

# A new probabilistic seismic hazard study of Spain

Julio Mezcua · Juan Rueda · Rosa M. García Blanco

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**Abstract** In this paper, we present a probabilistic seismic hazard analysis (PSHA) for mainland Spain that takes into account recent new results in seismicity, seismic zoning, and strong ground attenuation not considered in the latest PSHA of the Spanish Building Code. Those new input data have been obtained as a three-step project carried out in order to improve the existing hazard map for mainland Spain. We have produced a new earthquake catalogue for the area, in which the earthquakes are given in moment magnitude through specific deduced relationships for our territory based on intensity data (Mezcua et al. in *Seismol Res Lett* 75:75–81, 2004). In addition, we included a new seismogenetic zoning based on the recent partial zoning studies performed by different authors. Finally, as we have developed a new strong ground motion model for the area García Blanco (2009), it was considered in the hazard calculation together with other attenuations gathered from different authors using data compatible with our region. With this new data, a logic tree process is defined to quantify the epistemic uncertainty related to those parts of the process. A sensitivity test has been included in order to analyze the different models of ground motion and seismotectonic zonation used in this work. Finally, after applying a weighting scheme, a mean hazard map for PGA, based on rock type condition for 10% exceedance probability in 50 years, is presented, including 15th and 85th percentile hazard maps. The main differences with the present official building code hazard map are analyzed.

**Keywords** Seismic catalogue · Zone and ground-motion models sensitivity · Seismic hazard · Spain

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## 1 Introduction

The PSHAs carried out for mainland Spain in recent years were performed using the earthquake catalogue with intensities as a parameter to represent the size of the events (Martín 1984; Giner et al. 2003). In other hazard studies, a conversion from maximum intensity to mb(Lg) magnitude, Ms or moment magnitude  $M$  was considered prior to the earthquake potential assignment to each of the seismogenic zones (Molina 1998; Jiménez et al. 1999; Peláez 2000). These maximum intensity/magnitude conversions were made from local relationships deduced from the earthquake catalogue (Mezcua and Martínez Solares 1983), updated with the Instituto Geográfico Nacional Seismic Data File or using most general relationships deduced elsewhere (Johnston 1996a, b). In relation to the seismotectonic zoning used in those hazard studies, the authors considered simple tectonic relationships with seismicity, as no neotectonic or focal mechanisms data were included. The zonings provided by Martín (1984) and Molina (1998) were the most extensively used in most of the regional PSHA studies.

Finally, the ground motion models used to calculate the hazard are either in intensities deduced by Martín (1984), Molina (1998) and López Casado et al. (2000a) or in magnitude deduced by Ambraseys et al. (1996), (2005), Sabetta and Pugliese (1996). In both cases, the final results of these studies are expressed either in intensities or in acceleration, after converting the results using the empirical intensity–acceleration relationship  $\log \text{PGA} = 0.30103 I - 0.2321$  given in the Spanish Building Code Hazard Map NCSE-02 (Earthquake Code Permanent Commission of Spain 2002). In this paper, we present a PSHA for mainland Spain that includes a revised earthquake catalogue in moment magnitude, a new ground-motion attenuation model provided by García Blanco (2009) and new regional zoning based on different local hazard studies. The PSHA obtained through a tree methodology is presented.

The main purpose of the present study is to compare the results for the 475-year return period (10% probability in 50 years) from our PSHA obtained with these new data, with the values contained in the hazard map included in the Spanish Building Code. The results show the necessity of reconsidering the Building Code hazard map because, in some specific areas, the new results obtained in this paper are significantly different. A new hazard map, to be used in the Spanish Building Code, should incorporate new results about the seismicity and ground motion attenuation models developed recently. In addition, a new seismotectonic zonation should also be proposed, including as much neotectonic information as possible.

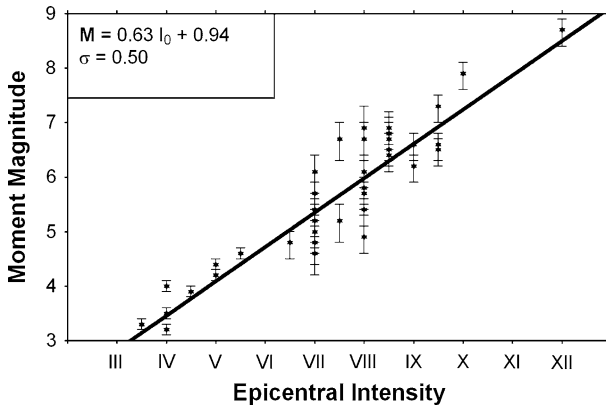
## 2 Seismicity of the Iberian Peninsula: a new seismic catalogue

The Iberian Peninsula is located at the limit where the ocean–ocean contact between the Eurasian and African plates is converted to continent–continent collision through the Betic and Atlas structures, with the Alboran Sea in between. From the eastern end of the Azores Islands, the Gloria Fault is running in almost E–W direction showing no seismicity associated. To the east up to (37°N, 12°W), a fairly linear seismicity band is associated with large events with strike-slip motion of right-lateral character. From this area centered at (37°N, 12°W) where the Gorringe Bank is located, there are several seismicity alignments in NE–SW and NW–SE directions, which have their extension on land in several well-defined faults. This marine area is the focus of large events; the most recent one is the February 28, 1969 Cape St. Vincent Earthquake of  $M = 7.9$  and one of the largest events

ever recorded, The November 1, 1755 Lisbon Earthquake. The stress regime of the area is changing from right–lateral strike slip to north–northwest south–southeast horizontal compression (Udias et al. 1976; Buforn et al. 1988; Argus et al. 1989; Borges et al. 2001; among others). To the west of the Strait of Gibraltar, the continent–continent collision between Africa and Eurasia is taking place through southern Iberia and northern Morocco and Algeria, and that contains an extensional basin (the Alboran Sea), Mezcua and Rueda (1997). To complete this picture, we also find seismicity in Galicia in the northern part of the peninsula, in the westernmost part of Spain, and in the Pyrenees on the border with France. We may summarize that the seismic activity of the Iberian Peninsula is the result of horizontal compression N–S to NNW–SSE direction consequence of the convergence of Eurasia and Africa.

The compilation of seismicity in a general catalogue for Spain goes back to Galbis (1932, 1940), Munuera (1963) and Mezcua and Martínez Solares (1983). Recently, Martínez Solares and Mezcua (2002) published a revision of Iberian seismicity for the period 880 B.C. up to 1900, which has also been considered in this work. In both Mezcua and Martínez Solares (1983) and Martínez Solares and Mezcua (2002) catalogues, the epicenters for the historical period are fixed at the location of the maximum intensity recorded, which serves to give the size of the events. For the instrumental interval, location is performed with a unique velocity model and an event characterization based on mb(Lg). To those catalogues from Mezcua and Martínez Solares (1983) and Martínez Solares and Mezcua (2002), the Seismological Service of Spain has added the recent instrumental epicenters forming what is called the Instituto Geográfico Nacional Seismic Data File (IGNSDF). This updated file has been used in all hazard studies performed for the Spanish territory. However, in different parts of the territory, Cataluña in the northeastern part, Valencia in eastern Spain, and Andalucía in the south, for example, complementary regional catalogues are available and are sometimes used for local or regional hazard calculations (Peláez and López Casado 2002; Secanell et al. 2003 and Giner et al. 2003). Some of the studies are performed either with intensity values or with magnitude obtained through maximum intensity–magnitude relationships (López Casado et al. 2000a, b). As is well known, such correlations with any type of magnitude such as mb(Lg) are very poor and may produce misleading results (Johnston 1996a, b) due to various reasons such as different focal depth of the events, or saturation of the different magnitude scales.

To overcome such difficulties, Mezcua et al. (2004) followed the approach of Bakun and Wentworth (1997) to obtain a location and magnitude evaluation of the most important events in the Spanish macroseismic data. In this process, Mezcua et al. (2004) used five training events with both types of information (intensity distribution and instrumental moment magnitude assignment), which made it possible to assign moment magnitude to the 30 greatest events in the area. In the same study, new epicenter determinations for each event were also obtained using the Bakun and Wentworth methodology. The main results were that the epicenters were moved between 10 and more than 100 km. The magnitude values found as compared with the values deduced by simple empirical relationships have differences of more than 0.5–1.0. In order to extend the moment magnitude assignment for the rest of the shocks included in the IGNSDF, we considered three sets of data: shocks with only information about the epicentral intensity, those with instrumental moment magnitude determination and the rest of the instrumental events with mb(Lg) magnitude assignment. For the first set of data, we converted the epicentral intensity into moment magnitude through a regional relationship carried out with the 30 described events in Mezcua et al. (2004) complemented with those events from the instrumental period with

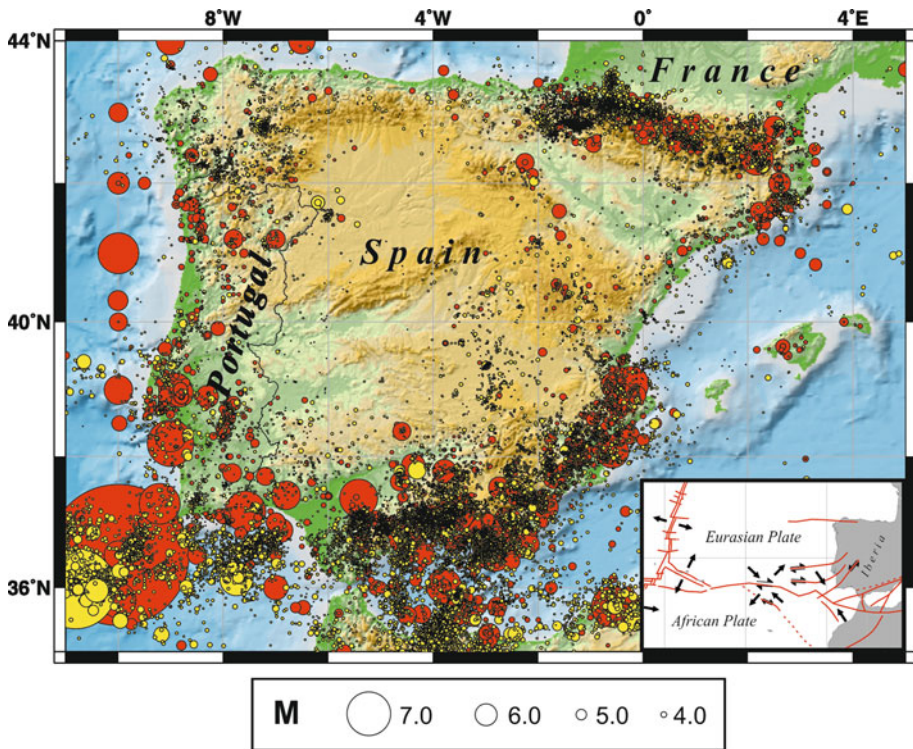


**Fig. 1** Plot of the Iberian Peninsula and surrounding events with moment magnitude assignment both instrumentally and for the historical period through the trained events methodology described by Mezcua et al. (2004) versus their epicentral intensity. The least square fit, the resulting equation, and the standard deviation obtained for the adjustment are shown

both moment magnitude and epicentral intensity values. For events with marine epicenters, the corresponding epicentral intensity is obtained by extrapolation of the onshore reported intensity values by means of the intensity attenuation law deduced for the area. From the data considered in Mezcua et al. (2004), we changed the epicentral intensity obtained for the 1755 Lisbon Earthquake from X (EMS) to a more realistic XII (EMS). These data are presented in Fig. 1, showing the standard deviation in magnitude together with the least square adjustment. For the last set of data, we proceeded in a similar way, through an  $M$ - $mb(Lg)$  relationship, which was published by Rueda and Mezcua (2002), using events with both types of magnitude evaluation. After applying such conversions, we obtained a new regional catalogue, which is given entirely in terms of moment magnitude either instrumentally obtained or from the regional empirical relationships described modifying the epicentral coordinates for the most important events. The resulting data set is presented in Fig. 2. This new catalogue, referred to hereafter as the Iberian Seismicity Catalogue (ISECAT), is the catalogue of reference for the present study. It covers the Iberian Peninsula and its surroundings ( $35^{\circ}\text{N}$ – $44^{\circ}\text{N}$  and  $5^{\circ}\text{E}$ – $11^{\circ}\text{W}$ ).

### 3 Seismogenetic zonation studies

The first probabilistic seismic hazard map for mainland Spain was performed by Martín (1984) and it was, with slight modifications, the one included in the last two building code versions of the country (Earthquake Code Permanent Commission of Spain 1994, 2002). The seismic zoning used in Martín (1984) was based mainly on the seismicity distribution and on some main structural and tectonic characterizations obtained from Julivert et al. (1972). The same zoning with slight changes was also used in the seismic hazard assessment for the Spanish area in the Ibero-Maghreb region (Jiménez et al. 1999). The 25 seismogenetic zones considered for the hazard map presented in the last Building Code, NCSE-02, from the Earthquake Code Permanent Commission of Spain (2002) are referred to here as CODE zoning and are shown in Fig. 3. Another hazard study performed for

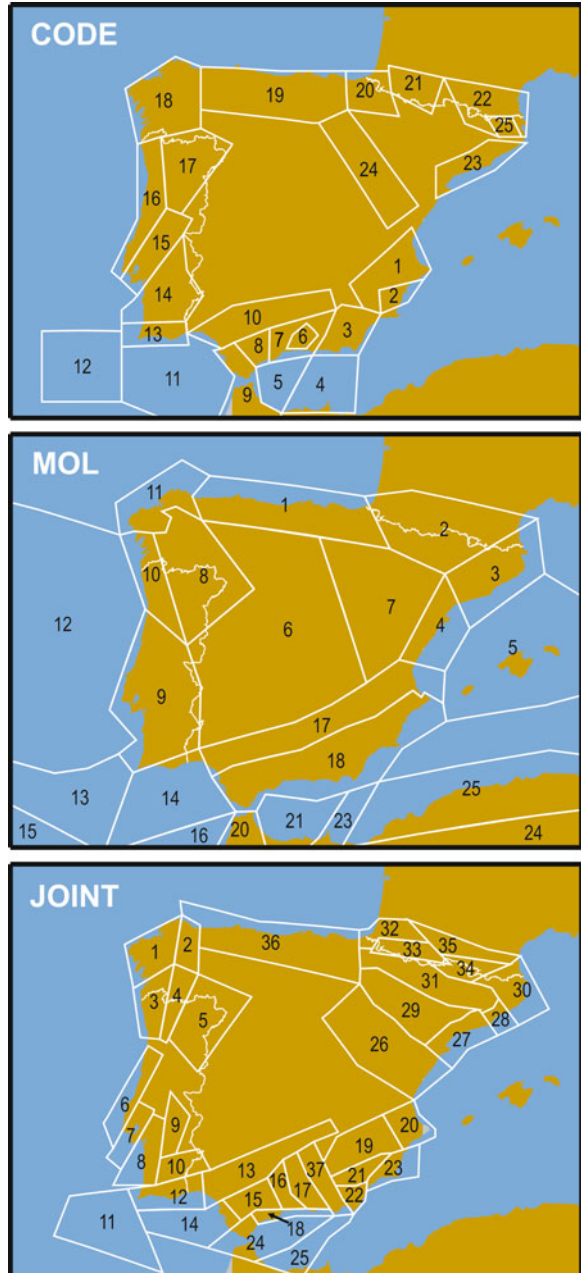


**Fig. 2** Seismicity map of the Iberian Peninsula and nearby regions included in the ISECAT catalogue obtained here. Size of circles depends on the moment magnitude of the event. *Red circles* correspond to seismicity prior to 1960, and *yellow circles*, from that date up to present

southern Spain (Molina 1998) divides the Iberian Peninsula and surroundings into 25 shallow (0–30 km) seismotectonic zones, five of intermediate depth (30–60 km) and two (60–90 km) deep zones. This zoning is also used in a general hazard map for Spain by Peláez and López Casado (2002). The corresponding shallow zoning is referred to, in this paper, as MOL and is also presented in Fig. 3.

Among the recent hazard studies performed in Spain that partially consider the potential of active faults, we find: Sanz de Galdeano et al. (2003) for the Granada Basin, Giner (1996) for the eastern part of the Iberian Peninsula and López Casado et al. (1995) for the Betic Cordillera, Rif and nearby areas. For the northeastern part of Spain, Secanell et al. (2008) proposed a seismotectonic zonation of the Pyrenees border region between France and Spain. The zonation they used is the result of the ISARD project between France and Spain (Roussillon et al. 2006) to establish a unified hazard map of the area. Giner et al. (2003) give a seismic zonation of the southern and eastern part of Spain, which was also recently studied by Buforn et al. (2005) as well as by García Mayordomo (2005). Rueda and Mezcuca (2001) studied the northwestern part of the Iberian Peninsula including Spain and part of the Portuguese territory with a seismotectonic zoning included in the study, and López-Fernández et al. (2008) studied the northwest of the Iberian Peninsula between the Pyrenees and the Galicia region. For the Portuguese mainland and the Atlantic Ocean nearby, two zonings are presented by Vilanova and Fonseca (2007), one based in

**Fig. 3** Seismic zonings used in this paper. CODE is used in the Building Code Hazard Map NCSE-02 (Earthquake Code Permanent Commission of Spain 2002) and is due with minor changes to Martín (1984). MOL is from Molina (1998) and used by Peláez and López Casado (2002). JOINT is a merging of different regional zonings from López Casado et al. (1995), Giner (1996), Rueda and Mezcua (2001), Giner et al. (2003), Sanz de Galdeano et al. (2003), Secanell et al. (2003) and García Mayordomo (2005)



seismicity data alone and another one, which is a modification of the Molina (1998) data presented by Peláez and López Casado (2002). In all those studies, zoning was performed using not only seismic and geologic data but also gravity, geomagnetic data and neotectonic information or geothermal flux information (García Mayordomo 2005) when it was available.

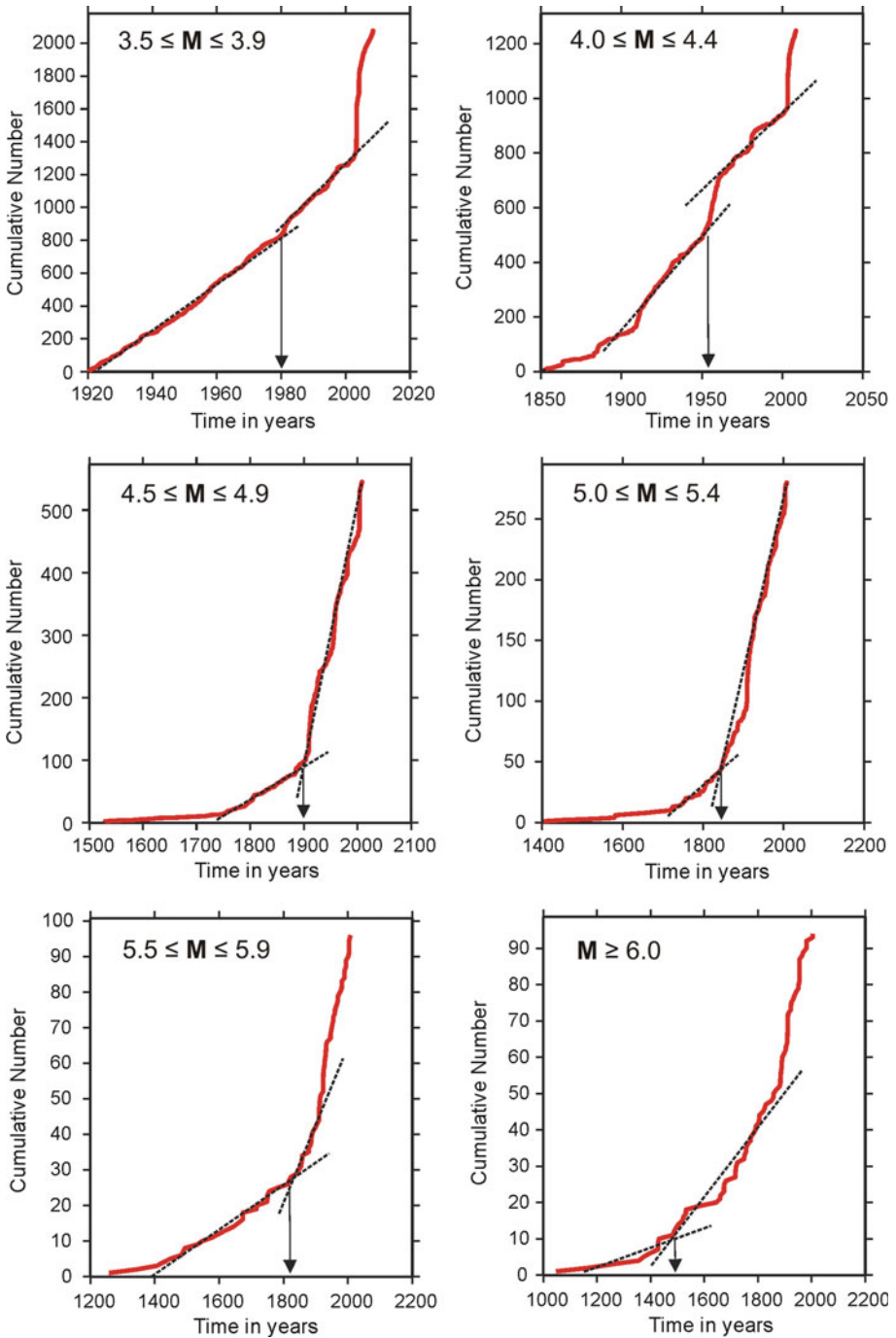
New seismic zoning needs to be performed for the Spanish mainland, and in order to improve the existing general zonings for the Iberian Peninsula (CODE and MOL), it could be of benefit to combine the aforementioned new regional zonings from López Casado et al. (1995), Giner (1996), Rueda and Mezcua (2001), Sanz de Galdeano et al. (2003), Giner et al. (2003), García Mayordomo (2005), López-Fernández et al. (2008) and Secanell et al. (2008). The zoning made of a sum of those partial zonings from all over Spain, which we named JOINT, is also presented in Fig. 3. This JOINT zoning has the advantage of being performed with the newest relevant seismotectonic data for each region. These three zonings will be considered in the hazard study of the Spanish mainland.

#### 4 Determination of the earthquake potential

All PSHA performed in Spain use the IGNSDF seismic catalogue. However, in some cases, the authors have added to this information data from regional seismic files, as in the case of Secanell et al. (2003) for the Pyrenees region or Giner et al. (2003) for the southeastern part of Spain. In all those studies, the seismic catalogues are characterized for the historical period in terms of seismic intensity and for the instrumental period either in mb(Lg) magnitude or local magnitude. In the present study, we will consider the new seismic catalogue ISECAT, described above, which we claim is unified in magnitude definition; the values are given in Moment Magnitude and include all epicenter changes obtained through the analysis of the most important seismic events and may be considered as homogeneous as possible.

In order to obtain the annual rates for each zone, it is necessary to make an estimation of the period of completeness. This has been done using the so-called linear method, which is based in the constant slope of the cumulative number of events of a certain magnitude class versus time, if the earthquake series is complete. That is, we represent the accumulated seismicity, classified in different magnitude ranges, per year for the Iberian region (Fig. 4), as given in the ISECAT catalogue. For each magnitude interval, we can detect the year in which this linear trend presents a slope change or a displacement. The considered magnitude intervals of 0.5 are due to the uncertainty obtained for the historical magnitude conversion. We found those changes for each interval and are represented by arrows and correspond to the starting completeness dates that are shown in Table 1. The completeness dates deduced are quite similar to those calculated for high intensity values in Martín (1984) and used in the NCSE-02 map. For intensity VIII (EMS), Martín (1984) gives the year 1505 as the completeness date. If we convert this intensity into moment magnitude through the relationship given in Fig. 1, the resulting  $M \approx 6.0$  has a completeness date in our study of 1500. However, for lower intensities, the differences are of the order of 100 years, our values being more conservative. For some regional studies performed in Spain, García Mayordomo et al. (2007) found that the obtained completeness dates for similar moment magnitude intervals are quite different; for the magnitude interval 6.0–6.4, the completeness date is 1200, and for 4.0–4.4, 1850, and in our study, 1954.

The completeness values obtained in this paper are also similar to those in other catalogues of nearby regions, as in the French case (Beauval and Scotti 2004). We found that our period of completeness for the lower magnitude interval  $3.5 \leq M \leq 3.9$  was shorter (starting in 1980) than the similar magnitude interval for the French catalogue (starting in 1962) (Beauval and Scotti 2004). The main reason for such discrepancy is that the new French seismic network was operating from the beginning of the 1960s, while in Spain it



**Fig. 4** The cumulative number of events as taken from the ISECAT catalogue for different magnitude intervals versus time of occurrence. Arrows indicate the trend changes that correspond to completeness periods



**Table 1** Completeness time period for different magnitude intervals

Magnitude interval	Completeness period
3.5–3.9	1980–2008
4.0–4.4	1954–2008
4.5–4.9	1902–2008
5.0–5.4	1838–2008
5.5–5.9	1838–2008
6.0– $M_{\max}$	1500–2008

was installed at the end of the 1970s. Another feature that may be observed in the lower magnitude intervals  $3.5 \leq M \leq 3.9$  and  $4.0 \leq M \leq 4.4$  is that the slope increases abruptly for the period of time around the 2000. The explanation is that in 1998 and 2002, the Seismological Service of Spain changed the magnitude formula to give magnitude values to those marine events with a very poor developed Lg phase. This fact makes an abnormal increase in the number of events in those classes. For the higher magnitude intervals ( $5.5 \leq M \leq 5.9$ ), the starting completeness date of ISECAT is 1838, similar to the values (1800, 1870) obtained by Beauval and Scotti (2004), corresponding to the two different catalogues used in their study.

Before we proceeded with the earthquake potential determination, a declustering of the catalogue by the Reasenber (1985) method was applied and 2,016 clusters were found. The resulting catalogue was limited to 35 km depth events, and sub-catalogues of CODE, MOL, and JOINT seismic zoning were extracted for each zone.

To calculate the annual rate and the slope of the recurrence curve ( $b$  value or the corresponding  $\beta$  value), we used the Weichert (1980) methodology. We used the different time periods deduced for the magnitude completeness ranges shown in Table 1. To calculate the annual rate, the magnitude threshold of 3.5 is appropriate for the range of  $\beta$  values deduced for the three different zonings considered in this study. In the CODE and JOINT seismic zonings, the Algerian area is not considered, but as the distance to the SW coast of Spain is near 200 km, it has a negligible influence in the hazard for the Spanish mainland.

Finally, a maximum magnitude value for each seismic zone needed to be determined which, with the values of annual rate and  $\beta$  values, constituted the earthquake potential of each of the three (CODE, MOL, and JOINT) zonings. There were several ways to determine such  $M_{\max}$ , which included estimation of the seismic moment from the observation of the fault area, displacement for historical events and conversion to magnitude through the Hanks and Kanamori (1979) relationship, or the use of the main fault length for each zone and its empirical relation with magnitude such as the one provided by Wells and Coppersmith (1994). However, in our case, it was difficult to use such methods since active faults for each zone were poorly known or, in most cases, not known. Instead, we considered the maximum historical magnitude observed as the maximum magnitude  $M_{\max}$ , since our time span was large enough for such an assertion. Alternatively, we have considered also the maximum magnitude as an unknown quantity obtained from a Gaussian distribution with a probability centered at  $M_{\max} + 0.5$  and a standard deviation  $\sigma = 0.3$  (Ordaz et al. 2007).

The final results of the earthquake potential for the three zonings are presented in Table 2.

**Table 2** Seismic potential for the different zonings used in the hazard calculation ann. rate is the annual rate for shocks with  $M \geq 3.5$  beta is  $b \times \ln 10$ , b being the slope in the Gutenberg-Richter relationship and  $M_{\max}$  is the maximum magnitude observed in each zone

Zone	Code			Mol			Joint		
	Ann. rate	Beta	$M_{\max}$	Ann. rate	Beta	$M_{\max}$	Ann. rate	Beta	$M_{\max}$
1	4.049	2.700	6.7	1.668	3.562	5.0	0.530	3.246	5.4
2	6.974	3.161	6.6	9.088	2.845	6.3	0.415	2.981	5.3
3	5.133	2.765	6.7	3.859	2.732	6.6	1.261	2.658	5.4
4	5.160	2.764	6.7	0.388	3.023	5.0	0.427	3.590	4.7
5	1.177	2.740	5.8	0.816	2.629	5.4	0.924	2.861	5.4
6	6.381	3.127	6.7	1.401	3.933	5.7	1.281	3.124	5.4
7	2.295	3.005	6.8	1.593	3.049	5.7	3.009	2.262	6.7
8	1.680	3.347	5.4	1.765	2.946	5.4	0.562	2.431	7.1
9	1.281	3.590	5.5	7.519	2.573	7.1	0.833	2.841	5.4
10	2.290	2.726	6.9	1.874	2.856	5.4	0.344	2.541	5.7
11	3.119	2.903	6.6	0.530	3.246	5.4	4.708	3.206	8.7
12	4.046	2.997	8.7	0.673	2.260	6.9	1.462	2.614	6.1
13	1.067	2.857	6.9	4.029	3.049	8.7	0.636	2.541	6.9
14	2.112	2.812	5.8	3.370	2.572	6.6	1.622	2.501	6.6
15	2.960	2.182	7.1				1.721	3.162	6.8
16	2.882	2.943	5.4	0.233	2.916	4.9	1.539	3.173	6.1
17	1.476	3.060	5.8	4.138	2.610	6.9	7.002	3.004	6.7
18	1.138	3.170	5.4	27.574	3.017	6.8	1.707	3.218	6.4
19	0.738	3.767	4.9				2.470	3.513	5.4
20	1.604	3.183	5.6	0.235	2.211	6.6	2.612	2.669	6.7
21	4.840	2.289	6.2	4.235	2.823	6.7	2.946	2.640	6.0
22	1.222	2.033	6.6				1.634	2.991	6.3
23	2.299	2.250	5.9	1.991	2.859	6.0	4.496	2.910	6.6
24	0.891	2.196	5.7	0.807	2.392	5.8	1.860	2.705	6.7
25	0.284	1.670	6.3	23.881	2.610	7.6	3.213	2.872	6.2
26							1.293	3.312	5.4
27							0.737	3.162	5.0
28							1.369	2.810	5.9
29									
30							1.934	2.541	6.6
31							1.082	2.804	6.0
32							1.010	3.800	5.4
33							5.562	2.832	6.2
34							1.501	2.781	6.3
35							0.429	2.830	5.3
36							0.892	3.377	5.0
37							1.953	2.840	6.5

## 5 Strong ground motion characteristics

In a recent study, Mezcua et al. (2008) concluded that for mainland Spain only one attenuation law may be used, in contrast with the attenuation derived from isoseismal maps where at least three regions were considered (Martín 1984; López Casado et al. 2000a). This apparent contradiction is the result of using intensity data from several earthquakes in which either the intensity assignment was overestimated or the intensity scale used was not known and different relationships were obtained. Furthermore, the analysis done by Mezcua et al. (2008) of the two biggest earthquakes ( $I_{\max} \geq IX$ ) recorded in two so-considered different attenuation zones—the south (December 25, 1884 Andalusian earthquake) and the eastern (March 21, 1829 Torrevieja earthquake)—shows an identical slope of the median of the distances for each seismic intensity value. This fact may be interpreted as proof that both regions have the same attenuation of the seismic intensity.

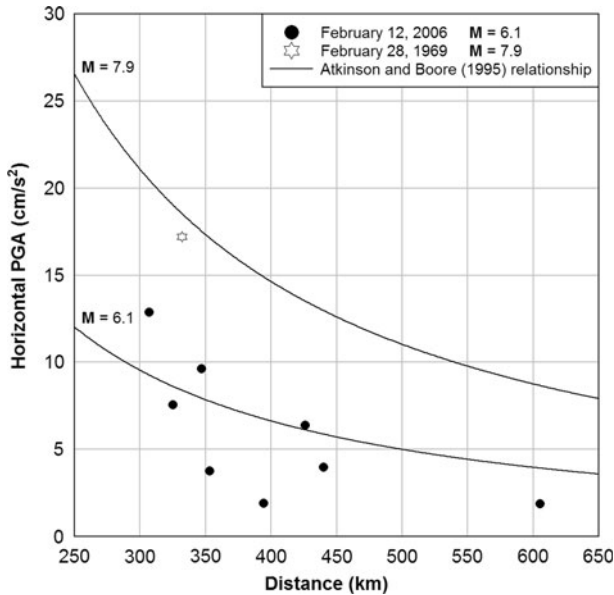
Using 149 shocks recorded in Spain, Mezcua et al. (2008) and García Blanco (2009) processed the PGA values in the epicentral distance range 10–100 km to obtain empirical attenuation relationships valid for the whole country. The ground-motion model selected in this study as given by García Blanco (2009) in terms of epicentral distance  $\Delta$  is:

$$\ln \text{PGA} = -0.2368 + 1.3285M - 1.0749 \ln \Delta$$

with  $\sigma = 0.76$ .

However, as this relationship was obtained for moderate magnitude events ( $M \leq 5.3$ ), as were the ground motion models developed for Spain from Benito and Gaspar (2007), we limited their applicability and we included those strong ground-motion models obtained for European and Middle Eastern events (including those Spanish events with  $M \geq 5.0$ ) by Ambraseys et al. (2005) or Akkar and Bommer (2010), and those generated in nearby regions such as Italy (Sabetta and Pugliese 1996).

Those seismic zones in the Atlantic Ocean between Iberia and Africa show lower intensity attenuation. It is worth mentioning that the November 1, 1755 Lisbon earthquake, which belongs to one of those oceanic zones, was felt as far as Germany including, of course, the whole Spanish territory. As Vilanova and Fonseca (2007) analyzed, the only record of the February 28, 1969 Cape St. Vincent  $M = 7.9$  earthquake, which occurred in the same seismic zone, was obtained at 332 km of distance and fits with the Atkinson and Boore (1995) relationship, as can be seen in Fig. 5. This last relation was chosen by us for those ocean zones because the data used to derive it included earthquakes of large magnitude ( $M > 8.0$ ) as in the case in Central and North America. In addition, as the North Atlantic margins (both margins are under compression) share a common tectonic evolution during the opening of the North Atlantic Ocean, and the regions to both sides of the North Atlantic Ocean did not experience the major deformation associated with the Cenozoic orogenic process, we concluded the similarity of both regions (Vilanova and Fonseca 2007). Very recently, the Spanish strong motion network recorded an event on February 12, 2007 of  $M = 6.1$  located in the same oceanic zone as the February 28, 1969 Cape St. Vincent earthquake. We checked the resulting PGA values with the Atkinson and Boore (1995) relationship (Fig. 5), and the fit was reasonable. In conclusion, in this study, we used the Atkinson and Boore (1995) relationship for those ocean regions, including the Gulf of Cadiz, which was also used by Vilanova and Fonseca (2007) for their study of Portugal.



**Fig. 5** Horizontal PGA values from the events of February 28, 1969 ( $M = 7.9$ ) and February 12, 2006 ( $M = 6.1$ ) with epicenter in the oceanic zone to the SW of Cape St. Vincent, offshore Portugal. Lines correspond to the empirical (Atkinson and Boore 1995) ground-motion attenuation model

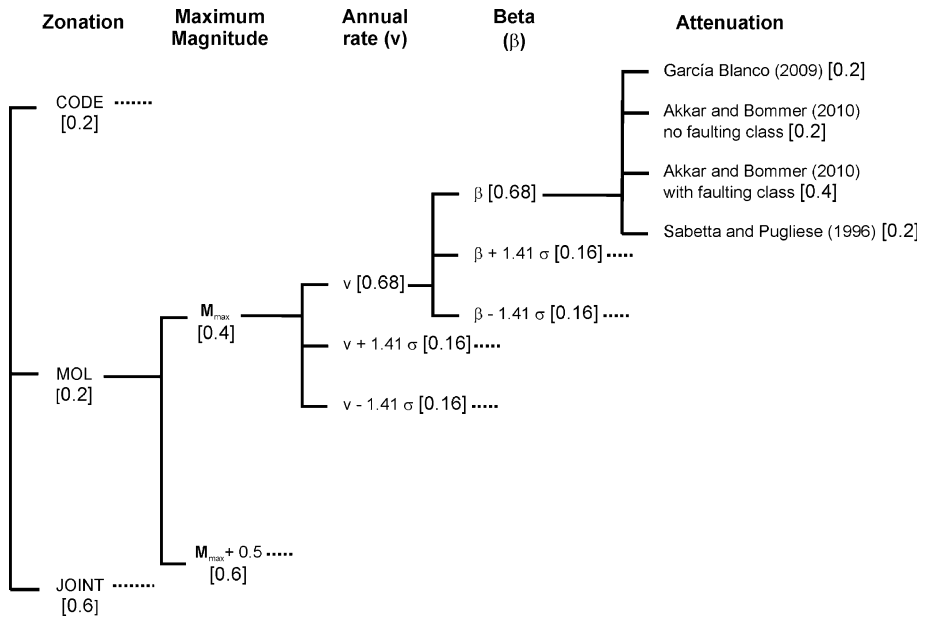
## 6 Seismic hazard calculation and sensitivity analysis

The hazard results in terms of PGA expressed in  $g$  were obtained for a 475-year return period in a  $0.2^\circ \times 0.2^\circ$  grid of the region limited by  $36^\circ\text{N}$ – $44^\circ\text{N}$  and  $10^\circ\text{W}$ – $3.5^\circ\text{E}$ , which covers the Spanish mainland. The code CRISIS2007 from M. Ordaz was used, considering a very shallow activity in each defined zone (5–15 km) deduced from main seismic activity, except for those corresponding to the Gulf of Cadiz and SW of Cape Saint Vincent, where most of the activity was deeper, reaching 20–30 km. Threshold magnitude for the hazard determination was the same used in the annual rate determination (3.5–3.9).

The uncertainties associated with the different variables and their handling are very important in a seismic hazard study. It has been a standard practice to incorporate the epistemic uncertainty through the use of logic tree methodology, Scherbaum et al. (2005), adding branches for each of the different ground-motion models considered applicable for the region. The aleatory variability of each ground motion model is represented by their standard deviation.

In Fig. 6, the logic tree used in the present study is shown with the variables included. The branches for every parameter with associated uncertainty are characterized with the corresponding weights. Each node includes all expected possibilities of the variable at the present time. This fact was the main objective of the logic tree methodology in capturing the epistemic uncertainty (Abrahamson and Bommer 2005).

The zoning branch was formed by the three presented zonings: CODE, MOL, and JOINT, with a maximum weight of 0.5 to the last one because it was obtained with recent detailed seismotectonic information. Weights of 0.3 and 0.2 were assigned to the zonings of CODE and MOL, respectively. In the case of the maximum magnitude, we considered



**Fig. 6** Logic tree for the different variables used in the seismic hazard calculation showing the considered weight for each branch

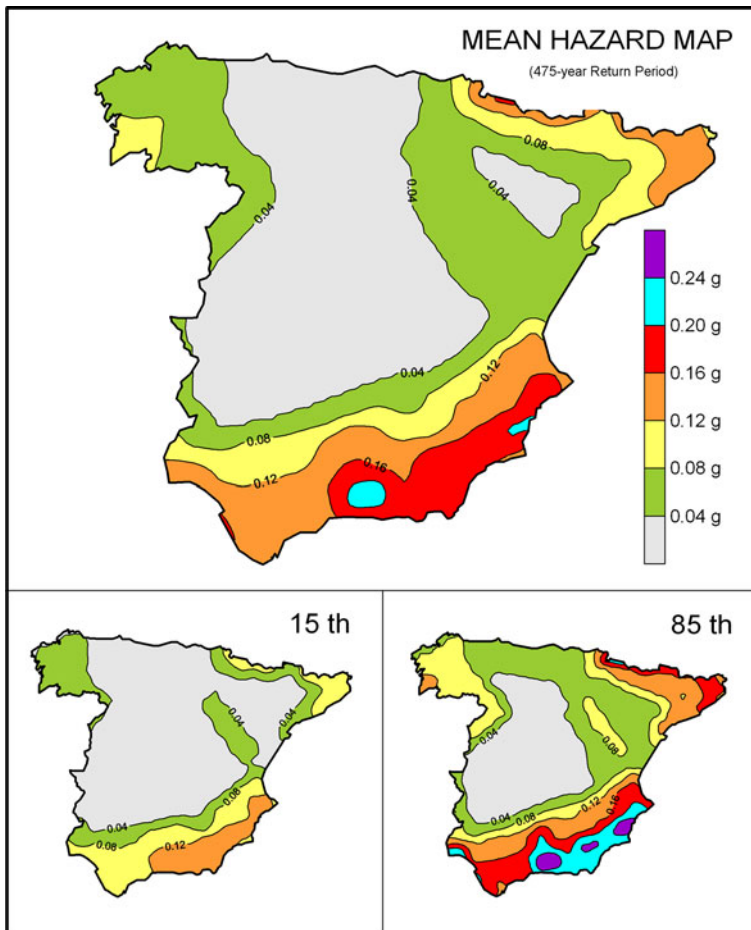
only two alternatives, because it is well known that the influence of this parameter in the hazard for small return periods ( $\leq 10^3$  years) is small, on the order of 10% (Beauval and Scotti 2004). The maximum of recorded magnitude +0.5 as the center of a Gaussian distribution is the greatest weight (0.6) and (0.4), for the maximum recorded magnitude. In relation to the annual rate,  $v$  and  $\beta$  uncertainties were considered by introducing  $v \pm 1.41\sigma$  and  $\beta \pm 1.41\sigma$  values. Those values were the medians of the  $\pm\sigma$  tails of the normal distribution curve. The corresponding weight for  $v$  and  $\beta$  was 0.68 each, and for  $v \pm 1.41\sigma$  and  $\beta \pm 1.41\sigma$ , their weights are 0.16 each (Grünthal and Wahlström 2006).

The attenuation relationships used in this paper are considered as follows: For the oceanic regions in the SW of the Iberian Peninsula, we used the Atkinson and Boore (1995) relationship. For the rest of the seismic zones, we used the relation obtained for Spanish data by García Blanco (2009) (weight 0.2), Akkar and Bommer (2010) with (0.2) and (0.4) if we consider the type of faulting of each zone and finally (0.2) for the ground motion model of (Sabetta and Pugliese 1996). The reason for this maximum weight for Akkar and Bommer (2010) was that the Spanish  $M > 5$  events with strong motion data were included and it was also calibrated with high magnitude events for comparable seismotectonic zones. Another way of combining two attenuation relationships for different magnitude ranges is to produce a mixed predictive relationship considering one local relation for magnitudes up to  $M > 5$  and another for greater magnitudes, as has been done by Secanell et al. (2008). As Sabetta et al. (2005) pointed out, once the ground motion models have been selected and adjusted, the weighting scenario considered becomes of less importance.

The 475-year return period seismic hazard map of mean PGA in g, due to the total logic tree, is presented in Fig. 7, with a maximum value of 0.22 g in the region of Granada, and two relative maxima in the eastern area of the Alicante-Murcia region and in the SW part

near the Portuguese border, with maximum values of 0.20 and 0.16 g, respectively. The PGA values obtained in this paper near Portugal are similar to the recent results presented by Vilanova and Fonseca (2007). In the Pyrenees region, another relative maximum of 0.16 g is also present in the western end and 0.14 g for the eastern end. The value corresponding to the western Pyrenees is very similar to the values recently found (126–150  $\text{cm/s}^2$ ) for the French side by Secanell et al. (2008). However, Marin et al. (2004) in the hazard study for Metropolitan France showed a lower PGA (25–50  $\text{cm/s}^2$ ) for the central Pyrenees area. In the same Fig. 7, we included the 15th and 85th percentile hazard maps that represent an estimation of the uncertainties considered in the logic tree methodology used in hazard calculation.

Sensitivity testing is a critical part of PSHA in order to identify the most important elements used in the model. As we considered three seismotectonic zonings in the tree methodology used in this paper, it was important to know which could be the influence of



**Fig. 7** Mean hazard map for the 475-year return period (10% exceedance probability in 50 years) on rock, obtained for the total logic tree. Also included are the 15th and 85th percentile maps. Isolines are expressed in values of gravity

those zonings in the PSHA. Moreover, as we used three different ground motion models in the tree, we analyzed also the sensitivity of those models to the seismic hazard. In relation with the former element, we present the PSHA results for the three different zonations in Fig. 8. The hazard pattern for the CODE zonation was similar to the hazard of the Building Code, which is presented in Fig. 9, with two relative maxima in the south and southeast parts of Spain. This maximum was also reproduced in the JOINT zoning, whereas in the northwest part, the values present in JOINT were higher than those presented in CODE. The MOL zonation, which was quite different from the other two, presented only a relative maxima in the southeast, while in the northwest, the maxima was similar to the results presented by Vilanova and Fonseca (2007) for northern Portugal. In the Pyrenees, at the northeastern part of the peninsula, the three zonings presented a similar hazard pattern with significant differences in the hazard values.

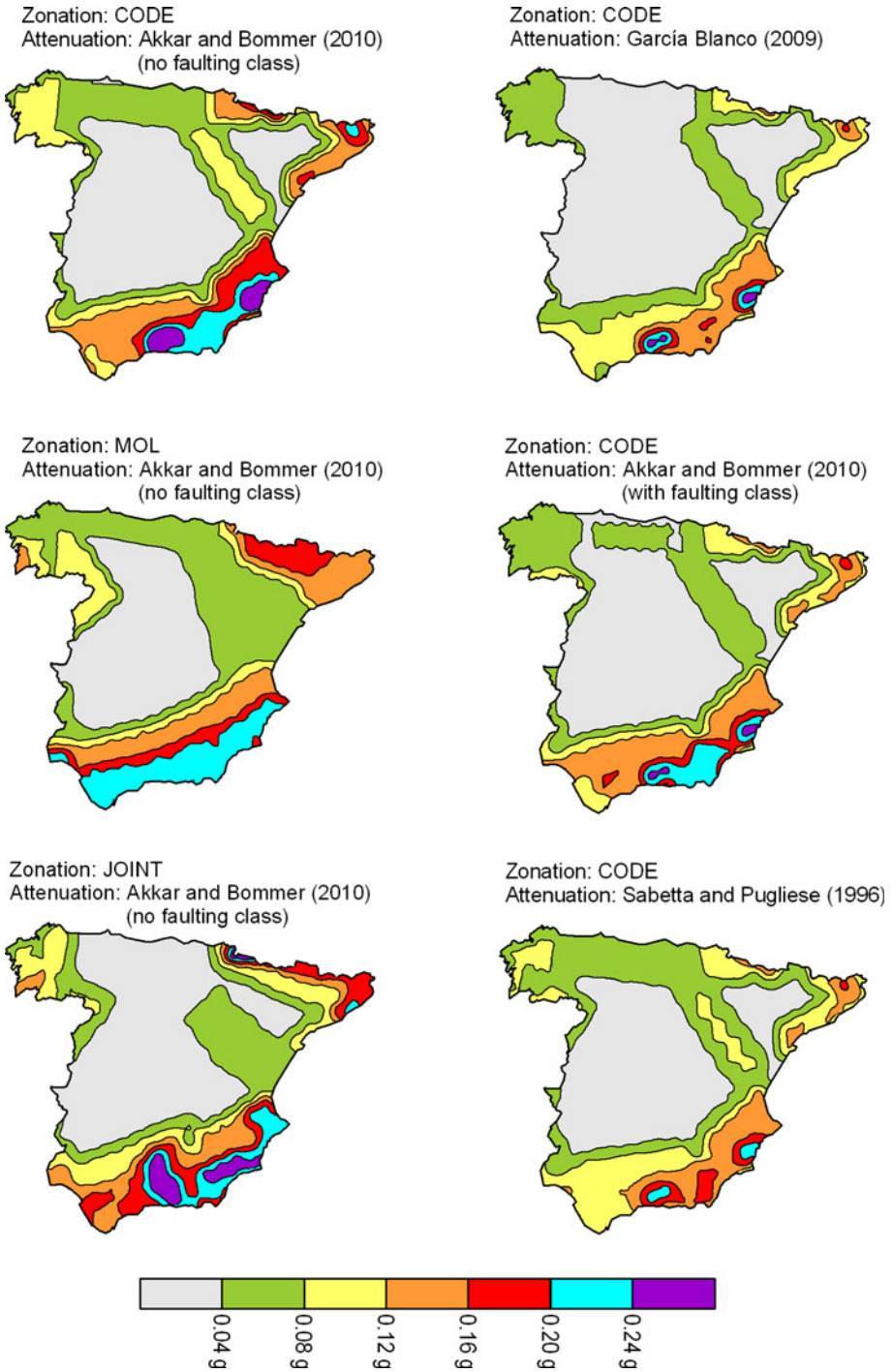
The influence of the three strong ground motion models used is shown also in Fig. 8. We considered also the Akkar and Bommer (2010) version for different types of faulting. Main results were that the García Blanco (2009) model produced similar results as the Sabetta and Pugliese (1996) attenuation model with two maxima around 0.26 and 0.22 g, respectively, in the south and southeastern part of Spain. The distribution of hazard values in the north part (Galicia in the west and the Pyrenees in the east) were similar with slightly higher values provided by the Sabetta and Pugliese (1996) ground-motion model. If we consider the ground motion model of Akkar and Bommer (2010) for the two alternatives (general and considering type of faulting), the hazard results for south and southeastern part of Spain were similar with two maxima of 0.36 and 0.26 g, respectively. However, for the northern part, the two models of Akkar and Bommer (2010) produce similar results as the García Blanco (2009) and Sabetta and Pugliese (1996) models.

## 7 Discussion and conclusions

A new revised earthquake catalogue, in which all events are characterized by their moment magnitude obtained with specific relations derived from the Spanish data (Mezcua et al. 2004), together with the proposed epicentral intensity–moment magnitude obtained in this paper, constitutes the input for the new estimation of the earthquake potential used in the present hazard study. This unified set of data considers not only recent well-defined intermediate and high magnitude events, but also the most important historical events of the area.

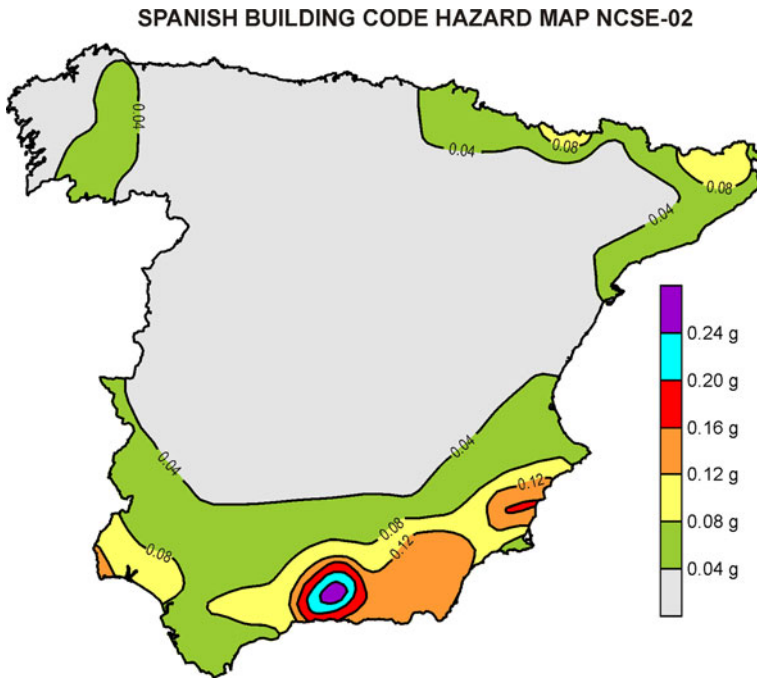
The analysis of strong ground attenuation performed in Mezcua et al. (2008) and García Blanco (2009) provides specific ground motion models for Spain. Besides that we also consider those European relations that may be applicable to the Spanish data, such as those presented by Sabetta and Pugliese (1996) and those recently published by Akkar and Bommer (2010), which embrace those previously published by Ambraseys et al. (2005). The results provided by those ground motion models are consistent and provide similar hazard values for mainland Spain. As Scherbaum et al. (2005) demonstrated for the overall median PGA shown in the tree methodology, the selection of the weighting is not as important as the selection of the ground motion models to be used. In other words, the selection of ground motion models in a hazard study is more important than the assignment of weights in the tree methodology (Sabetta et al. 2005).

In recent years, several regional hazard studies have been performed based in specific seismotectonic zonings; we join them, with this paper, in order to consider another zoning



**Fig. 8** Hazard Maps for 10% exceedence probability in 50 years. Sensitivity to zonation using Akkar and Bommer (2010) ground motion model (*left*) and to the ground motion attenuation models used (*right*)





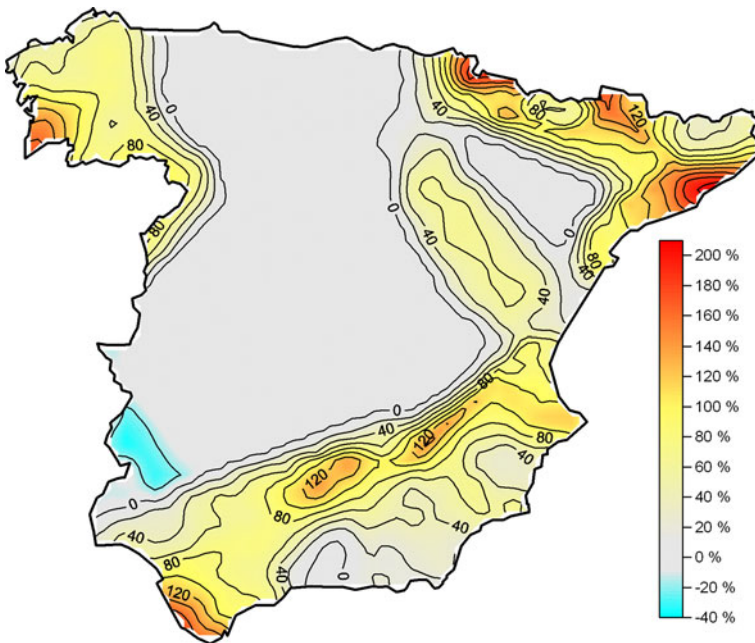
**Fig. 9** Hazard map for the 475-year return period included in the Building Seismic Design Code NCSE-02 of the Ministry of Public Works of Spain (Earthquake Code Permanent Commission of Spain 2002)

of Spain together with the two previous zonings from Martín (1984) and Molina (1998) in the logic tree process.

For the earthquake potential determination of each zoning, we determine the completeness period for each magnitude interval based on the linear method. The resulting dates for intermediate and higher magnitude values (greater than 5.5) are quite similar to those obtained for France.

The hazard map obtained represents the PGA values on rock type condition in mainland Spain corresponding to the 10% exceedance probability in 50 years (475-year return period). It is based on an average of each value for the different options in the tree with their corresponding weights. The weighting scheme used represents the relative confidence we have in each model of both seismic zoning and ground motion, and the resulting hazard values can be considered as representative of the hazards in Spain for such a relatively low return period (475 years). The objections to such an assertion proposed by Abrahamson and Bommer (2005) were against the longer (2500 years) return period values and indicate that our map may be used to compare with the existing hazard map for the building code. Figure 9 includes the official hazard map of the Building Code (Earthquake Code Permanent Commission of Spain 2002). Main trends for distribution of hazard are similar, with maximum values located in the south near Granada and two relative maxima both in the southeastern (Alicante-Murcia) and northern part (Pyrenees) of mainland Spain. If we look for differences in both hazard maps, it is very convenient to represent what is called impact or variability, after Beauval (2003). It is defined as the difference between the hazard values we present and the

official building code corresponding value, normalized to the official building code values expressed in percentage (Fig. 10). So, positive values mean that our hazard map shows greater PGA values than the Code Map and indicate the percentage of this increase. It can be deduced that in those maxima zones obtained, the impact is close to zero, showing lower values in our map in relation to the Building Code Map (negative impact) for the Granada region. However, to the north of those maxima (Granada and Alicante), we find zones of great impact (around 100%), in which the results of this study present greater values than the official map. Another important result is the relative increase in the PGA values corresponding to the northwestern part of the country, with impact on the order of 60–120%, mainly motivated by the Portuguese earthquake hazard influence. Finally in the northeastern part, we can distinguish the Iberian System in the NNW–SSE direction, with impact of around 60% caused by moderate PGA values around 0.06 g, while in the official map no hazard values were offered. However, in the Pyrenees the impact is high (>100%) with an important area close to Barcelona in which the impact goes up to around 200%, going from 0.04 g in the official map to 0.14 g in our study. We believe that such discrepancies between the Code Map and our results should be considered for study in future revisions of the Code Map. As the last map of the impact of our study, compared with the official map, does not distinguish at which level PGAs are related, we included in Table 3 a list of the differences in acceleration shown by our results and the official map for those cities that are capitals of provinces and those cities with a population of more than 60,000 inhabitants whose acceleration



**Fig. 10** Map of impact or variability of the Hazard Map calculated in this paper in relation to the Hazard Map included in the Building Seismic Design Code NCSE-02, expressed in percent. Positive values correspond to zones with greater PGA values than the Building Seismic Design Code NCSE-02 (Earthquake Code Permanent Commission of Spain 2002)

**Table 3** List of seismic hazard values for the province’s capital and towns with more than 60,000 inhabitants whose acceleration values are higher than 0.04 g included in this study (\*) and in the Spanish Building Code Map NCSE-02 (Earthquake Code Permanent Commission of Spain 2002)

City	(*) (g)	NCSE02 (g)	City	(*) (g)	NCSE02 (g)
Albacete	0.08	<0.04	Mataró (Barcelona)	0.14	0.04
Alcalá de Guadaíra (Sevilla)	0.11	0.06	Murcia	0.19	0.15
Alcoy (Alicante)	0.17	0.07	Málaga	0.15	0.11
Algeciras (Cádiz)	0.12	0.04	Orihuela (Alicante)	0.20	0.16
Alicante	0.19	0.14	Ourense	0.08	0.04
Almería	0.17	0.14	Pamplona (Navarra)	0.10	0.04
Badalona (Barcelona)	0.13	0.04	Ponferrada (León)	0.04	<0.04
Barcelona	0.13	0.04	Pontevedra	0.09	<0.04
Benidorm (Alicante)	0.16	0.09	Prat de Ll., El (Barcelona)	0.12	0.04
Bilbao (Vizcaya)	0.04	<0.04	P. de Santa María, El (Cádiz)	0.17	0.06
Cartagena (Murcia)	0.16	0.07	Reus (Tarragona)	0.09	0.04
Castellón	0.05	<0.04	Roquetas de Mar (Almería)	0.16	0.13
Chiclana de la F. (Cádiz)	0.16	0.05	Rubí (Barcelona)	0.13	0.04
Cornellà (Barcelona)	0.13	0.04	Sabadell (Barcelona)	0.13	0.04
Coruña, A	0.06	<0.04	Sagunto (Valencia)	0.07	0.04
Cádiz	0.16	0.07	San Fernando (Cádiz)	0.17	0.06
Córdoba	0.10	0.05	San Sebastián (Guipúzcoa)	0.09	0.04
Dos Hermanas (Sevilla)	0.12	0.07	S. V. de Barakaldo (Vizcaya)	0.04	<0.04
Ejido, El (Almería)	0.17	0.14	Sanlúcar de B. (Cádiz)	0.15	0.07
Elche (Alicante)	0.20	0.15	Sant Boi de Ll. (Barcelona)	0.12	0.04
Ferrol (A Coruña)	0.05	<0.04	Sant Cugat (Barcelona)	0.13	0.04
Fuengirola (Málaga)	0.14	0.07	Santa Coloma (Barcelona)	0.13	0.04
Gandía (Valencia)	0.15	0.07	Santiago de C. (A Coruña)	0.06	<0.04
Girona	0.14	0.08	Sevilla	0.11	0.07
Granada	0.21	0.23	Soria	0.06	<0.04
Huelva	0.16	0.1	Tarragona	0.10	0.04
Huesca	0.06	<0.04	Terrassa (Barcelona)	0.13	0.04
Jaén	0.15	0.07	Teruel	0.06	<0.04
Jerez de la Frontera (Cádiz)	0.15	0.06	Torrent (Valencia)	0.11	0.07
Linares (Jaén)	0.13	0.05	Torre Vieja (Alicante)	0.19	0.14
Lleida	0.04	<0.04	Valencia	0.11	0.06
Logroño (La Rioja)	0.05	<0.04	Viladecans (Barcelona)	0.12	0.04
Lorca (Murcia)	0.19	0.12	Vilanova i la G. (Barcelona)	0.10	0.04
Lugo	0.07	0.04	Vitoria (Álava)	0.04	<0.04
Línea de la C., La (Cádiz)	0.12	0.04	Vélez-Málaga (Málaga)	0.18	0.18
Manresa (Barcelona)	0.10	0.04	Zamora	0.04	<0.04
Marbella (Málaga)	0.14	0.07			

values are higher than 0.04 g. It can be seen that there are very important differences in some populated areas, such as those to the north of Barcelona, the region around Cadiz in the southwestern part of Spain and to the north of Alicante in the southeastern end.

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