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Seismic hazard zonation of Catalonia, Spain, integrating random uncertainties

R. Secanell[1,2,*], X. Goula[1], T. Susagna[1,2], J. Fleta[1] & A. Roca[1]
[1]*Servei Geològic de Catalunya, Institut Cartogràfic de Catalunya, Barcelona, Spain;* [2]*Observatory Fabra, Barcelona, Spain;* **Now at GEOTER sarl, Clapiers, France*

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Abstract

In order to analyse the seismic hazard in Catalonia a new parametric earthquake dataset, in terms of macroseismic intensities, has been used. A new seismotectonic zonation of the area under study and surrounding regions, which takes into account the geologic and seismic data, is proposed. From these input data, an estimation of the seismicity of the various seismotectonic zones has been carried out using both stationary and non-stationary models. As seismicity does not show important non-stationarities, a hazard analysis, has been carried out with the parameters from the stationary model. A sensitivity study, using the Montecarlo technique shows relatively small uncertainties. For each point of the studied area the maximum likely felt intensity was also considered. A seismic hazard map combining the probabilistic and deterministic models integrating uncertainties resulting from sensitivity analysis is proposed.

Introduction

A seismic hazard assessment for Catalonia, situated in the north-east of Spain, has been carried out and a seismic zonation of the region is proposed. Earlier studies on seismic hazard assessment (Roca y Suriñach, 1982; Muñoz, 1982; Martin Martin, 1984; Martin Martin, 1989; Egozcue et al., 1991; Mayer-Rosa et al., 1993) pointed out the need for better input data, particularly in regions such as Catalonia where seismicity is moderate in order to reduce the uncertainty obtained in those studies. With this purpose, research oriented toward the revision of the earthquake catalogue and to the definition of an 'objective' seismotectonic frame was undertaken in the last years. Thus, a new regional seismic hazard assessment has been performed according to the following steps:

- Consideration of a new earthquake dataset for Catalonia and its influencing area obtained from the revision and critical comparison of the macroseismic data from different catalogues (Susagna et al., 1996; Susagna and Goula, 1999). The patterns followed are in agreement with the criteria established in the preparation of a European Catalogue within the BEECD Project (Albini and Stucchi, 1997), which harmonises the information from different countries.
- Consideration of a new seismotectonic zonation of the study region taking explicitly into account the different geologic, tectonic and seismic knowledge of the area (Fleta et al., 1996; Autran et al., 1998).
- Seismicity parameters for the different seismotectonic zones have been estimated from these input data. Because seismicity is moderate, different models of distribution on intercurrence times (stationary and non-stationary) have been used together the exponential distribution for the size of earthquakes to estimate the rate of occurrence of earthquakes. An extreme value model has been also used.
- Determination of attenuation laws of the intensity versus distance, fitting the available seismic data points of the study region.
- Seismic hazard assessment is carried out using two methods: a probabilistic zonified approach and a deterministic non-zonified model. A sensitivity

analysis of the probabilistic assessment has been carried out in order to investigate the influence of the uncertainty of parameter values on the stability of the results. A Monte-Carlo method is used to determine the confidence of the results.

- Finally, a seismic hazard zonation associated to a return period of 500 years combining the most representative facts of both approaches is proposed.

In this paper the hazard assessment was produced in terms of epicentral intensity for two main reasons. First the earthquake database, and in particular the recent revision of the Catalan catalogue, is available in MSK epicentral intensities and many intensities data points are available and useful to propose attenuation relations. Second, this study is a first step of a complete seismic risk assessment that was carried out in our region for emergency plan purposes. Most of the available ground motion-vulnerability-damage relationships are in terms of macroseismic intensities as available damage observations are usually interpreted in terms of intensity. It would be correct to correlate PGA to percentage of damage through vulnerability but, as PGA data are scarce, intensity can be used as a rough ground motion indicator and fragility curves are expressed by intensity.

Input data

In order to analyse the seismic hazard for Catalonia a good earthquake dataset needs to be made both of information from this region and from the surroundings (Figure 1), including two areas which could contribute to the seismic hazard of Catalonia: the South-Eastern part of Spain (zone D in Figure 1), and the South of France (zone C in Figure 1). The working file used in this work contains parametric data of each earthquake according to the following information source.

1. For Catalonia (zone A in Figure 1) the seismic information has been obtained from a new earthquake catalogue (Susagna and Goula, 1999). This new catalogue contains information from earlier earthquake catalogues (IGN, 1991; BRGM-CEA-EDF, 1994; Fontserè and Iglésies, 1971; Suriñach and Roca, 1982). A critical comparison (Susagna et al., 1996) of the different information sources, together with the inclusion of specific studies on historical seismicity (Olivera et al., 1994; Susagna et al., 1994), lead to the creation of this new revised catalogue for the study area. Special effort was devoted to the revision of earthquakes with epicentre near the border line between Spain and France. The catalogue contains information about 800 earthquakes catalogued with different quality index. About 200 of them have epicentral intensity values equal or greater than V. This is the minimum value of intensity considered in this seismic hazard analysis.

2. For the Iberian Peninsula out of zone A (zones B and D in Figure 1), the catalogue used is the IGN (1991) completed with the work from Bisbal (1984).

3. Finally, for the Pyrenees out of zone A (zone C in Figure 1) the catalogues used are the IGN (1991) and the French working file BRGM-CEA-EDF (1994). To resume, the priority order used to make the catalogue was the following: 1) zone A, 2) zone C, 3) zone D and finally, 4) zone B.

For the evaluation of seismic hazard a seismotectonic zonation has been adopted because the knowledge on active faults is poor. The basic hypothesis is that the heterogeneity of the continental crust could explain the distribution and other characteristics of seismicity.

For this first step the methodology proposed by Grellet et al. (1993) has been applied which is based on the analysis and mapping of different geological aspects, named themes in this approach. Some modifications in the methodology have been introduced due to differences of scale and geological context. The variations of different parameters for selected themes allow homogeneous tectonic zones to be identified (Fleta et al., 1996). Thus, the tectonic zonation is the first step that has been applied taking into account the more representative parameters of the crustal structure, mainly coming from the inherited geological structures.

A seismotectonic zonation was obtained, for probabilistic analysis purposes, from the tectonic zonation, complemented by the seismicity distribution. Only three of the eleven seismotectonic zones (num. 7, 10 and 11 on Figure 2) are defined by a simple seismicity distribution criteria. The epicentres of all earthquakes considered with the eleven seismotectonic zones proposed are shown in Figure 2. For the border area between Spain and France the zones proposed are in agreement with the preliminary zones established in France (Autran et al., 1998).

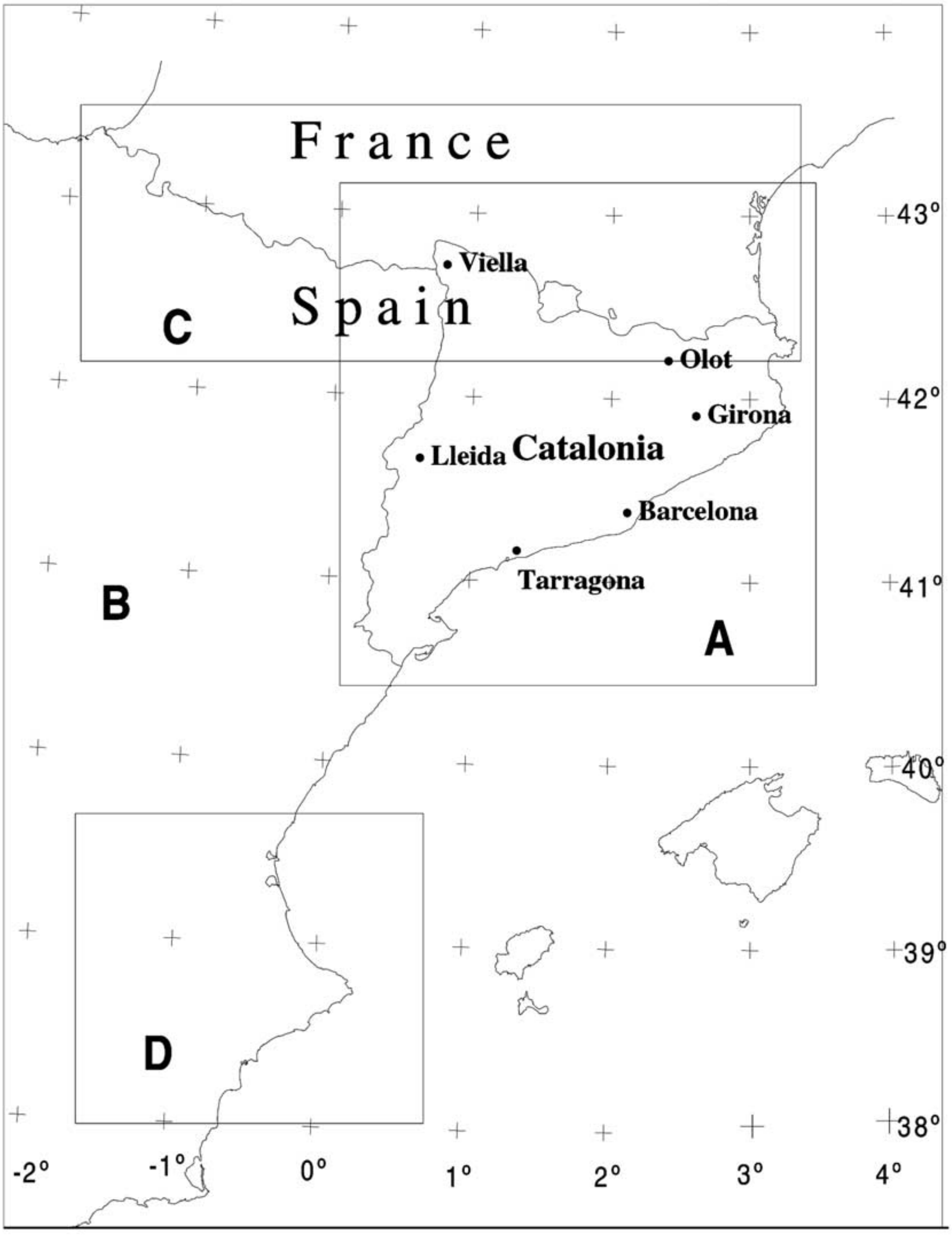

Figure 1. Geographic situation of the region considered. A = study zone; B, C, D = zones contributing to the seismic hazard of the study zone.

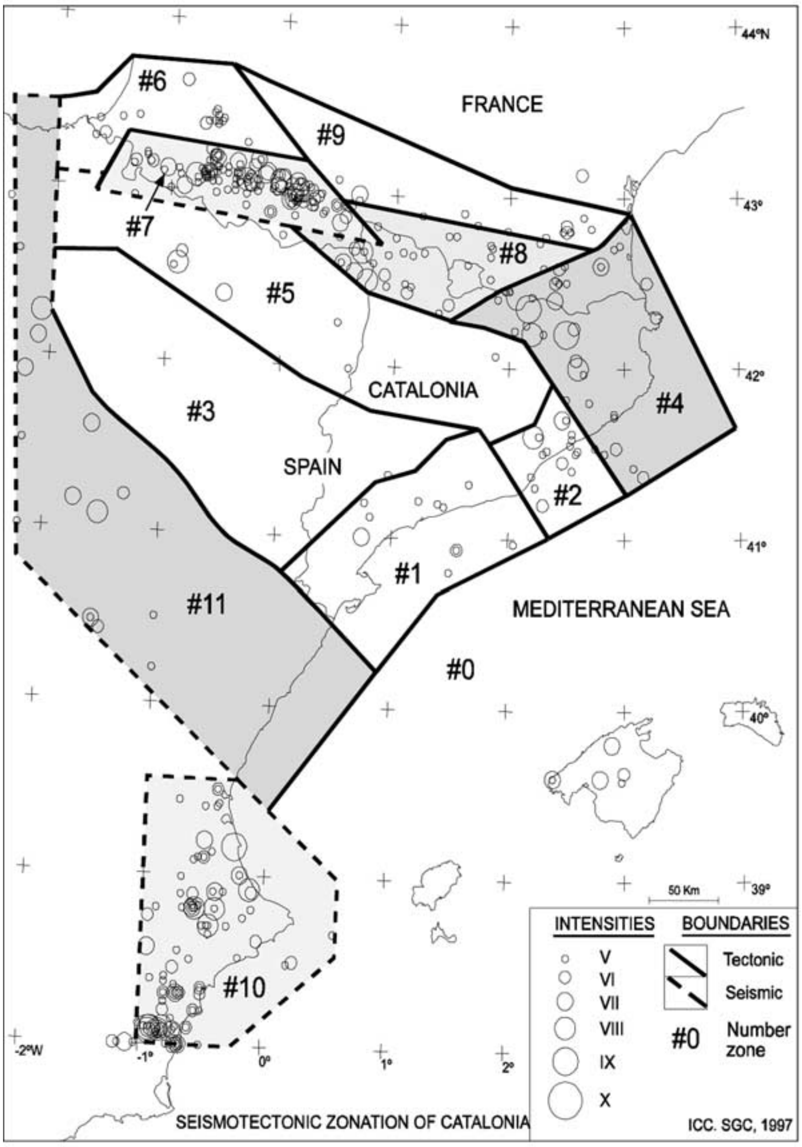

Figure 2. Seismotectonic zonation of Catalonia and the surroundings and epicentres of all the earthquakes considered. Zones defined on the basis of seismicity are represented by dashed borders.

Seismic occurrence models

The analysis of the seismicity has been carried out fitting various seismic occurrence models to the available seismic data for each seismotectonic zone. A stationary Poisson model was used as intercurrence time distribution and was combined with an exponential magnitude distribution. This leads to a Gutenberg-Richter distribution of seismicity. Secondly, a non-stationary Poisson model was used. This model considers the Poisson parameter depending on time, λ(t). Finally, two Gumbel (1954) distributions, Gumbel I and Gumbel III, have been also fitted.

A completeness study of the seismic catalogue has been carried out analysing the number of earthquakes of each intensity level that occurred in different periods of time starting from the present days and going back in time to the 13th century. The analysis of the completeness has been made, basically, with a visual analysis of the graphics of the seismicity of each zone. It is considered as the complete period, the period which first shows an earthquake rate decay. The max-

Table 1. Complete periods in years (counting from present time backward) for the different intensities recorded in each zone studied

INTENSITY	ZONE 1	ZONE 2	ZONE 4	ZONE 5	ZONE 6	ZONE 7	ZONE 8	ZONE 9	ZONE 10	ZONE 11
IV,IV-V	100	100	100	100	100	100	100	150	100	100
V,V-VI	100	100	150	150	150	100	100	150	150	150
VI,VI-VII	150	150	200	200	250	150	250	250	200	200
VII,VII-VIII	250	250	250	750	–	250	400	400	250	750
VIII,VIII-IX	–	750	750	750	–	400	750	–	750	750
IX,IX-X	–	–	750	–	–	–	–	–	750	–
X,X-XI	–	–	–	–	–	–	–	–	750	–

imum period considered is 750 years for the complete catalogue.

This completeness study is performed for each zone. It is possible to observe that periods of completeness obtained depend on the different circumstances of each zone. Thus, for low levels of intensity, for example, more populated zones have a period of completeness longer than less populated zones. The resulting completeness periods for each zone are shown in Table 1. In zone 3 and in the background zone (zone 0) there are not enough data to perform this analysis. We used a catalogue with aftershocks because we give a higher importance to the energy released than to the temporal dependence of the seismicity. This is a seismicity moderate region where the aftershocks are not very often.

Renewal process

Combining a stationary Poisson process for the intercurrence times, and an exponential distribution of magnitudes, we obtain the first model fitted (Goula and Godefroy, 1985):

$$\Pr(I \geq i) = \alpha * (\exp(-\beta * (i - i_0)) - \exp(-\beta * (I_{max} - i_0)))/ (1 - (\exp(-\beta * (i_{max} - i_0)))$$

where Pr(I ≥ i) is the annual probability of exceeding, or being equal, a value of the intensity i, i_0 is the minimum epicentral intensity considered, i_{max} is the maximum epicentral intensity allowed in each zone, α is the mean annual activity rate for intensities greater or equal to i_0, and β is a parameter related to the slope of the Gutenberg-Richter law. The minimum intensity considered in this study is V (M.S.K.). The maximum intensity allowed in each seismic zone is imposed according to the seismic conditions of each source zone: i_{max} values are deduced from the maximum observed intensity, for each zone, increasing one degree except for zone 7 where observed intensity is increased by two degrees because of the high level of seismicity and the short period of available data in this zone.

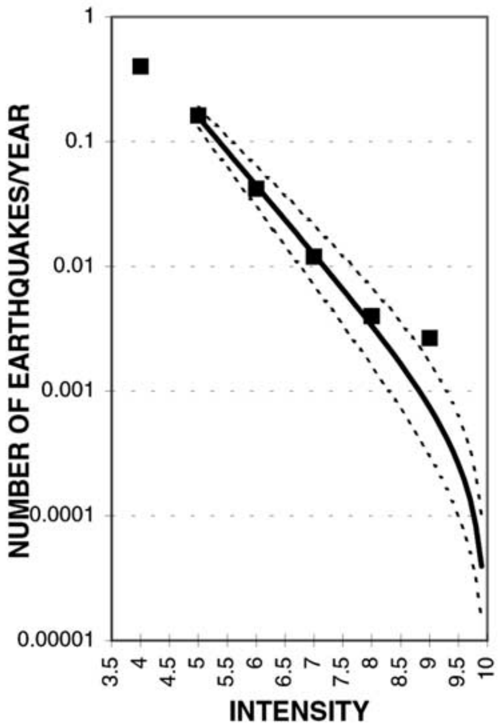

Figure 3. Truncated Gutenberg-Richter law for zone 4 (mean curve ± standard deviation). Squares represents observed number of earthquakes per year for each intensity degree.

Seismicity parameters α and β were computed following the maximum likelihood method proposed by Weichert (1980). Table 2 shows, for each zone, its surface in km^2 and the corresponding values of α and β (mean values and standard deviations) and i_{max}. The most actives zones are the central Pyrenees (Zone 7)

Table 2. Parameters of truncated Gutenberg-Richter relation for each seismotectonic zone; α and σ (α) are the mean value and standard deviation of the activity rate on number of earthquakes per year; β and σ (β) mean value and standard deviation of the negative exponential parameter related to the slope of the Gutenberg-Richter relation; Imax, the maximum epicentral intensity assigned to each zone

	Surface (km^2)	α	$\sigma(\alpha)$	β	$\sigma(\beta)$	h	i_{min}	i_{max}
ZONE 1	14100	0.100	0.030	1.864	0.559	7	V	VIII
ZONE 2	4600	0.128	0.033	1.608	0.324	7	V	IX
ZONE 4	16300	0.157	0.030	1.256	0.186	10	V	X
ZONE 5	23100	0.040	0.014	1.319	0.373	10	V	IX
ZONE 6	8000	0.099	0.025	1.977	0.640	10	V	VII
ZONE 7	7200	0.957	0.090	1.420	0.116	15	V	X
ZONE 8	7700	0.218	0.040	1.716	0.246	15	V	IX
ZONE 9	9600	0.070	0.020	1.737	0.214	10	V	VIII
ZONE 10	19700	0.635	0.059	1.201	0.083	10	V	XI
ZONE 11	40100	0.060	0.016	0.886	0.242	10	V	IX

and the zone 10 (situated outside Catalonia). Special attention is given to zones 1, 2 and 4 due to the fact that a great part of the population of Catalonia lives there. Figure 3 shows an example of fitting the truncated Gutenberg-Richter model to the seismic data of Zone 4.

Extreme value models

In order to test another way to estimate the parameters of the occurrence model, we used the extreme value law, widely used in the literature, that conceptually represents the same process but in practice, only the largest earthquakes are used.

The extreme-value, Gumbel I, distribution (Gumbel, 1954, 1958) was used:

$$G_n^1(z) = \exp[-\exp(-\beta_G(z-u))],$$

where z is the variable related to the hazard (intensity), G(z) is the distribution function and β_G and u are the parameters of the function (Epstein and Lomnitz, 1966; Secanell, 1999). These parameters were obtained using a linear regression analysis.

Gumbel III distribution (Gumbel, 1954, 1958) was also fitted to the data:

$$G_n^3(z) = \exp\left(-\left(\frac{w-z}{w-U}\right)^k\right),$$

where w, K and U are the parameters of the function. The parameter w is related to the maximum intensity expected to occur in a region and was fixed to be equal to i_{max} in each seismotectonic source considered. The other parameters were obtained using a linear regression analysis.

In order to fit Gumbel I and Gumbel III distributions to the seismic data, the original method proposed by Gumbel (1954) using intensities (Roca et al., 1984) has been applied. The observed extreme values of epicentral intensities, I_i, i = 1, . . ., N, corresponding to the N time intervals of length Δt in which the sample is divided, have been ordered in increasing size: $I_1 \leq I_2 \leq \ldots \leq I_j \leq \ldots \leq I_N$ and 'plotting points' G_j, computing using the original rule $G_j = G(I_j)$ = j /N+1, where j = 1, . . ., N (Gumbel, 1954). It is necessary to take into account two parameter estimations: the time interval duration and how the empty intervals have to be taken into account. Different time interval durations (5, 10, 20, 50 years) were used to fit the available data. Long time intervals do not provide enough data and short time intervals increase the problem of empty intervals. The analysis shows that the best fit to the available data is obtained when the time interval is fixed to 10 years (Secanell, 1999).

Concerning empty intervals different kind of estimations are possible as to eliminate empty time intervals or to replace the time intervals with the minimum observed intensities. After a sensitivity analysis using different time intervals (Secanell, 1999), it was proved that the best solution was obtained assigning to the empty time intervals the minimum observed intensity in each seismotectonic zone.

Figure 4 shows the comparison between the activity rates (number of earthquakes per year) obtained using the extreme value method and the Gutenberg-

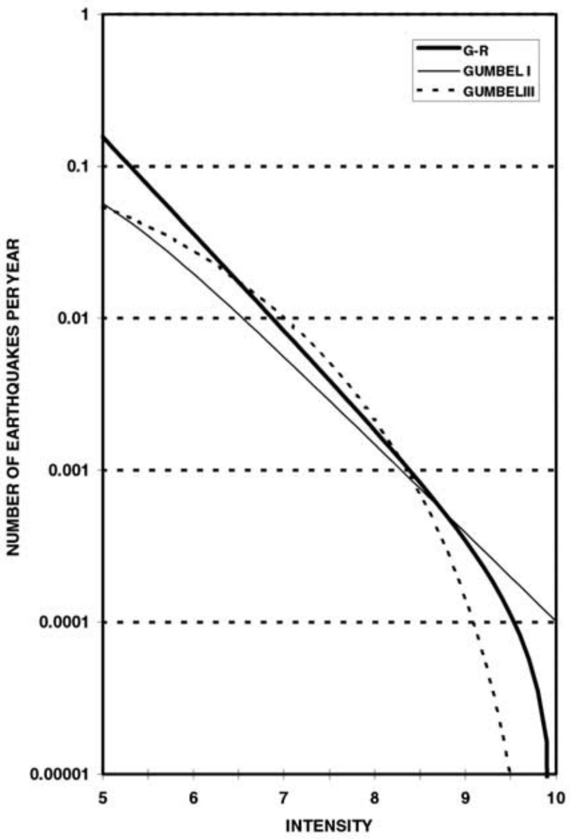

Figure 4. Comparison between the seismicity rates given by renewal process, Gumbel I and Gumbel III models for zone 4.

Richter law for a particular seismotectonic zone. It can be seen that there are no great differences among the different distributions, except for the largest intensities, around i_{max} value.

Non stationary models

The non-stationary Poisson model proposed by Savy (1978) and modified by Hong and Guo (1995) has been applied. The model proposes a temporal occurrence of earthquakes following a Poisson law including a temporal dependence of the mean occurrence. This temporal dependence in the parameter of Poisson, λ(t), gives to the model the name of non-stationary Poisson model. Thus, when a large period of time has elapsed without the occurrence of a great earthquake, its probability of occurrence is larger than in the years following a major event.

The counting process proposed by this model is based on the assumption of independent increments and, at most, one occurrence at any instant of time. It differs from a stationary Poisson model by the fact of having a varying average occurrence time. In this type of model, the number of arrivals in the time interval (t_1,t_2), $N(t_2)$-$N(t_1)$, is a random variable with a probability mass function (Hong and Guo, 1995):

$$p[N(t_2) - N(t_1) = n] = \frac{\int_{t_1}^{t_2} \gamma(\tau) d\tau}{n!}$$

$$*\exp\left(-\int_{t_1}^{t_2} \gamma(\tau) d\tau\right)$$

where the activity rate, γ, and the return period, T, are time dependent:

$$\gamma(t) = \mu\lambda t^{\lambda-1}$$

$$T(t) = \frac{1}{\mu\lambda t^{\lambda-1}}$$

The mean and the standard deviation are used to determine the parameters μ and λ.

The initial idea was to carry out such analysis in every seismotectonic zone, when the data were sufficient. Therefore, a dynamic map of earthquake occurrence and, in consequence, a dynamic hazard map should be obtained. The results show that only the analyses with intensities equal to or larger than VI are possible. However, the standard deviations are, in these cases, large. This fact is due to the lack of data when working with individual seismotectonic zones.

In order to avoid large errors, an analysis for the whole Catalan territory was carried out. Then the period of recurrence for only intensity VIII was studied.

Figure 5 shows the variation of the return periods obtained with the non-stationary Poisson model for different times elapsed since the occurrence of the last earthquake of intensity VIII. It can be noticed that, for the years following a major earthquake, the return period for an earthquake of the considered intensity is very long. This shows a low probability of occurrence of earthquakes after a big one, as expected. However, it can be noticed that the return period decreases slowly when the time elapsed since the last event increases with a near asymptotic trend to 85 years (which is the return period obtained through Gutenberg-Richter approach), i.e. the return period becomes independent of the elapsed time since the last event. Therefore, our catalogue gives evidence of a stationary behaviour.

From the analysis and comparison among the different occurrence models it is possible to deduce that:

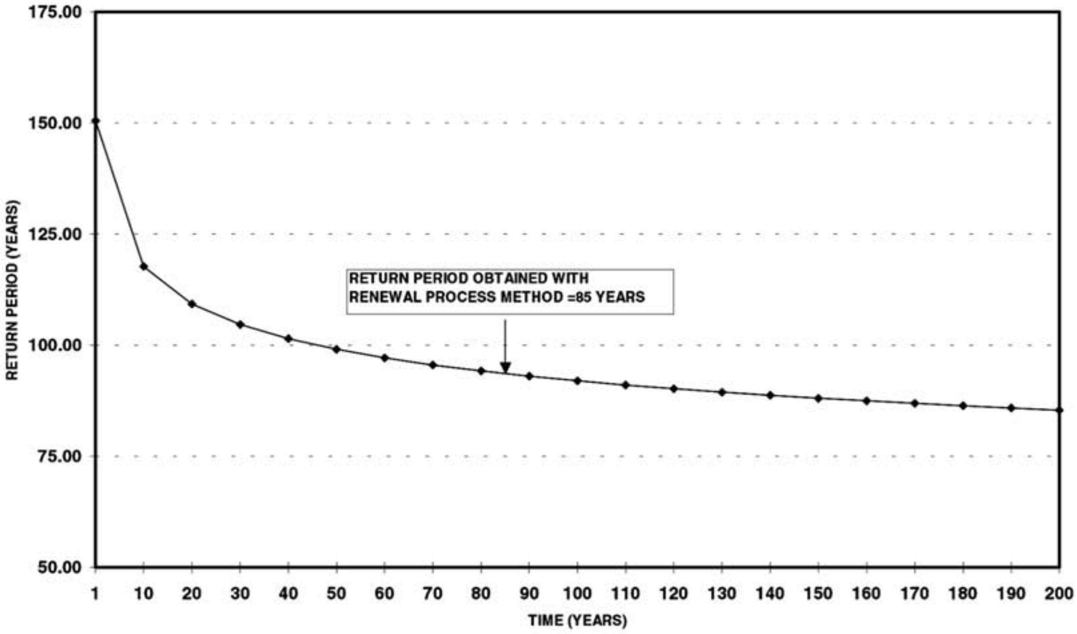

Figure 5. Variation of the return periods obtained with the non stationary Poisson model for different times elapsed since the occurrence of the last earthquake of intensity VIII, or greater, for the whole area of study.

- The truncated Gutenberg-Richter model can be applied to almost all seismotectonic sources.
- The extreme value models and the non stationary model can only be applied to the seismotectonic sources where there are enough data.
- The results obtained using extreme value models have a great variability depending on the input parameters used. In particular, the time intervals and the way that empty intervals are considered (deleting them or fixing an arbitrary intensity).
- In spite of above mentioned uncertainty, the mean values of obtained parameters using Gumbel I, Gumbel III and renewal process models lead to similar values of return periods associated to different intensities (except for major intensities) (Figure 4).
- The application of a non-stationary model shows an almost stationary behaviour for the seismicity of the whole territory.

For these reasons, the truncated Gutenberg-Richter model has been used to estimate, for each seismotectonic zone, the seismicity parameters (α, β, h and I_{max}) to be considered for probabilistic seismic hazard assessment.

Attenuation laws and seismic hazard assessment

It is well known that a crucial point in seismic hazard assessment is how to consider the attenuation process. In this study attenuation has been adapted to each seismotectonic zone.

The attenuation law used is the model proposed by Sponheuer (1960):

$$I_0 - I = k * \log\left(\sqrt{(r^2 + h^2)}/h\right)^b$$
$$+k * \gamma * \text{loge}\left(\sqrt{r^2 + h^2} - h\right)$$

where I_0 is the epicentral intensity, I the intensity value at a site located at epicentral distance r, h the focal depth, b the geometrical spreading parameter, γ the anelastic attenuation coefficient and k is a factor relating intensity to the logarithm of the ground motion amplitude. The model was applied to the available felt intensities of 100 moderate earthquakes that occurred in the 20th century and to the felt intensities maps of four major and well-documented historical earthquakes of the study area, mainly from the middle age (Secanell, 1998, 1999 and Ambraseys, 1985). These studies fixed the values of the parameters b and k equal to 1 and 3 respectively (Sponheuer, 1960). We have preferred to fix two parameters, b and k, and obtain a good control of the other parameters (h and γ) than to fit three parameters and to have a great uncertainty on them. As an example, the fit of the attenuation law to the data points for the earthquake occurred the 19^{th} of November of 1923 (from Susagna et al., 1994) is shown in Figure 6.

The obtained focal depths for the totality of fitted laws range between 5 and 15 km and very low values ($\sim$0.001 km^{-1}) of γ attenuation parameter are obtained.

The observed lower attenuation for some of the earthquakes that occurred in the Pyrenees is due to their higher depth in zones 4, 7 and 8; in these regions depth is supposed to vary between 10 and 15 km while for the rest of the zones the depth is supposed to range from 5 to 10 km. This choice is supported by geological and instrumental seismic data, by the analysis of attenuation data points and attenuation data maps of well-documented earthquakes and, finally, some studies made in France give to these zones a similar depth that we used (Autran et al., 1998).

The anelastic attenuation used was finally γ = 0.001 km^{-1} for all zones except for zone 10, where a greater value was applied. The value γ = 0.001 km^{-1} was already proposed by several earlier studies (Susagna et al., 1994; Secanell et al., 1996). The higher anelastic attenuation arbitrarily imposed (γ = 0.1 km^{-1}) to the zone 10 corresponding to the South of Spain is due to the fact that no earthquake that occurred in this zone has ever been felt in Catalonia.

With the attenuation law adapted for each seismotectonic zone, seismic hazard assessment was carried out using two models: a deterministic non-zonified method and a probabilistic zonified method. Seismic hazard maps based on both methods are proposed.

The maximum felt intensity map is obtained applying the attenuation relation to every earthquake existing in the catalogue, then computing for each grid point the maximum derived intensity. No attenuation was considered around the epicenter up to distances (R_o) between 2 and 10 km depending on the intensity of the event to take into account the seismic source size in cases of high epicentral intensities (major events).

The resulting map is presented in Figure 7 and shows the maximum intensity likely historically felt in each point of Catalonia.

The procedure used for the probabilistic assessment is essentially based on the Cornell method (1968), later modified by McGuire (1976) and adapted by Goula and Godefroy (1985) for using the Sponheuer attenuation law and a truncated Gutenberg-Richter recurrence model. Seismicity is considered distributed on homogeneous seismic sources, each of them characterised by the seismicity parameters defined in Table 2.

The probabilistic seismic hazard map presented in Figure 8 shows the intensity level (as a continuous parameter) corresponding to a return period of 500 years. The obtained intensities range from less than VI in the South to VII-VIII in the Northwest part of Catalonia.

It is important to remark that the random uncertainties on attenuation laws are integrated in the computation process. A standard deviation equal to 0.5 degrees of intensity was used in our calculation process.

Random uncertainty analysis

A sensitivity analysis has been carried out in order to investigate the influence of the uncertainty of the input parameters on the stability of the results of the probabilistic method. For this purpose a Monte-Carlo method has been applied.

For each seismotectonic zone the parameters controlling the seismicity were considered as probability distribution functions in the following way:

- α and β are considered as random variables following a Gaussian probability distributions with the mean and standard deviation values already presented in Table 2.
- Depth, h, and distance without attenuation, R_0, are considered as random variables following Gaussian probability distributions. The mean value of the depth corresponds to the value used to determine the seismic hazard and the standard deviation is considered to be equal to 5 km. The mean value R_0 corresponds to the value used in the hazard assessment and standard deviation of R_0 is taken equal to a half of R_0.
- The maximum possible intensity of each zone, I_{max} was considered as random variable following a triangular probability distribution, with $P(I_{max} = I_{obs}) = 0.25$, $P(I_{max} = I_{obs}+1) = 0.5$ and $P(I_{max} = I_{obs}+2) = 0.25$ where the I_{obs} corresponds to the maximum intensity observed in the zone.

One hundred random values of each one of the abovementioned parameters were generated for every seismotectonic zone. Then 100 random computations were performed in order to estimate the seismic hazard

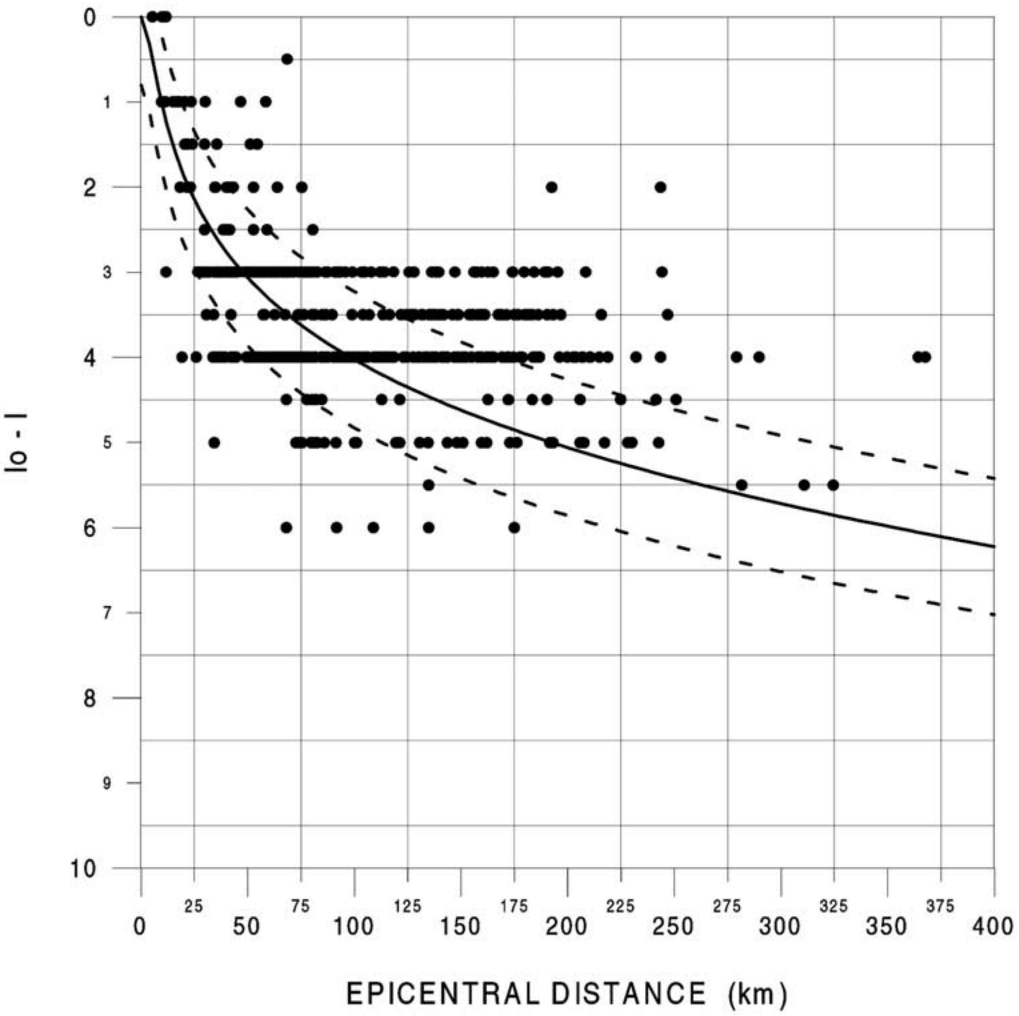

Figure 6. Available macroseismic data of the 19/11/1923 earthquake with epicentral intensity VIII and attenuation law (Sponheuer, 1960) adjusted (mean curve ± standard deviation). Focal depth = 5 km and 0.001 km^{-1} for γ parameter.

in six selected cities: Barcelona, Girona, Tarragona, Lleida, Olot and Viella.

The distributions of obtained intensities associated to the return periods of 500 years were characterised with the mean value and the standard deviation. It was proved that the results did not differ when more than 100 random samples were used.

The χ-square test does not show an unacceptable approximation to a Gaussian distribution in the cities studied. As an example, the results obtained with the Montecarlo method and the fitting Gaussian curve for Barcelona city is shown in Figure 9.

An analysis of the uncertainty of seismic hazard assessment, measured as the standard deviation of the intensity, has been carried out in four return periods, 500, 1000, 2000 and 10000 years. The analysis was performed in the six selected cities of Catalonia.

An example of seismic hazard curves, represented by mean values and one standard deviation is shown for 6 cities in the Figure 10. We can observe, for example, that the uncertainty varies from 0.3 degrees of intensity for the return period of 500 years to 0.4 degrees of intensity for the extreme return period of 10000 years in Barcelona. In the other cities the variation of the uncertainty between the return period of 500 years and the return period of 10000 years is also about 0.1 degrees of intensity. The mean values of intensities ($\bar{I}_t$) and their associated uncertainties with the return periods used, obtained in the six selected cities of Catalonia are shown on Table 3. However, we

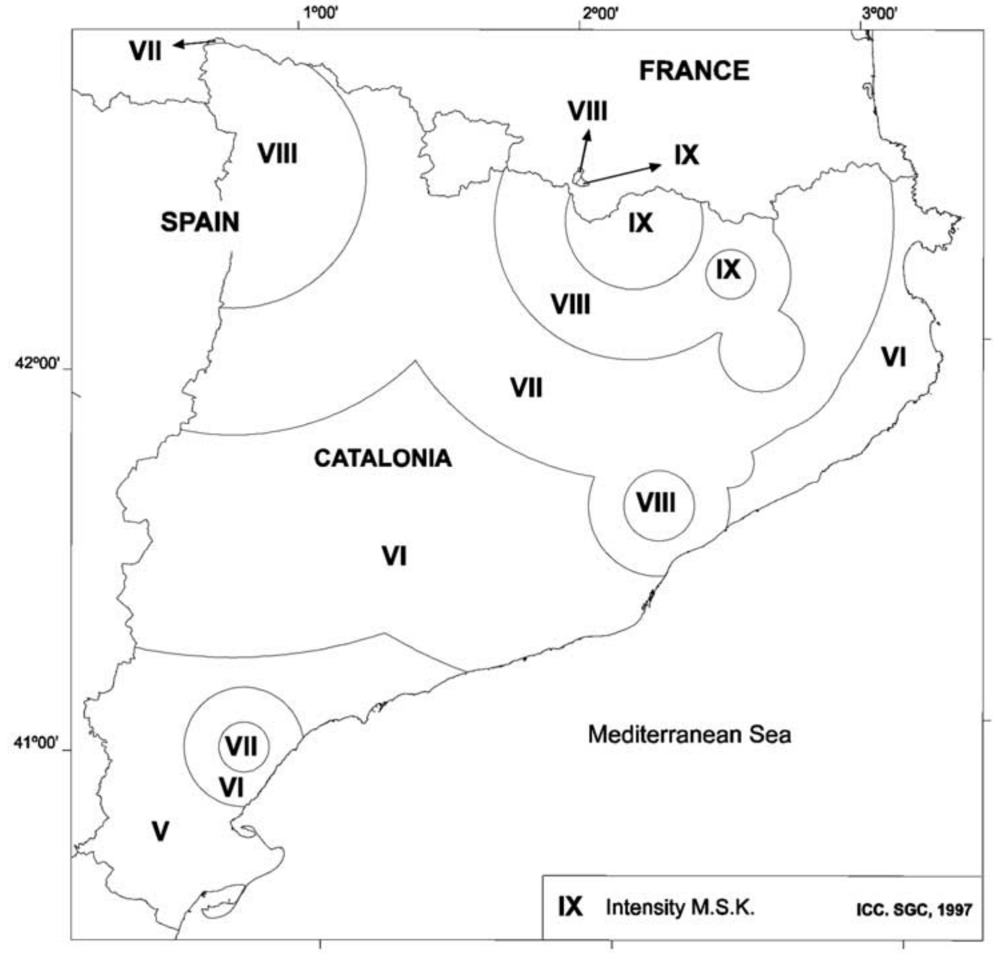

Figure 7. Map showing the maximum intensities historically felt in Catalonia.

Table 3. Mean values $\bar{I}_t$ and standard deviations σ $(\bar{I}_t)$ of the intensities obtained in some cities for return periods of 500, 1000, 2000 and 10000 years

	BARCELONA		LLEIDA		TARRAGONA		GIRONA		OLOT		VIELLA	
	$\bar{I}_t$	$\sigma(\bar{I}_t)$	$\bar{I}_t$	$\sigma(\bar{I}_t)$	$\bar{I}_t$	$\sigma(\bar{I}_t)$	$\bar{I}_t$	$\sigma(\bar{I}_t)$	$\bar{I}_t$	$\sigma(\bar{I}_t)$	$\bar{I}_t$	$\sigma(\bar{I}_t)$
500 years	6.52	0.31	6.16	0.3	5.92	0.25	6.89	0.32	6.99	0.34	7.34	0.26
1000 years	6.87	0.33	6.49	0.3	6.23	0.26	7.33	0.34	7.43	0.38	7.7	0.29
2000 years	7.19	0.33	6.8	0.35	6.51	0.29	7.74	0.37	7.83	0.4	8.04	0.3
10000 years	7.81	0.38	7.4	0.38	7.07	0.31	8.54	0.42	8.6	0.45	8.71	0.35

have to point out that values of 0.3 or 0.4 MSK degrees are meaningless. Therefore, the uncertainty due to the random variables in terms of intensity is not significant and future efforts will be needed to quantify epistemic uncertainties.

Resulting hazard map

Finally, a seismic hazard map based on the main facts of the probabilistic and considering also the deterministic model is proposed. The resulting map is based on the probabilistic map corresponding to a return period of 500 years. Then, the intensity values given in the

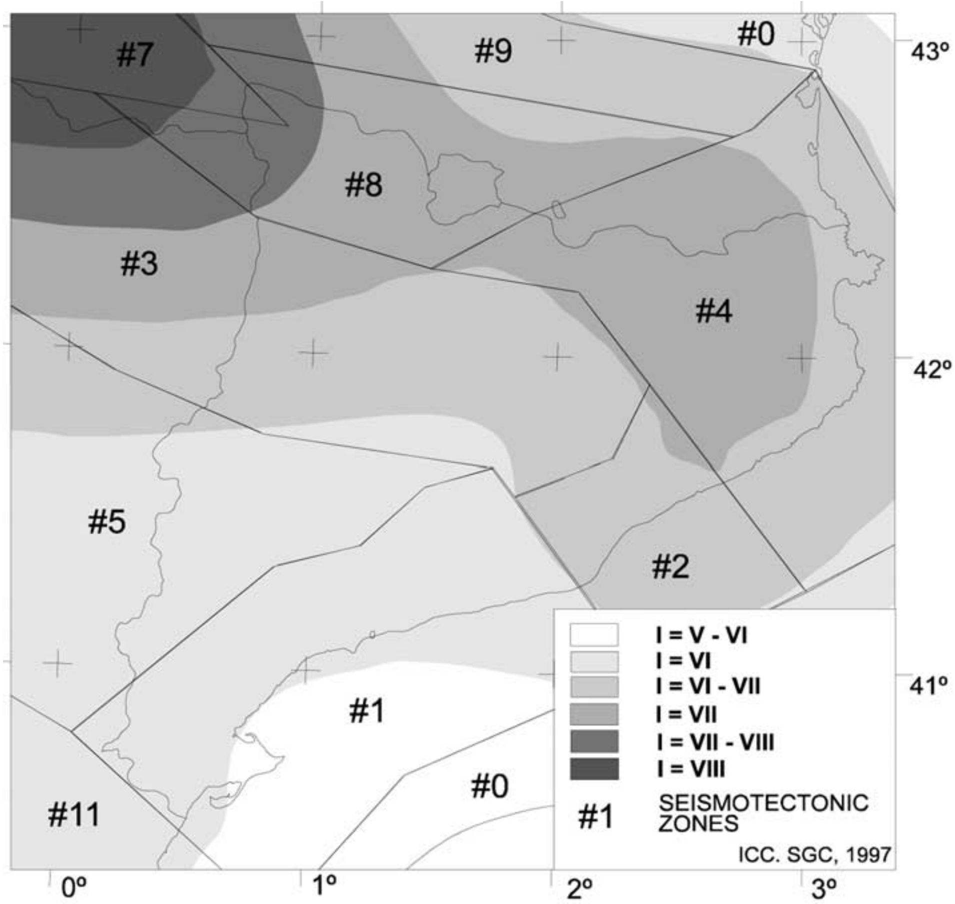

Figure 8. Probabilistic seismic hazard map associated to a return period of 500 years in terms of half degrees of intensity.

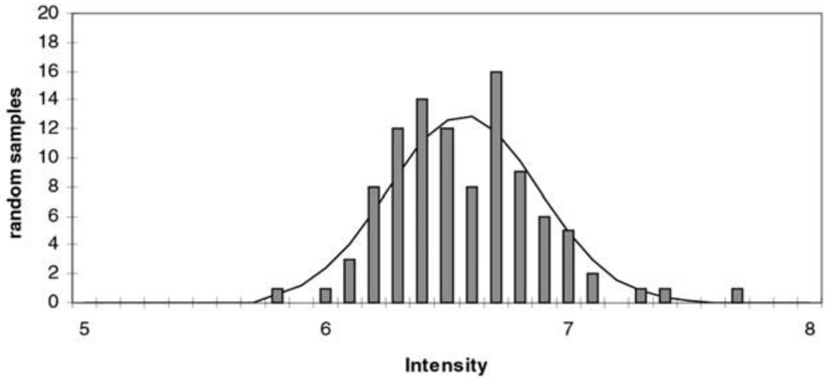

Figure 9. Frequency of the intensities for Barcelona associated to a return period of 500 years obtained using 100 computations (Montecarlo method) and their fit with a gaussian distribution characterised by the mean and the standard deviation of the obtained distribution.

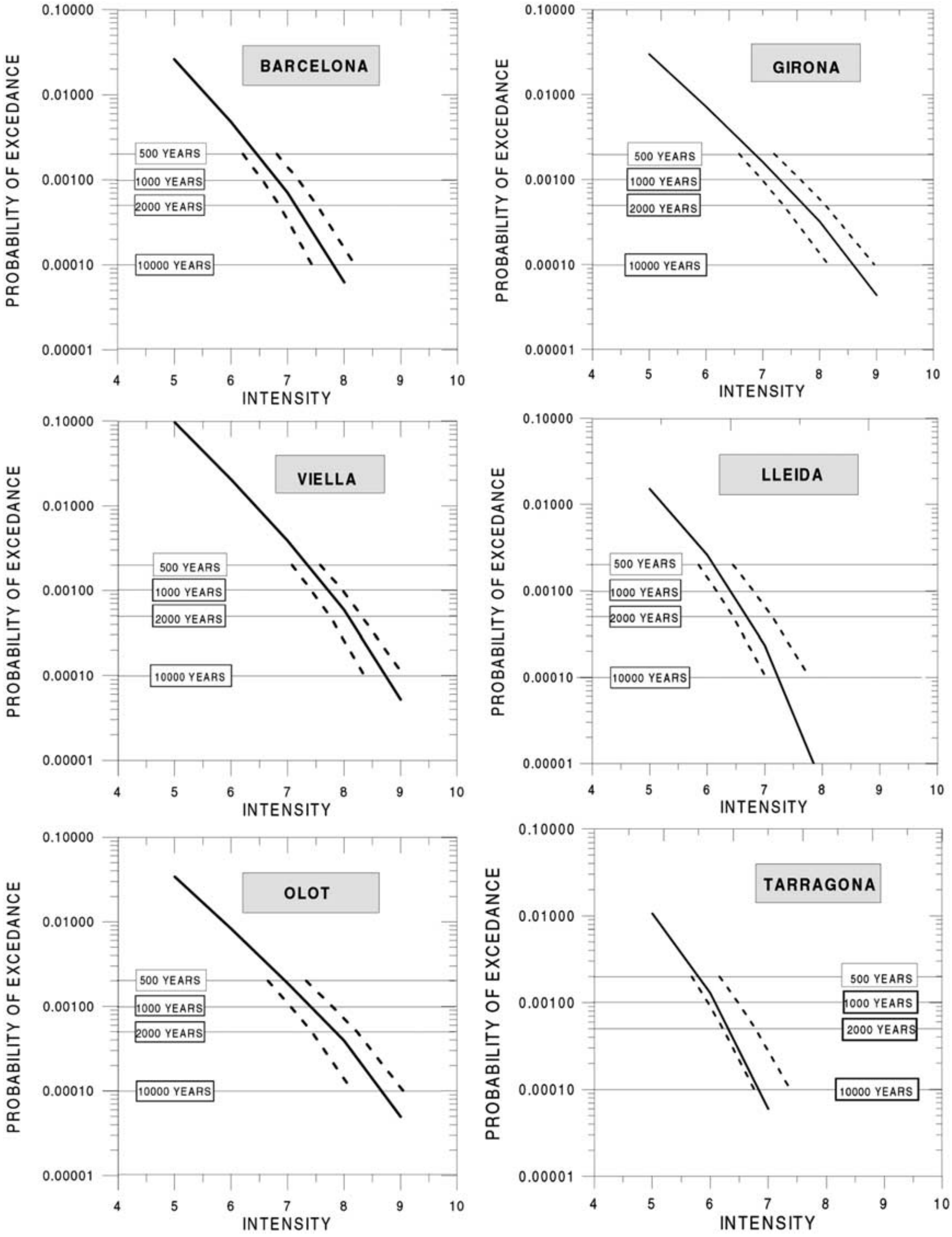

Figure 10. Seismic hazard curves (mean values and one standard deviation) obtained for the cities of Barcelona, Viella, Olot, Girona, Lleida and Tarragona.

probabilistic (Figure 8) and the deterministic maps (Figure 7), are compared. Let I_D and I_{500} be the estimated intensities, for each point, in the deterministic and probabilistic maps, respectively. If $I_D > I_{500} + 1$ then an intensity $I = I_{500} + 0.5$ is assigned in the finally proposed map. If $I_{500} > I_D + 1$ then $I = I_{500} - 0.5$. We added or subtracted 0.5 degrees because this is the minimum value having some sense taking into account the MSK scale. This value is near to the standard deviation obtained in the uncertainty analysis.

Therefore, the proposed map considers two facts: the main historic characteristics of the seismicity of Catalonia shown in the deterministic map and the statistics of the whole available data provided by the probabilistic map. It can be pointed out that the increases or decreases of intensity applied are quite similar to the standard deviation observed in the sensitivity analysis. The resulting seismic hazard map is shown in Figure 11.

Therefore, the proposed map still can be considered a probabilistic hazard map associated to a return period of 500 years according to the following considerations:

- In the Southern part of the region, the intensities proposed by the resulting map are equivalent to the mean values less a standard deviation deduced from the sensitivity analysis of the probabilistic assessment.
- In the central part of Catalonia, the intensities proposed are equal to the mean value deduced from the sensitivity analysis of the probabilistic assessment.
- In the Northern part of the study region, the intensity degree proposed corresponds to the mean value plus, approximately, a standard deviation deduced from the sensitivity analysis of the probabilistic assessment.

Given that the proposed map will be used for a regional risk analysis and for seismic codes, the boundaries of the seismic zones drawn in fig 11 correspond to administrative limits (municipalities).

Conclusions

A new seismic hazard assessment for Catalonia has been carried out, taking into account a recently revised earthquake catalogue and a seismotectonic zonation defined by tectonic zonation and seismicity.

Different seismicity models of occurrence are applied to deduce the seismicity behaviour of the Catalonian territory. First, a renewal process was used as a stationary Poissonian model. Secondly, two extreme value models developed by Gumbel (1954) were used in some source zones showing, for high intensities, a good agreement with return periods calculated by means of the stationary Poisson process. Finally, a non-stationary model initially developed by Savy (1978) and modified by Hong and Guo (1995) was successfully used. Its application shows an almost stationary behaviour for the whole region. Therefore, the seismic hazard has been calculated by using a model based on the Cornell (1968) method, later modified by McGuire (1976), and adapted for the possibility of using the Sponheuer attenuation law and a truncated Gutenberg-Richter recurrence model (Goula and Godefroy, 1985).

The analysis of the attenuation law in Catalonia shows a low anelastic attenuation with values less than 0.001 km^{-1} for the γ parameter and focal depth ranging between 5 and 15 km. A standard deviation of 0.5 intensity degrees was used in the code of calculus.

The sensitivity analysis carried out using Monte-Carlo method in six selected cities of Catalonia shows a Gaussian behaviour with standard deviation of the intensity associated to return periods of 500 years less than 0.5 intensity degrees.

The resulting seismic hazard map proposed for a return period of 500 years is based on the main characteristics of the probabilistic map and is modified incorporating some characteristics of the deterministic analysis. The intensity values range from V-VI in the Southern region of Catalonia to VII-VIII to the North.

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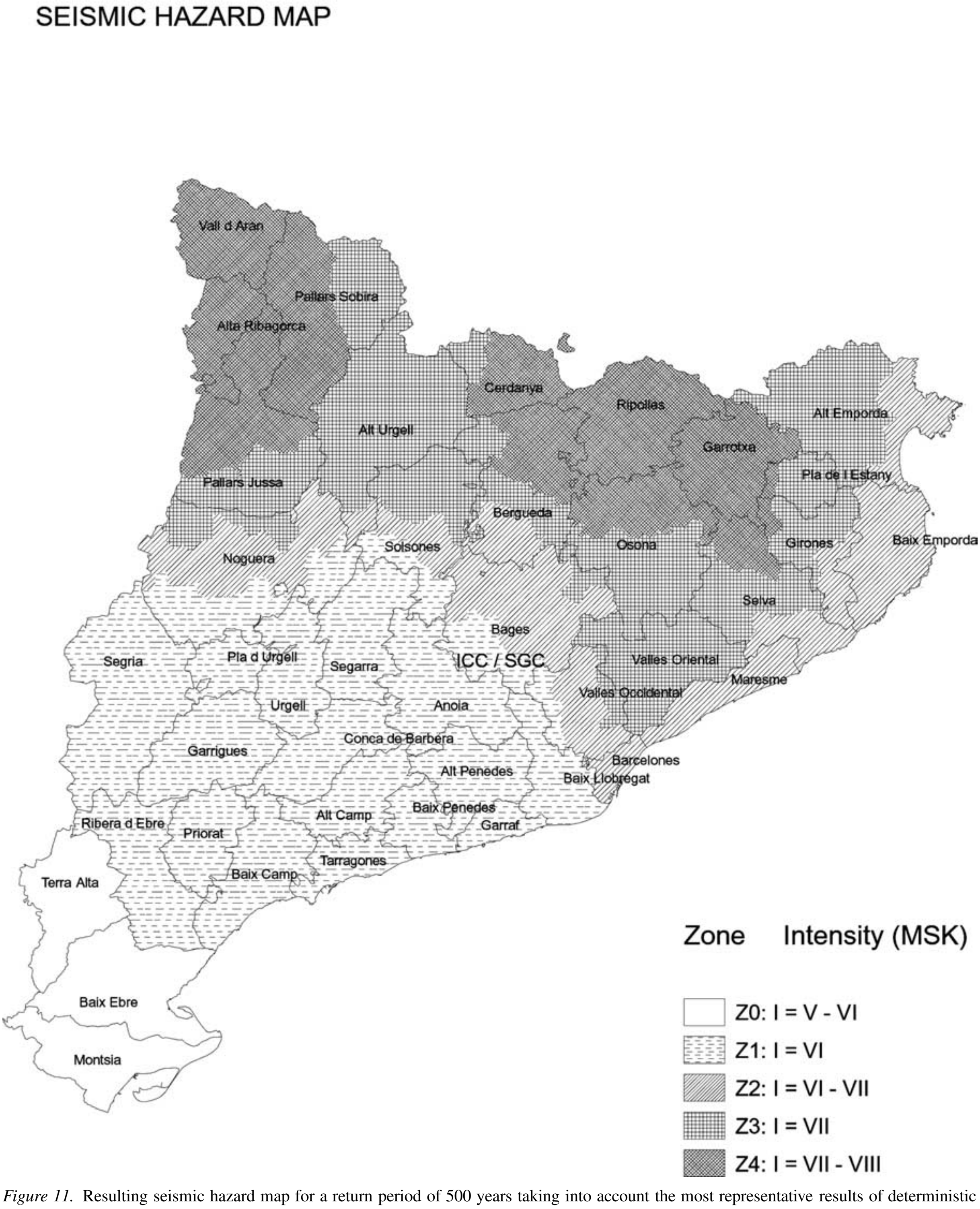

Figure 11. Resulting seismic hazard map for a return period of 500 years taking into account the most representative results of deterministic and probabilistic seismic hazard assessments.

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