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Seismic Hazard Analysis in Zones of Time and Space Interdependence: An Application to São Miguel Island, Azores*

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Abstract. The Azores Islands are located in the mid-Atlantic region near the triple junction where the Euro-Asiatic-African-American plates join together. Seismic activity in the area is very high, as can be observed either from historical events since the fifteenth century, from present day microseismicity, and from direct and indirect measurements of recent tectonic deformation. Volcanic activity is also present throughout the region.

All available information, even data exhibiting low quality, was used to develop hazard models of São Miguel Island. Source zones were established based on both the global tectonic behaviour of the region and on the local active fault structures. Recurrence laws for São Miguel Island, for which historical information seemed quite incomplete, were obtained from the large events in the entire archipelago and from their remarkable pattern of time and space dependence, and complimented by information on long-term fault deformation (for the longer recurrence periods) and on high precision instrumental network (for the very short recurrence periods).

Attenuation laws were derived from data on events felt and/or recorded in the Island.

Hazard maps were obtained through a modified version of McGuire's algorithm for several geometries of source areas and results compared with the maximum observed intensity of historical events.

Key words. Hazard analysis, recurrence, probability of exceedence, zoning, uncertainties, time-space interdependence.

1. Introduction

Seismic hazard in the Azores Islands is defined in the Portuguese Code of Actions, RSA (1983), based on the studies performed by Oliveira (1977). A uniform seismic action for the whole of São Miguel Island is considered in that code. Since the conclusion of the above-mentioned studies, there has been a considerable widening of knowledge as

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regards the earth sciences connected with tectonics, at both regional and local levels, and as regards the instrumental seismicity of the Azores Archipelago. It has therefore become essential to revise the 1977 seismic hazard studies in the light of the new data and information now available.

The present work refers to the main options chosen along the study and discusses the degree of uncertainty on final hazard estimates. Further details can be found in Oliveira and Costa (1987).

2. Data Analysis

2.1. *Morphology and Tectonics*

The Azores region is located at the triple junction of the Euro-Asiatic, African and North American plates, with present formation of the Earth's crust at the Mid-Atlantic Ridge (MAR), Figure 1. This ridge separates the North American Plate from the other two to the east. The contact zone between the Euro-Asiatic and African plates is prolonged eastward towards the Strait of Gilbraltar. A precise definition of this zone, however, is extremely difficult. In effect, and as regards only to the Azores Archipelago, the transition between the MAR and the so-called Gloria Fault (Krause and Watkins, 1970; Laughton and Whitmarsh, 1974), a well defined tectonic structure running eastward from Santa Maria Island, is not known.

The islands are divided in two groups: Corvo and Flores to west of the MAR and Faial, Graciosa, Pico, São Jorge, Terceira, São Miguel, and Santa Maria east of it. All of them are situated in a trench about 2 km deep, aligned from one end to the other in the form of a 'horseshoe'.

Although several models have been proposed for explaining the geodynamic mechanism of the zone (Dias, 1955; Krause and Watkins, 1970; McKenzie, 1972; Machado *et al.*, 1972; Udias and Arroyo, 1972; Bonnin, 1978; Feraud *et al.*, 1980; Searle,

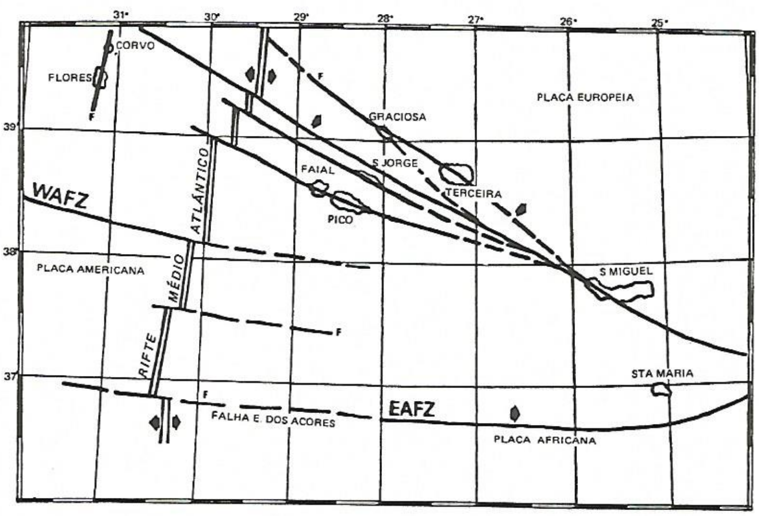

Fig. 1. Morphology and tectonic sketch for the Azores region according to Forjaz (1983).

1980; Forjaz, 1983; Moreira, 1985; Victor and Nunes, 1986; Ribeiro, 1987; Madeira and Cabral, 1988; Udias *et al.*, 1988), data on the morphology, geophysics, and geology are still insufficient for a really satisfactory interpretation.

The survey of the main active geological structures in São Miguel Island was carried out by Forjaz (1988) on the basis of studies of alignments obtained in aerial photos, field studies, etc. Figure 2 shows the geological map and faults on São Miguel Island, and the possible geological structures in the immediate vicinity. The faults were classified according to Slemmons (1977) as active, potentially active, and probably not active.

Among the main active geological structures, mention must be made of the Mosteiros graben at Sete Cidades, Ribeira Grande graben, and the Congro fault. All these structures show a similar tectonic mechanism, of a right lateral strike-slip with slight extension. Figure 2 shows the zones on São Miguel where the seismic crises of 1967, 1985, and 1987 occurred and correlates them with the presence of the tectonic structures.

This figure also shows the two points where a creepmeter was installed for short

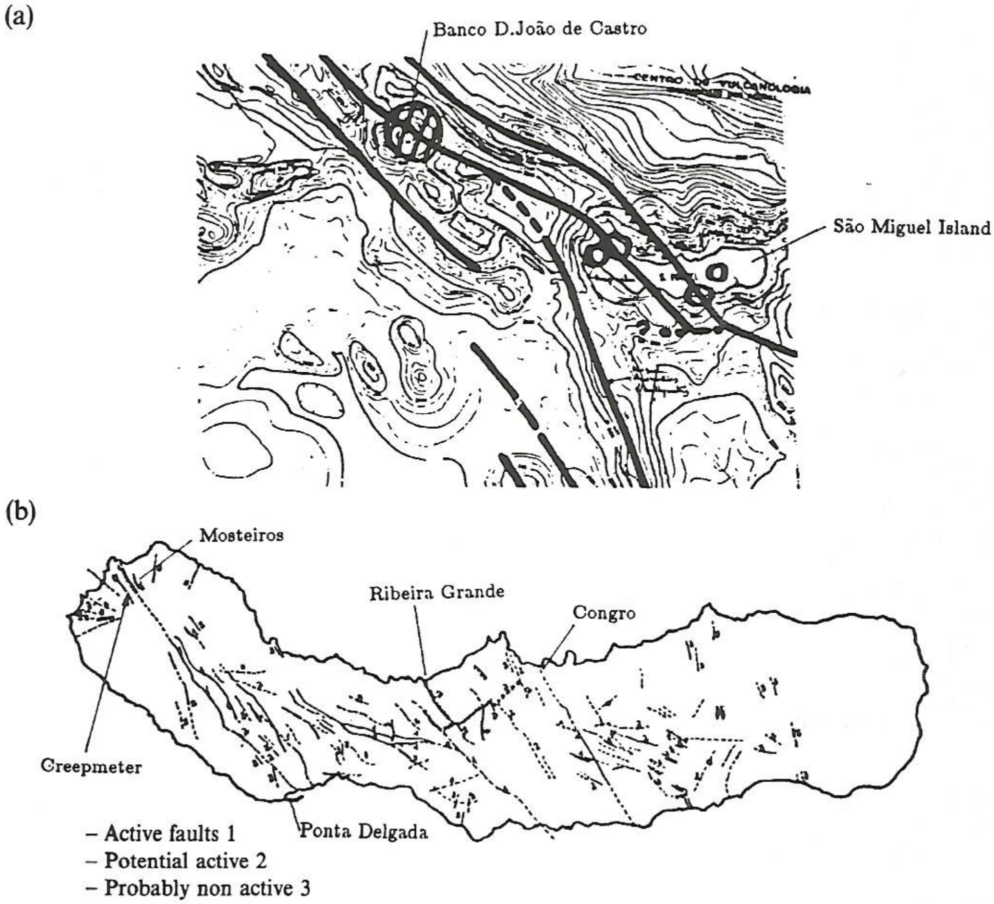

Fig. 2. Geological structures of São Miguel Island according to Forjaz (1988): (a) principal structures on São Miguel and neighbouring zones; (b) existing faults.

periods. This instrument recorded horizontal right lateral differential displacements of 1.2 cm/yr between the two edges of the fault, Forjaz (1986). This rate of relative movement leads to distortions of 60 m after 5000 yr, a value that is in agreement with observations of volcanic cones. Vertical displacement in the graben, proved by the existence of a dislocation of 1 to 2 m since 1444, leads to far lower rates.

2.2. *Historical and Instrumental Seismicity*

Seismicity in the Azores Archipelago is very high, as it is on São Miguel Island itself, this being attested by important earthquakes since the fifteenth century [Table I and Machado (1972)]. Volcanic activity is also present throughout the region (Weston, 1964). The data on seismicity used in this study come from two sources, expressly requested from the National Institute of Meteorology and Geophysics, (INMG), in the early stage of the study:

(a) Catalogues of 4579 earthquakes felt in the Azores from 1444 to 1980 (Nunes *et al.* 1986);
(*b*) Instrument earthquakes recorded in the zone of São Miguel Island in the 1980–1986 period (Nunes, 1986).

Table I. Most important historical seismic events that affected São Miguel Island (MMI ⩾ VII)

Local	Date
Sete Cidades	30/December/1444
Vila Franca	22/October/1522
Lagoa do Fogo	27/June/1563
D. João Castro	15/June/1571
Vila Franca	26/July/1591
Furnas	2/September/1630
Ferraria	3/July/1638
L. Pico do Fogo	9/October/1652
Hirondelle	13/December/1682
Ginetes	8/December/1713
D. João Castro	1/March/1718
D. João Castro	1/April/1718
D. João Castro	10/July/1720
D. João Castro	10/December/1720
Praia Victoria	26/January/1801
Ginetes-Sabrina	1/February/1811
Sete Cidades	16/April/1852
Furnas	18/February/1881
SW Ter – 1902 – MAR	1/June/1902
1907 – MAR	2/April/1907
1911 – MAR	11/May/1911
Povoação	6/August/1932
Povoação	26/April/1935
Povoação	28/June/1952

Data up to 1900 are extremely scanty, with summary descriptions of the most intense earthquakes. Only the date of occurrence and Modified Mercalli maximum intensity are included. From 1900 to 1975, the data were mainly taken from the *Bulletins of the National Seismological Yearbook*, which gives date, hour, epicentre, intensity at one or various places, magnitude, and other observations. In only a few earthquakes, however, is this information complete. From 1975 to 1980, the existing information is essentially instrumental, since the seismographic network after 1975 has had good resolution. Although there is information for reasonable determination of the seismic parameters (epicentre, focal depth, magnitude, etc.), the values transcribed to the Catalogue were obtained from 'traditional' techniques in the seismic analysis.

Figure 3(a) gives the map of epicentres of earthquakes occurring between 1912 and 1984, in the entire Archipelago. The instrument earthquakes of the 1980–1986 period were recorded on the network of seven stations in the central zone of São Miguel that were installed after 1980. This network made it possible to record a large number of

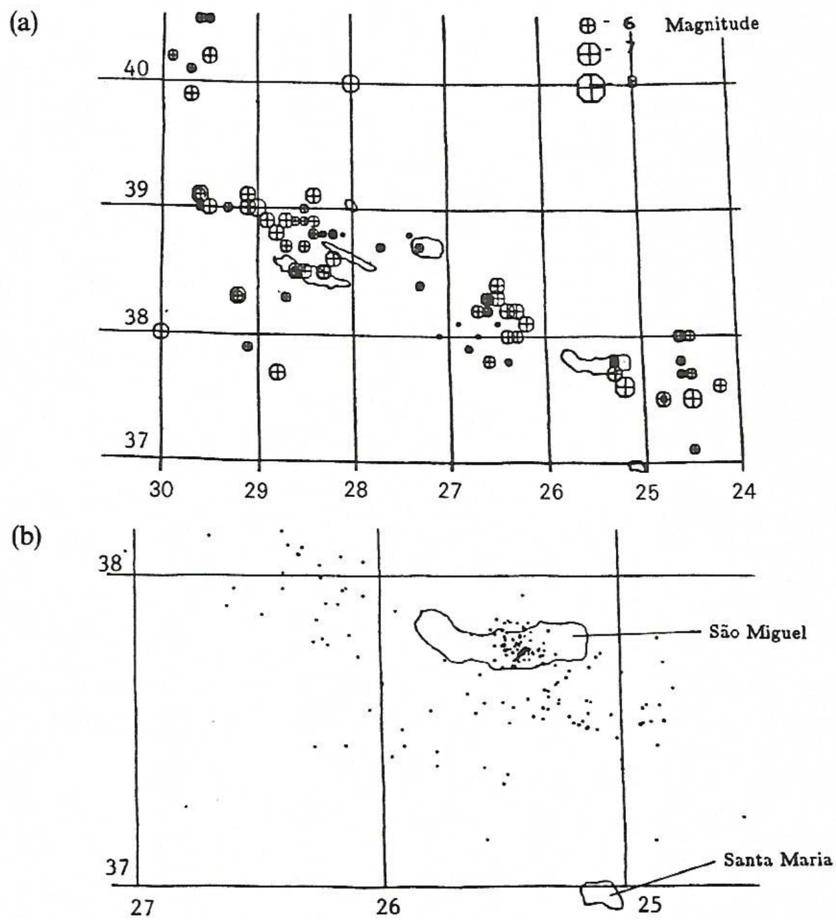

Fig. 3. Map of epicentres of earthquakes in the Azores according to Nunes *et al.* (1986) and Nunes (1986): (a) in the whole Archipelago for the 1912–1984 period; (b) in São Miguel and neighbouring zones for the 1980–1986 period.

earthquakes of small and medium magnitude occurring in the interior of the island or its vicinity.

From the figures presented, it is seen that present seismicity is located in the central zone of São Miguel associated with the Congro fault and Ribeira Grande graben. This confirms the results obtained by Dawson *et al.* (1985) using a portable network in the centre of the island during a short period in 1983. The Mosteiros graben zone at Sete Cidades shows reduced activity. The recent swarms which occurred in late 1988 and early 1989, emphasized the activity in Congro and Ribeira Grande and revealed a new area of activity in Hirondelles, east of Banco D. João de Castro (Forjaz, 1989).

2.3. *Synthesis of the Information. Interpretations*

The standard approach to the occurrence problem considers the time-space-size process broken down into three independent processes (Oliveira, 1987) in the following way: (a) Definition of the zones of seismic generation, which is done by resorting to the seismo-tectonic characteristics. (b) For each zone, the law of recurrence is defined, simultaneously involving time and magnitude.

In the present study, the standard linear recurrence law $\ln N = \alpha - \beta M (M \text{ or } I)$ has been considered sufficient, provided that a given interval of magnitudes is not exceeded. The minimum value of magnitude M_0 must be such that the sample can be regarded as complete. The maximum value M_1 is closely connected with the length of rupture of the fault that causes the earthquake and was obtained either by tectonic interpretation or by analyzing the maximum values of magnitude in the historical earthquakes.

Since the information in the Seismic Catalogues for the Azores (Nunes *et al.*, 1986) does not consider the value of all parameters required for characterizing seismic occurrences, mainly regarding earthquakes before 1912, two distinct analyses were carried out: one of them covers the 1912–1980 period for which there was complete information, i.e. date, latitude, longitude, and magnitude; and the second covers the 1444–1980 period for which there was only the date and MM intensity felt at villages on São Miguel Island. The apparent overlap in the 1912–1980 period has hardly any significance, since the number of earthquakes felt on São Miguel in that period was rather small.

2.3.1. *Time-Space Model of Seismic Occurrences.* A study of historical seismicity indicates that seismic crises, major earthquakes, and volcanic crises recorded since the fifteenth century, have a noteworthy repetition as regards the spacetime evolution of the release of energy. Victor and Nunes (1986) showed clearly that there was a cyclic phenomenon in the way that the major occurrences were located during the last five centuries (Figure 4). Except for the period between 1710 and 1800, when the occurrences seem to break a marked regularity, in the rest of the period there are phenomena that migrate along the almost linear strip which runs from the Capelinhos zone, east of Faial Island, to the eastern end defined by Santa Maria Island. This space migration is so regular that it is possible to estimate by mere visual inspection in

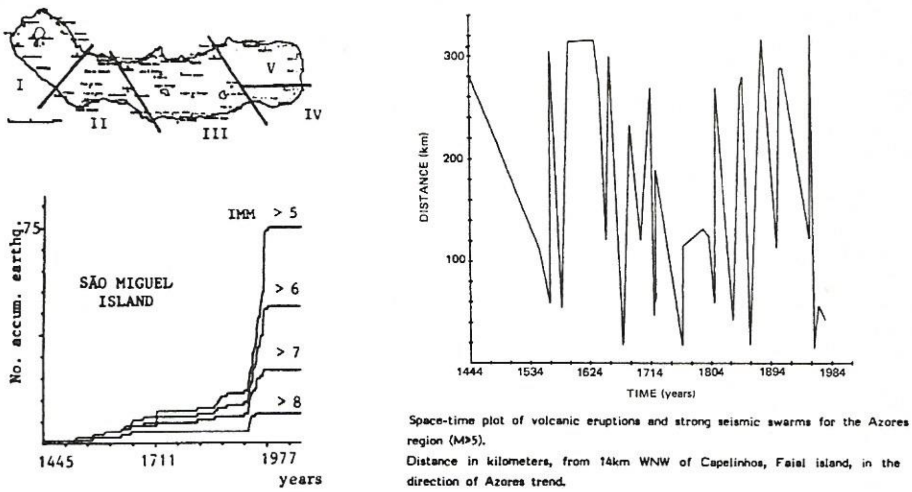

Fig. 4. Analysis of occurrences: time-space interdependence according to Victor and Nunes (1986).

approximately 50 years, the frequency of the seismic phenomena. The same result could have been obtained using Fourier's technique in space and time (Delsemme and Smith, 1979).

The frequency observed was used as the basis for fixing 42 years as the minimum period of observation for calculating the seismicity of any of these zones. Observations corresponding to shorter periods than this must, therefore, be corrected accordingly; otherwise underestimation of the seismicity, if our sampling period were to coincide with a period of quiescence, or overestimation if it coincided with a period of great activity, may take place.

The existence of this memory mechanism has aroused some doubts as to the application of Poisson's models for representing seismic occurrences. This problem, which calls for the closest attention when studying the Azores as a whole, will be dealt with in due course. It is not so important in the case of the study of an isolated locality.

Owing to the problems of the quality of the seismic data and in order to establish the laws of occurrence in time, the following procedure was used. For the case of complete information, five different situations were considered (Figure 5(a)): (1) the whole Archipelago; (2) São Miguel and vicinity; (3) Zone A of the D. João de Castro Bank; (4) Zone B to east of São Miguel; (5) Zone C of São Miguel and south. As regards the incomplete information for which only the intensities at villages on São Miguel are known, six different situations were considered (a given earthquake is attributed to a given zone on the island, according to the location of the village where there was greater seismic intensity, (Figure 5(a)): (1) whole of São Miguel Island; (2) Zone I; (3) Zone II; (4) Zone III; (5) Zone IV; (6) Zone V. Results corresponding to each of the previous situations are presented in Table II.

Aftershocks may significantly alter the value of the estimated parameters, principally when their number constitutes a high percentage of the total occurrences. In order to

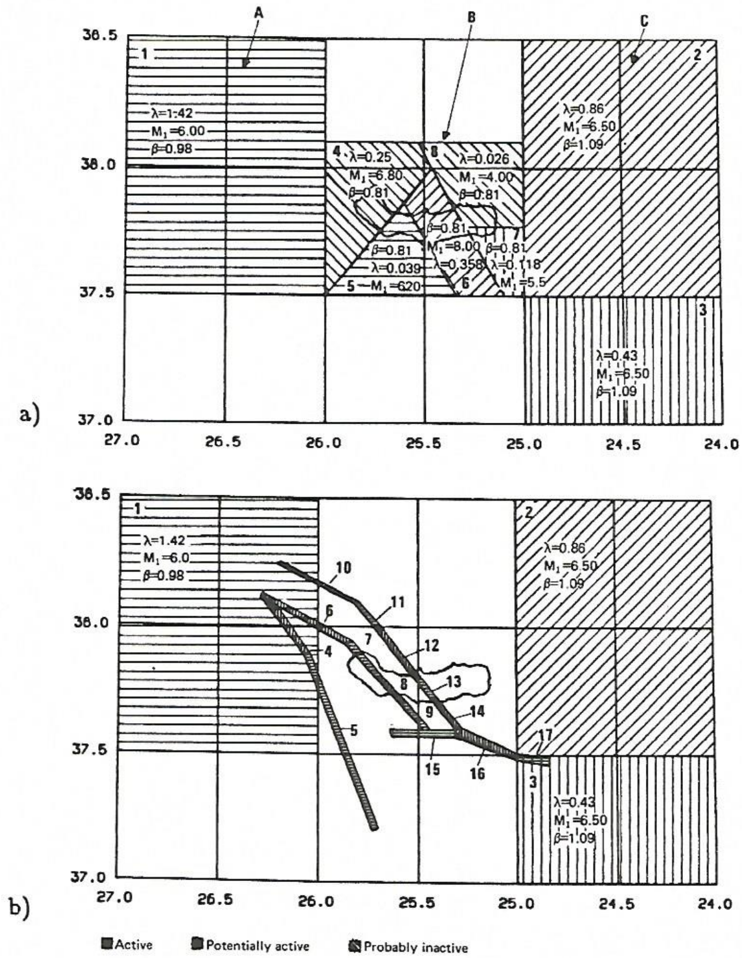

Fig. 5. Tectonic model for São Miguel Island and surroundings: (a) Model I; (b) Model II.

eliminate their influence, filtration by time windows of 1, 2 and 3 days was used. It was concluded for São Miguel that the presence of the aftershocks is no longer important after 1 or 2 days.

2.4. *Seismic Sources Models.*

Due to the lack of a comprehensive tectonic model, several alternative source models were used. The three main models are described below.

Model I – Based mainly on historical and instrumental seismicity (Figure 5a)
The zone of São Miguel and vicinity was divided into eight zones, three being large zones in the vicinity and five small zones covering the island as a whole, and the recurrence law for each zone was obtained by merging the concepts referred to above.

For the Santa Maria zone, owing to a lack of sufficient data, and in accordance with

Table II. Characterization of the law of recurrence for different situations under study

Situation	Mag/Int	Time period	λ	β	A	ρ (correl.)	No. of events
Whole Archipelago	Mag	1918–1976 (58 years)	23.27	1.39	4.94	−0.954	287
S. Miguel & Surroundings	Mag	1933–1975 (42 years)	3.593	1.112	3.624	−0.896	50
ZONE A D. J. Castro	Mag	1933–1975 (42 years)	1.415	0.98	3.048	−0.818	25
ZONE B S. Miguel & South	Mag	1952–1967 (15 years)	2.231	0.898	2.699	−0.868	9
ZONE C East S. Miguel	Mag	1959–1968 (9 years)	3.994	1.093	3.004	−0.962	15
ZONE D S. Miguel Island	Int	1444–1979 (523 years)	0.480	0.542	2.645	−0.984	158
ZONE I[a]	Int	1444–1979 (523 years)	0.151	0.538	2.140	−0.984	59
ZONE II[a]	Int	1811–1969 (158 years)	0.079	0.319	1.234	−0.919	9
ZONE III[a]	Int	1522–1978 (455 years)	0.254	0.493	2.277	−0.988	70
ZONE IV[a]	Int	1947–1978 (31 years)	1.243	0.641	1.868	−0.949	16
ZONE V[a]	Int	1967–1969 (2 years)	4.127	0.615	1.079	−0.979	4

[a] without aftershocks.
$\log N = A - BM$ or $\ln N = \alpha - \beta M, \lambda =$ no. earthq./year, ($M_o > 3$ or $I_0 > III$)

the tectonic characteristics, it was decided to attribute to it a seismicity equal to that of the eastern zone of São Miguel.

The M_1 values were obtained either from instrumental or from historical seismicity. In the first case, about half a degree higher than the maximum observed value was taken. In the second case, there was first of all conversion of maximum intensities observed into magnitudes by means of a simplified formula $M = 1 + 2/3\ I_0$ (in which I_o − epicentral intensity, was considered the maximum, even when the epicentre was visibly away from the island) and then the value found was increased by half a degree.

Model II – Based mainly on fault activity (Figure 5b)
It was considered that the principal seismicity originates in well-defined tectonic structures. The other seismicity comes from activity of a diffused kind that is not directly connected with recognized faults.

To each fault was attributed a rate of occurrence according to the classification of the type of fault, in compliance with the following principle (see Section 2.1): (a) active fault – 0.1 earthquakes/yr; (b) potentially active fault – 0.01 earthquakes/yr; (c) probably nonactive fault – 0.001 earthquakes/yr. The sum of the rates of occurrence/yr for all the faults must not, however, exceed that found in the whole of São Miguel and vicinity, which is rated at 0.79. The rate of occurrence refer to $M_0 \geqslant 3$. The recurrence law for each fault is identical to that of the most ample zone (Model I) in which it is located. The variant to Model II in which the faults are assumed to act together, forming a single active fault that is much longer, was also analyzed.

Maximum magnitudes that may occur in a given seismic zone, were computed from the maximum length of rupture that the fault may acquire (Slemmons, 1977). The values are in agreement with the ones based on the study of historical and instrument seismicity, using estimates of analysis of the distributions of extremes. All events were assumed to be shallow.

Model III – Mixture of Models I and II

It is considered that there exist both well defined active faults and background seismic activity originating in larger zones but differentiated from zone to zone. For instance, the faults and their rate of occurrence are kept, as in Model II, and the large zones, as in

Table III. Characterization of the zones of seismic generation (source), according to Models I and II

Model I – Source areas. Reference period, 42 years

Source	Zones	M_0	M_1	β	λ	h(km)	Attenuation (equation)
1	A- D. J. Castro	3.0	6.0	0.980	1.420	8	1
2	C- East	3.0	6.5	1.090	0.860	8	3
3	S. Maria	3.0	6.5	1.090	0.430	8	4
4	I-	3.0	6.8	0.810	0.250	5	3
5	II-	3.0	6·2	0.810	0.039	5	3
6	III-	3.0	8.0	0.810	0.358	5	2
7	IV-	3.0	5.5	0.810	0.118	5	3
8	V-	3.0	4.0	0.810	0.026	5	3

Model II – Source areas and source lines

Source	Zone	L(km)	M_0	M_1	β	λ	h(km)	Attenuation (equation)
1	Zone A	32	3.0	6.7	0.98	0.10	8	1
2	Zone B	83	3.0	7.7	0.81	0.01	8	3
3	S. Maria	44	3.0	7.0	0.98	0.10	8	1
4	Zone 4	20	3.0	6.1	0.81	0.01	5	2
5	Zone 5	16	3.0	5.9	0.81	0.001	5	2
6	Zone 6	16	3.0	5.9	0.81	0.01	5	2
7	Zone 7	38	3.0	6.9	0.98	0.10	8	1
8	Zone 8	15	3.0	5.8	0.81	0.10	8	3
9	Zone 9	24	3.0	6.3	0.81	0.10	8	2
10	Zone 10	12	3.0	5.6	0.81	0.10	8	2
11	Zone 11	16	3.0	5.9	0.81	0.10	5	2
12	Zone 12	28	3.0	6.5	0.81	0.01	5	3
13	Zone 13	28	3.0	6.5	0.81	0.01	8	3
14	Zone 14	13	3.0	5.7	1.09	0.01	8	4
Backgrd.			3.0	5.6	0.90	0.029	5	

L-rupture length, h-focal depth

Model I. The activity of the latter is obtained from the values of Model I by subtracting that part which is directly attributed to the faults existing in the zone.

Table III summarizes the parameter values for Models I and II.

3. Attenuation of the Seismic Waves

There are several techniques for determining the curves of attenuation in a given region, Oliveira (1987). This study has given preference to the empirical data obtained in the Azores region, since it has very specific geomorphological characteristics that are not found in many other parts of the globe.

Based on the isoseismals of the most important earthquakes felt in São Miguel (Figure 6), four different equations were obtained using the standard fitting techniques (Oliveira and Costa 1987), reflecting the zone of origin, the azimuth of preferential propagation, etc. Instrumental records obtained for small magnitude events in the local network, and the only two strong motion records recorded in other islands of the archipelago, were used for the calibration of these equations. Table IV presents the fitted parameter values.

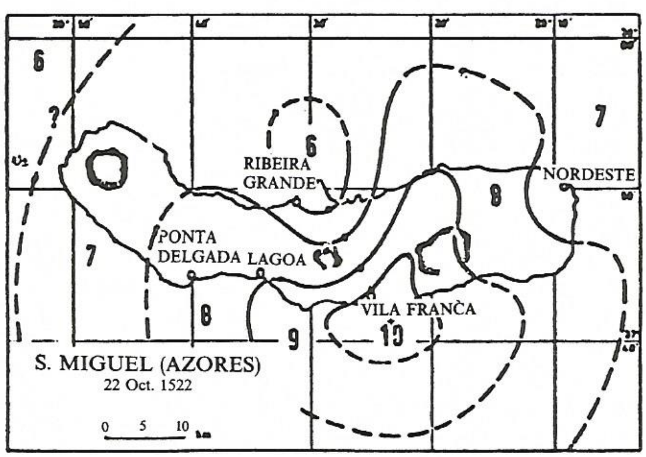

Fig. 6. Typical isoseismals map of an earthquake felt in São Miguel (MMI Scale).

Table IV. Attenuation equations

Type	Source	C_1	C_2	C_3
1	ZONE A	12.0	1.5	−5.8
2	ZONE C	6.22	1.5	−3.05
3	S. Maria	1.65	1.5	−1.49
4	ZONE D	9.14	1.5	−3.0

$I = C_1 + C_2 M + C_3 \ln(R + R_0)$

$\sigma = 0.5$ $R_0 = 5\,\text{km}$

4. Seismic Hazard on São Miguel Island

The method proposed by Cornell (1971) and the algorithm developed by McGuire (1976) were used for calculating the seismic hazard on São Miguel Island. Further information can be obtained in Oliveira (1977) and Oliveira (1989).

The choice of the Modified Mercalli Intensity as representative parameter of seismic action is justified by the fact that practically all existing information is based on intensities.

5. Results and Discussion

With the models and parameters referred to previously, the seismic hazard calculation programme (adapted from the EQRISK basic programme, McGuire, 1976) was run for a set of localities defined by a mesh of parallels and meridians covering the island with intervals of 0.1 degree and the neighbouring zones with intervals of 1 degree.

As is traditional in studies of this kind, when one is working with a large number of variables (models, parameters, attenuations, etc.), here too it is proposed that the final seismic hazard be obtained by a weighted analysis of the different hypotheses (Oliveira, 1989). Figure 7 therefore gives the mean seismic hazard and mean value ± 2 standard deviations for the locality of Ponta Delgada, coordinates 37.75N and 25.66W, corresponding to the study of 10 different hypotheses. Figure 8 gives the hazard map for São Miguel corresponding to the above-mentioned mean value, for annual probabilities in exceedence of 0.01 and 0.002.

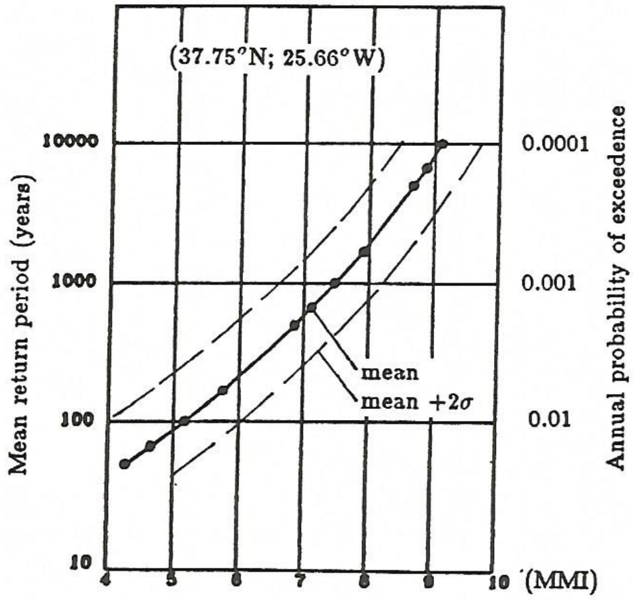

Fig. 7. Probability distribution of maximum intensities for Ponta Delgada and influence of the uncertainties in the final results.

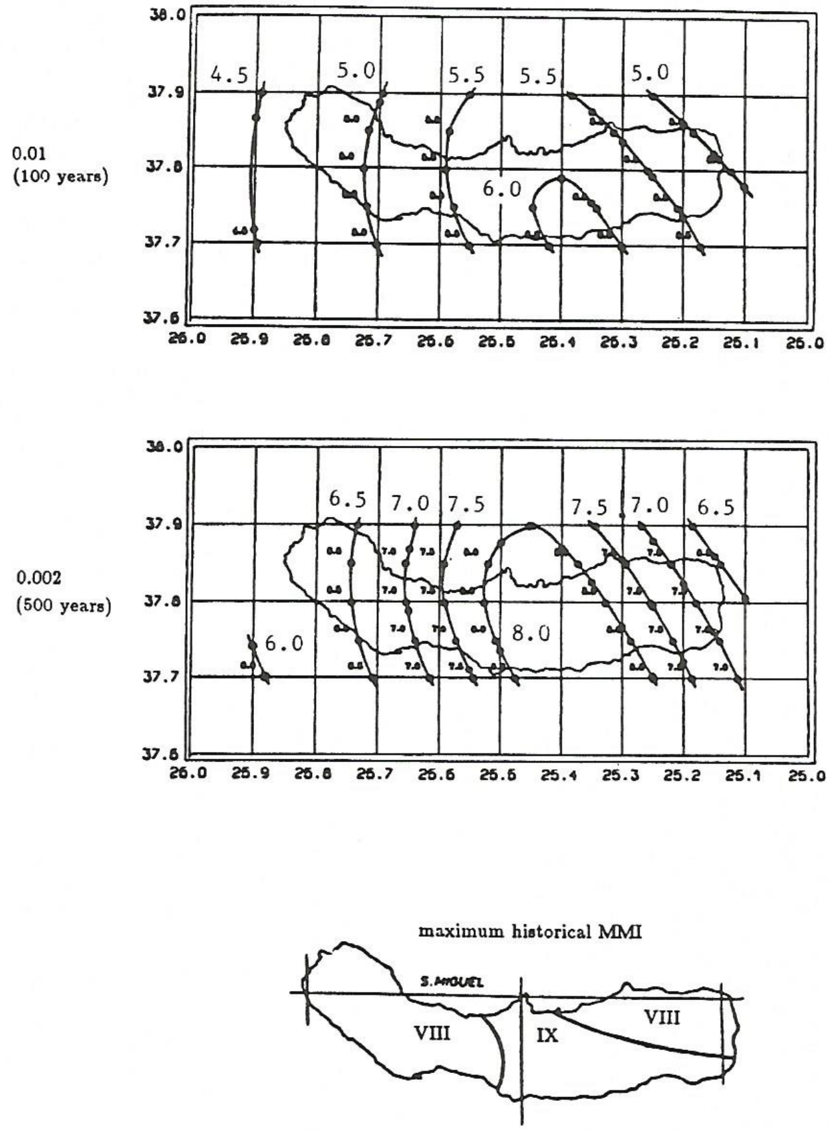

Fig. 8. Seismic risk maps for São Miguel Island for an annual probability of exceedence of 0.01 and 0.002. Comparison with maximum historical MMI observed in São Miguel (as obtained by Victor and Nunes, 1986).

From the results given in Figures 7 and 8, the following considerations can be made:

- Uncertainties on final hazard estimates as measured by ±2 standard deviation are still quite large; one MMI degree at the 0.01 level.
- São Miguel Island presents hazard variations of 1 and 2 degrees on the MMI Scale from place to place and this therefore precludes the hypothesis of previous studies, that there is uniform seismicity throughout the island.

- The mean values corresponding to 0.002 (500 years of recurrence period) are slightly different from those represented on the maps of historical maximum isoseismals (Victor and Nunes 1986) where the geographical distribution is similar to that now obtained, though the present values are lower by about 1 degree MMI, (Figure 8).

6. Future Work for Improving Characterization of Seismic Hazard

The constant advance in knowledge of the seismicity of a territory calls for periodical revision of hazard studies. The main consequence is a diminuation of the intervals of uncertainty in the final estimates. In the specific case of the study of São Miguel, it is necessary to invest, in the medium term, in the following points:

- Improvement of the basic catalogue – in order to eliminate repetitive information and complete it with further seismic parameters for each important occurrence.
- Improved definition of the seismic generation zones (source) through better knowledge of the tectonics of the island and its neighbouring zones.
- Improved formulae of attenuation by plotting further isoseismals of earthquakes with complete information and using further instrument information. This last aspect should include the calculation of spectra of the main earthquakes affecting the island, permitting the definition of spectra-consistent hazard maps.

The estension of these studies to the entire Archipelago as a whole, cannot be made without considering the time-space interdependence (Oliveira, 1989).

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