regional stress field, while the Congro region exhibits a highly heterogeneous stress field with permutations between σ_2 and σ_1 (Silva et al. 2012). For the period 2002–2012, the stress tensor is characterised by a maximum compressive sub-horizontal stress axis (σ_1) striking WNW-ESE and minimum compressive stress axis (σ_3) striking NNE-SSW.

Furnas Volcano has very low seismic activity. GPS data show low rates of deformation (Jónsson et al. 1999) which could be explained, firstly, by spreading in the region between the Eurasian and Nubian plates, and secondly, by a source of inflation located on the northwest of the caldera. Nunes and Forjaz (1998) describe two seismic swarms that occurred inside Furnas caldera in June 1989 and in January 1992. The first seismic swarm had 111 events with magnitude lower than 2.4, the strongest event occurring near the fumarole field in Furnas village. The second swarm had 30 events with magnitude lower than 2.4 but released more energy than the first. Zandomeneghi et al. (2008) found low Vp values and Vp/Vs ratio, related to an active geothermal system embedded in low density pyroclastic deposits.

The study of seismic hazard assessment in São Miguel shows that for the annual exceedance probabilities of 0.01 and 0.002, the central part of São Miguel is likely to experience an earthquake of VI and VIII MMI, respectively (Oliveira et al. 1990).

In terms of seismic activity, cell 8 has a signature completely different to CELLs 1–7. The cumulative number of earthquakes (Fig. 12a) highlights low seismic activity up to 2004, followed by a period of increasing seismicity becoming intense until 2007 and declining later. The period 2004–2006 is characterised by seismic swarms located in the Fogo-Congro region. From 2005 to 2007, more than 8,300 events with magnitude (M_L) lower than 4 were reported in the Seismological Bulletins. Comparing cumulative numbers of earthquakes (Fig. 12a) with those of the seismic swarm of 1989 (see Fig. 5b of Nunes and Oliveira 1999), both swarms have the same features; initially, there is a subtle increase in the number of earthquakes followed by a peak of seismic activity during a short period of time, then a return to normal background activity. The range of magnitude is between 0.5 and 1.3.

The temporal distribution of events in the graph of Fig. 12b shows periods of low activity before and after the seismic swarms of 2004 and 2005–2006, M_L magnitude varying in the range of 1.5–3.5. A low number of events is found between 2007 and 2012 with $0.5 < M_L < 4.2$. Magnitude for the seismic swarm varies between 0.1 and 4.0.

Figure 12c shows that the FMD fits the power law for magnitude range of between 2.2 and 3.4.

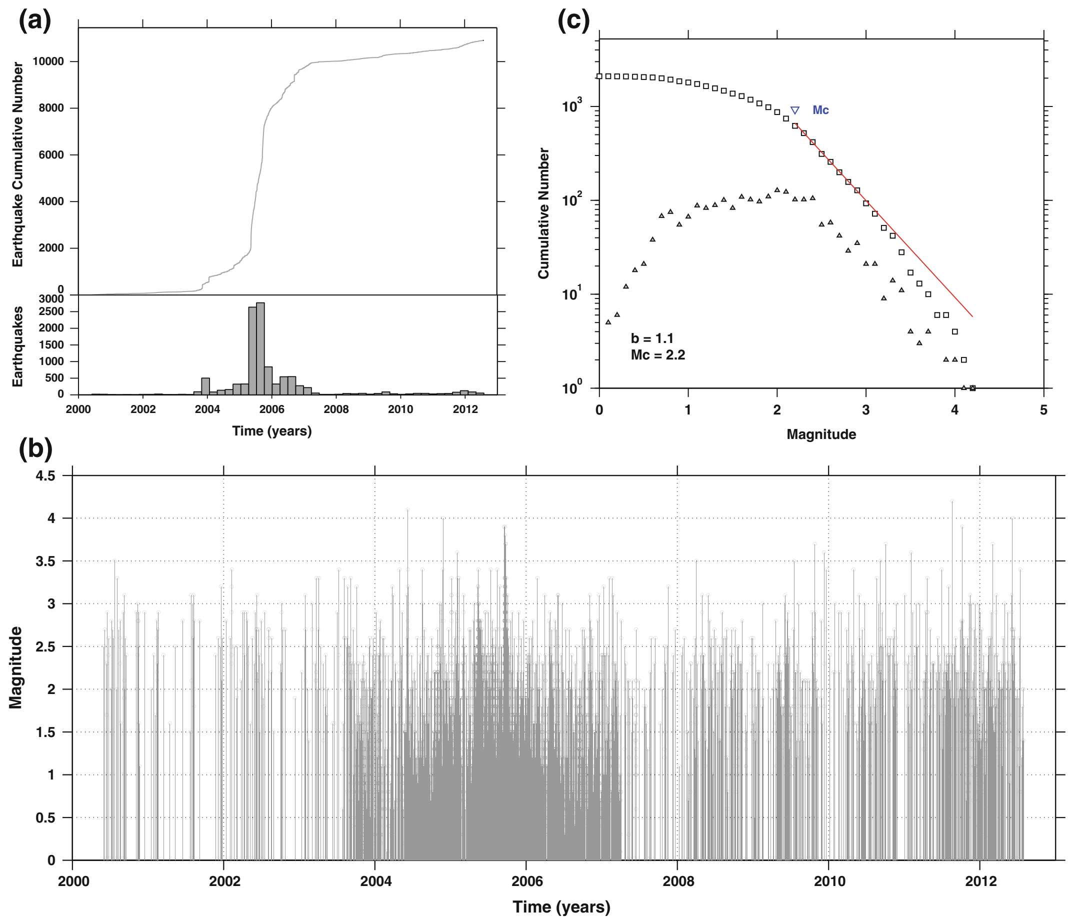


Fig. 12 Temporal distribution of earthquake in cell 8. **a** cumulative earthquake number (top) and annual distribution (bottom). **b** Annual number of event. The lack of seismicity for the first semester 2000 is due to the shift on reported magnitude. In December 2010, data are not available. **c** Frequency magnitude distribution. Triangles are noncumulative frequency magnitude distribution and empty squares are cumulative frequency magnitude distribution. The estimated error in magnitude completeness is ±0.3 and b-value ±0.2. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle)

The values obtained in this cell were: $Mc = 2.2 \pm 0.3$; $a = 5.6$ and $b = 1.0 \pm 0.2$.

CELL 9 includes São Miguel and Santa Maria Islands, Povoação and São Miguel basin, and the Formigas Islets; all of them known to be seismically active areas. This cell is in the transition of the Terceira Rift to the Gloria Fault. Searle (1980) stated that the western end of the Gloria Fault stops abruptly at latitude 36°48′N and longitude 24°30′W.

Most of the significant earthquakes recorded in cell 9 are around M_L 5–5.9, with few earthquakes of higher magnitude. One located east of Santa Maria Island on 8 May 1939 of $M_b = 7$ caused heavy damage on Santa Maria, and another on 5 April 2007 of $M_w = 6.2$ (Global CMT) occurred in the Formigas Islets.

Seismicity in cell 9 (electronic supplement S8) is like that in cell 8 (Fig. 12a) up to the first quarter of 2007. Thenceforth, seismicity has been continuous above background values, up to now particularly, due to the earthquake of April 2007. Magnitude distribution is similar to that of cell 8 for events with magnitudes up to 4, but the number of earthquakes with magnitude greater than 3 is higher. FMD fits the power law for magnitude ranging from 2.2 to 3.5. The values obtained were: Mc = 2.2 ± 0.49; a = 4.8 and b = 0.8 ± 0.17. However, we must remember that some seismogenic sources are in areas where the seismic network has poor azimuthal coverage.

CELL 10 covers the transition of the Terceira Rift to the Gloria Fault (Fig. 10). The seismicity was very low until 2007, and increased after the earthquake of April 5th, 2007 ($M_w = 6.2$, Global CMT), remaining higher than before. The range of magnitude for most of the events is 1.8–2.6. Evolution of magnitude (M_L) with time exhibits a period with few earthquakes, with magnitude lower than 3, between mid-2000 and the first quarter of 2003. From then on, the seismicity slightly increases up to the end of 2006 with magnitudes ranging from 2 to 3.5, up to 4.5. Since the M_W 6.2 event of April 5th, 2007 the seismic rate has remained high. FMD is correlated with the power law for magnitudes up to 4.1. The *Mc*, *a*- and *b*-values are: $Mc = 2.4 \pm 0.5$, $a = 4.6$ and $b = 0.8 \pm 0.2$, respectively.

Table 3 summarizes the *a*- and *b*-values and *Mc* calculated for each cell, as well as the latitude and longitude coordinates of the upper left corner and lower right corner of each cell.

4 Discussion and Conclusions

The different seismicity parameters estimated for the Archipelago of Azores exhibit variability in different regions. The deployment of a new generation of broadband sensors as well as improvements in data treatment by the seismological observatories have increased the quality of data, as well as the level of detectability of the seismic network. It is noticeable a decrease of Mc (from 3.2 in cell two to 2.2 in cell nine) during the 12 years under analysis. This decrease is related to a better azimuthal coverage of some seismic clusters provided by the seismic network. Nevertheless, some significant seismic clusters cannot be adequately surveyed because of the geographic disposition of the islands, such as the ones located towards the edges of the strip of the Azores; to the west of Graciosa, São Jorge and Faial, and to the east of São Miguel and Santa Maria. Furthermore, even between the islands there are clusters with poor azimuthal coverage such as between the islands of Terceira and São Miguel. In fact, our results demonstrate that cells 1, 2, 3, 4 and 5 with poor azimuthal coverage have high Mc (2.8–3.2). Comparing cells 5 and 6, which overlap 0.5°, we notice a decrease from 2.8 to 2.4, mostly due to a better azimuthal

Table 3 *a*- and *b*-value and minimum magnitude of completeness (*Mc*) calculated for each cell

Cell	Northwest		Southeast		*b*-value	*a*-value	Magnitude of completeness (*Mc*)
	Lat.	Long.	Lat.	Long.			
1	41.9	−30.1	39.9	−28.1	1 ± 0.2	5.2	3.1 ± 0.2
2	40.9	−31.1	38.9	−29.1	1.4 ± 0.3	6.7	3.2 ± 0.3
3	39.9	−31.1	37.9	−29.1	1.2 ± 0.2	5.9	2.8 ± 0.2
4	38.9	−32.1	36.9	−30.1	0.9 ± 0.3	4.1	2.8 ± 0.2
5	39.9	−30.1	37.9	−28.1	1.3 ± 0.2	6.5	2.8 ± 0.2
6	39.4	−29.1	37.4	−27.1	1.2 ± 0.1	5.9	2.4 ± 0.2
7	38.9	−28.1	36.9	−26.1	1.3 ± 0.2	5.8	2.5 ± 0.2
8	38.4	−27.1	36.4	−25.1	1.1 ± 0.1	5.6	2.2 ± 0.1
9	37.9	−26.1	35.9	−24.1	0.8 ± 0.2	4.8	2.2 ± 0.5
10	36.4	−25.1	35.4	−23.1	0.8 ± 0.1	4.6	2.4 ± 0.4

Estimated errors for each parameter is given. The coordinates correspond to the NW and SE corners of the rectangular cells coverage between the triangle formed by São Jorge, Graciosa and Terceira. In cell 6 the Mc is 2.4 but in cell 5 it increases due to poor coverage between Terceira and São Miguel. The next two cells (8 and 9) have the lowest Mc in the Azores region. In cell 10 Mc increases to 2.4, mostly due to poor azimuthal coverage to the east of São Miguel and Santa Maria. In fact, Fontiela and Nunes (2008) studied a seismic cluster in the area of Fogo-Congro (in the central region of São Miguel), and obtained *Mc* values of between 0.9 and 1.5. The Mc values obtained herein highlight that in some regions it is possible to perform studies with microseismicity.

Concerning *b*-values, it is known that they vary in space even in short distances (Ogata et al. 1995; Wiemer and Benoit 1996; Wiemer and McNutt 1997; Wiemer and Wyss 1997; Wyss et al. 1997; Power et al. 1998; Murru et al. 1999; Wiemer and Katsumata 1999; El-Isa 2013; El-Isa and Eaton 2014). Another factor that should be taken into consideration is the tectonic complexity that coexists with volcanic activity in the Azores region. In this complexity of tectonic and magmatic processes, we discuss the results under the hypothesis that *b* is inversely proportional to the mean magnitude (Aki 1965). Despite this approach we consider that our FMD of each cell fits well to a power law.

Experiments in rock failure depict a prevalence of small earthquakes due to the increased heterogeneity of rock samples (Mogi 1962), or due to lower stress (Scholz 1968), which can be described as a state of high heterogeneity of stress increased *b*-value. Consequently, low *b*-values are due to an increase in applied shear stress (Scholz 1968), or an increase in effective stress (Wyss 1973). In the Azores region, we found cells with high as well as low *b*-values. In a coarse analysis, a decrease from west toward east is noticeable. Nevertheless, some cells have poor azimuthal coverage which may introduce some bias on the *b*-value. Thus, the physical meaning of the *b*-values of cells 1, 2, 3, 4, 10 will not be discussed. The significant seismicity in the Azores is to be found in cells 5–9. Fontiela et al.(2014) studied seismic clusters in the Azores, and found *b*-values varying from 0.7 to 1.6.

The *b*-values of the western part of the Azores obtained in this study and those of Fontiela et al. (2014) show that different stress regimes cohabit in the region. In fact, the volcanism emplacement is marked by two distinct buoyant mantle upwelling's (Adam et al. 2013, see also Vogt and Jung, Chapter "The "Azores Geosyndrome" and Plate Tectonics: Research History, Synthesis, and Unsolved Puzzles", O'Neill and Sigloch, Chapter "Crust and Mantle Structure Beneath the Azores Hotspot—Evidence from Geophysics"). One is located in a wide area that comprises the islands of Graciosa, São Jorge, Faial and Pico, and the another one between Terceira and São Miguel. In reality, these islands and the whole region have had more than one eruption since settlement, with exception of Graciosa. This buoyant region can justify the high *b*-values found. Moreover, the crust is likely to be cracked as illustrated by mean magnitude and the high number of small events. Another aspect that we cannot discard is the thermal gradient which increases the *b*-value (Warren and Latham 1970). Forjaz (1994) identified high-enthalpy geothermal fields (temperature > 250 °C) at shallow depths (<2.5 km) in some parts of São Miguel, Terceira, Graciosa, Faial and Pico islands. To the west of Terceira b-values are >1, but here *b* is very low (0.7—Fontiela et al. 2014). However, our analytical approach does not allow identification of a low b-value in this island. Anyway, this could be interpreted as an increase of shear stress, or effective stress due to the lateral compression detected in the island by Navarro et al. (2003) and Miranda et al. (2012).

The *b*-values to the east of Terceira Island exhibit behaviour different from that of the previous zone. In fact, Borges et al. (2007) identified from the total seismic moment tensor that the Azores region is divided into two zones. The western zone (30°W–27°W) is consistent with strike-slip faulting, with horizontal pressure in an E-W direction and extension N-S; and the eastern zone (27°W–23°W) corresponds to normal faulting, with a horizontal tension axis in a NE-SW direction. The region between Terceira and São Miguel (cell 8) has high *b*-values as shown in the study by Fontiela et al. (2014).

These high *b*-values suggest more strongly the presence of buoyant mantle upwelling, as referred to previously. Another feature is the presence of a submarine volcano with its last known eruption in 1720, and a shallow crater rim at a depth of 12 m (Nunes et al. 1998). The temperature in the fumarole field within the crater varies between 39 and 83 °C. According to these facts we can link the high b-values to high pore pressure and high geothermal gradient.

Moving further east (cell 9) the b-values change in relation to the previous cells, decreasing to values less than 1. The seismicity between 2000 and 2012 is located, essentially, in the central part of São Miguel, and in a wide region that comprises the southeast of São Miguel up to the transition of the TR with the Gloria Fault. In this region Fontiela et al. (2014) identified three clusters, all of them with b less than 1, which agrees with the value obtained by Carvalho et al. (2001). From the b-values we infer a change in the stress regime. The non-existence of a plume or plumbing system supports the low b-values in this part of the Azores region. In contrast, studies have identified intense geothermal activity in the central part of São Miguel, from Vp/Vs ratios and seismic tomography (Dawson et al. 1985; Zandomeneghi et al. 2008). This is the same area where Fontiela and Nunes (2008) identified volumes with b-values around 1.6 between 2003 and 2006. As already noted, spatial variation of b-values of 1 to even more are commonly found in volcanic areas at distances of only a few kilometres (Wyss et al. 2001; Wyss and Stefansson 2006; Cerdeña et al. 2011). Another aspect to take into consideration is the temporal variation of the b-value (see references listed in Wiemer and Wyss 2002). Yet another feature that may help explain the low b-values is the hypothesis that 75% of the relative displacement between the Eurasian and Nubian plates is found in a narrow, 10–15 km zone in the central part of São Miguel Island (Jónsson et al. 1999). The focal mechanisms in this region (Silva et al. 2012) show that the compression axis oriented WNW-ESE and the NNE-SSW tension axis are in agreement with the stress regime proposed by Madeira and Ribeiro (1990). Additionally, Silva et al. (2012) state that a stress regime at shallow depths (<5 km) is different from one at depths greater than 5 km. Surely the central part of São Miguel Island exhibits a complex tectonic fabric because of the boundary interactions between the Eurasian and Nubian plates. These interactions may explain the low b-values; however, they do not explain the observed geothermal gradient (Forjaz 1994), nor the presence of hydrothermal fluids at depth.

The low b-values persist to the southeast of São Miguel in a wide seismically active area. This could be related to the fact that this wide area is magmatically extinct (Hübscher et al. 2016). In this case, the low b-value may be explained by the tectonic regime. In fact, the focal mechanism in this region corresponds to normal faulting with a horizontal axis NE–SW normal the TR (Borges et al. 2007) which could accommodate the rifting activity at Povoação Basin (Weiß et al. 2015), increasing the shear or the effective stress and decreasing the b-value.

The *a*-values indicate the total or the annual seismicity rate of a region, and do not have such a clear physical meaning as the *b*-value. The *a*-values in Table 3 refer to the annual seismicity rate. Cells 1, 4, 6, 7 and 8 have an a-value between 4 and 4.9, while cells 2 and 5 have values around 5.5, and the remainder lie between 3 and 3.7.

The geodynamic context of the Azores plays a fundamental role in the geomorphology, the type of volcano activity, and also in the seismicity of the region. In terms of seismology, the western islands (Flores and Corvo) lie in a stable tectonic environment. The remaining seven islands lie on the plate boundary between the Eurasian and the Nubian, under the influence of regional deformation whose seismicity is constrained between those two plates. In fact, the seismicity in the Azores region could be divided into two main zones driven by different stress regimes as we move away from the MAR in the direction of the Gloria Fault.

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3

Azores seismogenic zones

3.1. Summary

The Seismogenic Zones of the Azores is a short paper submitted to the IX Congresso Nacional de Geologia and published in the special volume of Comunicações Geológicas. Subjects like recent significant earthquakes and earthquake catalogue are in section 2. The methodology used is described in section 3. In section 4, I discuss the results and present conclusions. Nevertheless, due to editorial limitations, I could not go deeper into subjects like the earthquake catalogue, and about the results of the analysis of focal mechanism nor their discussion in the definition of seismogenic zones. Hence, these subjects are addressed in the following paragraphs.

A seismogenic zone is where the earthquakes occur, and earthquakes are the result of shear failures in faults. Earthquakes are one of the natural hazards that can cause severe damage to society depending on the magnitude, time, and location. Although the study of the processes that control a seismogenic zone are very important, I prefer before go forward distinguish seismic source (SS) from a seismogenic zone (SZ). Here, I define the SS as the faults whose rupture type, size, location and recurrence period are known; and SZ are regions which are seismically actives, where it is not distinguishable from an SS, in which the earthquakes may occur anywhere.

SZ and SS are crucial to the seismic hazard assessment through a probabilistic approach or even a deterministic one. The study of SZ relies exclusively on earthquake catalogues, while SS not. Thus, earthquake catalogues play a key role in the definition of SZ. These problems are related to the time extension, accuracy and completeness introduced in the earthquake catalogue by the historical seismicity. The earthquake catalogues of the instrumental period enclose artefacts such as reported events which are human-made (i.e., explosions), heterogeneity of resolution of small events as a function of space and changes of the magnitude scale.

The earthquake catalogue available to the Azores region is the one of Nunes et al (2004) to the period 1850 - 1998. From 1998 onward, I compiled a new instrumental earthquake catalogue from IRIS, ISC and *Boletim Sismológico Preliminar dos Açores* and added this data to the earthquake catalogue of Nunes et al. (2004). Further details of earthquake catalogues are in section 2 of chapter 2. Additionally, a focal mechanism catalogue was created based on the compilation of parameters from the ISC catalogue, GCMT (former CMT), USGS and from isolated studies such as thesis, papers and reports.

The delineation of SZ in the Azores Archipelago is based on earthquake density (number of earthquakes by km^2), and on the b-values of the frequency magnitude distribution of Gutenberg and Richter (1944). To accomplish this aim we use the earthquake catalogue prepared to this purpose and calculate the earthquake density (background of figure 2a). The magnitude scale was ignored since the important issue is the earthquake location. In the analysis of frequency magnitude distribution, I selected events from 2000-2012 due to the homogeneity of the magnitude scale reported. The delimitation of SZ was based in a trial and error test of different areas in the same zone. This approach was repeated until I obtained stable b-values. Through this approach, I identified 11 SZ (figure 2a) whose b-value varies from the maximum 1.57 at Mid-Atlantic Ridge (MAR) (SZ1) and minima at Terceira Island in SZ6.

Concerning focal mechanism, the number of solutions available for the whole Azores region is low. Nevertheless, from the analyses of the Frolich diagrams for each one of the SZ (figure S3.1), I identified the following five patterns of SZ:

- cluster of pure normal events in SZ 4, SZ7 and SZ11;
- cluster pure strike-slip events in SZ5;
- events located in the range normal up to reverse faults in SZ8 and SZ10;
- SZ with events distributed over all "ternary diagram"

The small number of focal mechanism available is not enough to characterize in detail the seismic source of each SZ, and SZ6 and SZ8 don't have a focal mechanism. In general, pure normal events dominate, followed by pure strike-slip and the ones located on the transition of both mechanisms. Concerning SZ 3, the high number of earthquakes is related to the seismic sequence of the July 9th, 1998, in Faial Island. The Frolich diagram (Frolich, 1992) does not exhibit a clear seismotectonic trend able to characterize the SZ3. The small number of reverse events present in SZ2 (one earthquake), SZ8 e SZ10 (two earthquakes each one, respectively) all of them located in the eastern group (includes SZ 7 - SZ 11) which has low b-value. Focal mechanisms are helpful to distinguish different sources but, has the handicap that all earthquakes have the same weight independent of their magnitude. With such limitations, it is not possible to infer a stress regime of each area. Thus, the use of total seismic moment tensor (TSMT) fills the gap left by Frolich diagrams. To achieve a full comprehension of each seismic zone should use TSMT as was done in the Azores by Borges et al. (2007) and Bezzeghoud et al. (2014). Both authors, based on TSMT split the Azores region into two groups by the slip velocity. Indeed, that seismic moment release TSMT of each SZ coupled with focal mechanisms outlines the geometry of SZ and characterizes their tectonics and kinematics.

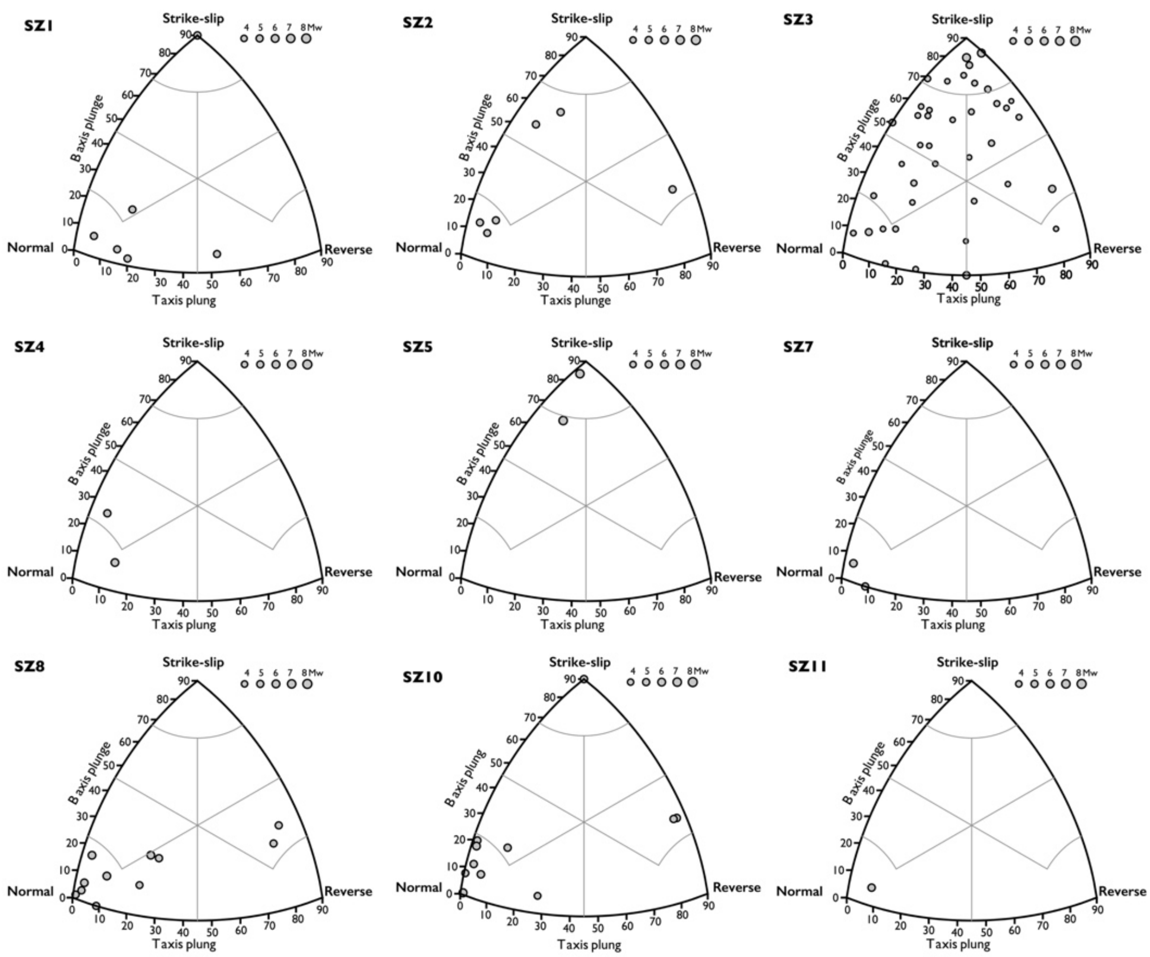

Figure. S1. Ternary diagrams of nine SZ identified on the upper left corner. SZ6 and SZ8 are not represented because do not exist focal mechanism for this two SZ.

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3.2. Paper: *Azores Seismogenic zones*

Versão online: http://www.lneg.pt/iedt/unidades/16/paginas/26/30/185
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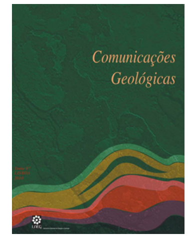

Azores seismogenic zones

Zonas sismogénicas dos Açores

J. Fontiela[1,2*], M. Bezzeghoud[1], P. Rosset[3], J. F. Borges[1], F. Cota Rodrigues[2,4]

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 sísmogénicas 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 log10N = 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 $M \geq 5$ 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).

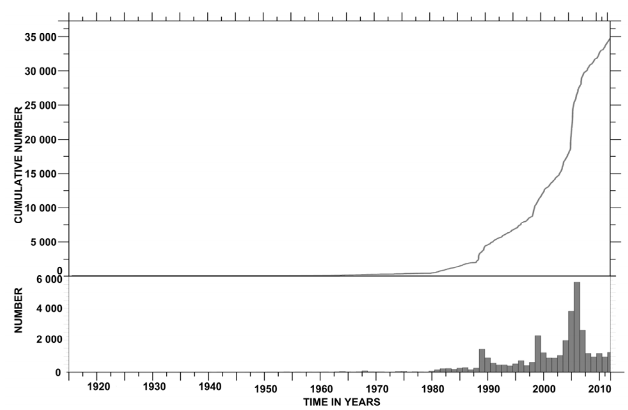


Fig. 1. Distribution of the recorded seismicity since 1915. The upper graph shows the cumulative number of earthquakes while the lower graph is the annual earthquake frequency.

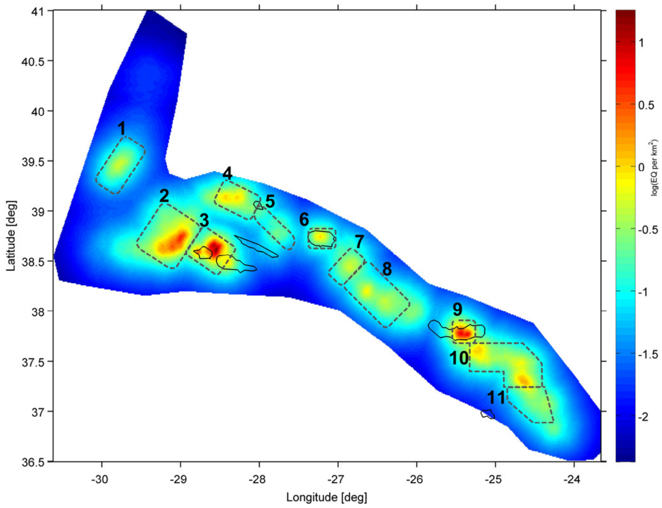
Fig. 1. Evolução da sismicidade desde 1915. O gráfico superior mostra o número cumulativo de sismos enquanto que o inferior mostra a frequência dos sismos.

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

a

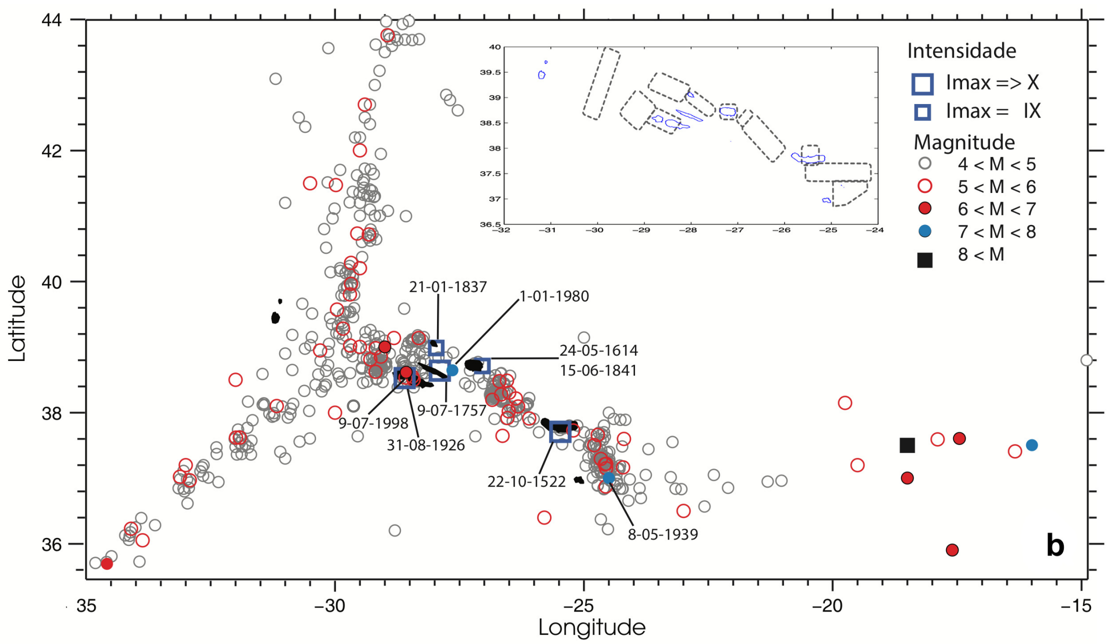


Fig. 2. a) Definition of seismogenic sources. The colored background expresses the earthquake density calculated for the time span 2000 -mid 2012; cold colors mean low rate of earthquakes (blues) while warm colors (orange - reddish) mean high density. Each seismogenic source (dashed line) is defined 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 periodo 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.

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4

Maximum Observed Intensity Map for the Azores Archipelago (Portugal) from 1522 to 2012. Seismic Catalog

4.1. Summary

The actual chapter is about the paper *Maximum Observed Intensity Map for the Azores Archipelago (Portugal) from 1522 to 2012. Seismic Catalog* published in the Seismological Research Letters (SRL). In the introduction (section 1), I did a brief state-of-the-art of maximum observed intensity (MOI) maps and the actual techniques to do these maps. In the next section, I described significant earthquakes that struck the Azores Islands. Section 3 is subdivided into two subsections, in the first one I described sources I used to extend the Catálogo Sísmico da Região dos Açores (Nunes et al., 2004), and in the second subsection I did a brief explanation of the kriging technique. In section 4 of Maximum Observed Intensity Mapping, I described the calibration procedure applied on four earthquakes, and then, I presented the results of MOI maps. The last section are the final remarks. The paper includes an electronic supplement with the intensity dataset (*Seismic Catalog)* used to calculate the MOI maps.

In 1858 Mallet and Mallet published a map containing the seismicity where the authors differentiate by a color scale the areas of high seismicity regarding intensity. Undoubtedly it is a remarkable work considering the knowledge and resources available at the time. In fact, the authors unconsciously did the first map of the maximum observed intensity (MOI). Later in the 80's Karnik (1980) prepared a MOI map to Europe. Recently, the University of Évora prepared MOI maps to the north of Algeria (Ayadi and Bezzeghoud, 2015), Portugal (Ferrão et al., 2016) and Azores region (actual chapter).

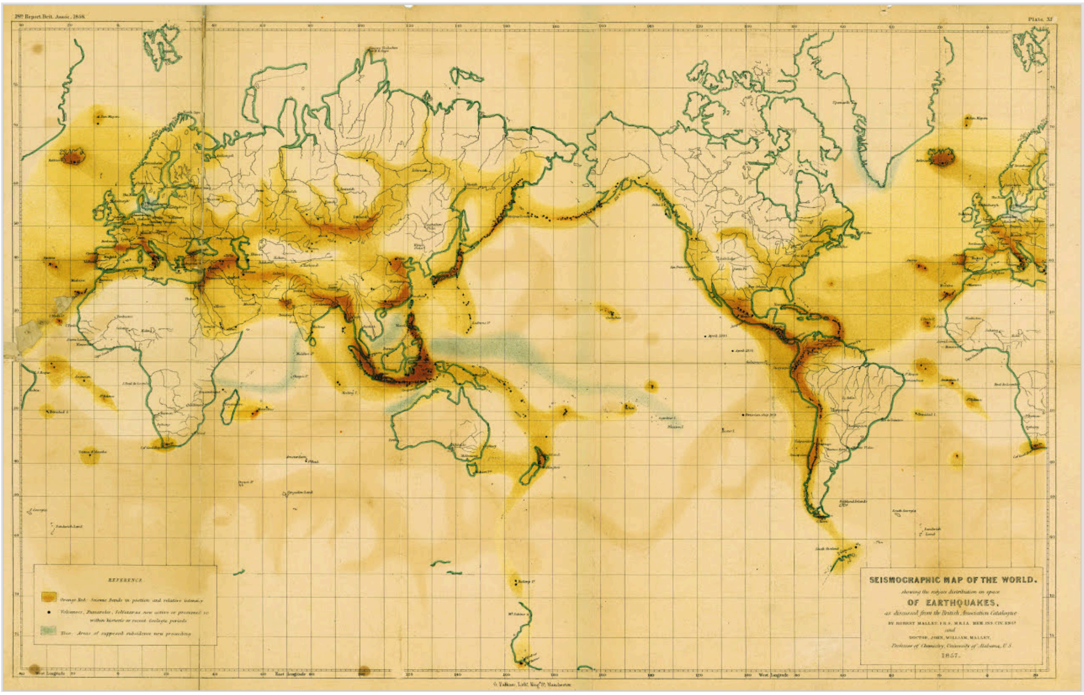

Figure S1. Seismicity map of Mallet and Mallet (1858) based on felt reports. Dark brown areas have high number of intensity reports and the yellowish areas with low number of intensity reports.

A MOI map is a method that converts maximum ground shaking effects into a unified map with the areas that in the past were affected by strong ground shaking. These maps are an expedite technique to predict vulnerable areas by future earthquakes and a helpful tool to assess seismic hazard based on the historical earthquakes. In fact, this technique is a simplified approach of deterministic seismic hazard with the condition that if an earthquake that occurred in the past, it will occur in the future, in the same fault with similar magnitude and focal parameters. This condition is based on the fact that earthquakes are produced by brittle shear fracture of rock or frictional sliding in pre-existing faults (Scholz, 1990). Moreover, Aki (1984), Ruff (1992) have shown evidence that a family of earthquakes sharing the same fault plane show a vast range of variation in the amount of slip. Nevertheless, we recognize that to fully accomplish the deterministic seismic hazard assessment aspects like distance to the seismogenic source, ground motion prediction equation, and recurrence period are also not considered in the aim of the paper. This subject caused intense discussion with the John Ebel, paper reviewer and editor of SRL, since he did not believe that MOI maps could be considered a way to assess seismic hazard because it could not predict the ground motion. In reality, as we demonstrated to the reviewer, converting intensity into ground peak acceleration (PGA) is possible to estimate the strongest PGA that each settlement experienced in the past.

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4.2. Paper: *Maximum Observed Intensity Map for the Azores Archipelago (Portugal) from 1522 to 2012 Seismic Catalog*

Maximum Observed Intensity Map for the Azores Archipelago (Portugal) from 1522 to 2012 Seismic Catalog

by João Fontiela, Mourad Bezzeghoud, Philippe Rosset, and Francisco Cota Rodrigues

ABSTRACT

The Azores archipelago is a seismically active region composed of nine islands and located at the triple junction of the American, Nubian, and Eurasian plates. Since its settlement in the fifteenth century, 33 earthquakes with intensity higher than VII have been reported. This article shows areas that experienced strong ground shaking using maximum observed intensity (MOI) mapping. For this purpose, 323 records from 167 earthquakes in the period 1522–2012 have been compiled, and MOI values are interpolated on a regular grid of points using the kriging method. The comparison of observed and calculated MOI for four damaging and deadly earthquakes indicates a good calibration of the procedure relative to the available dataset. For the islands of the central group, which comprises Terceira, Graciosa, São Jorge, Pico, and Faial, the highest calculated intensities (XI) are located in the eastern part of São Jorge Island. Intensities (X) are observed on Faial along a northwest–southeast stripe. For Graciosa, Terceira, and Pico, the estimated maximum intensities are IX, VIII, and VII, respectively. For the eastern group of islands, the highest intensities (X) are located in the southeastern part of São Miguel Island, and on Santa Maria Island the maximum intensity of VI is observed in its eastern part. Finally, Flores and Corvo Islands, located on the American plate, have a very low seismicity.

Electronic Supplement: List of the earthquakes that were used to draw the maximum observed intensity (MOI) map for the Azores archipelago.

INTRODUCTION

Among the multiple methods to assess seismic hazard (i.e., Panza *et al.*, 2014; Parvez and Rosset, 2014; Stirling, 2014), a maximum observed intensity (MOI) map gives the areas that in the past were affected by strong ground shaking. An MOI map can be rapidly computed using macroseismic observations of past earthquakes. This method is useful in regions where information about large historical earthquakes exists and when instrumental seismic data are limited (Ayadi and Bezzeghoud, 2015). Such zonation maps have been produced for Algeria, Portugal, Greece, Italy, and Europe (Ayadi and Bezzeghoud, 2015; Ferrão *et al.*, 2016; Galanopoulos and Delibasis, 1972; Boschi *et al.*, 1995; and Kárnik *et al.*, 1980, respectively). However, the applicability of this method to knowledge of seismic hazard is conditioned by the stationarity of the events, the locations of the events, and the tectonic regime of the area being mapped.

The macroseismic data available in the Azores are often limited to the maximum intensity averaged across a settlement, sometimes by an average across a larger administrative unit, and in the worst case at the scale of an island. Generally, this does not allow an estimation of the influence of site conditions on the intensity reports. Nevertheless, the elaboration of discrete MOI mapping using nondiscrete macroseismic reports for distant islands is possible using the kriging method (Krige, 1951; Matheron, 1965). Indeed, this is an interpolation procedure that estimates values for locations without data using neighboring sites where data exist. However, kriging requires a variogram to give the degree of spatial correlation between neighboring sites. With this information, kriging can interpolate sites without bias, minimize the error, and assess the uncertainty of the result (Davis, 2002). The application of the kriging method in isoseismal mapping was tested and validated by several authors (e.g., Gasparini *et al.*, 2003; De Rubeis *et al.*, 2005; Schenková *et al.*, 2007; or Linkimer, 2008).

Considering the lack of instrumental data and the gaps between each island, MOI mapping remains a good means to map out the areas that in the past experienced the effects of strong earthquakes in the Azores archipelago. In this study, first the kriging procedure is calibrated using four single events, and then the MOI zonation maps are calculated and drawn based on the calibration procedure.

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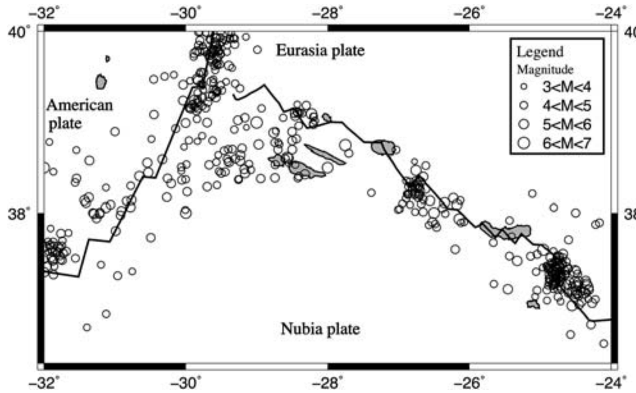
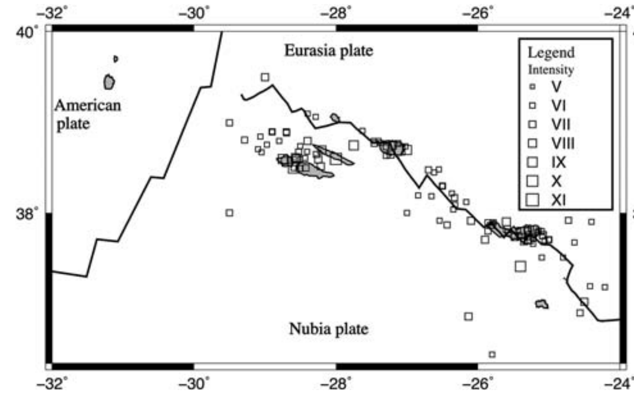


▲ **Figure 1.** Instrumental seismicity (M_b) in the Azores between 1926 and 2015.



▲ **Figure 2.** Earthquake catalog used to calculate the maximum observed intensity (MOI).

SEISMICITY

The Azores archipelago is located at the triple junction of the American, Nubia, and Eurasian plates (Fig. 1). Flores and Corvo Islands are on the American plate, whereas the other seven islands are at the boundary of the Nubian and Eurasian plates. The latter islands are divided into two groups: (1) a central group formed by Terceira, Graciosa, São Jorge, Faial, and Pico Islands and (2) an eastern group including São Miguel and Santa Maria Islands. Earthquakes recorded in the Azores between 1926 and 2015 (M_b 3 in Fig. 1) are located in two major segments first identified by Machado (1959). One segment, oriented from northwest to southeast, follows Graciosa, Terceira, and São Miguel Islands to the west transition of the Gloria fault. A second segment crosses Faial and Pico Islands.

Nunes *et al.* (2001) inventoried 33 destructive earthquakes that caused more than 6200 fatalities. The deadliest events occurred in 1522 at São Miguel Island (around 5000 deaths, maximum modified Mercalli intensity [MMI] $I_{max} = X$), in 1757 at the São Jorge Islands (1046 deaths, $I_{max} = XI$), in 1614 at Terceira Island (more than 200 deaths, $I_{max} = IX$), and also at Terceira Island in 1980 (61 deaths, $I_{max} = IX$).

On Graciosa Island, the strongest events with MMI IX occurred on 13 July 1730 and 21 January 1837 (Nunes *et al.*, 2001). More recently, on 1 January 1980 an M_w 6.8 earthquake with MMI IX occurred between Graciosa, São Jorge, and Terceira Islands and caused extensive damage in Angra do Heroísmo (a city on, Terceira Island) as well as on Graciosa Island and São Jorge Island.

On São Miguel Island, the seismicity is mainly associated with the Sete Cidades, Fogo, and Furnas volcanoes. Fontiela *et al.* (2014) also mentioned seismogenic zones in the southeastern part of the island which caused heavy damage in the village of Povoação in 1881 (MMI VII), 1932 (MMI VII), 1937 (MMI VII), and 1952, when two earthquakes occurred on the same day, each with MMI VII.

The seismicity of the second segment is concentrated in the region of Faial Island, mainly on the western part, and on Pico Island. Faial Island was struck by an earthquake on 31 August 1926 with MMI X and on 9 July 1998 by an M_w 6.0 earthquake (Borges *et al.*, 2007) with maximum intensity of VIII. An earthquake of M_b 5.0 (I_{max} VIII) struck Pico Island on 23 November 1973. São Jorge island, which is located between the first and the second segment described above, was struck by a major earthquake with MMI XI on 9 July 1757. Nowadays, the seismicity on this island is very low, as depicted in Figure 2. Table 1 presents an overview of the historical and recent seismicity with intensity equal to or greater than VIII on the islands as well as the reported damage and death tolls caused by earthquakes.

Volcanic activity is an important source of earthquakes in the archipelago. França *et al.* (2003) state that since the fifteenth century, 26 volcanic eruptions have occurred, with 12 of them being subaerial (5 at São Miguel, 3 at Pico, 2 at São Jorge, and 1 each at Terceira and Faial). Among the submarine eruptions, some were located close to the islands. Seismic tremor occurring before the eruptions, as a precursory signal due to magma ascent, and during the volcanic eruptions threatened local population and affected building strength due to continuous shaking. For example, the Capelinhos eruption on Faial Island in 1957–1958 generated hundreds of felt earthquakes, the strongest one with intensity IX. In 1964, the onshore eruption on São Jorge Island also induced earthquakes with a maximum reported intensity of VIII.

DATA AND METHOD

Macroseismic Dataset

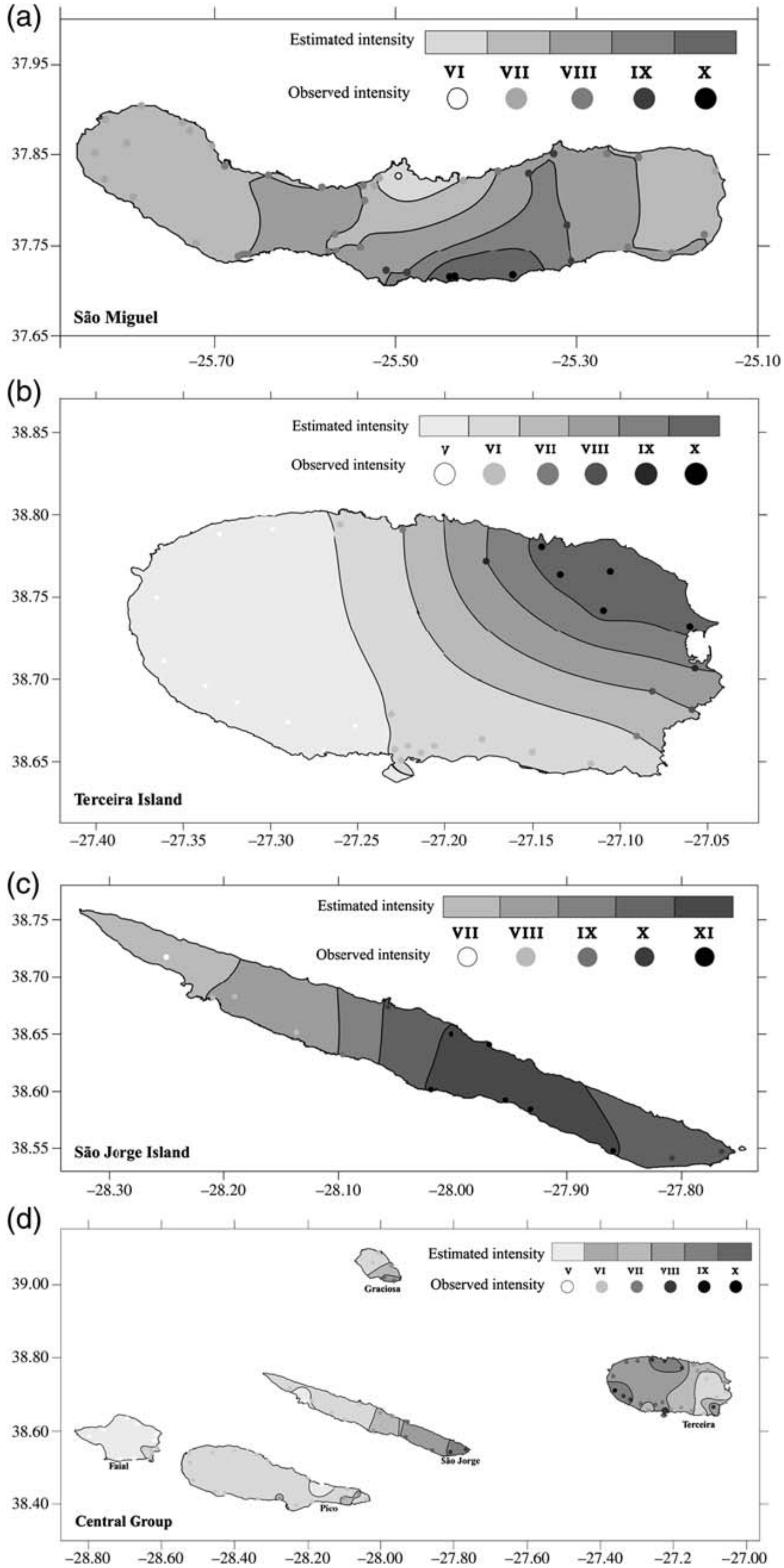
The dataset analyzed in this study includes all records with maximum intensity (I_{max}) equal to or greater than V in the catalogs provided by the Catálogo Sísmico da Região dos Açores (CSRA) (Nunes *et al.*, 2004), the Instituto Meteorologia (1999, 2000, 2002, 2003), and other sources (Machado, 1949, 1966; Madeira, 1998; Nunes *et al.*, 2001; Silveira, 2002; Silva, 2005). In total, 323 records from 167 earthquakes for the period 1522–2012 were selected to be used in the kriging (Fig. 2). Fourteen historical events with intensities greater than or equal to VII that occurred between 1522 and 1912 (Nunes *et al.*, 2001) were added to this catalog to increase the dataset

Table 1
Historical Earthquake in Azores with Intensity ≥VIII (See Sources at the Seismicity Section)

Date (yyyy/mm/dd)	Location/Island Most Affected	I_{max}	Magnitude	Observations
1522/10/22*	Vila Franca/São Miguel	X		Inland epicenter. Death toll: 4000–5000.The earthquake triggered a landslide that buried Vila Franca do Campo located on the south coast of São Miguel island.
1547/05/17	North zone/Terceira	VII/VIII		Several earthquakes struck the island causing minor damage. More than three deaths.
1591/07/26	Vila Franca/São Miguel	VIII/IX		Destructive earthquake that destroyed Vila Franca do Campo.
1614/05/24*	Praia da Vitória/ Terceira	IX		The earthquake was inland and caused heavy damage at Vila da Praia and neighboring settlements. More than 1600 houses collapsed. Death toll: >200.
1713/12/08	Ginetes/São Miguel	VIII		Heavy damage in the southwest settlements of São Miguel Island. No casualties reported.
1730/06/13	Luz/Graciosa	VIII/IX?		Heavy damage at the settlement of Luz.
1757/07/09*	Calheta/São Jorge	XI	M 7.4	Severe damage on São Jorge Island. Reported damage on neighboring islands. Death toll: 1046.
1800/06/24	Praia da Vitória/ Terceira	VII/VIII		Heavy damage on the eastern part of Terceira Island.
1801/01/26	São Sebastião/ Terceira	VIII		High damage on the southeastern part of Terceira Island, especially at Vila da Praia, and heavy damage at São Sebastião. Two people died.
1837/01/21	Guadalupe and Santa Cruz/Graciosa	IX?		Heavy damage at some settlements on Graciosa Island. Death toll: 3.
1841/06/15	Praia da Vitória/ Terceira	IX		Severe damage on Vila da Praia. No casualties reported.
1852/04/16	Ribeira Grande/São Miguel	VIII		Heavy damage to most of the settlements on São Miguel. Death toll: 9–12. Several tens injured.
1912/11/06	Praia da Vitória/ Terceira	VII/VIII		Light damage reported at Vila da Praia and neighboring settlements.
1926/08/31	Horta/Faial	X	M_b 5.3–5.9	Heavy damage reported at Horta and in neighboring settlements. More than 200 injuries and 9 fatalities.
1946/12/27	Serreta/Terceira	VII/VIII		Light damage reported at the settlements on the northwest and north parts of Terceira Island. No casualties reported.
1952/06/26	Ribeira Quente/São Miguel	VIII		Heavy damage in some areas of the settlements on the south and southeast part of São Miguel. No casualties reported.
1958/05/13	Praia do Norte and Ribeira Funda/Faial	VIII/IX		The event occurred during the Capelinhos eruption and caused heavy damage at the northwestern settlements of Faial Island.
1964/02/21	Rosais/São Jorge	VIII	M_b 5.5	The event occurred during the onshore eruption of Rosais on São Jorge Island. Heavy damage on the western side of the island.
1973/11/23	Bandeiras/Pico	VII/VIII	M_b 5.0	Heavy damage at the settlements on the northern part of the island. No casualties reported.
1980/01/01*	Doze Ribeiras[a]/ Terceira	VIII/IX	M_w 6.8	Heavy damage at several settlements of Terceira and São Jorge Islands and on Graciosa Island. Death toll: 61.
1998/07/09	Ribeirinha/Faial	VIII/IX	M_w 6.0	Heavy destruction at several settlements of Faial and Pico. Death toll: 8.

*Events select to calibrate kriging technique.

time span. Clustered earthquakes associated with volcanic eruptions (1957–1958 and 1964), as well as aftershocks that lasted several months after the mainshock, were removed because our interest is on the mainshock to map the maximum intensity by the kriging technique. The dataset is expressed in terms of the MMI scale of 1956 (MMI-56; Gutenberg and Richter, 1956), rounded to the next integer. It is listed in Ⓔ Table S1 (available in the electronic supplement to this article).



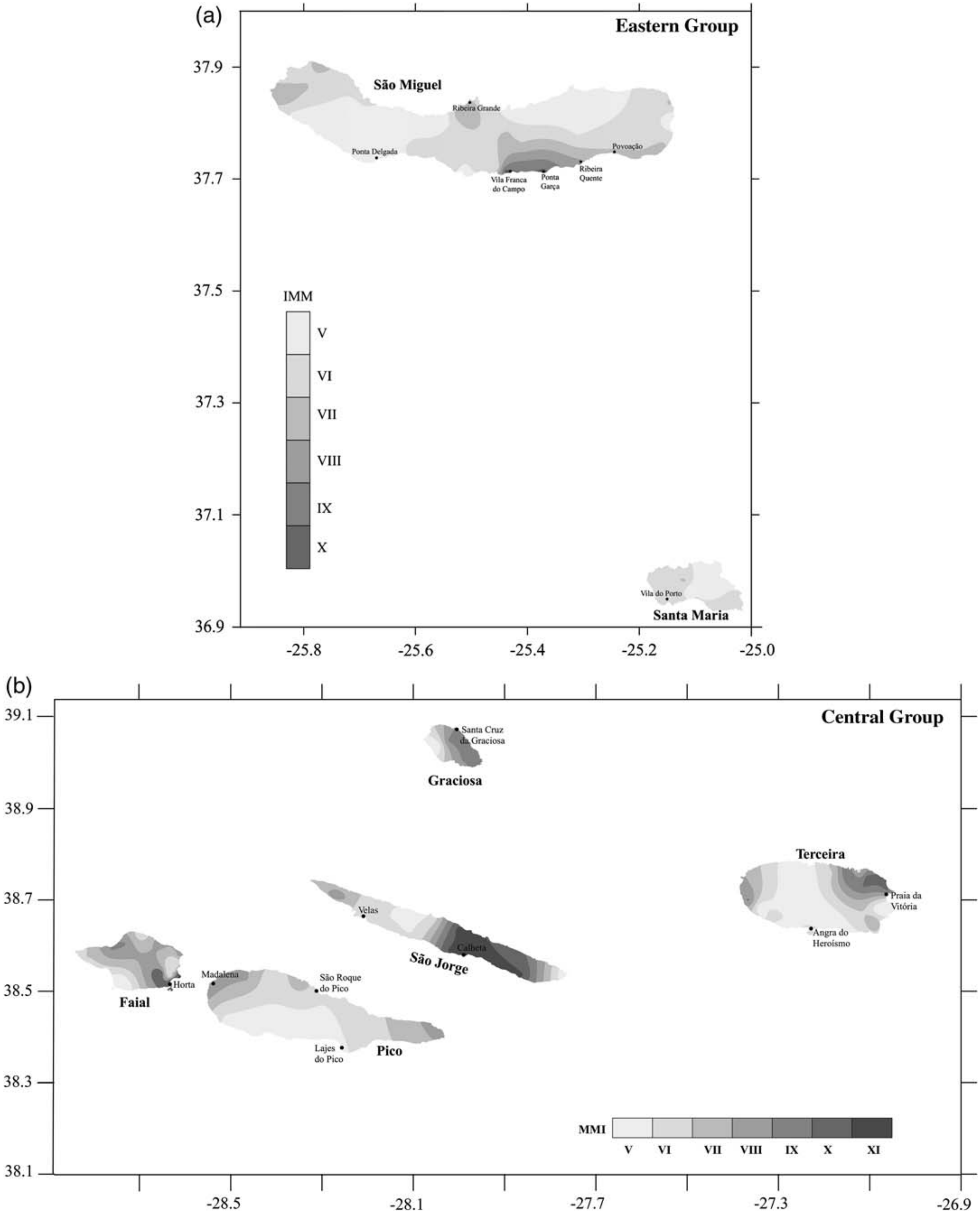
▲ **Figure 3.** Isoseismal maps interpolated by kriging for the (a) 1522, (b) 1614, (c) 1757, and (d) 1980 earthquakes.

Kriging Technique

The kriging method (Krige, 1951; Matheron, 1965) is a well-known method to interpolate spatial data. It uses an interpolation function based on a variogram model derived from the data. The variogram expresses the spatial variation, the error estimation, the confidence interval, and the degree of spatial autocorrelation of the dataset. This interpolation method is appropriate for drawing regional trends and local anomalies without bias because the expected values of the estimates and of the observed values at the same locations are equivalent. Among the numerous types of kriging methods, the ordinary kriging (OK) is the best for drawing isoseismal maps (De Rubeis *et al.*, 2005). It requires a dataset of measurements and their geographic coordinates. One assumes stationarity of the spatial data and an average regionalized variable, that is, the variable is distributed in space. The OK is based on the assumption that the random process is essentially stationary with constant mean, and the variance depends on the distance and direction between places (Oliver and Webster, 2015).

MAXIMUM OBSERVED INTENSITY MAPPING

Before we produced MOI maps we needed to verify if kriging is suitable to draw isoseismal maps with large and small macroseismic datasets and with different spatial extents. The calibration is a process introduced to check if the results are accurate. It consists of using some earthquakes that were studied in detail by other authors (Machado, 1949, 1966; Madeira, 1998; Nunes *et al.*, 2001; Silveira, 2002; Silva, 2005) to verify if kriging is able to replicate macroseismic maps of those earthquakes. To avoid drawing macroseismic or MOI maps under different conditions, we prefer to use the same kriging parameters as stated by Schenková *et al.* (2007). To calibrate our kriging method, we selected four earthquakes based on their large I_{max} values, death tolls, and spatial extents of the observed data. We selected the 1522, 1614, 1757, and 1980 events (summarized in Table 1). The observed data of the 1522, 1614, and 1757 earthquakes come from a single island, whereas the data of the 1980 earthquake come from five islands. During calibration, the OK interpolation method was applied individually to the data from each one of the four selected earthquakes (see Ⓔ Table S1) to produce isoseismal maps (as shown in Fig. 3a–d). The calibration



▲ **Figure 4.** Maps of MOI for the (a) eastern and (b) central groups. The islands of the western groups are not represented, due to the low level of seismicity (Fig. 1).

maps replicate well the observed intensities except in some areas of the isoseismal map for the 1522 earthquake, for which the observed intensities are underestimated. From these results, we consider that the OK is calibrated, and it can be used to generate accurate MOI maps.

On the MOI maps, we used all earthquakes of the dataset to produce a single MOI map. The results show an MOI map that is greater than VII for the eastern and the central groups (Fig. 4a and 4b, respectively). For the eastern group (Fig. 4a), Santa Maria Island has the highest I_{max} of VII. On São Miguel Island, the I_{max} estimated on the MOI map is XI. For the islands of the central group (Fig. 5b), São Jorge Island has the highest I_{max} at XI, followed by Terceira and Faial Islands with I_{max} X. On Graciosa Island, I_{max} is IX, and on Pico Island I_{max} is VIII.

The historical seismicity of the Azores is marked by the settlement of the islands in the fifteenth century; consequently, our catalog has a relatively short time period that started in 1522. In comparison, the earthquake catalog for the Portugal mainland has a time span that is more than 200 yrs longer (the first description belongs to the 1309 earthquake) (Ferrão *et al.*, 2016). Considering the time period of the earthquake data, it is likely that from the fifteenth century to the present some or much of the Azores area has not experienced the strongest ground shaking that can take place. Thus, the MOI maps do not represent the highest possible MMI values that can be experienced across the islands. The maps accurately represent the MOI for the time period of the data, but for most places they probably are not the highest intensity that can take place.

FINAL REMARKS

This study provides the first MOI maps for the Azores region based on the seismicity of the last five centuries. Through these maps, we assess past maximum shaking of the largest earthquakes based on the macroseismic observations of past earthquakes. This study reveals that São Miguel is the island of the eastern group that in the past suffered the greatest effects of very destructive earthquakes, especially the central part of the south coast, with maximum intensities ranging between VIII and X. All the islands of the central group experienced very destructive or devastating earthquakes. São Jorge has maximum intensity ranging from VIII to XI; Terceira and Faial have values in the VIII–X range; Graciosa is in the VIII–IX range; and Pico has a maximum intensity of VIII. Because intensity qualitatively describes the ground shaking, the MOI maps are helpful to assess the ground shaking from past seismicity of the Azores. However, they neither describe nor quantify the level of expected future ground shaking, nor allow inference about the seismic hazard; that is, it is not possible to observe that earthquakes repeatedly ruptured on a given part of a fault. In conclusion, the MOI mapping is an approach able to assess maximum intensity of areas that in the past were struck by damaging earthquakes, even if it has a poor instrumental dataset. The good results obtained here confirm that the OK method is able to reproduce the observed macroseismicity, to estimate maximum intensity, and to handle spatial gaps in the data. Thus, the information contained in the MOI maps is a valuable spatial instrument that stakeholders can use to establish their seismic-hazard mitigation plans.

DATA AND RESOURCES

Data are provided by the literature listed in the references in this article and in the Ⓔ electronic supplement, by the Catálogo Sísmico da Região dos Açores (CSRA) (Nunes *et al.*, 2004), and by the Instituto Português do Mar e da Atmosfera (IPMA, Lisbon, Portugal; https://www.ipma.pt, last accessed April 2016).

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5

Human losses and damage expected in future earthquakes on Faial Island - Azores

5.1. Summary

This chapter is about the *Human losses and damage expected in future earthquakes on Faial Island - Azores* submitted to Georisk. In the first section (introduction), I did a brief description of the QLARM achievements, and the importance of human loss estimation after an earthquake in real-time and scenery mode. The following section (Seismicity in the Azores) describes the deadliest earthquakes in the Azores since the 15th Century. Section three describes the different steps needed to validate QLARM in order to obtain accurate human losses estimates. Subjects like validation of the european macroseismic method for vulnerability analysis (EMMVA) and initial casualty matrix (ICM) are addressed in the first part. Then, in sub-section 3.1, it is presented the validation of the ground motion model selected. Sub-section 3.2 is about the construction practices in Faial Island as well as the population and building distributions by settlements. Sub-section 3.3 is the

earthquakes parameters used to validate QLARM and sub-section 3.4 is about the human loss estimates expected in future earthquakes in Faial Island. We finish the paper (section 4) with the discussion and conclusions. Reliable loss estimates in a scenario depends on the knowledge of the building and population distribution, as well as ground motion prediction equation (GMPE) and site conditions. Data to the former parameters provided by CENSUS 2011, and it's count by settlement and then is distributed by age, type of construction, state of maintenance and by other types of info that are not relevant. QLARM as several GMPE embedded can be used in different tectonic contexts (Rosset et al. 2015). Fontiela et al. (2016) tested Munson and Thurber (1997) attenuation relationship developed to volcanic environments, nevertheless the results obtained during the validation didn't fit the observed data (cf figure 2 of Fontiela et al. 2016). Therefore, we used the equations from Shebalin (1968, 1985) since it is possible tune parameters. Thus, adjusting C2 parameter to 5.2 and 5.7 (cf equation 1, section 3.1, chapter 5) residuals were minimized to 1.5% of both earthquakes 1980 and 1998, respectively. Concerning site conditions, the shear wave mapping presented by Forjaz et al. (2004) overestimates the velocity for all site classes. Thus, we used an amplification factor deduced from macroseismic surveys of past earthquakes which were complemented by expert judgements on local geology to attest site amplification. Then, we added the observed incremental value to intensity calculations.

Validation results of QLARM show that the fatalities number estimated is in the range of the observed for booth earthquakes 1980 and 1998. Nevertheless, the maximum number of calculated patients is slightly underestimated. We selected two scenarios based on the tectonic and on past earthquakes. The first scenario comprises the set of faults of Espalamaca, Lomba do Meio, and Capelo, that cross

Faial Island with magnitude 6.9 while the second one is located at the offshore in the region of the 1926 earthquake with magnitude 6.0. On the first scenario the fatalities range between a minimum of 570 and a maximum of 715, and the patients in between 1530 and 1945 depending on the C2 parameter selected (cf table 4). On the second scenario the fatalities number range between a minimum of 50 and a maximum of 190, and patients vary from 160 up to 545, depending on the C2 parameter selected (cf table 4).

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5.2. Paper: *Human losses and damage expected in future earthquakes on Faial Island - Azores*

Human losses and damage expected in future earthquakes on Faial Island - Azores[1]

Fontiela, J., Rosset, P., Wyss, M., Bezzeghoud, M., Borges, J., Cota Rodrigues, F.

ABSTRACT:

Since the 15th century, the death toll due to large earthquakes has reached approximately 6,300 in the Azores and 17 for Faial Island. The likely number of fatalities and injuries in future large earthquakes (M6+) in Faial Island is estimated using the software QLARM and its dataset, validated at the regional scale. The current population for the 13 settlements on this island is extrapolated from the 2001 and 2011 census. The distribution of buildings into EMS-98 vulnerability classes is based on detailed census information and damage reports written after the 1980 (M7.2) and 1998 (M6.2) earthquakes. The most appropriate ground motion prediction equation is selected and coupled with site amplification information to adjust calculated ground shaking with observed intensities for the aforementioned events. The good agreement of fatalities and injuries calculated by QLARM with the observed numbers in both earthquakes was the motivation for proposing scenarios for likely future earthquakes. Based on these scenarios, fatalities and injuries may range between 110 to 620 and 330 to 1750, respectively, depending on the likely large earthquake.

Keywords: QLARM, earthquake loss-estimation, attenuation models, EMS-98, volcanic islands, Azores

[1] Paper submitted to Georisk

1. Introduction

In the past, the population of the Azores islands has suffered several large earthquakes, suggesting that a worst case scenario should be considered for risk preparedness and prevention. Wyss (2017a) showed that it is possible to reduce the number of losses, if the stakeholders use loss estimations to take precautions. Loss estimation depends on reliable models, which should be able to predict scenarios within a factor of confidence of two or three. In the specific case of the Azores region, the rescue operations after a strong earthquake could be tricky, due to the travel between distant locations of the rescue teams within the different islands.

The software tool QLARM is used to estimate building damage and losses as it has been for different regions of the world at different geographical scales such as North India (Wyss et al., 2017), Central Myanmar (Wyss, 2008), Mexico (Wyss and Zuniga, 2016), Himalayas (Wyss, 2005, and Wyss et al., 2018), Algeria (Rosset and Wyss, 2017), Southern Sumatra and Central Chile (Wyss, 2010).

The present paper reports on an effort to build the dataset used in QLARM in the context of the volcanic islands of the Azores. It includes a detailed compilation of the building stock at the scale of settlements, the population distribution into these buildings, as well as the soil conditions which may amplify seismic waves. Efforts have also been made to validate both ground motion and vulnerability models using past observations from several damaging earthquakes.

The seismicity of the Azores is first discussed, pointing out the specific tectonic and geological context combining seismic and volcanic activities. Secondly, the dataset used in QLARM is explained and validated using past observations to run scenarios of likely earthquakes for Faial Island, based on knowledge of regional tectonics.

2. Seismicity in the Azores

The Azores archipelago is a seismically active zone, as attested by historical and instrumental earthquakes plotted in Figure 1. Since the 15th century, several large earthquakes have caused heavy damage with Modified Mercalli Intensities (MMI) ranging from VII to XI, killing more than 6,300 people (Nunes et al. 2001), as listed in table 1. The most severe earthquakes that have occurred in the Central Group struck Terceira Island in 1614 and 1980, São Jorge Island in 1757, and Faial Island in 1926, 1958 and 1998.

The May 24, 1614 earthquake affected mainly the eastern part of Terceira Island with heavy damage to the building stock (maximum MMI of X), and killed more than 200 people. The July 9, 1757 earthquake (M7.4), the second deadliest earthquake in the Azores, had a maximum MMI of XI and a death toll of 1,046 persons (Machado, 1949). The earthquake of August 31, 1926 at 10h40 with Mb 5.3-5.9 (Nunes et al. 2001) caused nine fatalities and more than 200 injuries (Lima, 1934). According to Agostinho (1927), 15% of the buildings collapsed in Horta city, the area with the highest intensity (MMI=X) and its neighboring settlements, as exemplified in the photo of Figure 2. The 27th of September 1957, a volcanic eruption started off the west coast of Faial Island and lasted until October 1958. A swarm of around 450 earthquakes were felt during May 12, 1958 night, two of them with a maximum MMI of X (Machado et al. 1962). Lobão (1999) counted 273 collapsed houses among the 508 reported damaged, but amazingly no fatalities were registered.

On the 1st of January 1980, an M_S7.2 earthquake occurred in the evening affecting Terceira, São Jorge, and Graciosa Islands. The death toll reached 61 with more than 300 injured and around 5,400 houses collapsed or heavily damaged (MMI=IX), leaving

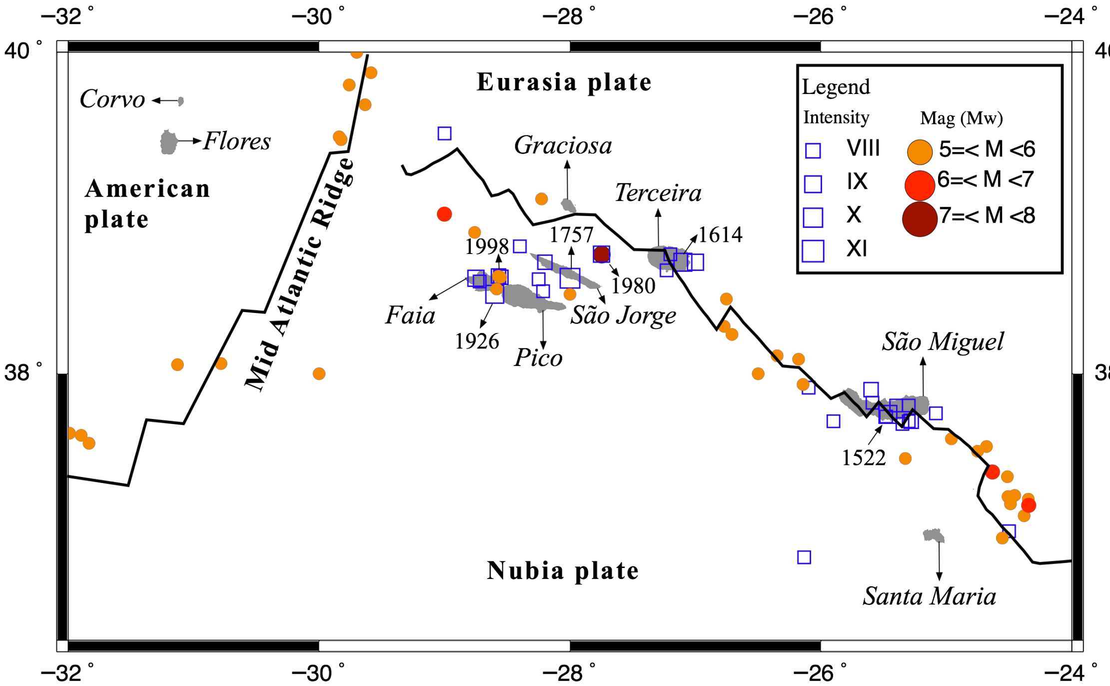


Figure 1. Seismicity map of the Azores archipelago. Colored circles instrumentally located seismicity with magnitude M ≥ 5 for the period 1926-2017 and empty blue squares show historical earthquakes with MMI ≥ VIII since 1522 (Sources: Nunes et al., 2004; Fontiela et al., 2017). The year of the historical event is indicated when more than four deaths were reported (Table 1). The islands are filled in light grey and the main faults forming the boundaries of the three tectonic plates are drawn in black (source: Bird, 2002).

Table 1. Main characteristics of the earthquakes for which more than four fatalities were reported. These earthquakes are plotted in the map of Figure 1. * Magnitude estimated by Machado (1949) reported with more than four deaths.

Date and Time (Local Time) (yyyy/mm/dd hh:mm)	Long (°)	Lat (°)	Magnitude	Maximum Intensity	Island	Death Toll
1522/10/22 ~02:—	−25.400	37.400		X	São Miguel	~5,000
1614/05/24 15:15	−27.100	38.700		X	Terceira	~ 200
1757/07/09 —:—	−28.000	38.600	M 7.4 *	XI	São Jorge	1,043
1926/08/31 10:40	−28.600	38.500	Mb 5.3	X	Faial	9
1980/01/01 16:42	−27.605	38.590	M_S 7.2	VIII/IX	Terceira	61
1998/07/09 05:19	−28.523	38.634	M_W 6.2	VIII	Faial	8

21,296 people homeless. The event caused heavy damage in Angra do Heroísmo city, as well as in other settlements of Terceira Island. In São Jorge Island, it caused heavy damage to the settlements around the epicenter. In Graciosa Island, the building stock also suffered considerable damage.

Figure 2. Illustration of a collapsed house in Flamengos during the 1926 earthquake in Faial Island (courtesy of Paulo Borges).

On the 9th of July 1998, an Mw 6.2 earthquake occurred at 05h19 and was largely felt in Faial but also in Pico, São Jorge, Graciosa, Terceira and São Miguel Islands (Senos et al. 1999; Fernandes et al. 2002; Matias et al. 2007; Borges et al. 2007). At the end of October 1998, 10,600 aftershocks were recorded, and the number rose to around 15,000 by the end of 2003. The population felt 410 events in the first four months (Matias et al. 2007). Despite the magnitude and the early time of its occurrence, only eight fatalities (mainly children and seniors), and 128 hospitalized people were reported (Gonçalves, 2008). According to Ferreira and Oliveira (2008), around 35% of the building stock was affected, the strongest damage (degrees 4 and 5 on a scale from 0 to 5) occurring at epicentral distances up to 19 km. The strongest damage occurred around the epicenter, with a maximum intensity of VIII according to Ferreira (2008), except for the most distant villages of Flamengos and Castelo Branco where damage was relatively high (Senos et al. 2008). In Flamengos, Pena et al. (2001) estimated that the soil amplification increases by two units the intensity that would be expected for hard rock sites, mainly due to the volcanic alluvium deposits, which have a strong frequency response around 9-10 Hz. In Castelo Branco, still no clear explanation is given to justify the high level of damage.

3. Use of QLARM to estimate losses in the Azores

QLARM (the acronym coming from Quake Loss Assessment for Response and Mitigation) has been functioning for more than 10 years, distributing human loss estimates in real time (Wyss, 2014), as well as scenario modelling, worldwide (e.g. Wyss et al., 2006; Wyss, 2008; Trendafiloski et al., 2009; Wyss and Wu, 2014; Wyss and Zuñiga, 2016; Wyss et al., 2017; Wyss, 2017a, 2017b, Wyss et al., 2018). Its dataset includes around 1.9 million settlements, each documented with name, coordinates, building and population distribution, and in some cities, site conditions (Wyss, 2010; Rosset et al., 2015). Using the supplied magnitude, depth and epicenter coordinates, QLARM estimates ground motion at each settlement around the earthquake source. Several Intensity relationships and Ground Motion Prediction Equations (GMPEs) are available to adapt seismic attenuation to the tectonic context of the investigated region. When available, a soil condition factor is applied for a given settlement. The estimation of the expected damage to a building stock is performed using the European macroseismic method for vulnerability analysis, hereafter noted as EMMVA (Trendafiloski et al., 2009). The method itself was developed by Lagomarsino and Giovinazzi (2006) using the implicit vulnerability model included in the European Macroseismic Scale (EMS-98). The EMMVA uses seismic intensity to express the earthquake demand, which can be derived from intensity, or any other ground motion parameter using appropriate relationships.

The building stock can be modeled either by the EMS-98 vulnerability classes or corresponding building types. The concept of “vulnerability index” and its calibration makes QLARM flexible and gives the possibility to define specific building types not included in EMS-98, consequently enlarging the database of available building types and corresponding vulnerability models for a worldwide use. The mean damage grade M_D is calculated from the damage rate divided into six damage degrees (from 0 to 5, where 0 stands for no damage and 5 for collapse). The EMMVA is extended with a casualty estimation module that uses the concept of initial casualty matrix, hereafter ICM (Vacareanu et al., 2004; Trendafiloski, 2007). The ICM determines the probability of occurrence P(Di|Ci) of a certain casualty state Ci for the expected damage degree Di.

When data are available, discrete city models have been developed consisting of the division of a settlement into a set of districts corresponding to the center of administrative districts. In this case, each district is documented, increasing the resolution and therefore the details in the loss calculation (see examples in Parvez and Rosset, 2014).

As much as possible, a procedure of validation of QLARM using observed earthquake consequences is performed to adjust the different parameters involved in the loss calculation for a specific region. It includes, by order of importance, (1) choice of the attenuation model that best fits the observed ground shaking, (2) adjustments of the building and population distribution, (3) improvement of the collapse models and (4) of the casualty matrices. For the last three steps a comparison is needed of past earthquake losses with calculated ones. One considers that QLARM is validated when the difference between observed and calculated losses is less than a factor 2.

3.1. Validation of the ground motion model

QLARM includes several published attenuation relationships that can be used in different tectonic contexts (Rosset et al., 2015). For example, intensities may be calculated using the equations by Shebalin (1968, 1985), Ambraseys (1985) or by downloading precalculated shakemaps in the USGS format (Allen et al., 2008). PGA relationships are those of Huo and Hu (1992), Ambraseys et al. (1996), Youngs et al. (1997), Munson and Thurber (1997), Boore et al. (1997). For the present work, intensities are calculated using the Shebalin's (1968, 1985) formula expressed by:

$$I = C1 * M - C2 * \log(r^2 + h^2)^{0.5} + C3 \qquad (1)$$

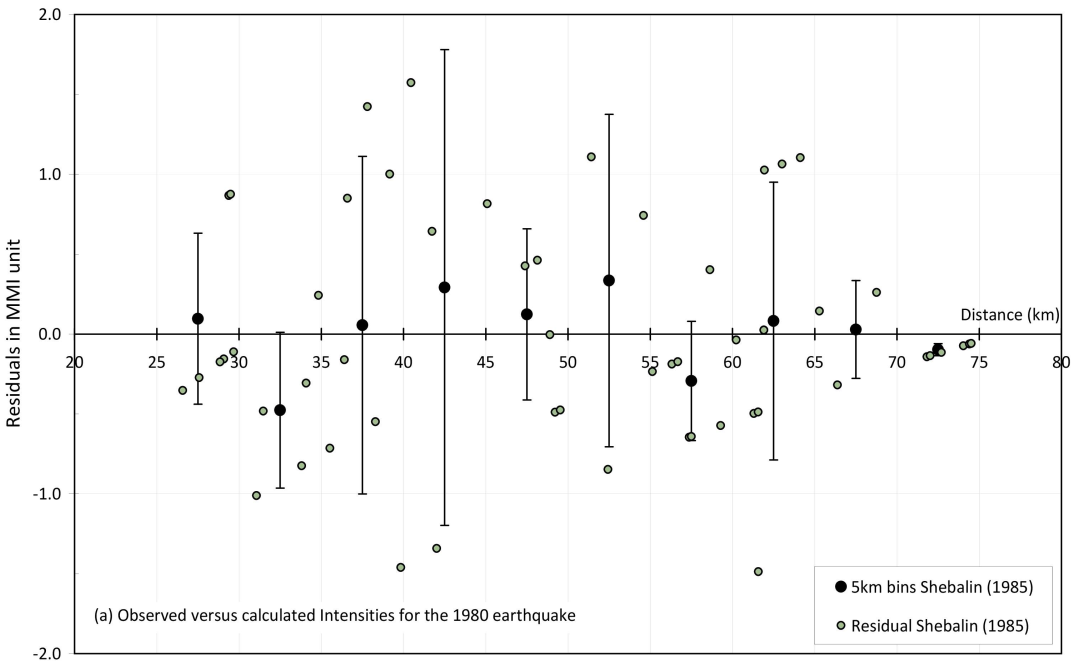
where, I is the intensity (MMI scale), M the magnitude, r the hypocentral distance, h the depth, and C1, C2 and C3 are constants as described hereafter

Observed intensity data from Nunes et al. (2004) are used to verify the validity of equation 1 for a specific seismic event. They have been compiled after the 1998 Faial earthquake (M_w6.2) in 63 settlements located between 10 and 120 km of the epicenter with intensities ranging from III to VIII, and after the 1980 Terceira earthquake (Ms7.2) at distances from 25 km to 75 km with intensities between IV+ to VIII+.

The influence of local soil conditions is also considered in this validation phase by adding intensity units to the calculated intensity for settlements where evidence of site amplification is known. Indeed, the analysis of existing macroseismic surveys, complemented by expert judgments on the local geology, has permitted us to estimate the intensity's increase in several settlements compared to the surrounding ones. An increment of one or two intensity units has been attributed to 8 of the 13 settlements in Faial, as shown in Table 2.

Intensity data plotted against epicentral distance show a large scatter, which suggest that a modification of the slope of the curve (C1 factor of the equation 1), calculated with the attenuation relationship of Shebalin (1968, 1985), is not warranted, and thus is fixed to 1.5. However, for the 1998 event, intensity values decrease rapidly in the range 10-50 km for settlements in Pico and Faial Islands, indicating a strong attenuation, which is simulated by tuning the value of the factor C2 of equation 1 which controls the attenuation relative to epicentral distance. The factor C3 is fixed to 3.5 which is a value generally used in our analysis.

In Figure 3, the calculated MMI are compared with observed ones for both earthquakes: Terceira (1980) and Faial (1998). Figures 3a and 3b plot residuals, grouped by 5 km bins, of observed intensities for the 1980 and 1998 earthquakes versus calculated ones, respectively. By adjusting the value of C2 to 5.2 and 5.7, the average residual for the calculated distance is minimized to 1.5% for the 1980 and 1998 earthquakes,respectively. At this stage, the ground motion model is considered to be validated.



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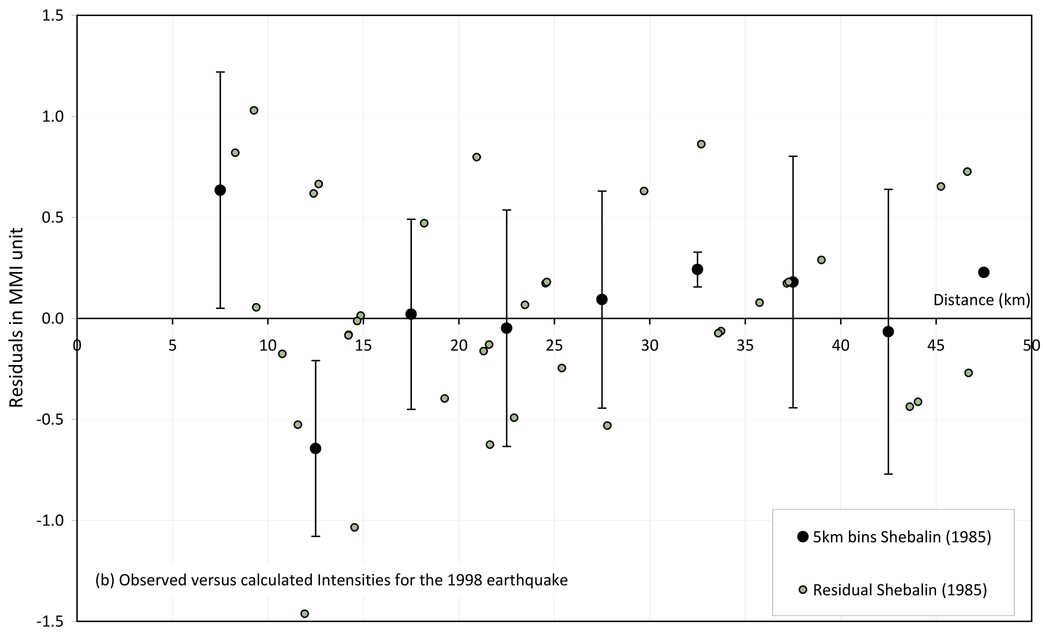

Figure 3. Observed versus calculated residuals for the (a) 1980 and (b) 1998 earthquakes. Black dots represent the average values grouped by 5 km epicentral distances derived from Shebalin (1985), and small grey dots are the individual residual values.

3.2. Construction practices and population on Faial Island

The elements at risk in QLARM concern both the buildings and their occupants. The level of resistance to the ground shaking of the buildings is expressed in terms of EMS-98 classes ranging from A to F, A being the least resistant buildings and F the most resistant buildings. The damage surveys conducted by Costa and Arêde (2006) after the 1998 earthquake in Faial, as well as the compilation of main characteristics of buildings done by Neves et al. (2012), are used to distribute the building stock of each settlement of the island into three main types:

1. single story rural houses; usually modest and located in flat areas.
2. two-storied semi-rural houses, common in urban centers of rural wards.

3. two or three-storied urban buildings, located in towns.

Rural and semi-rural houses typically have external walls made of stone masonry and a wooden roof structure. In some cases, internal walls are also made of stone masonry. Semi-rural houses have external walls supporting the floor, ceiling and wooden roof elements. Urban houses have stone masonry walls with large stones at the corners to improve the cross-link between side walls. The internal walls are made of plastered lattices acting as building structural elements, since they often contain a wood beam column frame supporting several wood floors up to the roof.

The resistance of each house type depends on the disposition of the stones within the external walls. Costa and Arêde (2006) and Costa (2006) distinguish three different types of stone walls: First, high-quality walls, formed with a single stack of stones, which are often laid out in an angular manner so they wedge together, and are typically quite large. Second, irregular stone walls, built with “burnt stone" playing an important role to strengthen the structure. Voids are filled with small size materials or clay. Finally, the double wall, made of selected stones slightly larger than half thickness of the wall, where the stones are interlocked and form vertical layers. According to Costa (2006), the second and third types are predominant in rural areas, and these three wall types are highly vulnerable to ground shaking.

Reinforced concrete (RC) buildings found in the island are made of beams and columns connected by rigid joints, with or without infill walls, or with reinforced concrete walls. The typical infill wall material is concrete blocks. This RC type has one to six-stories, 1-2 stories being the most common for a single family. Safety regulations and actions for building and bridge structures introduced in 1983 (Law nº 235/83) have improved the RC frame building resistance to earthquake actions.

The different building types aforementioned are distributed into the vulnerability classes of the EMS-98 classification as follows:

- Reinforced concrete buildings in class D.
- Buildings with masonry walls of mortar with concrete slab built before 1971 are in class B, and in class C for those built between 1971 until 2001.
- Buildings with walls made of mortar without concrete slab are in class B.
- Buildings constructed with adobe or stone masonry are in class A.
- All other constructions are in class A.

The last census conducted in 2011 by the Instituto Nacional de Estatística of Portugal is firstly used to count the population by settlement and secondly, distribute this population into the different building classes. In 2011, Faial Island had 14,799 regular inhabitants (about 6% of the total population of the Azores), whereas the town of Horta concentrated around 40% of the population. It counted 6,447 buildings in 13 settlements. The city of Horta counted 2,311 buildings (36% of the total), followed by Feteira, Flamengos, and Castelo Branco, while Salão had the smallest number with 174 buildings. Table 2 shows how the building stock has been distributed by vulnerability classes in each settlement of the Island. The prevailing class is B, except for Flamengos, Pedro Miguel, Praia do Almoxarife, Ribeirinha, and Salão, where class C is the most representative. Castelo Branco is a particular case, since buildings of classes A and C represent each one third of the total.

3.3. Validation of the vulnerability model

Calculated data for this analysis are validated using observed losses (building damage and casualties) after the 1980 (Ms7.2) and 1998 (Mw6.2) earthquakes, which both occurred close to Faial island.

Table 2. Population and building distributions by settlements of Faial Island, as well as their distribution by EMS-98 classes are based on 2011 census data. The incremental value given to intensity is provided to take into account site amplification.

Settlements	Population (2011)	Number of buildings	Amplification factor (in units of MMI)	Distribution of buildings by EMS-98 classes (%)				Distribution of population by EMS-98 classes (%)			
				A	B	C	D	A	B	C	D
Capelo	486	416		1.5	58.8	17.3	22.3	1.9	60.9	16.9	20.3
Castelo Branco	1304	563	+1	35.4	14.7	33.7	16.1	33.6	14.3	35.7	16.4
Cedros	906	547	+1	4.7	76.7	16.3	2.3	3.9	70.6	23.7	1.9
Feteira	1896	768	+1	7.9	53.9	32.9	5.3	7.5	52.9	34.0	5.6
Flamengos	1599	594	+2	1.6	40.5	55.3	2.6	1.6	40.3	55.6	2.6
Horta (Angústias)	2402	996		3.8	48.6	22.8	24.8	3.6	46.5	25.2	24.7
Horta (Conceição)	1138	459		8.3	41.4	21.4	28.8	6.6	36.8	23.0	33.6
Horta (Matriz)	2404	856		1.2	64.4	13.2	21.1	1.3	57.1	17.0	24.7
Pedro Miguel	753	313	+1	25.4	13.2	45.6	15.8	24.2	13.3	46.4	16.1
Praia do Almoxarife	834	361	+1	4.3	37.5	52.1	6.1	4.7	38.4	50.9	6.0
Praia do Norte	250	225		5.8	75.3	17.4	1.6	5.2	49.3	43.7	1.8
Ribeirinha	426	175	+1	1.3	23.5	73.8	1.3	1.3	18.9	78.4	1.4
Salão	401	174	+1	11.3	16.5	53.4	18.8	10.7	14.3	55.7	19.2

The 1st January 1980 earthquake, which devastated Terceira, São Jorge, and Graciosa Islands, occurred at 16:42 local time. The source parameters used for this event of Ms7.2 are based on the aftershock distribution studied by Hirn et al. (1980). An offshore line source located at 38.81°N and 27.78°W of 60 km length and oriented with an azimuth of

N150 is selected, with a hypocenter at a 10 km depth. The fault length is an average between the calculated one from Wells and Coppersmith (1994), using a relation for a strike-slip fault for this magnitude, and the estimate from aftershocks given by Hirn et al. (1980).

The July 9, 1998 earthquake shook Faial, Pico, and São Jorge Islands, at 5:19. The fault plane solution of the main shock indicates NNW–SSE strike-slip faulting with the aftershocks ranging from 2 km to 16 km depth and concentrating between 8 km and 12 km depth (Matias et al., 2007). Borges et al., (2007) determined the rupture initiation between 7-8 km depth, from body-wave inversion. Based on these observations, we modeled the energy release in this earthquake along a line source located at 5 km depth. The hypocenter is chosen to be located offshore (38.638°N and 28.524°W) and a line source of 11 km is chosen using the Wells and Coppersmith (1994) relation for strike-slip faults at a magnitude M of 6.2. The details of the source parameters selected for both validation events are listed in Table 3.

QLARM provides the calculated fatalities and patients for each individual settlement. Patients are defined as injured people who need hospitalization. The comparison of observed and calculated casualties for both earthquakes are shown in Table 3. The range of fatalities estimated for the 1980 earthquake includes the observed number of 61 killed people. The number of calculated patients varies between 38 and 285, under-estimating slightly the estimated and unofficial number of 300. Nevertheless, around 90 seriously injured people were mentioned in a report by USAID (1980), which better fits the term(??) patients calculated in QLARM. The calculation done with population data from the 2001 census doesn't affect the results since it overestimates the 1980 population by less than 0.1%, according to the 1981 census.

For the 1998 earthquake, calculated fatality numbers, based on population data and building stock from the 2001 census, vary between 3 and 15 compared to the official death toll of 8 people. The calculated patients are in the range 7 – 111, slightly underestimated compared to the official number of patients.

The two validation cases are satisfying both the correct estimate of the ground shaking field in terms of calculated intensity and the accurate estimation of the killed and seriously injured people on Faial Island. It therfore justifies the use of QLARM to provide loss estimate for scenarios of likely future earthquakes.

4. Scenarios for potential earthquakes in Faial

The proposed earthquake scenarios are based on paleo-seismological studies by Madeira (1998) and Madeira et al. (2015) of Faial Island. These authors describe the seismogenic potential of active faults with magnitude, rupture length, and recurrence period. The two active faults selected to estimate losses in future likely earthquakes are the inland Espalamaca fault, hereafter called inland scenario, and the offshore one between the Faial and Pico Islands, called offshore scenario (as shown in Figure 4).

According to Madeira (1998) and Madeira et al. (2015), the extent of the Espalamaca fault is about 22.5 km. Three events have been identified during the last 4,000 years generating displacements of 0.73m, 1.65m and 0.46m, respectively, for a return period estimated around 1,300 years (Madeira (1998). The offshore scenario is located on the seismogenic source of the 1926 earthquake. The knowledge of this fault is scarce and parameters such as length, displacement, and return period are still unknown.

For the inland scenario, a maximum historical magnitude of 6.9 is selected, which corresponds to a rupture length of 27.5 km using Wells and Coppersmith (1994) relation for normal faulting. A magnitude of 6 is assigned to the offshore scenario which corresponds to a fault length of 8 km. The depth is fixed at 5 km for each of the two scenarios since the seismogenic crust in the Azores varies between 8 and 11 km (Luís and Neves, 2006), and agrees with the focal depths of the recent large earthquakes in the island (1926, 1958 and 1998). The input parameters used in QLARM to estimate losses are listed in table 4. For both scenarios, the losses are calculated using a line source centered on the epicenter with a general NW-SE orientation, in agreement with the major tectonic structures of the island.

Table 3. Parameters and scenario results for the 1980 and 1998 validation earthquakes

Name	Fault Length (km) L	Z (km)	C2	M	Fault location (in decimal degrees)		Cal. Imax	Casualties			
								Fatalities		Patients	
					X1 Y1	X2 Y2		Calc. min-max	Observed	Calc. min-max	Observed
1980	60	10	5.2	7.2 M_s	-27.878 38.967	-27.682 38.653	VIII+	8-75	61	38-285	>300
1998	11	5	5.7	6.2 M_w	-28.544 38.675	-28.504 38.601	VIII	3-15	8	7-111	128

The number of fatalities and injuries requiring hospitalization is calculated for these two scenarios. The results are provided using the values 5.2 and 5.7 for the factor C2 in equation (1), given the uncertainty about the ground motions estimates observed in the 1980 and 1998 cases. Both of these estimates are based on worst case assumption of 90% of the population being inside during the night.

The M6 offshore scenario affects both Pico and Faial Islands with a maximal intensity of X in Flamengos. The population affected by intensities VI+ is estimated as about 22,500. Average numbers of estimated fatalities and patients are 110 and 330, respectively. Values of 95% and 5% for confidence levels are given in Table 4 for both applied seismic attenuation factors.

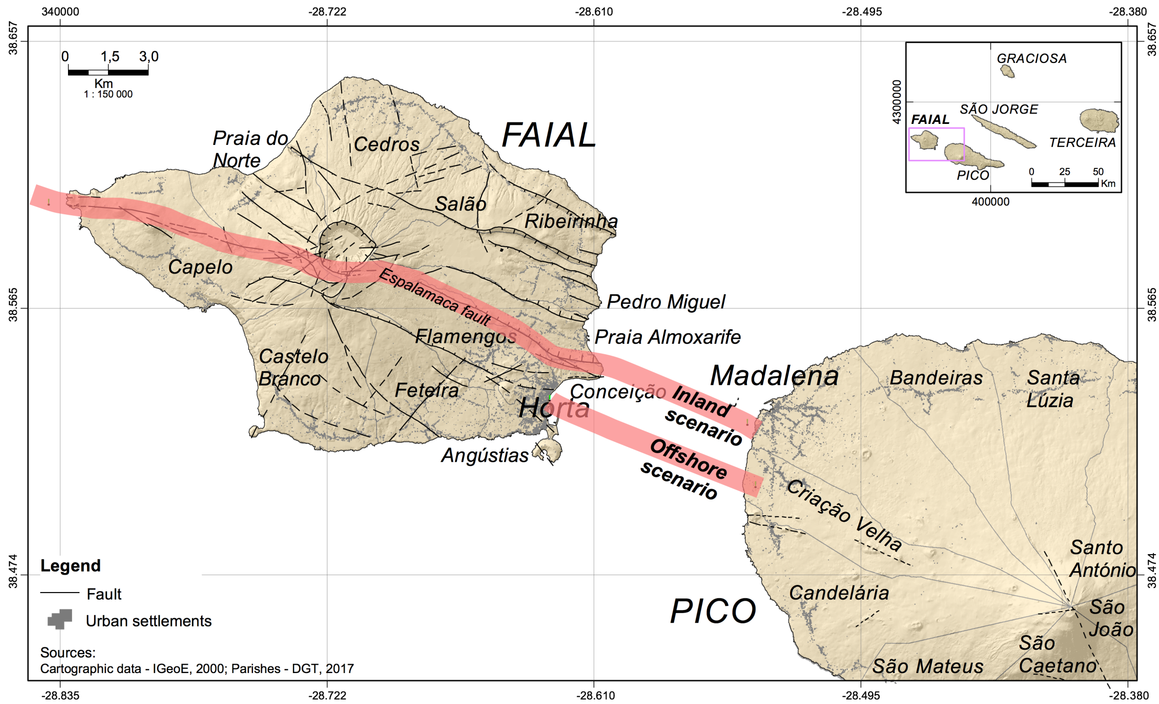

Figure 4. Location of faults selected (thick red lines) for earthquake scenarios.

The M6.9 inland Faial scenario strongly affects most of the settlements of the island, Flamengos being the village where highest damage is expected, because the calculated intensities are higher than XI due to site amplification. The population affected by intensity VI and higher is estimated to be on average 25,600, which is the total population of Faial and the western part of Pico Island. Average estimated fatalities and patients are 640 and 1,750, respectively. The influence of the seismic wave attenuation is reduced in this case because the distances to affected settlements are low. Compared to nighttime scenarios, similar scenarios calculated for a daytime occupancy rate of 50% reduce by two the numbers of casualties, on average.

Figure 5 shows, for each settlement of Faial, the percentage of building damage divided into six degrees from D0 (no damage) to D5 (very important with collapse) for the worst case scenario of the M6.9 earthquake with low attenuation (C2=5.7). In general, the settlements affected by the 1998 earthquake will show a strong resilience because houses have been rebuilt. Flamengos is calculated to be the most damaged village because of its proximity to the epicenter. In other cases, houses located near or over-identified faults were built in areas considered safe. The un-damaged buildings in Horta city, Capelo and Praia do Norte, Pedro Miguel after the 1998 earthquake could be suspected to be less resistant during the next strong ground motion. On average, around 50% of the building stock will be heavily damaged or collapse in an event of such magnitude.

Table 4. Parameters and scenario results for the two scenarios proposed in Faial Island. Values are given for the nighttime case when 90% of the population is inside. C2 refers to the constant in equation (1). Z is the depth. L is the length of the fault. M is the magnitude. X1, Y1 and X2, Y2 are the coordinates of the fault ends. Imax is the maximum calculated MMI.

Scenario	C2	Z (km)	L (km)	M	X1 Y1 (deg)	X2 Y2 (deg)	Imaxcalc	Fatalities			Patients		
								mean	min	max	mean	min	max
Offshore	5.2	5	8	6	-28.625 38.537	-28.536 38.509	IX	70	50	90	215	160	280
	5.7						X	155	125	190	445	355	545
Inland	5.2	5	27.5	6.9	-28.842 38.600	-28.540 38.530	XI	650	580	715	1770	1585	1945
	5.7						XII	635	570	700	1720	1530	1900

5. Discussions and conclusions

A procedure has been applied to update and validate the QLARM software tool and database in the region of the Azores, Portugal. The global intensity relationship from Shebalin (1985) can reproduce the intensity field better than other regional GPMEs and PGA-intensity conversion relations for the 1980 and 1998 Azores earthquakes. The

Shebalin relation is used routinely for the alert service since 2003 (Wyss, 2014) and generally well validated using past earthquakes in other regions of the world. In this particular case, the average residual between observed and calculated intensities for a large range of distance is less than 0.2 intensity units.

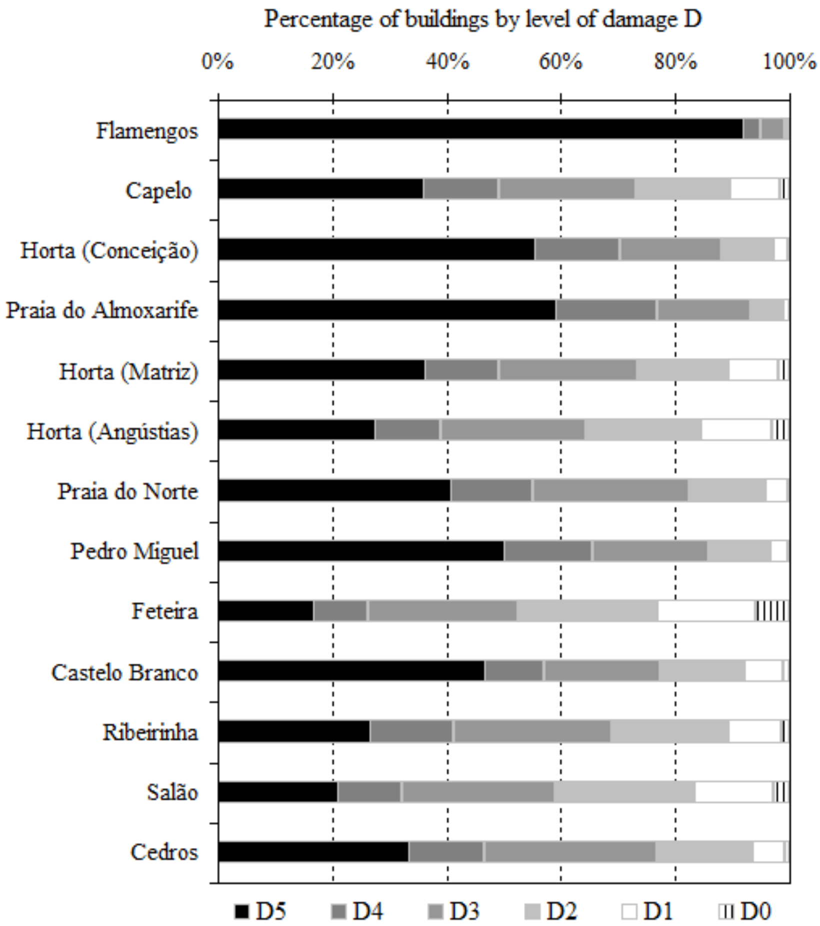

Figure 5. Building damage for the M6.9 scenario with C2=5.7. Settlements are ordered by increasing epicentral distance. Damage is divided into 5 degrees; D0: no damage, D1, slight; D2, moderate; D3, important; D4, very important without collapse; D5, very important with collapse.

Soil conditions revealed to play a major role in the level of ground shaking in the Azores (Santos et al., 2011; Lopes et al., 2013; Veludo et al., 2013; Teves-Costa and Veludo, 2013; Teves-Costa et al., 2008). The existing soil classification mapping is limited to the

Central group of the islands (Terceira, Graciosa, S. Jorge, Pico, and Faial) and overestimates shear wave velocity for all site classes. In settlements where observations from past earthquakes attested to site amplification, the observed incremental value has been added to intensity calculations.

The 2001 and 2011 Census data have been used to document settlement population and has been extrapolated to 2016. Information related to houses in the census have been interpreted to characterize the Faial Island building stock regarding EMS-98 vulnerability classes for each settlement as shown in Table 2. On average, the building stock is composed of 8% of class A; 47% of class B; 30% of class C and 14% of class D. The distribution of the population into these classes is further deduced from the census.

Two scenarios for likely earthquakes are proposed based on past earthquake activity and recent studies of active tectonics. The scenario of M6.9 is located inland on Faial, and the other scenario is assumed to be located offshore with M6. The average return period is approximately 1,300 years for the first scenario and unknow for the second one.

The inland scenario is the worst case proposed for Faial, yielding a range of fatalities between 580 and 710 and approximately three times more injuries. It represents 3% and 5% of the total population of the island, respectively. The percentage of population affected by the earthquake due to building damage is almost the total population of the island; 35% of the buildings are estimated to be highly damaged or collapsed. For the offshore earthquake, the human losses are six times lower than for the onshore scenario, but the affected population by damage to houses remains high: around 24,000.

For the first time, QLARM is tested in the context of small volcanic islands with large heterogeneities in the geological processes, inducing specific soil condition and attenuation behavior. This work shows that QLARM gives satisfactory results to estimate human losses despite the limited knowledge of the shallow structure of the islands. Human loss scenarios of future earthquakes is a valuable tool to mitigate the effects caused by such events and prepare emergency plans based on realistic scenarios. The seasonal variation of the population due to touristic activities is an issue that should be further investigated since the number of visitors is estimated at around 1.5 million each year.

6. Data and resources

Data from census are provided by the Instituto Nacional de Estatística available online at www.ine.pt (last accessed October 2017) and intensities were extracted from the Catalágo Sísmico da Região Açores (CSRA) (Nunes et al., 2004) and Electronic Supplement of Fontiela et al. (2017) available online at https://doi.org/10.1785/0220160159

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6

Conclusions and outlook

6.1. Conclusions

In this study, I published four papers (Fontiela et al., 2014, Fontiela et al., 2017, Caldeira et al., 2017, Fontiela et al., 2018) and submitted another one (Fontiela et al., submitted) that contribute to improving the seismic hazard knowledge of the Azores region. This contribution is divided into different four groups: i) analysis the seismicity in the Azores, ii) the establishment of a seismogenic zone model to the Azores region, iii) identification of the settlements that in the past had maximum strong ground motion, and lastly, iv) human losses in likely future earthquakes. The last two groups are a novelty since this is the first time they are applied in the Azores.

The seismicity in the Azores shows a sharp contrast between the central region and the eastern region (Fontiela et al., 2018). Notice that these seismotectonic regions are much vaster than the typical ones which comprise the Central and Eastern groups of islands. The Central region includes the area between the eastern end of Terceira Island up to the Middle Atlantic Ridge while the eastern region extends from east Terceira up to the transitions of the Gloria fault. The contrast is observable through b-values of the frequency magnitude relation (chapter 2 of the present study), focal mechanisms (Borges et al. 2007) and total seismic moment tensor (Bezzeghoud et al. 2014). The Central region has high b-values as depicted by the low MC relative to the ones of the MAR. The b-values ≥ 1 could be related to the presence of buoyant mantle upwelling slightly south of Terceira rift (Adam et al., 2013), and with lower stress (Scholz, 1968) that can be described as a state of high heterogeneity. The complexity of the seismicity in the eastern region arises from the cohabitation of different stress regimes from the main tectonic structures of the Archipelago and by active volcanism. The complex seismicity in the central part of São Miguel which comprises the Fogo, Congro and Furnas volcanoes is in part due to the accommodation of the relative displacement of Eurasian - Nubian plates (Jónsson et al., 1999; Okada et al. 2015) which also host episodes of inflation-deflation caused by hydrothermal sources and magmatic intrusion (Okada et al. 2015). The analysis based on a grid of 2º x 2º likely only distinguishes the frequency magnitude distribution of the boundary of Eurasia-Nubia plates. The b-values obtained to the southeast of São Miguel agrees with Hübscher et al. (2016) that states that this broad area is magmatically extinct. Concerning the transition of Terceira Rift to Gloria fault, this is marked by a broad shear zone of oblique extensional deformation (Hipólito et al., 2013) which fits with low b-values obtained in the area. The results obtained with our approach are good at a large scale but do not enclose enough detail to analyse the seismicity at a local scale.

The use of seismogenic zones is a valid alternative to identify areas with similar characteristics (Fontiela et al., 2014). In the Azores there exists a large number of seismogenic sources in the bottom ocean, and likely there are much more tectonic structures that remain hidden and which are accumulating strain up to the next earthquake. The absence of an earthquake catalogue of focal mechanisms of M > 3 makes it almost impossible to detail and distinguish seismogenic sources in the bottom ocean except for earthquakes of M > 5. Considering the limitation of focal mechanisms, we applied the b-values of the frequency magnitude distribution to distinguish seismogenic zones. With the methodology proposed I identify ten zones around the islands plus the Middle Atlantic Ridge (Fontiela et al., 2014).

Maximum observed intensity maps were done for the first time in the Azores (Fontiela et al., 2017). With MOI maps we assess past maximum shaking of the largest earthquakes based on the macroseismic observations of past earthquakes. This study reveals that the Island of São Jorge is the one that experienced maximum ground shaking in the past with Imax XI, followed by São Miguel, Terceira and Faial Islands with Imax X, Graciosa had Imax IX, Pico Imax VIII, and Santa Maria Imax VII. Indeed, MOI maps are a helpful tool that provide a fast reading of maximum ground shaking, and facilitates the access of the regions under threat for likely earthquakes in the future (Fontiela et al., 2017).

For the first time, QLARM was calibrated to estimate human losses in a volcanic island, which is a novelty either to QLARM tool as well as to the Azores (Fontiela et al., submitted). Volcanic islands have the particularity of amplification of the ground motion caused by volcanic products ejected during the eruption (i.e., volcanic ash, tephra, vesicular lava flows) as well as by the piles of lava flows. We validate QLARM with two known earthquakes: the 1980 Terceira earthquake (Ms 7.2), and the 1998 Faial earthquake (Mw 6.2). After QLARM validation, we selected two scenarios. One scenario is in a tectonic structure that crosses all the Island of Faial with M6.9 and the second scenario is offshore in the channel in between Faial - Pico Islands with M 6.0. The worst scenario is the one inland that can yield a minimum of 570 deaths and maximum 715 deaths, and the patients vary between 1530 and 1945. The event affects both Faial and Pico Islands strongly. In the second scenery number of deaths varies between 50 minimum and 190 maximum; the patients vary between 160 minimum and 545 maximum

(Fontiela et al., submitted).

This thesis, therefore, reveals a comprehensive study of the seismicity and seismic hazard assessment. It starts with the analysis of the different seismic patterns observed in the Azores, then based on this knowledge, we identify and characterize seismogenic sources responsible by most of the seismicity in the Archipelago. With the seismicity from the historical and instrumental period we assessed the regions that in the past were under strong ground shaking, and we did the transition from the seismic hazard to the seismic risk estimating human losses in future earthquakes.

6.2. Outlook

Results of this thesis improved the knowledge of the seismicity in the Azores which contribute to assessing seismic hazard but as well as the seismic risk. Nevertheless, several questions raised during this thesis must be further investigated or even evaluated due to the complexity of the geodynamic setting of the regions. Some of these questions for future or ongoing work are outlined below.

Considering the complexity of the seismicity along the Azores region (Fontiela et al., 2018), the earthquake catalogue of the last 20 years should be re-evaluated since the previous study concerns only 12 years. It is important to observe the evolution of seismicity in space-time to identify changes in the seismicity pattern and in which way these changes are related with significant earthquakes that happen around the Azores

Seismogenic zones of the Azores needs further investigation as the focal mechanism of earthquakes with minimal magnitude 3 or 4 are available in quantity enough to perform a re-analysis of the model proposed in this thesis (Fontiela et al., 2014).

The site effects play a crucial role in assessing seismic hazard in the Azores. The work which started evaluating site effects in Praia da Vitória (Terceira Island) (Fontiela et al. 2016) using HVSR must move forward and complement with MASW or other geophysical techniques to characterize shallow structure.

In this thesis, we opted to use MOI maps as a deterministic approach in assessing seismic hazard (Fontiela et al., 2017). Nevertheless, we should analyse the seismic hazard using probabilistic methods as in the work started by Fontiela et al. (2017a).

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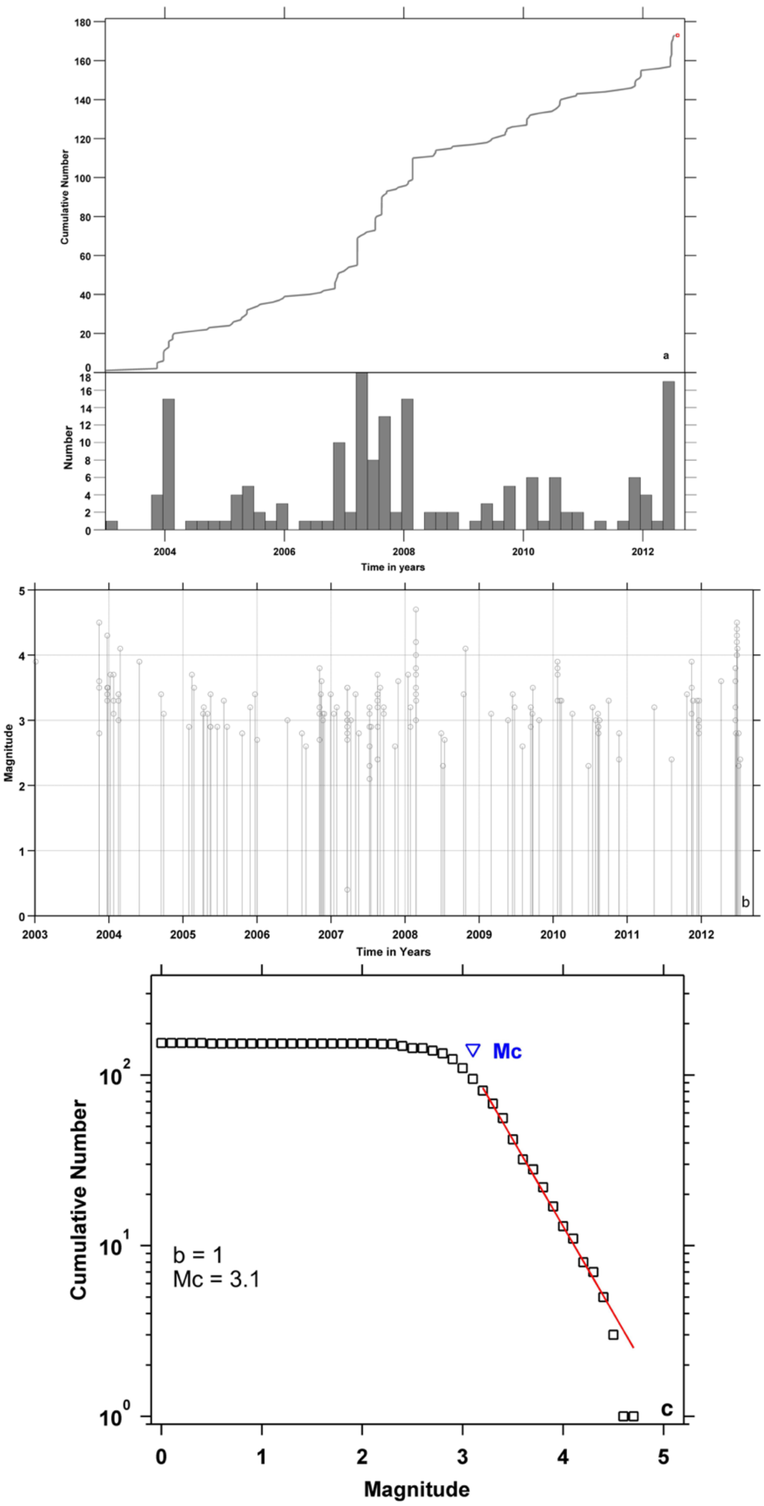
Annex I

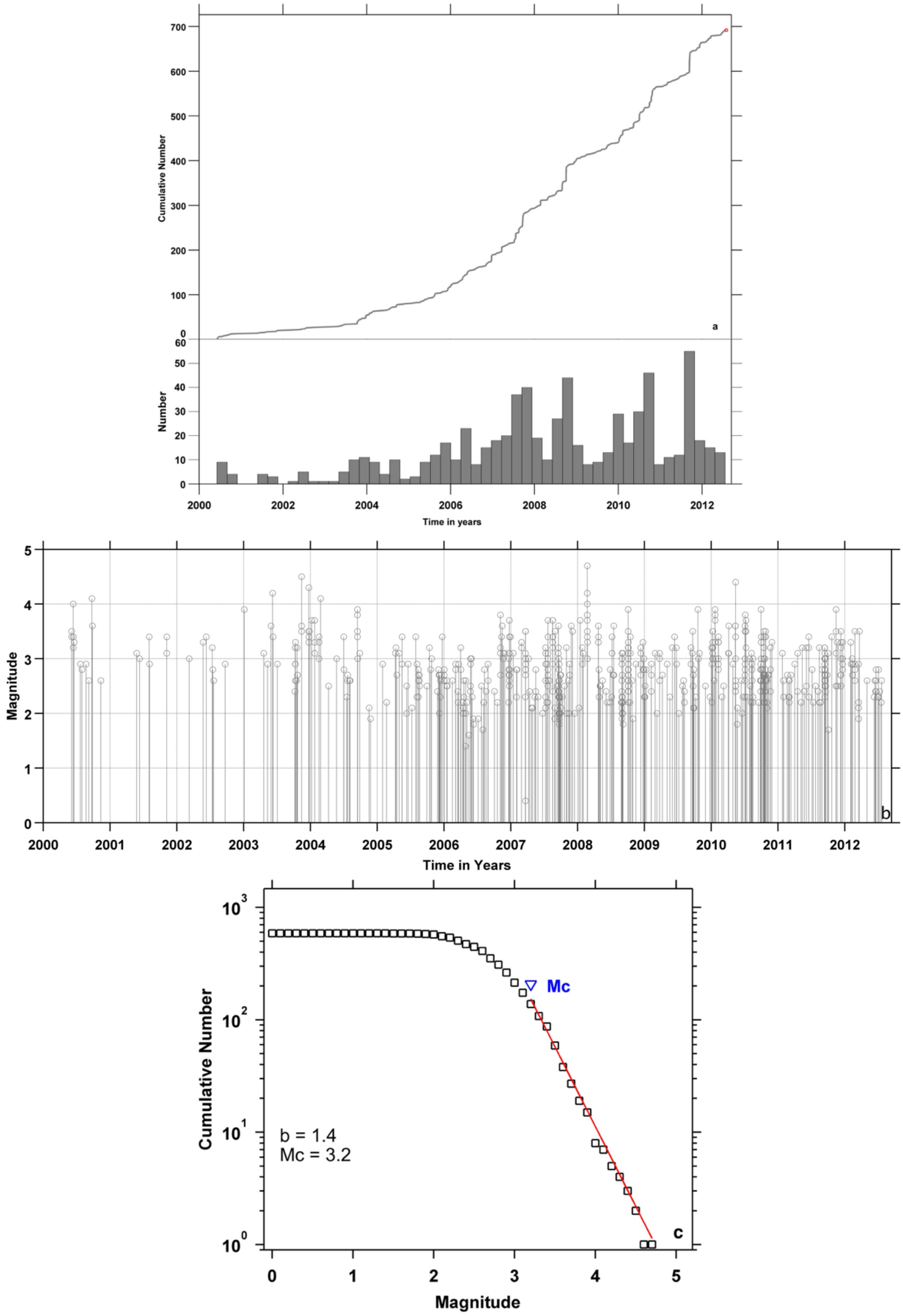
Electronic Supplement of *Characterisation of Seismicity of the Azores Archipelago: An Overview of Historical Events and a Detailed Analysis for the period 2000 - 2012* (chapter 2)

Electronic Supplement S1



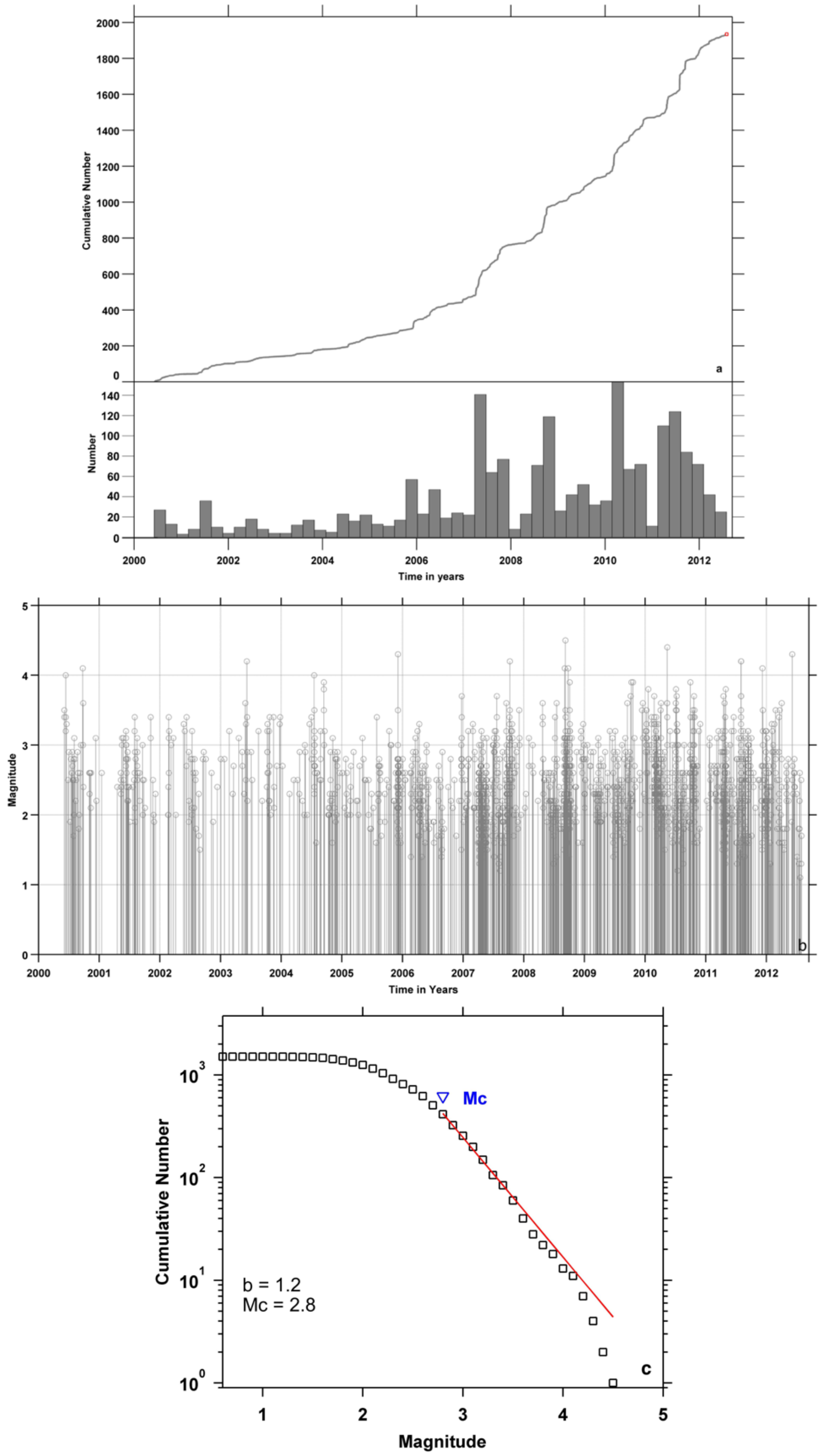
S1. Temporal distribution of earthquake in cell 1. (a) cumulative annual distribution. (b) Annual number of events. Before December 2003, no events were reported in this area of the Mid Atlantic ridge. (c) Frequency magnitude distribution. The error in magnitude completeness is ± 0.2 and b-value ± 0.2. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle). For this cell, data are from 2003 to July 2012.

Electronic Supplement S2



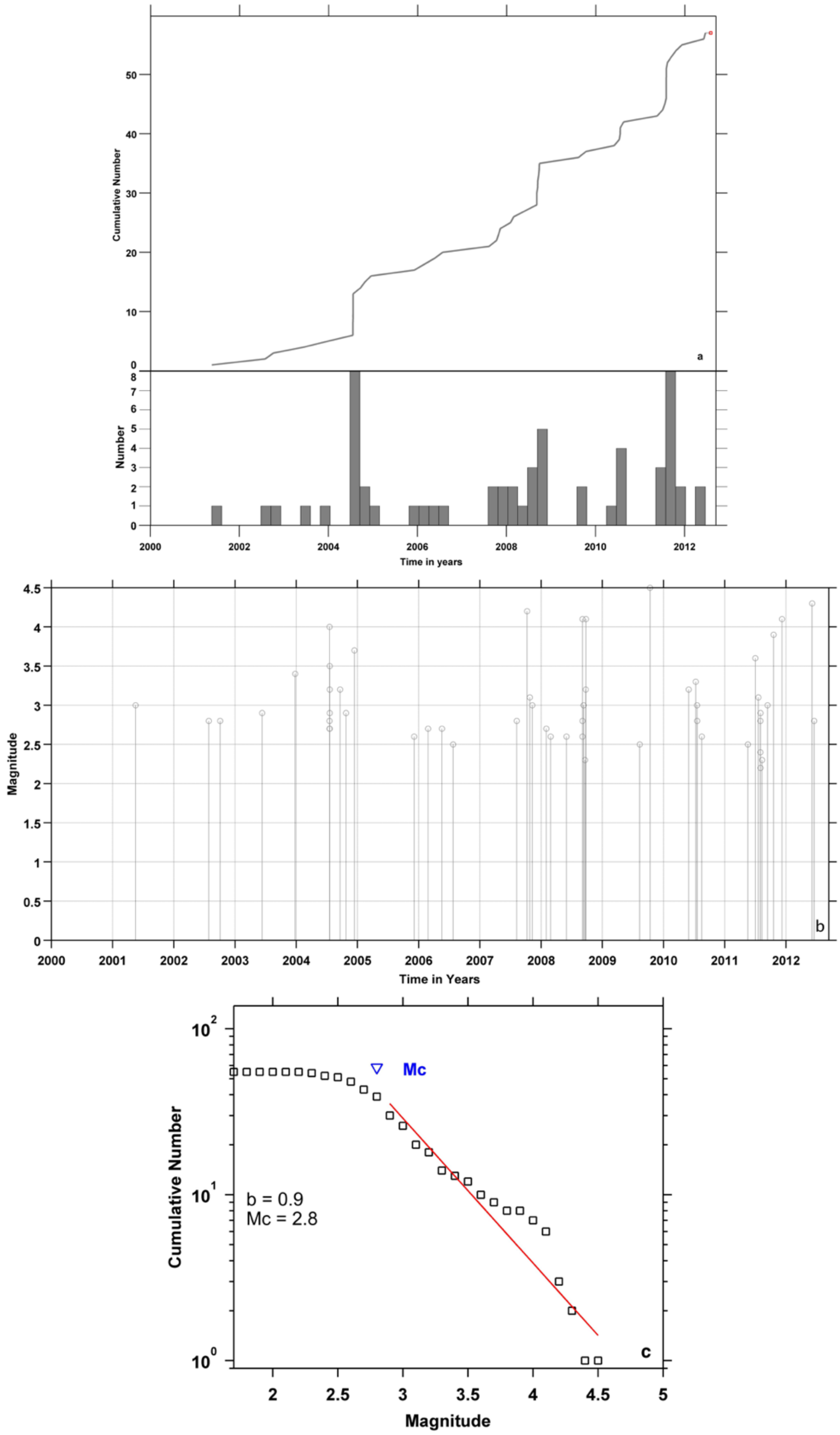
S2. Temporal distribution of earthquake in cell 2. (a) cumulative annual distribution. (b) Annual number of events. The lack of seismicity for the first semester 2000 is due to the shift on reported magnitude. In December 2010, data are not available. (c) Frequency magnitude distribution. The error in magnitude completeness is ± 0.3 and b-value ± 0.2. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle).

Electronic Supplement S3



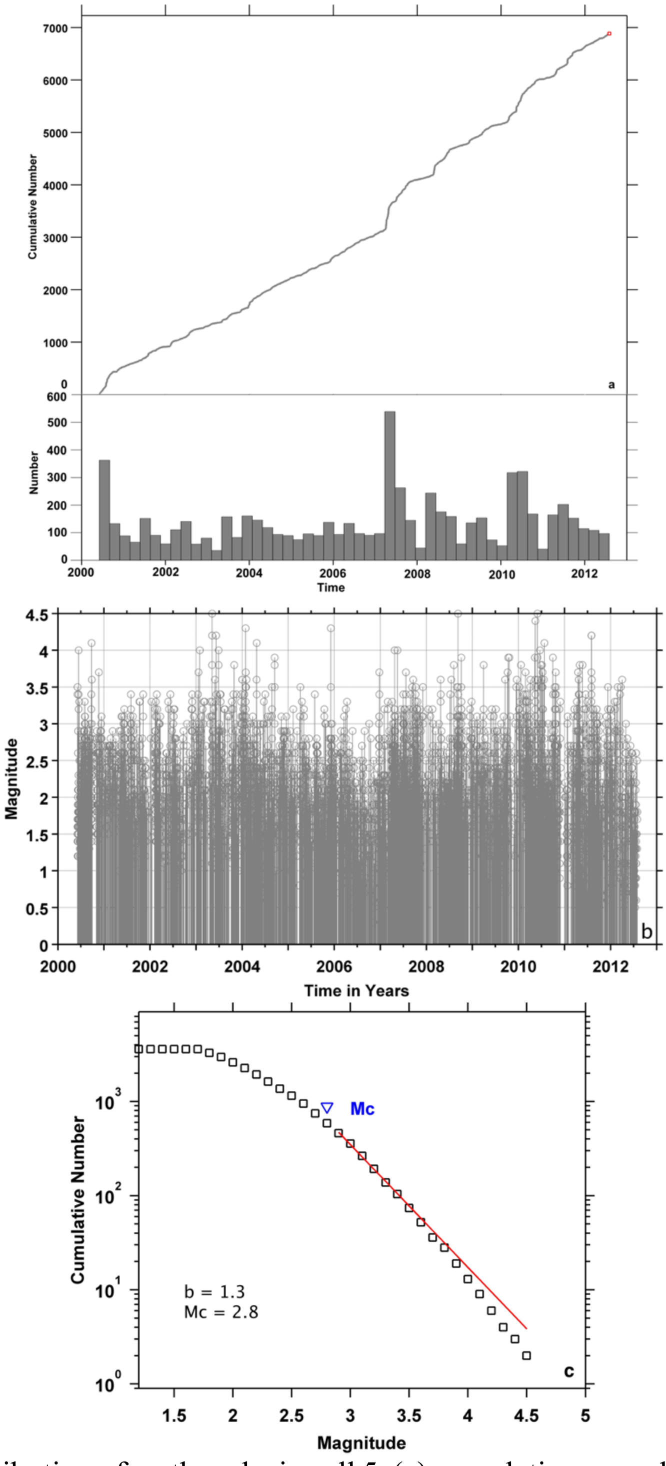
S3. Temporal distribution of earthquake in cell 3. (a) cumulative annual distribution. (b) Annual number of events. The lack of seismicity for the first semester 2000 is due to the shift on reported magnitude. In December 2010, data are not available. (c) Frequency magnitude distribution. The error in magnitude completeness and b-value is ± 0.2. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle).

Electronic Supplement S4



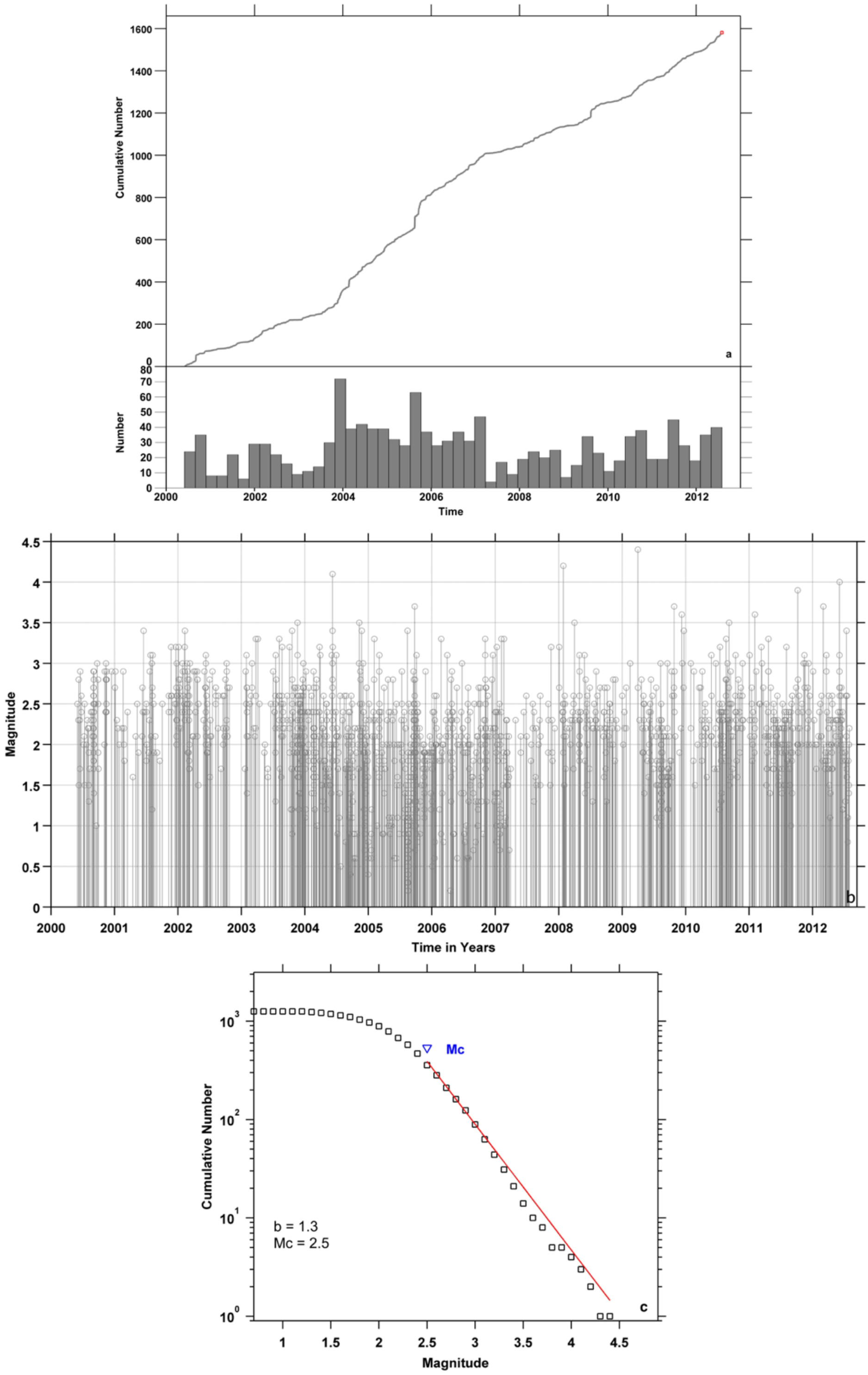
S4. Temporal distribution of earthquake in cell 4. (a) cumulative annual distribution. (b) Annual number of events. The lack of seismicity for the first semester 2000 is due to the shift on reported magnitude. In December 2010, data are not available. (c) Frequency magnitude distribution. The error in magnitude completeness is ± 0.2 and b-value ± 0.3. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle).

Electronic Supplement S5



S5. Temporal distribution of earthquake in cell 5. (a) cumulative annual distribution. (b) Annual number of events. The lack of seismicity for the first semester 2000 is due to the shift on reported magnitude. In December 2010, data are not available. (c) Frequency magnitude distribution. The error in magnitude completeness is ± 0.2 and b-value ± 0.2. The error in magnitude completeness is ± 0.2 and b-value ± 0.3. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle).

Electronic Supplement S6



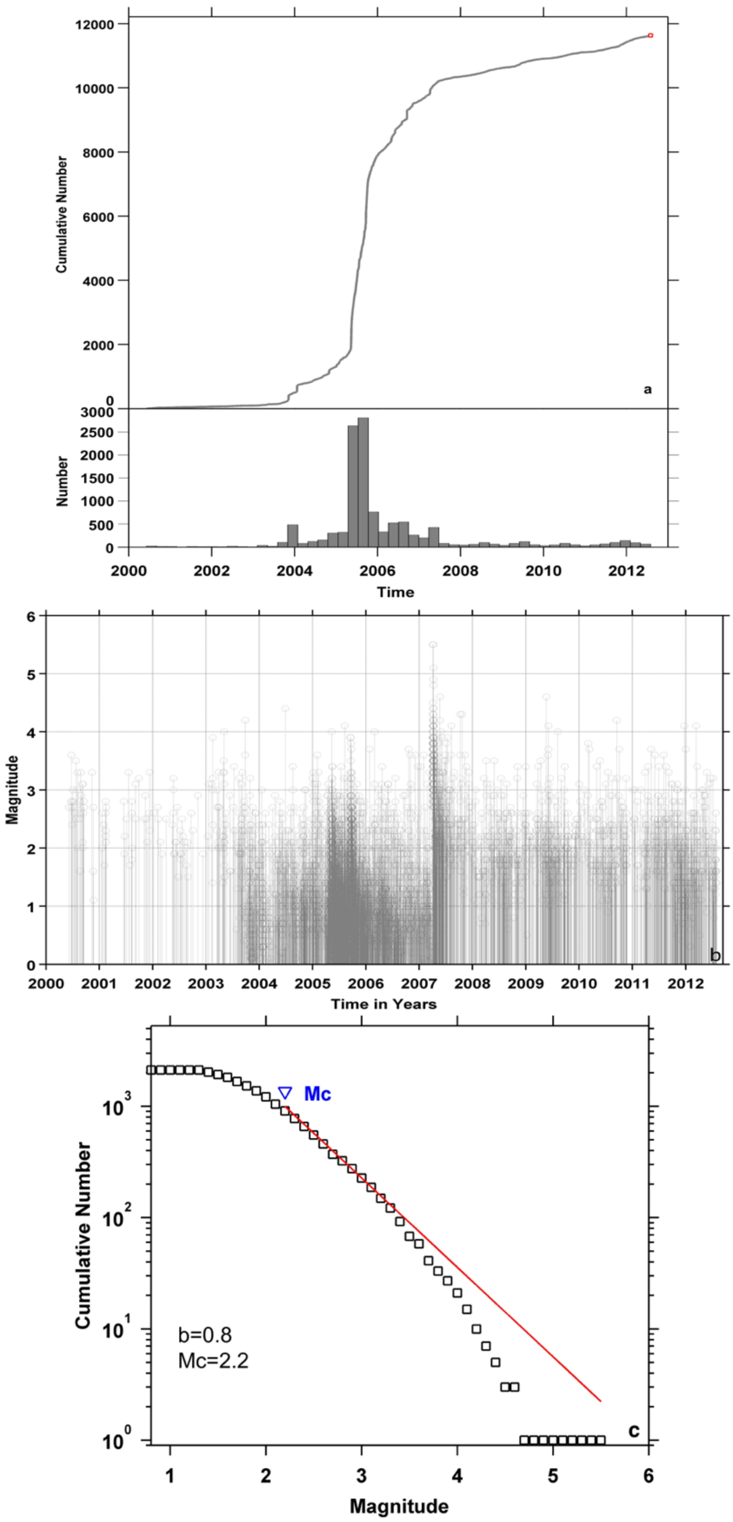
S6. Temporal distribution of earthquake in cell 7. (a) cumulative annual distribution. (b) Annual number of events. The lack of seismicity for the first semester 2000 is due to the shift on reported magnitude. In December 2010, data are not available. (c) Frequency magnitude distribution. The error in magnitude completeness is ± 0.2 and b-value ± 0.2. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle).

Electronic Supplement S7

Characteristics of the main earthquakes located in the Terceira Rift segment between Terceira and São Miguel Islands. Earthquakes marked with * are the ones recorded around D. João de Castro bank. (*ISC = International Seismological Centre; CSRA = Earthquake Catalog for the Azores Region; GCMT = Global Centroid Moment Tensor.*

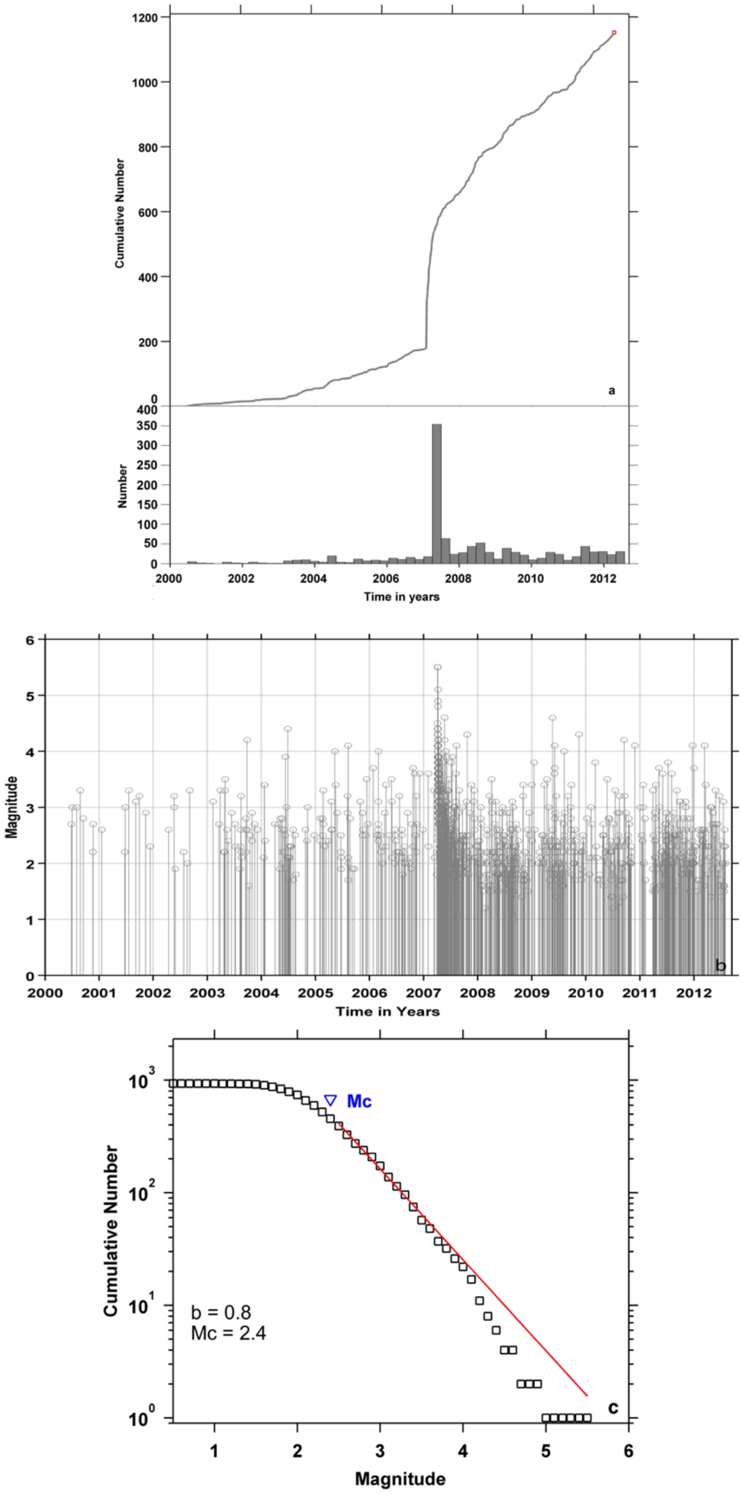
Date	Time	Latitude	Longitude	Magnitude	Source
5/4/1926	23:29:19	39.0000	-29.0000	6.0 (MS)	ISC
9/7/1926	15:05:34	38.0000	-30.0000	5.6 (MS)	ISC
31/8/1926	10:40:08	38.5000	-28.0000	5.6 (MS)	ISC
15/8/1933*	00:45:04	38.0000	-26.5000	5.6 (MS)	ISC
13/4/1950	11:51:19	38.3000	-26.5000	5.8	CSRA
10/11/1953	15:08:29	38.8875	-28.7585	5.2 (MS)	ISC
9/6/1960*	17:47:45	38.1135	-26.3490	5.2 (MS)	ISC
20/4/1968	10:18:00	38.3000	-26.7700	5.0 (mb)	ISC
11/12/1973	00:10:09	38.6059	-28.5519	5.0 (mb)	ISC
16/11/1978	22:02:34	39.8003	-29.7601	5.0 (mb)	ISC
1/1/1980	16:42:39	38.7510	-27.7495	6.8 (MS)	ISC
12/2/1981	01:50:05	38.4703	-26.7531	5.4 (mb)	ISC
22/7/1988	21:16:04	39.8747	-29.5851	5.0 (mb)	ISC
16/10/1988	06:15:30	37.4639	-25.3252	5.0 (mb)	ISC
21/11/1988*	16:55:53	37.9325	-26.1414	5.6 (mb)	ISC
21/1/1989	02:52:20	38.0921	-26.1764	5.3 (mb)	ISC
26/6/1989	10:38:40	39.0951	-28.2271	5.6 (mb)	ISC
23/9/1989	15:31:16	39.4799	-29.8390	5.1 (mb)	ISC
2/8/1990	06:38:38	39.9039	-29.6499	5.1 (MS)	ISC
23/6/1991	10:44:03	39.4627	-29.8232	5.1 (mb)	ISC
27/6/1997*	04:39:53	38.2482	-26.7073	5.8 (Mw)	CSEM
27/6/1997*	17:23:58	38.2200	-26.7600	5.2 (Mw)	GCMT
28/06/1997 *	13:32:03	38.3400	-26.8400	5.1 (Mw)	GCMT
9/7/1998	05:19:07	38.6144	-28.5708	5.6 (mb)	ISC
23/12/2003	14:02:03	39.6783	-29.6324	5.3 (mb)	ISC
8/12/2011	08:54:45	38.0646	-30.7819	5.0 (mb)	ISC

Electronic Supplement S8



S8. Temporal distribution of earthquake in cell 9. (a) cumulative annual distribution. (b) Annual number of events. The lack of seismicity for the first semester 2000 is due to the shift on reported magnitude. In December 2010, data are not available. (c) Frequency magnitude distribution. The estimated error in magnitude completeness is ± 0.5 and b-value ± 0.2. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle).

Electronic Supplement S9



S9. Temporal distribution of earthquake in cell 10. (a) cumulative annual distribution. (b) Annual number of events. The lack of seismicity for the first semester 2000 is due to the shift on reported magnitude. In December 2010, data are not available. (c) Frequency magnitude distribution. The estimated error in magnitude completeness is ± 0.4 and b value ± 0.1. The red line is the fitted power law beginning at the minimum magnitude completeness (triangle).

Annex II

Electronic Supplement of Maximum Observed Intensity Map for the Azores Archipelago (Portugal) from 1522 to 2012 Seismic Catalog (chapter 4)

Electronic Supplement to

Maximum Observed Intensity Map for the Azores Archipelago (Portugal) from 1522 to 2012 Seismic Catalog

by João Fontiela, Mourad Bezzeghoud, Philippe Rosset, and Francisco Cota Rodrigues

This electronic supplement contains the list of the earthquakes that were used to draw the maximum observed intensity map for the Azores archipelago.

Table

Table S1. Earthquake database used in the preparation of the maximum observed intensity (MOI) map for the Azores archipelago. The information was extracted from the earthquake catalog for the Azores region and from the Portugal Macroseismic Yearbook with Mercalli intensity greater than V and provides the date, time, and localization of the epicenters, the locality where the event was strongly felt, and the references (authors or agencies) that reported the event.

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Table S1. Earthquake Database Used in the Preparation of the Maximum Observed Intensity (MOI) Map for the Azores Archipelago

Date and Time (Local Time) (yyyy/mm/dd hh:mm)	Longitude (°W)	Latitude (°N)	Magnitude	Maximum Intensity	Locality Where Event Was Strongly Felt	Island	Source
1522/10/22 ~02:—	−25.4	37.4		X	Vila Franca do Campo Ponta Garça	São Miguel	Machado (1966), Silveira (2002)
1591/07/06 —:—	Unknown	Unknown		VIII/IX	Vila Franca do Campo	São Miguel	Nunes *et al.*(2001)
1614/05/24 15:15	−27.1	38.7		X	Praia da Vitória Lajes São Brás Vila Nova Fontinha	Terceira	Madeira (1998), Silva (2005)
1713/02/08 —:—	Unknown	Unknown		VIII	Ginetes	São Miguel	Nunes *et al.*(2001)
1730/06/13 —:—	Unknown	Unknown		VIII/IX	Caldeira	Graciosa	Nunes *et al.*(2001)
1757/07/09 —:—	−28.0	38.6		XI	Calheta Fajã dos Vimes Ribeira Seca Norte Pequeno Fajã de São João Fajã dos Cubres	São Jorge	Machado (1949)
1800/06/24 13:45	Unknown	Unknown		VII/VIII	Praia da Vitória	Terceira	Nunes *et al.*(2001)
1801/06/15 15:30	Unknown	Unknown		VIII	São Sebastião	Terceira	Nunes *et al.*(2001)
1837/01/21 —:—	Unknown	Unknown		IX	Guadalupe Santa Cruz	Graciosa	Nunes *et al.*(2001)

1841/06/15 —:—	−27.0	38.7		IX	Praia da Vitória	Terceira	Nunes *et al.*(2001)
1852/04/16 22:05	−25.6	37.9		VIII	Ribeira Grande	São Miguel	Nunes *et al.*(2001), Silveira (2002)
1881/02/09 —:—	Unknown	Unknown		VII	Povoação	São Miguel	Nunes *et al.*(2001)
1912/01/26 14:00	Unknown	Unknown		VII	Angra do Heroísmo	Terceira	Nunes *et al.*(2004)
1912/11/06 23:20	Unknown	Unknown		VII/VIII	Praia da Vitória	Terceira	Nunes *et al.*(2004)
1917/06/30 16:19	Unknown	Unknown		V/VI	Praia da Vitória	Terceira	Nunes *et al.*(2004)
1922/04/21 03:—	Unknown	Unknown		VII	Vila Franca do Campo	São Miguel	Nunes *et al.*(2004)
1924/10/24 10:53	Unknown	Unknown		IV/V	Angra do Heroísmo	Terceira	Nunes *et al.*(2004)
1925/11/14 22:35	Unknown	Unknown		VI	Angra do Heroísmo	Terceira	Nunes *et al.*(2004)
1926/04/05 23:29	Unknown	Unknown		VIII	Horta	Faial	Nunes *et al.*(2004)
					Farrobo		
					Lomba		
1926/08/31 10:40	−28.6	38.5	M_b 5.3	X	Horta	Faial	Nunes *et al.*(2004)
					Flamengos		
					Praia do Almoxarife		
1932/08/05 21:24	−25.083	37.750		VII	Povoação	São Miguel	Nunes *et al.*(2004)
					Faial da Terra		
					Água Retorta		
1933/08/15 00:45	−26.367	38.217	5.6	V	Ponta Delgada	São Miguel	Nunes *et al.*(2004)
					Praia da Vitória	Terceira	
					Fonte do Bastardo	Terceira	
1935/04/27 18:05	−25.350	37.683		VII	Lomba do Cavaleiro	São Miguel	Nunes *et al.*(2004)
					Povoação		
					Nordeste		
	−26.133	36.833		VII	São Pedro		

1937/11/21 20:30					Santo Espírito	Santa Maria	Nunes *et al.*(2004)
1939/05/08 01:47	−24.500	37.000		VII	Santo Espírito	Santa Maria	Nunes *et al.*(2004)
1942/10/14 20:26	Unknown	Unknown		VI	Capelinhos	Faial	Nunes *et al.*(2004)
1942/10/15 14:53	−29.500	38.000		VI	Capelinhos	Faial	Nunes *et al.*(2004)
1942/11/08 18:16	Unknown	Unknown		VI/VII	Bandeiras	Pico	Nunes *et al.*(2004)
1943/08/03 —:—	Unknown	Unknown		VI	Vila Franca do Campo	São Miguel	Nunes *et al.*(2004)
1943/08/05 15:23	Unknown	Unknown		VI	Água d'Alto Vila Franca do Campo Água de Pau Ponta Garça	São Miguel	Nunes *et al.*(2004)
1943/10/03 00:52	−26.500	38.300		V	Angra do Heroísmo	Terceira	Nunes *et al.*(2004)
1945/01/05 20:55	Unknown	Unknown		VI	Angra do Heroísmo	Terceira	Nunes *et al.*(2004)
1945/06/15 01:40	Unknown	Unknown		VII	Capelo	Faial	Nunes *et al.*(2004)
1945/10/25 14:30	Unknown	Unknown		VII	Agualva	Terceira	Nunes *et al.*(2004)
1946/05/12 13:20	−29.000	39.500		VII	Capelo	Faial	Nunes *et al.*(2004)
1946/12/27 18:30	Unknown	Unknown		VII/VIII	Serreta	Terceira	Nunes *et al.*(2004)
1947/01/30 10:30	Unknown	Unknown		V	Povoação	São Miguel	Nunes *et al.*(2004)
1947/06/10 19:40	−29.500	39.000	5.6	VI	Capelinhos Candelária	Faial Pico	Nunes *et al.*(2004)
1947/06/23 08:45	Unknown	Unknown		V	Horta	Faial	Nunes *et al.*(2004)
1947/12/11 23:20	Unknown	Unknown		V	Flamengos	Faial	Nunes *et al.*(2004)
1948/02/04 08:17	Unknown	Unknown		VI	Capelinhos	Faial	Nunes *et al.*(2004)
1949/01/30 01:50	−27.000	38.000		V	Ginetes Bretanha	São Miguel	Nunes *et al.*(2004)

1950/04/13 11:51	−26.500	38.300	5.8	V/VI	Porto Judeu	Terceira	Nunes *et al.*(2004)
1950/06/21 23:44	Unknown	Unknown		V	Pedro Miguel Flamengos	Faial	Nunes *et al.*(2004)
1950/11/27 02:50	Unknown	Unknown		VI	Castelo Branco Flamengos Capelinhos	Faial	Nunes *et al.*(2004)
1950/11/27 04:41	Unknown	Unknown		V	Capelinhos	Faial	Nunes *et al.*(2004)
1950/12/29 16:03	−27.200	38.750	4.0	VII	Agualva	Terceira	Nunes *et al.*(2004)
1951/01/12 11:38	−27.230	38.650		VI/VII	Angra do Heroísmo	Terceira	Nunes *et al.*(2004)
1951/03/15 15:57	Unknown	Unknown		V	Cinco Ribeiras	Terceira	Nunes *et al.*(2004)
1951/06/13 00:45	−25.300	37.730		V	Furnas	São Miguel	Nunes *et al.*(2004)
1952/03/02 04:16	−26.330	38.170		VI	Ginetes Mosteiros Candelária Várzea Sete Cidades Capelas Santo António Santa Bárbara (Ponta Delgada)	São Miguel	Nunes *et al.*(2004)
1952/06/26 13:06	−25.300	37.700		VII	Povoação Ribeira Quente Ponta Garça Vila Franca do Campo Água de Pau	São Miguel	Nunes *et al.*(2004)
1952/06/26 15:32	−25.280	37.700		VIII	Ribeira Quente	São Miguel	Nunes *et al.*(2004)

1952/09/01 02:19	Unknown	Unknown		V	Povoação Vila Franca do Campo	São Miguel	Nunes *et al.*(2004)
1953/02/22 21:58	−25.800	36.400	5.9	V	São Pedro Azenha Santo António Almas Santo Espírito Terras do Raposo Calheta	Santa Maria	Nunes *et al.*(2004)
1953/09/05 10:22	−28.400	39.100		IV/V	Santa Cruz	Graciosa	Nunes *et al.*(2004)
1953/09/06 07:59	Unknown	Unknown		IV/V	Praia da Vitória Cabo da Praia Fonte do Bastardo São Sebastião Santa Luzia Lajes	Terceira	Nunes *et al.*(2004)
1953/10/09 03:57	−28.900	38.900		V/VI	Capelinhos	Faial	Nunes *et al.*(2004)
1953/11/02 02:55	−28.800	38.800		V	Capelinhos	Faial	Nunes *et al.*(2004)
1953/11/10 15:08	−28.900	38.900		V	Horta	Faial	Nunes *et al.*(2004)
1953/11/19 07:41	Unknown	Unknown		V/VI	Água de Pau Vila Franca do Campo	São Miguel	Nunes *et al.*(2004)
1954/01/23 00:03	−25.480	37.730		VI/VII	Água de Pau	São Miguel	Nunes *et al.*(2004)
1954/12/26 00:26	−28.700	38.900		V/VI	Cedros Praia do Norte	Faial Faial	Nunes *et al.*(2004)
1956/03/28 20:02	−27.470	38.800	3.8	V	Serreta	Terceira	Nunes *et al.*(2004)

1956/04/15 05:10	28.600	38.600	3.8	IV/V	Praia do Almoxarife	Faial	Nunes *et al.*(2004)
1956/08/11 05:46	Unknown	Unknow n		VI	Serreta	Terceir a	Nunes *et al.*(2004)
					Cinco Ribeiras		
1956/12/02 23:20	Unknown	Unknow n		IV/V	Ginetes	São Miguel	Nunes *et al.*(2004)
1957/09/16 10:11	−28.600	38.500	3.6	V	Horta	Faial	Nunes *et al.*(2004)
1957/09/28 06:15	Unknown	Unknow n		IV/V	Capelinhos	Faial	Nunes *et al.*(2004)
1958/05/08 17:23	Unknown	Unknow n		IV/V	Ribeira Quente	São Miguel	Nunes *et al.*(2004)
					Povoação		
1958/05/13 02:23	−28.750	38.600		VIII/IX	Praia do Norte	Faial	Nunes *et al.*(2004)
					Ribeira Funda		
1958/05/14 02:34	−28.720	38.580	4.4	VI/VII	Canto	Faial	Nunes *et al.*(2004)
1959/01/24 19:55	−24.724	37.917		VI	Ribeira Quente	São Miguel	Nunes *et al.*(2004)
1959/09/01 01:48	Unknown	Unknow n		IV/V	Ginetes	São Miguel	Nunes *et al.*(2004)
1959/12/31 20:53	Unknown	Unknow n		VI	Água Retorta	São Miguel	Nunes *et al.*(2004)
					Ribeira Quente		
					Povoação		
					Faial da Terra		
1960/06/09 17:47	−26.541	37.914	5.9	IV/V	Mosteiros	São Miguel	Nunes *et al.*(2004)
1961/02/27 22:38	−27.130	38.770	4.4	VI	Cavouco dos Ventos	Terceir a	Nunes *et al.*(2004)
1961/09/16 11:00	Unknown	Unknow n		V/VI	Povoação	São Miguel	Nunes *et al.*(2004)
1962/07/12 06:23	−25.570	37.780	4.1	V/VI	Ribeira Seca (Ribeira Grande)	São Miguel	Nunes *et al.*(2004)
					Santa Bárbara (Ribeira Grande)		
					Cabouco		

					Livramento		
1963/08/21 08:05	−28.697	38.889		V/VI	São Roque	Pico	Nunes *et al.*(2004)
1964/02/15 16:00	Unknown	Unknown		VI	Urzelina Manadas Norte Grande Norte Pequeno	São Jorge	Nunes *et al.*(2004)
1964/02/15 18:15	Unknown	Unknown		VI	Urzelina Manadas	São Jorge	Nunes *et al.*(2004)
1964/02/15 20:00	Unknown	Unknown		VI	Urzelina Manadas Norte Grande	São Jorge	Nunes *et al.*(2004)
1964/02/15 21:10	Unknown	Unknown		VI	Urzelina Manadas	São Jorge	Nunes *et al.*(2004)
1964/02/15 22:05	Unknown	Unknown		VI	Urzelina Manadas	São Jorge	Nunes *et al.*(2004)
1964/02/16 00:41	Unknown	Unknown		VI	Urzelina Manadas Norte Grande	São Jorge	Nunes *et al.*(2004)
1964/02/16 01:27	Unknown	Unknown		VI	Urzelina Manadas Norte Grande	São Jorge	Nunes *et al.*(2004)
1964/02/17 12:25	Unknown	Unknown		VI	Manadas Norte Grande	São Jorge	Nunes *et al.*(2004)
1964/02/18 08:01	−28.275	38.650	4.6	VI	Rosais	São Jorge	Nunes *et al.*(2004)
1964/02/18 12:19	−28.400	38.800	4.6	VII	Rosais	São Jorge	Nunes *et al.*(2004)
1964/02/19 00:34	−28.250	38.594	4.5	VII	Rosais	São Jorge	Nunes *et al.*(2004)
1964/02/19 06:33	−28.214	38.519	4.5	VI/VII	Rosais	São Jorge	Nunes *et al.*(2004)
1964/02/20 21:54	Unknown	Unknown		VI	Velas	São Jorge	Nunes *et al.*(2004)

1964/02/21 17:14	−28.2	38.7		VIII	Rosais	São Jorge	Nunes *et al.*(2004)
1964/03/18 11:17	−27.291	38.640	4.4	V/VI	São Bartolomeu	Terceira	Nunes *et al.*(2004)
1964/04/30 21:43	Unknown	Unknown		IV/V	Rosais Velas	São Jorge	Nunes *et al.*(2004)
1965/06/01 15:18	−26.434	37.866	4.9	V/VI	Mosteiros	São Miguel	Nunes *et al.*(2004)
1966/04/29 10:56	Unknown	Unknown		IV/V	São Caetano	Pico	Nunes *et al.*(2004)
1966/07/04 12:15	−24.800	37.500	5.5	V	Água Retorta Faial da Terra Povoação Ribeira Quente	São Miguel	Nunes *et al.*(2004)
1967/03/31 06:43	−28.515	38.495	4.4	VI	Salão Ribeirinha	Faial	Nunes *et al.*(2004)
1967/07/30 11:20	Unknown	Unknown		IV/V	Povoação	São Miguel	Nunes *et al.*(2004)
1967/08/10 03:58	−25.300	37.800	3.9	VI	Monte Escuro	São Miguel	Nunes *et al.*(2004)
1967/08/10 04:05	−25.300	37.800	3.9	VI	Monte Escuro	São Miguel	Nunes *et al.*(2004)
1967/08/10 04:08	−25.300	37.800	4.6	VI/VII	Monte Escuro	São Miguel	Nunes *et al.*(2004)
1967/08/10 04:17	−25.300	37.800	3.9	VI	Monte Escuro	São Miguel	Nunes *et al.*(2004)
1967/08/10 04:44	−25.300	37.800	4.6	VI/VII	Monte Escuro	São Miguel	Nunes *et al.*(2004)
1967/08/10 05:26	−25.4	37.8	4.6	VII	Monte Escuro	São Miguel	Nunes *et al.*(2004)
1967/08/10 07:00	−25.300	37.800	4.6	VI/VII	Monte Escuro	São Miguel	Nunes *et al.*(2004)
1967/08/24 05:43	−24.400	37.900	4.5	IV/V	Água Retorta Ribeira Quente	São Miguel	Nunes *et al.*(2004)
1968/04/20 10:17	−26.550	38.484	5.1	IV/V	Biscoitos	Terceira	Nunes *et al.*(2004)
1968/06/17 17:21	−25.9	37.7	4.6	VII	Várzea	São Miguel	Nunes *et al.*(2004)

1968/10/14 16:34	Unknown	Unknown		IV/V	Várzea Ginetes Candelária	São Miguel	Nunes *et al.*(2004)
1968/11/15 18:03	−25.100	37.500	4.1	IV/V	Água Retorta Ribeira Quente	São Miguel	Nunes *et al.*(2004)
1968/12/20 00:56	−25.000	37.700	4.3	V/VI	Água Retorta	São Miguel	Nunes *et al.*(2004)
1969/03/31 01:24	−27.400	38.800	3.7	IV/V	Serreta	Terceira	Nunes *et al.*(2004)
1969/06/25 10:43	−25.000	37.700		IV/V	Água Retorta Ribeira Quente	São Miguel	Nunes *et al.*(2004)
1970/01/31 23:02	−27.020	38.740		V	Praia da Vitória	Terceira	Nunes *et al.*(2004)
1970/04/15 06:10	−27.300	38.730		V	Serra de Santa Bárbara	Terceira	Nunes *et al.*(2004)
1973/08/07 17:54	−27.461	38.773	3.3	V/VI	Serreta	Terceira	Nunes *et al.*(2004)
1973/09/15 03:12	Unknown	Unknown		IV/V	Ribeira Quente	São Miguel	Nunes *et al.*(2004)
1973/11/01 13:12	−28.435	38.611	4.2	IV/V	Terra do Pão São Mateus Santa Luzia Santa Ana	Pico	Nunes *et al.*(2004)
1973/11/23 13:36	−28.4	38.5	M_b 5.0	VII/VIII	Santo António Bandeiras	Pico	Nunes *et al.*(2004)
1973/12/11 00:10	−28.423	38.500	M_b 5.0	VI	São Roque Santo António Santa Luzia São Miguel Arcanjo	Pico	Nunes *et al.*(2004)
1977/05/14 21:13	−25.589	37.817		VI/VII	Casal da Lagoa do Fogo	São Miguel	Nunes *et al.*(2004)

1980/01/01 16:42	−27.605	38.590	7.2	VIII/IX	Doze Ribeiras	Terceira	Nunes *et al.*(2004)
1981/02/12 01:50	−26.697	38.479	5.4	V/VI	São Brás	Terceira	Nunes *et al.*(2004)
1981/04/09 12:50	−27.627	38.912	4.1	V	Topo	São Jorge	Nunes *et al.*(2004)
1983/01/17 14:35	−26.347	38.038	4.2	IV/V	Mosteiros	São Miguel	Nunes *et al.*(2004)
1983/02/01 04:13	−24.640	37.669	4.5	IV/V	Água Retorta	São Miguel	Nunes *et al.*(2004)
1983/02/15 20:57	−25.061	37.690	3.8	IV/V	Água Retorta	São Miguel	Nunes *et al.*(2004)
1984/07/16 23:29	−27.370	38.777	3.3	IV/V	Serreta	Terceira	Nunes *et al.*(2004)
1984/09/09 13:06	−24.561	36.874	5.3	VI	Praia	Santa Maria	Nunes *et al.*(2004)
					Malbusto		
					Castelhana		
					Glória		
					Fonte do Jordão		
					Terras do Raposo		
					Calheta		
					Maia		
					Santo Espírito		
					Almas		
1985/05/30 00:11	−25.093	37.740		IV/V	Furnas	São Miguel	Nunes *et al.*(2004)
					Povoação		
					Ribeira Quente		
1985/06/20 07:25	−29.065	38.848	3.7	V	Praia do Norte	Faial	Nunes *et al.*(2004)
1988/05/23 16:30	−25.436	37.803		V	Porto Formoso	São Miguel	Nunes *et al.*(2004)
1988/10/16 06:15	−25.220	37.725	5.1	VI	Vila Franca do Campo	São Miguel	Nunes *et al.*(2004)
					Povoação		
1988/10/19 21:54	−25.223	37.653	3.7	V	Povoação	São Miguel	Nunes *et al.*(2004)
1988/10/23 22:57	−26.654	38.187	4.8	IV/V	Angra do Heroísmo	Terceira	Nunes *et al.*(2004)

					São Mateus		
					Ribeirinha		
					Praia da Vitória		
					Agualva		
1988/11/21 16:56	−26.098	37.912	5.8	VII	Pilar da Bretanha	São Miguel	Nunes *et al.*(2004)
					Amoreiras (Bretanha)		
					Sete Cidades		
1989/01/21 02:52	−26.321	38.092	5.4	V	Mosteiros	São Miguel	Nunes *et al.*(2004)
					Bretanha		
1989/04/08 08:06	−24.420	37.176	M_b 4.9	IV/V	Feteiras	Santa Maria	Nunes *et al.*(2004)
					Almagreira		
					Santa Bárbara		
1989/06/11 04:22	−28.286	39.065	4.3	IV/V	Guadalupe	Graciosa	Nunes *et al.*(2004)
					Santa Cruz		
					Ribeirinha		
1990/12/08 22:05	−25.140	37.803	4.1	V	Furnas	São Miguel	Nunes *et al.*(2004)
					Povoação		
					Água Retorta		
					Pedreira		
					Nordeste		
					Achadinha		
1990/12/11 02:57	−25.108	37.792	3.9	V/VI	Furnas	São Miguel	Nunes *et al.*(2004)
1990/12/13 16:53	−25.252	37.828	2.9	V	Furnas	São Miguel	Nunes *et al.*(2004)
					Povoação		
1990/12/18 08:00	−25.225	37.748	2.7	IV/V	Ribeira Quente	São Miguel	Nunes *et al.*(2004)
1990/12/19 07:36	−25.292	37.761	3	IV/V	Ribeira Quente	São Miguel	Nunes *et al.*(2004)
1991/02/07 17:11	−25.160	37.783	3.6	V	Povoação	São Miguel	Nunes *et al.*(2004)
1991/06/18 17:58	−26.165	38.122	4.9	IV/V	Mosteiros	São Miguel	Nunes *et al.*(2004)

1993/01/20 14:49	−29.288	38.810	M_b 5	VI	Capelo	Faial	Nunes *et al.*(2004)
					Canto		
1993/01/28 03:07	−29.050	38.674	M_b 4.9	IV/V	Capelo	Faial	Nunes *et al.*(2004)
					Praia do Norte		
1993/02/15 02:58	−29.098	38.708	M_b 4.8	IV/V	Capelo	Faial	Nunes *et al.*(2004)
					Praia do Norte		
					Lombega		
					Ribeira Funda		
					Cedros		
1993/06/17 02:43	−28.407	38.681	4.6	IV/V	Conceição	Faial	Nunes *et al.*(2004)
					Volta		
					Lomba		
					Fernandeg a		
					Flamengos		
					Santa Luzia	Pico	
					Santo António		
					São Roque		
					Bandeiras		
1996/03/09 22:35	−24.211	37.166	5.2	V	Vila Franca do Campo	São Miguel	Nunes *et al.*(2004)
					Maia		
1996/03/24 06:19	−26.618	38.450	4.9	V	Mosteiros	São Miguel	Nunes *et al.*(2004)
1997/06/27 04:40	−26.842	38.195	5.6	V	Angra do Heroísmo	Terceir a	Nunes *et al.*(2004)
1998/07/09 05:19	−28.523	38.634		VIII	Salão	Faial	Nunes *et al.*(2004)
					Espalhafat os		
					Ribeirinha		
					Farol da Ribeirinha		
1998/07/11 00:49	−28.526	38.677	5.7	VI	Horta	Faial	Nunes *et al.*(2004)
1998/07/17 18:58	−28.505	38.597		IV/V	Santa Luzia	Pico	Nunes *et al.*(2004)

1998/09/02 20:24	−25.858	37.796	3.1	V/VI	Várzea	São Miguel	Nunes *et al.*(2004)
1998/09/10 15:50	−25.779	37.896		V	Mosteiros	São Miguel	Nunes *et al.*(2004)
1998/09/19 18:42	−25.864	37.896	3.2	V	Várzea Ginetes	São Miguel	Nunes *et al.*(2004)
1998/12/06 19:20	−25.790	37.854		IV/V	Várzea Ginetes Candelária Sete Cidades Feteira	São Miguel	Nunes *et al.*(2004)
1999/07/21 21:19	−25.822	37.860		V/VI	Várzea Mosteiros	São Miguel	Instituto de Meteorologia (1999)
2000/02/08 02:35	−28.5050	38.7420	3.8	V	Ribeirinha Espalhafatos Salão Pedro Miguel	Faial	Instituto de Meteorologia (2000)
2000/08/01 04:35	−28.9730	38.7580	4.9	V	Capelo Praia do Norte Cedros Salão	Faial	Instituto de Meteorologia (2000)
2003/09/07 10:02	−25.418	37.752	3.3	IV/V	Vila Franca do Campo Água d'Alto Ponta Garça Ribeira Grande	São Miguel	Instituto de Meteorologia (2003)

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