

## Seismic hazard for the Central Group of the Azores Islands

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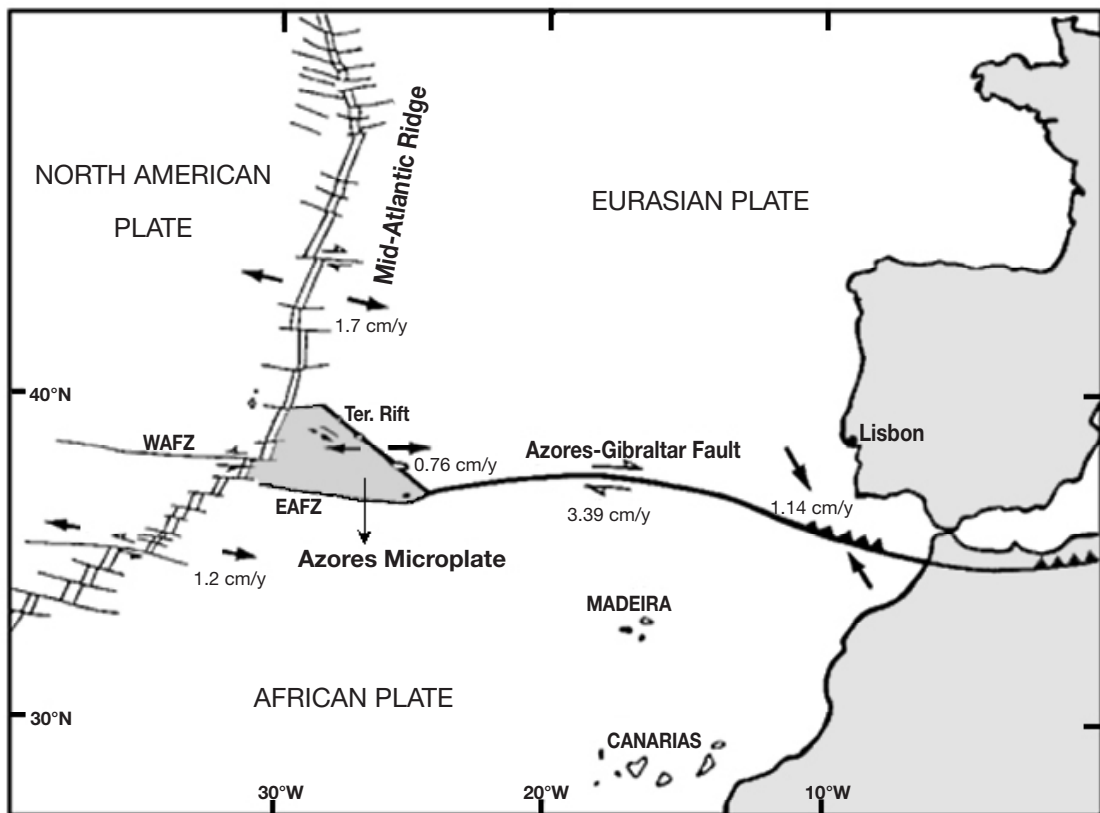
**Abstract** - Probabilistic seismic hazards maps have been prepared either for the archipelago of the Azores in general terms, or for the islands of the Central Group using updated seismic information for the region, including a revision of the earthquake catalogue for the period 1522-1998. Two different approaches were used: (i) a standard seismic source model and (ii) a semi-zonified source model based on spatially smoothed seismicity where no delineation of seismic sources is needed. Preliminary data point out that high PGA values were obtained for an area located to the west of the Central Group and for an area between Terceira and the São Miguel Islands. Deaggregation of hazard for some counties was evaluated and results are presented in terms of mean and modal values of magnitude and distance, showing that the main contributions to hazard in all counties are from close-in and not very severe earthquakes.

### 1. Introduction

The Azores Islands are located in the North Atlantic Ocean, between 37° and 40° N latitude and 25° and 31° W longitude, placed along a narrow area that extends for about 600 km with a general WNW-ESE trend (Fig. 1). It includes the Western Group (the Flores and Corvo Islands), the Central Group (the Terceira, Graciosa, São Jorge, Pico and Faial Islands) and the Eastern Group (the São Miguel and Santa Maria Islands and the Formigas Islets). All the Azores Islands are of volcanic nature and emerge from an anomalously shallow and rough topographic zone – the so-called “Azores Plateau” – that has a general triangular shape and depths of less than 2000 m (Figs. 1 and 2). The Azores Plateau marks the transition to the nearby abyssal plains, with depths of over 3500 m.

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**Fig. 1** - General geotectonic framework of the Azores archipelago (after Forjaz, 1983 and Buform et al., 1988; in: Nunes, 1999). Displacement rates from Nunes (1991). WAFZ – West Azores Fracture Zone; EAFZ – East Azores Fracture Zone; Ter. Rift – Terceira Rift.

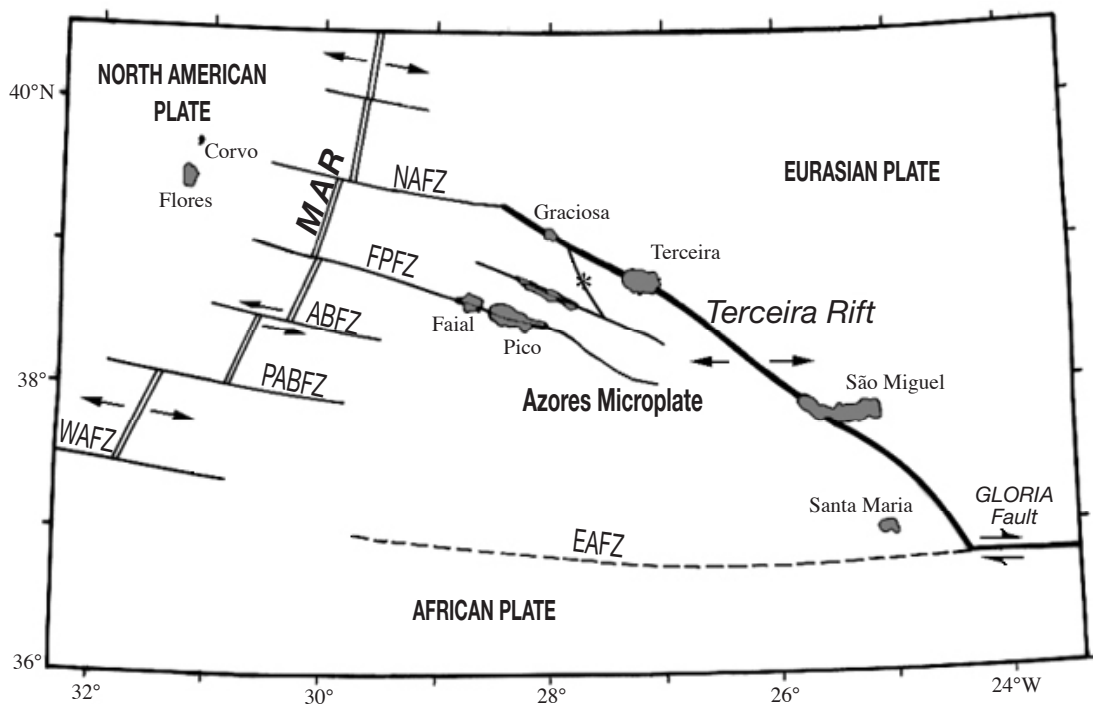
After human settlement, in the 15<sup>th</sup> century, almost 30 earthquakes of tectonic origin were felt in Azores Islands with a maximum Modified Mercalli (MM) intensity higher than, or equal to, VII, killing about 4300 to 5300 people and causing important damage and economic disruption. In the same period, about 30 volcanic eruptions took place in the Azores region, causing almost 240 deaths, and characterised by different volcanic styles (from Hawaiian to Plinian or sub-Plinian type eruptions, including also Surtseyan activities).

The last volcanic eruption, lasting from late 1998 till the beginning 2000, took place in the sea, west of Terceira Island (“Serreta oceanic eruption”), and the last important earthquake occurred on July 9, 1998, off-shore Faial Island, with a moment magnitude  $M = 6.0$  and intensity VIII-IX MM. This important event, together with the occurrence of other two strong damaging earthquakes, in 1973 and 1980 with epicentres in the Central Group, emphasised the need for a revision of the actual seismic code which is based on hazard studies from late 1970 (Oliveira, 1977). In that code, all islands, besides Flores and Corvo, are located in the zone of highest hazard.

Oliveira et al. (1990) re-evaluated the seismic hazard for São Miguel Island, in terms of macroseismic intensity (MM scale), showing important differences within the island itself that recommend the introduction of a non-uniform zoning approach.

## 2. Seismotectonics of the Azores region

The Azores region is located at the triple junction between the Eurasian, African and North American lithospheric plates, with islands aligned along major tectonic lineaments with a general WNW-ESE trend on the so-called Azores “microplate” or “block” (Searle, 1980; Forjaz, 1983; Luis et al., 1994), an approximately triangular area with active volcanism and high seismicity (Fig. 1). The location and nature of the northern and southern arms of the Azores triple junction correspond to the Mid-Atlantic Ridge (MAR), a pure distensive structure which is placed between the Flores and Faial Islands and constitutes the boundary between the North American plate and the other two plates, including the microplate (Fig. 2).



**Fig. 2** - Location of islands and main tectonic lineaments of the Azores triple junction (Nunes, 1999). Asterisk shows the location of the January 1, 1980 earthquake. MAR – Mid-Atlantic Ridge; NAFZ – North Azores Fracture Zone; FPFZ – Faial-Pico Fracture Zone; ABFZ – Açor Bank Fracture Zone; PABFZ – Princess Alice Bank Fracture Zone; WAFZ – West Azores Fracture Zone; EAFZ – East Azores Fracture Zone.

The type and location of the third branch (the Azores-Gibraltar branch) is still controversial, in spite of several models proposed to explain the present kinematics of the Azores triple junction, especially in what concerns the Azores region itself. However, in general terms the Azores-Gibraltar Fault System can be considered as the frontier among Eurasian and African plates, which presents three sectors with distinct geodynamic behaviour (Figs. 1 and 2):

1. an eastern sector (east of 15°W), with collision tectonics between the Eurasian plate and the African plate;
2. a central sector, west of 15°W and 800 km long, that corresponds to a well-defined right-

lateral strike-slip fault (e.g. Gloria Fault);

3. a western branch (roughly between Santa Maria Island and the MAR), that acts as a leaky transform boundary, with oblique spreading.

Available data and the pattern of the seismic and volcanic activity point to the general idea that the Terceira Rift (Fig. 2) acts as the western part of the third arm of the Azores triple junction. However, other important tectonic lineaments are present in the region, most of them with a WNW-ESE to W-E trend cutting the MAR. These are, from north to south (Figs. 1 and 2), the North Azores Fracture Zone (NAFZ), the Faial-Pico Fracture Zone (FPFZ), the Açor Bank Fracture Zone (ABFZ), the Princess Alice Bank Fracture Zone (PABFZ) and the West Azores Fracture Zone (WAFZ). While the last, non seismic zone, can be considered the extension of the East Azores Fracture Zone (EAFZ) to the west of the MAR, the FPFZ, displaying high seismicity and having clear bathymetric and magnetic expression, probably defines the location of the Azores triple point (Luis et al., 1994) at the intersection with the MAR.

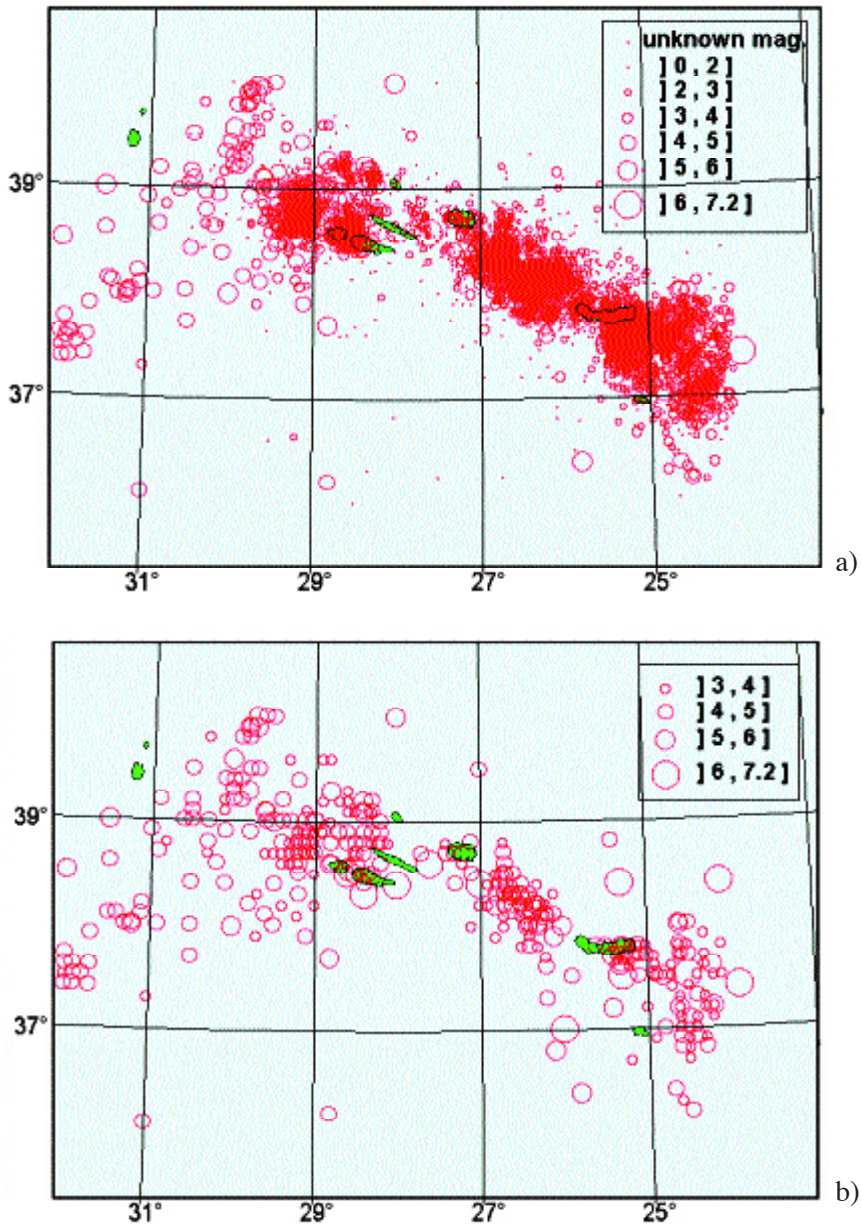
The above-mentioned major tectonic lineaments and the local fault systems that cross the islands are responsible for an important seismic and volcanic activity, reported essentially for the Central Group and the São Miguel Islands. Since 1980 the installation, in the Azores, of a telemetric seismological network as well as digital stations (after 1997) on several islands (SIVISA, 1998), has significantly increased the perceptibility of earthquake activity, recording hundreds of microearthquakes each year and pointing out the major seismogenic areas of the archipelago. In fact, most of the earthquakes are located on the Terceira Rift, the FPFZ, the MAR and associated areas, such as the D. João de Castro submarine volcano (between the Terceira and São Miguel Islands) or the Povoação Trough (to the SE of São Miguel Island).

### 3. Seismicity database

In the absence of an homogeneous earthquake catalogue for the Azores region, based on uniformly treated original data, a seismicity working-file was compiled from available national and international sources (Sousa and Martins, 2000) for the region under study, namely:

1. the Azores University catalogue (Nunes et al., 2000a) that covers, in a first stage, the period 1980-1998;
2. a catalogue developed for the re-evaluation of seismic hazard of São Miguel Island (Costa Nunes, 1986) covering the period between 1917 and 1979;
3. the Seismological Bulletin of the Azores (SIVISA, 1998) with data for the 1998 Faial seismic crises;
4. an international catalogue for the North Atlantic Region (NGDC and NEIC, 1996) that covers the period between 1591 and 1995.

A uniformly treated seismic catalogue for the Azores region was then obtained by cautiously merging all input catalogues into a single file. When different catalogues had different information for the same event, priority was given to local catalogues (e.g. the Azores University). In addition, the coordinates of the macroseismic location of a few important



**Fig. 3** - The Azores Archipelago epicentral map for the period 1522-1998: a): entire catalogue, 9833 events with known epicentral locations; b): events with magnitude  $\geq 3.5$  and without aftershocks and foreshocks, 451 events.

historical events were added to the catalogue, like the events of 1522, 1958 and the 1973 swarm. The catalogue thus obtained, covering a time period between October 1522 and October 1998, contains more than 15000 records (Fig. 3, left), of which 9833 events have known epicentral location and were recorded essentially since 1980 by the Azores seismological network. Due to the lack of complete information on magnitude or macroseismic intensity, most of the events could not be considered in the present study. Seismic events with intensity  $\geq X$  MM or  $M \geq 6$  are presented in Table 1.

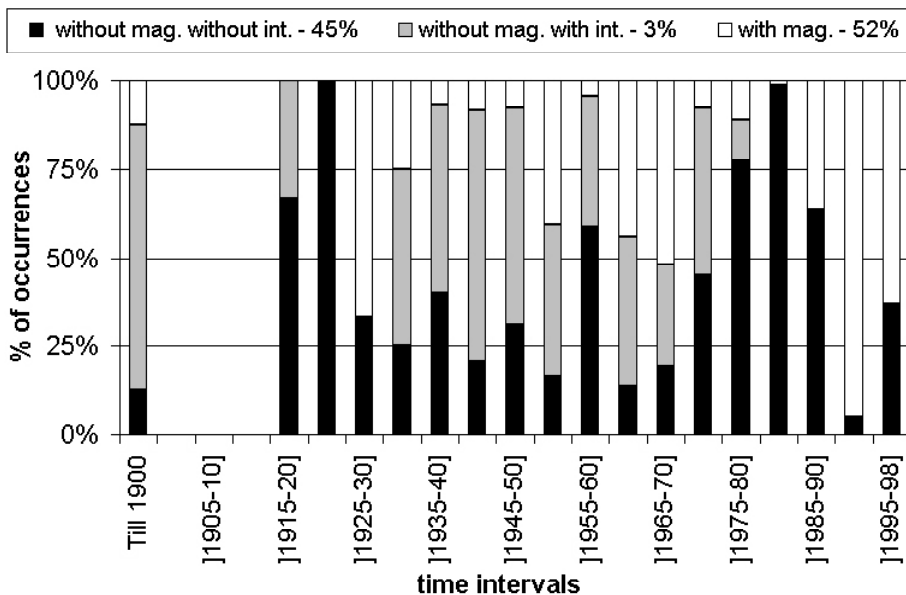
**Table 1** - Earthquakes with intensity  $\geq$  X MM or  $M \geq 6$ , from the Azores catalogue.

Year	Month	Day	Long. (°W)	Lat. (°N)	M	Intensity (MM)
1522	10	22	25.4	37.7	-	X
1757	7	9	28.0	38.6	7.2	XI
1926	4	5	29.0	39.0	6.0	-
1926	8	31	28.6	38.5	5.6	X
1931	4	15	28.0	40.0	6.0	-
1939	5	8	24.5	37.0	7.1	VII
1959	1	24	24.5	37.5	6.5	VI
1980	1	1	27.8	38.8	7.2	VIII-IX
1998	7	9	28.5	38.6	6.0	VIII-IX

Fig. 4 illustrates the lack of completeness of the final catalogue. It shows a large number of events without magnitude from 1980 to 1990, because the main source catalogue used in the compilation for this period, the Azores University Catalogue, although it provides information on date and epicentral location, does not specify the magnitude due to the fact that the number of stations that recorded the same earthquake was not enough to estimate an instrumental magnitude (Nunes, 2001).

Macroseismic intensities were converted into magnitudes after performing a quadratic regression using all events for which both magnitude and intensity were known. When the type of magnitudes was not specified in the original catalogues, it was considered to be equivalent to moment magnitude,  $M$ .

Aftershocks and foreshocks were removed from the catalogue using the Gardner method (Gardner and Knopoff, 1974) adapted to the region considering the pattern of aftershock sequences for recent mainshocks (Nunes, 2000), with magnitude greater than 3.7. The filtering process



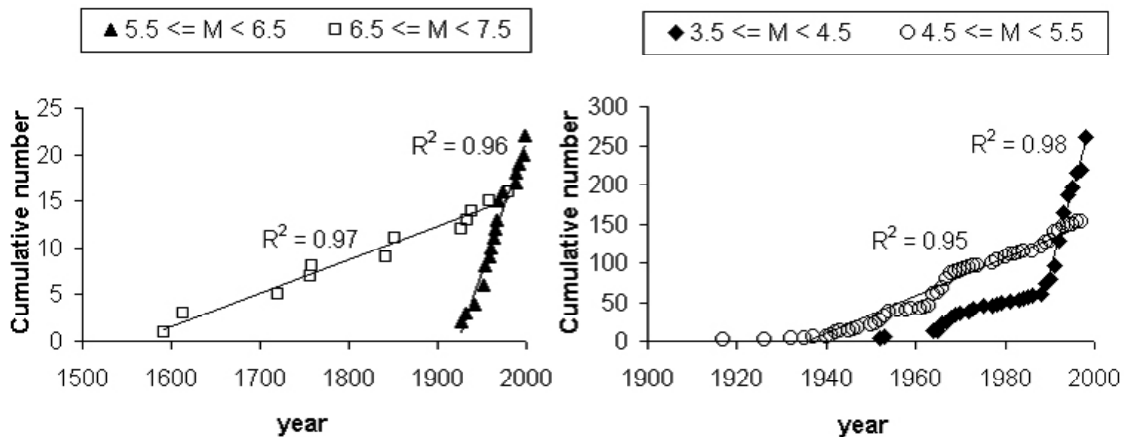
**Fig. 4** - Percentage of earthquakes with magnitude or intensity information per time interval, illustrating the lack of completeness of the catalogue.

of the catalogue led to a database reduced to 451 events (Fig. 3, right), considering magnitudes  $\geq 3.5$ . The magnitude of 3.5 was chosen as the threshold for completeness reasons and because it was assumed that from an engineering point of view earthquakes with magnitude smaller than 3.5 are not important for hazard studies.

#### 4. Data pre-processing

The catalogue completeness along time was analysed (Fig. 5), using a method based on a simple graphical test, which assumes that the catalogue is complete when the cumulative number of events over time, for each class of magnitudes, starts exhibiting a constant slope. From the analysis of Fig. 5, one can conclude that the beginning years of the completeness periods are, for the entire catalogue, 1988 for the magnitude range 3.5 - 4.4, 1917 for the range 4.5 - 5.4, 1899 for the range 5.5 - 6.4 and 1591 for  $M \geq 6.5$ .

#### 5. Attenuation relationships



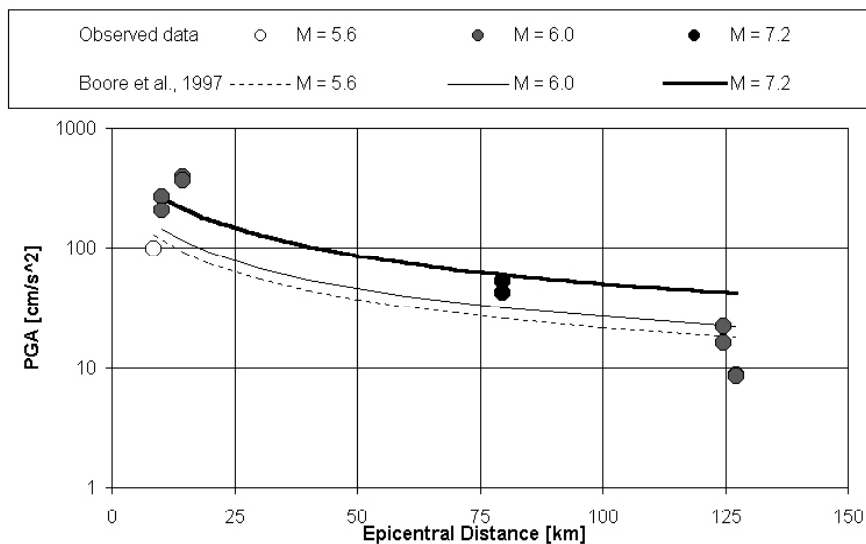
**Fig. 5** - Analysis of the catalogue completeness. Cumulative number of events over time, for magnitude classes between 3.5 and 7.5, and the best fit to data by a least squares method. Left: large events; right: smaller events.

In 1995, before the creation of the “Azores Digital Strong Motion Network” only two acceleration analogic records had been obtained at the archipelago (Oliveira et al., 1997): one during the 1973 Pico Island seismic crisis with a duration magnitude  $M_d = 5.6$  (Nunes et al., 1997) and the other for the Terceira, 1980 earthquake, with  $M = 7.2$ .

The first event recorded at the digital accelerographic network was the January 5, 1996, earthquake with  $M = 3.9$ . Since then this network has been improved and extended to São Miguel and to the Central Group Islands, and presently includes 15 strong motion stations, some connected by modem to a central unit.

A first attempt to derive peak ground acceleration (PGA) attenuation laws for the Azores Islands (Oliveira et al., 2000) was recently made but the compiled instrumental data is still

scarce, mainly in the range of higher magnitudes (see observed data in Fig. 6). Therefore, a trial computation of seismic hazard was carried out using the Boore et al. (1997) attenuation law. This law accounts for different types of soil conditions, a parameter to consider in a future development, and was found to be the most suitable when fitted to PGA data of the Azores network. Fig. 6 illustrates the horizontal PGA data recorded during a few of the higher magnitude recent events at the archipelago and the Boore et al. (1997) attenuation model, for firm-rock site. Notice the high horizontal PGA values ( $\approx 390 \text{ cm/s}^2$ ) recorded during the July 9, 1998 Faial/Pico/São Jorge earthquake ( $M = 6.0$ ) at a station located 14.4 km away from the epicentre. This value was obtained at the Prince of Monaco Observatory located on the top of a scoria cone in Horta town (Faial Island). Studies carried out on topographic effects of this cone are still inconclusive (Lopes and Oliveira, 2000) and, therefore, cannot be used to correct those high PGA values.



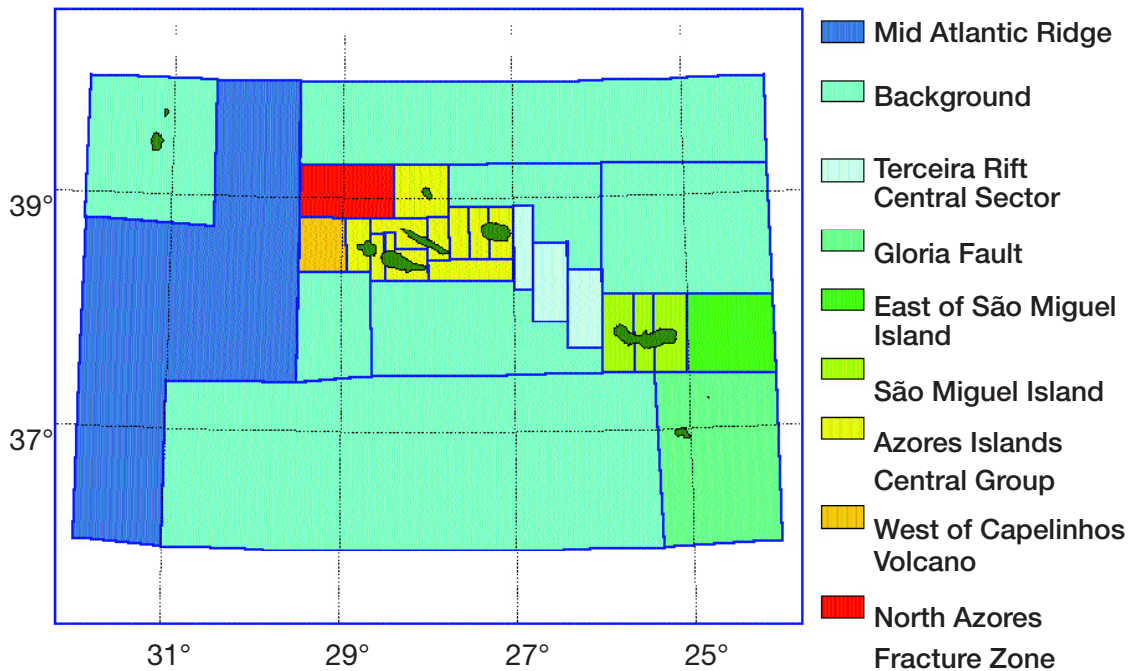
**Fig. 6** - Horizontal PGA data recorded by the strong motion Azorian network, for some of the higher magnitude recent events; Boore et al. (1997) attenuation model, firm-rock site, magnitudes 5.6, 6.0 and 7.2.

## 6. Seismic hazard assessment

### 6.1. A seismic source model

Nunes et al. (2000b) delineated a 28 seismic source zone model (Fig. 7) based on the distribution of epicentres and on the tectonics of the Azores region. For the hazard assessment this model with 28 source zones was transformed into a more simple one where those zones were grouped into 9 main zones (Fig. 7) due to the lack of seismic data allowing a reliable statistical characterisation of the initial model.





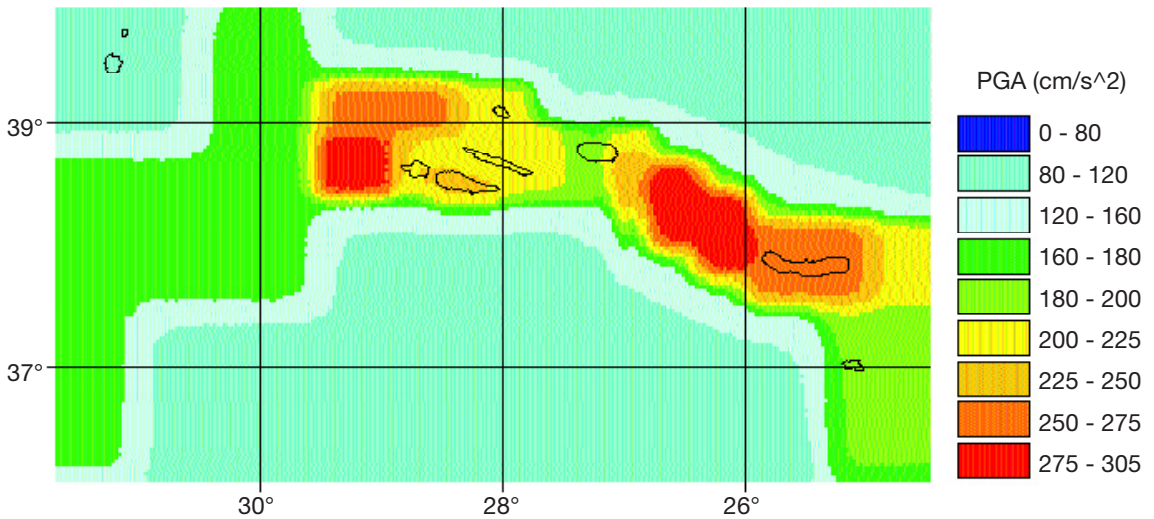
**Fig. 7** - Azores seismic source zones. The original 28 source model (lines inside the main seismogenic zones) of Nunes et al. (2000b) was condensed into 9 larger zones (coloured zones).

For each one of the 9 sources the activity rate,  $\lambda$ , the b-value of the Gutenberg-Richter relation and the maximum magnitude were estimated (Table 2) based on a maximum likelihood method (Weichert, 1980) using the different completeness periods for the different magnitude ranges as stated in section 4.

Hazard calculations were performed using the Cornell (1968) methodology, as applied by McGuire (1976), for a grid of points with space  $0.08^\circ \times 0.08^\circ$  (latitude and longitude). The attenuation law mentioned before was used, for firm-rock site conditions. Fig. 8 presents the mean PGA values for 10% probability of exceedance in 50 years, for the Azores region, corresponding to a return period of 475 years.

**Table 2** - Input parameters for the area source zones: b-values, maximum magnitude estimated and rate of occurrence  $\lambda$  for each area source zone.

Zone	$\lambda$	b-value	Mmax	$\lambda / \text{km}^2$
Mid Atlantic Ridge	2.33	0.64	5.9	$3.97 \cdot 10^{-5}$
Background	1.57	0.84	6.5	$8.17 \cdot 10^{-6}$
Terceira Rift Central Sector	2.82	0.97	7.2	$5.37 \cdot 10^{-4}$
Gloria Fault	2.72	1.34	7.1	$1.38 \cdot 10^{-4}$
East of S. Miguel Island	1.47	1.14	6.5	$2.18 \cdot 10^{-4}$
S. Miguel Island	1.41	0.77	6.5	$2.22 \cdot 10^{-4}$
Azores Island Central Group	1.99	0.76	5.1- 7.2	$1.33 \cdot 10^{-4}$
West of Capelinhos Volcano	4.86	1.87	5.1	$2.01 \cdot 10^{-5}$
North Azores Fracture Zone	1.63	0.99	6.0	$3.41 \cdot 10^{-4}$

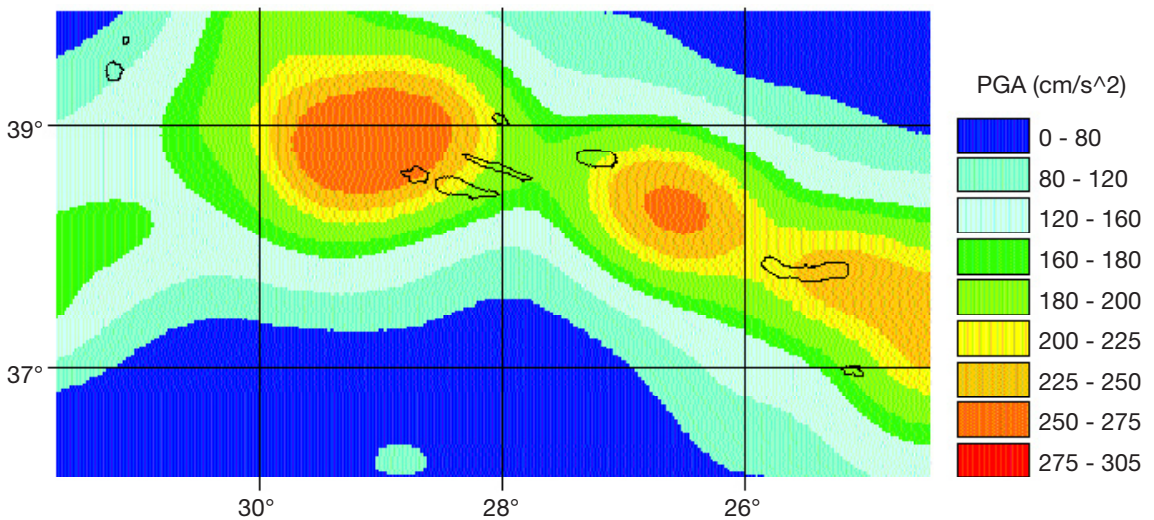


**Fig. 8** - Hazard map for the Azores Archipelago, for mean PGA values, exceedance probability of 10% in 50 years. A source model methodology.

6.2. A semi – zonified source model

The methodology of spatially smoothed seismicity proposed by Frankel (1995), where no delineation of seismic sources is needed, was applied. As before, the entire area was divided into a grid with spacing of  $0.08^\circ \times 0.08^\circ$ .

The same spatially-varying values of maximum magnitude considered in the source method (Table 2) were used. This means that maximum magnitude is zone dependent. Because of this zone dependence, in what follows, this model will be called a semi–zonified source model. A regional b-value of  $0.96 \pm 0.03$  was estimated for the entire region, following the maximum



**Fig. 9** - Hazard map for the Azores Archipelago, for mean PGA values, exceedance probability of 10% in 50 years. A semi-zonified source methodology.

likelihood method recommended by Weichert (1980) using the same complete part of the catalogue used in the source model.

The number of events with magnitude greater than 3.5 was counted for each cell. The logarithm of this number represents the maximum likelihood a-value for each grid cell. These a-value grids were then smoothed with Gaussian smoothing functions with a correlation distance of 50 km.

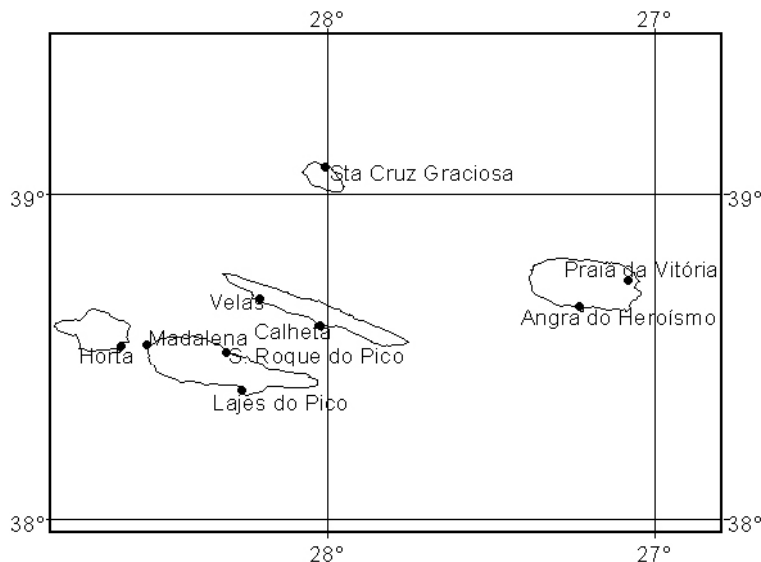
Hazard was obtained by summing the frequencies of exceedance for all the grid cells, and results for mean PGA values for 10% probability of exceedance in 50 years are illustrated in Fig. 9.

### 6.3. Analysis of hazard and comparison of the two different methods

It is obvious from Fig. 8 that the geographical distribution of hazard was clearly influenced by the seismic source model and the input seismic catalogue. The seismic hazard near the source boundaries is directly and strongly affected by the changes in the delineation of these boundaries.

In Fig. 9 hazard distribution was controlled by the spatially smoothed seismicity and seems to be higher in recently active seismogenic zones. This figure shows a difference in the hazard within the São Miguel Island, which is in good agreement with Oliveira et al. (1990) although this first study was based on a less complete seismic catalogue and analysed a smaller region.

Taking into account all these constraints, the location of higher hazard regions from both models can be considered quite similar. High PGA values were obtained for an area located to the west of the Central Group and for an area between Terceira and the São Miguel Islands. The highest hazard region is found around 38.5°N and 29°W ("West of the Capelinhos



**Fig. 10** - Localization of counties of the Central Group of the Azores.

Volcano” zone). This is not an area commonly associated with large earthquakes, but shows a relatively large number of events (see Table 2), like the 1992-1993 seismic swarm. Another high hazard region is found around 38°N and 26.5°W (the “Terceira Rift Central Sector” zone). As before, this higher hazard region seems to reflect mostly the rate of occurrence more than the occurrence of large magnitude earthquakes in this zone, even considering the fact that several moderate events do occur here.

Considering now the Central Group of Azores alone, the source method does not show significant variations in hazard for the Central Group counties (see Fig. 10 for localization of the considered counties) since, for this study, they were considered in the same source zone. Using a semi-zonified source method, hazard is highest in the western zone (Faial and Pico Islands) of the Central Group, dominated by the recent seismic swarms that occurred at the archipelago, and in the eastern part of Terceira Island.

Fig. 11 shows a set of mean hazard curves for the Central Group counties, obtained by the semi-zonified source method.

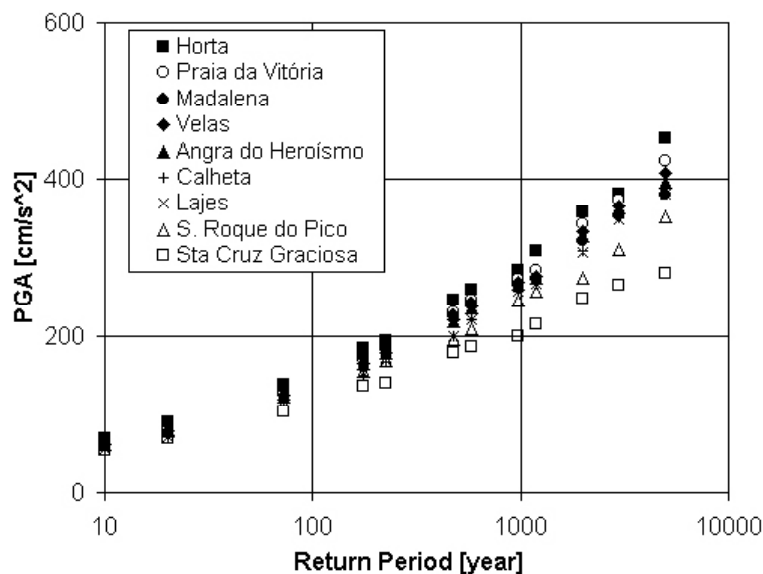


Fig. 11 - Hazard curves obtained by a semi-zonified source methodology for the Central Group counties.

#### 6.4. Deaggregation of hazard

To derive a potential design earthquake or simply a hazard dominating scenario event at a site from a probabilistic seismic hazard analysis, it is important to perform the hazard deaggregation. Although this analysis has been recently developed, it has already been extensively discussed and applied (e.g., Chapman, 1995; Frankel, 1995; Cramer and Petersen, 1996; McGuire, 1995; Bazzurro and Cornell, 1999; Harmsen et al., 1999).

Seismic hazard deaggregation consists in the assessment of the hazard contributions in a space of bins of the random variables of the process. The bin space most used is bi-dimen-

sional; that is, the relative contribution to the hazard is studied in terms of elementary bins of magnitude  $M$ , and source-to-site distance  $R$ . Therefore, hazard deaggregation represents a conditional probability that, given the exceedance of a specified ground motion level (hazard value), has been caused by a certain combination of  $M$  and  $R$  (McGuire, 1995).

Bazzurro and Cornell (1999) also emphasise that when the aim of a deaggregation procedure is to estimate the expected or the most likely event that causes the exceedance of the specified ground-motion level at the site, the results of hazard deaggregation are often summarised into central statistics like means or modes.

Discussion on whether the design earthquake resulting from the analysis should be defined by a pair of mean values or by modal values has already taken place. Harmsen et al. (1999) pointed out that modal values can be dependent on the dimension of the bins, whereas mean values “may correspond to earthquakes with little contribution to the hazard”.

In order to identify hazard dominating scenario events, for the counties of the Central Group of the Azores, deaggregation was performed using results from the semi-zonified source model. Deaggregation was achieved in two steps:

1. accumulate in each bin its contribution to the global hazard;
2. divide the total contribution accumulated in each bin by the total annual frequency of exceedance.

Results are presented in Table 3. One can conclude that:

1. in general, the main contributions to the hazard are from close-in earthquakes, as both mean and modal distances are shorter than 14.3 km, for all return periods. Mean distances decrease and modal distances are constant as the return period increases;

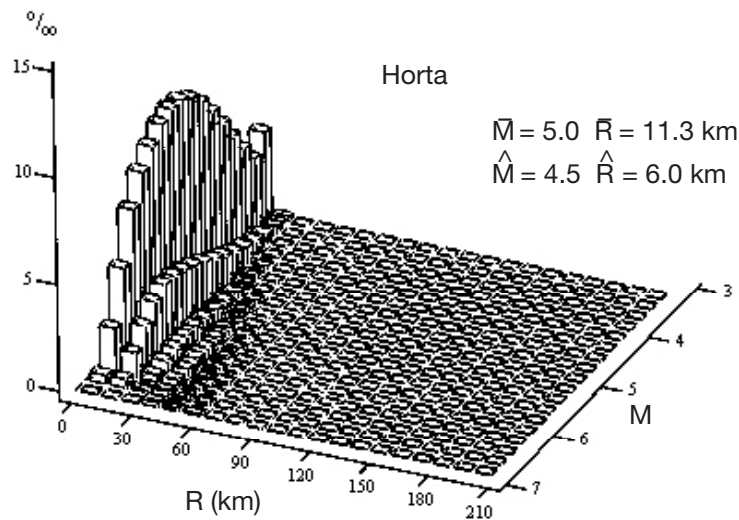
**Table 3** - Pairs of mean and modal values of magnitude and distance, ( $\bar{M}$ ,  $\bar{R}$ ) and ( $\hat{M}$ ,  $\hat{R}$ ) respectively, for three exceedance probabilities in 50 years, and the contribution [%] of those pairs to the total hazard of each county.

County	10% in 50 years				5% in 50 years				1% in 50 years			
	$\bar{M}$ Contrib.	$\bar{R}$ [%]	$\hat{M}$ Contrib.	$\hat{R}$ [%]	$\bar{M}$ Contrib.	$\bar{R}$ [%]	$\hat{M}$ Contrib.	$\hat{R}$ [%]	$\bar{M}$ Contrib.	$\bar{R}$ [%]	$\hat{M}$ Contrib.	$\hat{R}$ [%]
Horta	5.0	11.3	4.5	6.0	5.1	10.6	4.7	6.0	5.4	9.0	5.7	6.0
		0		38		0		39		21		54
Madalena	4.9	11.7	4.3	6.0	5.0	10.9	4.7	6.0	5.3	9.5	5.3	6.0
		0		3		0		39		20		46
S. Roque do Pico	4.8	11.8	3.9	4.0	4.9	10.4	4.3	4.0	5.2	8.8	4.9	4.0
		4		24		4		24		21		27
Lajes do Pico	4.8	12.1	3.9	4.0	4.9	10.4	4.3	4.0	5.2	8.5	5.1	4.0
		11		29		10		29		8		34
Velas	4.9	11.3	4.1	4.0	5.0	10.2	4.5	4.0	5.2	7.1	5.3	4.0
		15		26		15		26		21		42
Calheta	4.8	12.0	3.9	4.0	5.0	10.3	4.3	4.0	5.2	8.5	5.1	4.0
		4		26		6		26		16		31
Sta Cruz Graciosa	4.8	14.3	3.9	6.0	4.9	13.5	4.1	6.0	5.3	11.6	4.7	6.0
		8		36		8		35		0		34
Praia da Vitória	4.8	9.4	3.9	2.0	5.0	8.6	4.3	2.0	5.3	6.7	5.1	2.0
		24		38		24		38		0		45
Angra do Heroísmo	4.8	9.8	3.9	2.0	4.9	8.7	4.3	2.0	5.2	7.0	5.1	2.0
		24		38		24		37		0		43

2. both mean and modal magnitudes increase with the return period;
3. modal distances are always smaller than mean distances for all counties and return periods. The same applies to magnitudes except for Horta and Velas counties and for a 1% exceedance probability in 50 years;
4. the contribution of the modal values is significantly higher than the contribution of mean values and there are pairs of mean values without physical meaning for design purposes, as they represent an almost null contribution to the hazard.

Fig. 12 shows the deaggregation plot for Horta for a 10% probability of exceedance in 50 years. This county is representative of the highest hazard of the analysed region.

Hazard at Horta (on Faial Island) has major contributions for earthquakes closer than 30 km. This means that an earthquake like the January 1, 1980 one (epicentre in sea, west of Terceira Island,  $M=7.2$ ), 80-90 km away from Horta, does not affect the hazard in this county excessively. However, the July 9, 1998 Faial/Pico/São Jorge earthquake ( $M = 6.0$ , 14 km away from Horta) is associated to a bin that contributes with 8‰ to the total hazard at this site. In fact, the January 1, 1980 earthquake was felt in Horta town with a IV-V MM, while the July, 9, 1998, earthquake was felt in that town with an intensity VI.



**Fig. 12** - Deaggregation plot for Horta, exceedance probability of 10% in 50 years. It includes the mean and modal magnitude and mean and modal distance. Contributions were separated into bins of 0.2 width in magnitude (the first magnitude bin beginning at 3.5) and of 10 km in distance. The height of each bar on this plot represents the contribution of magnitude and the distance bin to the annual rate of exceeding the ground motion (hazard value) corresponding to the specified probability level.

## 7. Conclusions and future work

The seismic source zones adopted in the source method are very broad and tend to homogenise the hazard of the Central Group of the Azores, presenting little hazard variations from island to island. On the contrary, the semi-zonified source methodology displays larger variations. Taking into account the Azores region, high PGA values were obtained to the west of

the Capelinhos Volcano and at the Terceira Rift Central Sector. Considering the Central Group of the Azores Islands, the most severe hazard is present at Horta (west of the Central Group) and Praia da Vitória (east of the Central Group) and the least severe at Santa Cruz da Graciosa.

Deaggregation shows that the main contributions to hazard in all counties are from close-in and not very severe earthquakes. Furthermore, the flatness of the joint probability distribution functions of magnitude and distance for all counties explains why the contribution to the global hazard of the pairs, of mean and modal values, are so reduced. This constitutes a shortcoming for selecting the scenario by means of modal values, and caution should be taken in choosing that scenario.

These assumptions can be justified by the fact that the Azores region is controlled by recent events. Nevertheless, the unimodal characteristic of those distributions shows that a seismic hazard scenario, if it is possible to choose it, can be uniquely identified.

The events that most contribute to hazard results, the dominating scenario events, should be characterised by a pair of modal values of magnitude and distance and not by a pair of mean values, as in some cases the pair of mean values has no physical meaning as it represents an almost null contribution to the hazard.

For all counties, modal values of magnitude are lower than 4.5, 4.7 and 5.7 for the exceedance probabilities of 10%, 5% and 1% in 50 years, respectively. These modal values of magnitudes were estimated at Horta County.

Finally, the analysis of deaggregation of probabilistic seismic hazard has given feasible results, coping with the knowledge of seismic activity in the Azores and allowing us to interpret the relative contribution to the hazard of the values of the variables involved. This substantiates the studies on seismic scenarios and the establishment of seismic action levels for design purpose.

In conclusion, available data and ongoing studies that are being done on the evaluation of seismic hazard of the Central Group of the Azores Islands, seem to point out the need for a revision of the actual seismic code that should include a non-uniform zonation of the Central Group.

Future seismic hazard maps will benefit from additional information, namely slip-rates of identified crustal faults and the influence of site specific conditions. Site studies presented here are only for firm-rock conditions and on-going work will take into account soil and rock types and local geological constraints.

A great effort should also be made to gather information related to past earthquake occurrences, namely paleoseismic and historical studies, in order to complete data on magnitude and, consequently, use a more complete catalogue in hazard studies. The estimation of magnitudes from intensity data and attenuation laws is already under study.

Attenuation from the digital accelerographic network data is another topic of great relevance when the number of records covering a large spectrum of magnitudes become of significance.

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## References

- Bazzurro P. and Cornell C.A.; 1999: *Disaggregation of seismic hazard*. Bull. Seism. Soc. Am., **89**, 501-520.
- Boore D.M., Joyner W.B. and Fumal T.E.; 1997: *Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: a summary of recent work*. Seism. Res. Letts., **68**, 128-153.
- Bufo E., Udías A. and Colombás M.A.; 1988: *Seismicity, source mechanism and tectonics of the Azores-Gibraltar plate boundary*. Tectonophysics, **152**, 89-118.
- Chapman M.C.; 1995: *A probabilistic approach to ground-motion selection for engineering design*. Bull. Seism. Soc. Am., **85**, 937-942.
- Cornell C.A.; 1968: *Engineering seismic risk analysis*. Bull. Seism. Soc. Am., **58**, 1503-1606.
- Costa Nunes J.; 1986: *Sismicidade histórica e instrumental do Arquipélago dos Açores. Catálogo preliminar: 1444-1980*. Not published (computer file prepared for the São Miguel hazard study of Oliveira et al., 1990).
- Cramer C.H. and Petersen M.D.; 1996: *Predominant seismic source distance and magnitude maps for Los Angeles, Orange and Ventura Counties, California*. Bull. Seism. Soc. Am., **86**, 1645-1649.
- Forjaz V.H.; 1983: *Azores tectonic sketch*. Centro de Vulcanologia. Azores University. Sketch, 1 page. Not published.
- Frankel A.; 1995: *Mapping seismic hazard in the Central and Eastern United States*. Seismic. Res. Letts., **66**, 8-21.
- Gardner J.K. and Knopoff L.; 1974: *Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian?* Bull. Seism. Soc. Am., **64**, 1363-1367.
- Harmsen S., Perkins D. and Frankel A.; 1999: *Deaggregation of probabilistic ground motions in the Central and Eastern United States*. Bull. Seism. Soc. Am., **89**, 1-13.
- Lopes H. and Oliveira C.S.; 2000: *Analysis of weak-strong motion records obtained at the top of a volcanic hill*. XXVII General Assembly of the European Seismological Commission (ESC), Lisbon, Portugal. Book of abstracts and papers, 104.
- Luis J.F., Miranda J.M., Galdeano A., Patriat P., Rossignol J.C. and Mendes Victor L.A.; 1994: *The Azores triple junction since 10 Ma from an aeromagnetic survey of the Mid-Atlantic Ridge*. Earth and Planet. Sc. Lett., **125**, 439-459.
- McGuire R.K.; 1976: *EQRISK, Evaluation of earthquake risk to site*. Open File Report 76-67. United States Dept. of the Interior Geological Survey, USA.
- McGuire R.K.; 1995: *Probabilistic seismic hazard analysis and design earthquakes: closing the loop*. Bull. Seism. Soc. Am., **85**, 1275-1284.
- NGDC and NEIC; 1996: *Seismicity catalogs, vol. 2: Global and regional, 2150 B. C. – 1996 A. D.* (CD-ROOM), Colorado, USA.
- Nunes J.C.; 1991: *Microssismos e neotectónica – Contribuição para o seu estudo nos Açores*. Azores University, Ponta Delgada, Portugal.
- Nunes J.C.; 1999: *Volcanic activity on the island of Pico in upper Pleistocene to Holocene times: eruption mechanism and volcanic hazard*. Ph.D. thesis, Azores University, Ponta Delgada, Portugal.
- Nunes J.C.; 2000: *Janelas para a identificação de réplicas na região dos Açores. Database and report*. PPERCAS Project – Azores University. Report no. 2/2000, Ponta Delgada, Portugal.
- Nunes J.C.; 2001: Personal communication.
- Nunes J.C., Forjaz V.H. and França Z.; 1997: *Novos elementos sobre a crise sísmica de 1973, Ilha do Pico (Açores)*. Proc. 3º Encontro de Sismologia e Engenharia. Sísmica, pp 39-48, Instituto Superior Técnico, Lisbon, Portugal.
- Nunes J.C., Forjaz V.H. and Oliveira C.S.; 2000a: *Catálogo sísmico da região dos Açores, Vol I (1980-88), Vol. II (1989-98)*. PPERCAS Project, Azores University, Ponta Delgada, Portugal.



- Nunes J.C., Forjaz V.H. and Oliveira C.S.; 2000b: *Zonas de geração sísmica para o estudo da casualidade do Grupo Central do Arquipélago dos Açores* PPERCAS Project, Report no. 3/2000, Azores University, Ponta Delgada, Portugal.
- Oliveira C.S.; 1977: *Sismologia, sismicidade e risco sísmico. Aplicações em Portugal*. Relatório LNEC. Proc. 36/11/4394, Lisbon, Portugal.
- Oliveira C.S., Campos-Costa A., Forjaz V.H. and Nunes J.C.; 1990: *Seismic hazard analysis in zones of time and space interdependence: an application to São Miguel island, Azores*. Natural Hazards, **3**, 15-29.
- Oliveira C.S., Correia Guedes J.H. and Lucas A.; 1997: *Registos obtidos na rede acelerométrica dos Açores durante a crise sísmica de Junho-Outubro de 1997*. Proc. 3º Encontro sobre Sismologia e Engenharia Sísmica, Instituto Superior Técnico, Lisbon, Portugal, 49-58.
- Oliveira C.S., Sousa M.L., Nunes J.C. and Martins A.; 2000: *Seismic hazard for Central Group of Azores islands*. XXVII General Assembly of the Europ. Seism. Commission (ESC), Lisbon, Portugal. Book of abstracts and papers, 97.
- Searle R.; 1980: *Tectonic pattern of the Azores spreading centre and triple junction*. Earth and Planet. Sc. Lett., **51**, 415-434.
- SIVISA; 1998: *Boletim sismológico preliminar dos Açores. Centro de Coordenação do Sistema de Vigilância Sismológica dos Açores (SIVISA)*. Instituto de Meteorologia and Azores University, Portugal.
- Sousa M.L. and Martins A.; 2000: *Compilação de um catálogo sísmico para a região dos Açores*. Relatório LNEC. Proc. 260/18/13343, Lisbon, Portugal.
- Weichert D.; 1980: *Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes*. Bull. Seism. Soc. Am., **70**, 1337-1346.

