

Probabilistic seismic hazard assessment in SE-Spain based on macroseismic site histories

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Abstract In many countries such as Spain earthquake databases still mainly comprise macroseismic data from felt effects. The full exploit of this information is of basic importance for seismic risk assessment and emergency planning, given the strict link between macroseismic intensity and damage. A probabilistic procedure specifically developed to handle macroseismic data, mostly relying on site information and seismogenic-source free, has been applied to evaluate seismic hazard in SE-Spain (Alicante-Murcia region). Present seismicity is moderate-low with largest magnitudes slightly over Mw5.0. The historical record includes very destructive earthquakes, maximum EMS98 intensities reaching IX–X and X in the nineteenth century (e.g., Torrevieja 1829 earthquake). Very recently, two events in the area on 11 May 2011 (Mw4.5, Mw5.2) killed nine people, injured 300, and produced important damage in the city of Lorca. Regional hazard maps for the area together with specific hazard curves at selected localities are obtained. Results are compared with the maximum observed intensities in the period 1300–2012, and with the values in the seismic hazard map from the Spanish Building Code in force. In general, the maximum felt intensity values are closer to the hazard values calculated for 2 % probability of exceedance in 50 years, using felt and expected intensity. The intensity-based probabilistic hazard maps obtained through the applied approach reduce the inherent smoothing of those based on standard probabilistic seismic hazard assessment approaches for the region, allowing identifying possible over- or sub-estimates of site hazard values, providing very valuable information for risk reduction strategies or for future updates of the building code hazard maps.

Keywords Macroseismic intensity · Seismic hazard · PSHA · SE Spain · Vega Baja · Lorca

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1 Introduction

A probabilistic procedure specifically developed to handle macroseismic data has been applied to evaluate seismic hazard in SE-Spain (Alicante-Murcia region). The procedure rely on local information concerning the effects of past earthquakes documented at the site where the hazard is being computed (Albarello and Mucciarelli 2002; D'Amico and Albarello 2008). This region (Fig. 1) corresponds to Test Area 3 in UPStrat-MAFA project. It includes several Neogene-Quaternary basins that developed in the Betic Cordillera. Among these, the Lower Segura River Basin, which corresponds to the most southerly district of the Alicante province, called the 'Vega Baja'; and the Lorca Basin, near the city of Lorca, SW of the Murcia province.

The present seismicity in SE Spain is, in general, characterised by the occurrence of moderate earthquakes, most of which have a shallow focus (<http://www.ign.es/ign/layoutIn/sismoTerremotosEspana.do?value=2>). The strongest events that occurred during the instrumental period reached only moderate magnitudes slightly over $M_w 5.0$, although the historical seismicity as recorded in the Spanish earthquake catalogue reveals the occurrence of very destructive earthquakes with maximum EMS98 intensities reaching IX–X and X (Martínez Solares and Mezcuca 2002). In the Vega Baja, the strongest event, known as the Torreveja earthquake, occurred on 21 March 1829. It was the main shock in a seismic sequence of at least 42 events that occurred from 1828 to 1830, with EMS98 intensities reaching IX–X (Albini and Rodríguez de la Torre 2001). EMS98 VIII intensities were also reported in the region in 1048, 1482 and 1673 in Orihuela, and in 1919 in Jacarilla (Martínez Solares and Mezcuca 2002). On 11 May, 2011, two damaging earthquakes ($M_w 4.5$, $M_w 5.2$) killed nine people, injured more than 300, and produced important building damage in the city of Lorca (Martínez-Díaz et al. 2012). According to the Spanish earthquake record, in the Lorca Basin and surrounding regions, significant damaging events have also occurred in historic times, such as those in 1674 (Lorca), 1855 (Alhama de Murcia), 1911 (Lorquí) and 1948 (Cehegín). The most recent activity before the 2011 Lorca earthquakes includes events of around magnitude $M_w 5.0$ in 1999, 2002 and 2005, which produced slight damage in several localities of Murcia region (Benito et al. 2007). Figure 2 depicts epicentres in the Alicante-Murcia region for the period 1048–2012 as obtained from the Spanish earthquake catalogue database (<http://www.ign.es/ign/layoutIn/sismoFormularioCatalogo.do>).

Intensity-based hazard maps are produced for the whole region; with more detailed site analysis at some localities selected in the areas of Vega Baja and Lorca (Fig. 1), where one of the strongest earthquake in the Spanish catalogue (1829 Torreveja earthquake, $I_{\max} = IX-X$), and the latest damaging one (2011 Lorca earthquake, $I_{\max} = VII$) occurred, respectively. The results are compared with the maximum observed intensities in the period 1300–2012, as compiled and harmonized by Jiménez et al. (2015), as well as with the values in the Spanish Building Code in force (NCSE-02 2003), and those from the most recent Seismic Hazard Map of Spain related to the ongoing revision and update of the Spanish Building Code (Martínez Solares et al. 2013).

2 The 'site approach' and its implementation: the code SASHA

Due to the strict link between macroseismic intensity and damage, seismic hazard estimates in terms of intensity as ground-shaking measure are of basic importance for seismic risk assessment and emergency planning. Furthermore, in many countries, such as Spain,

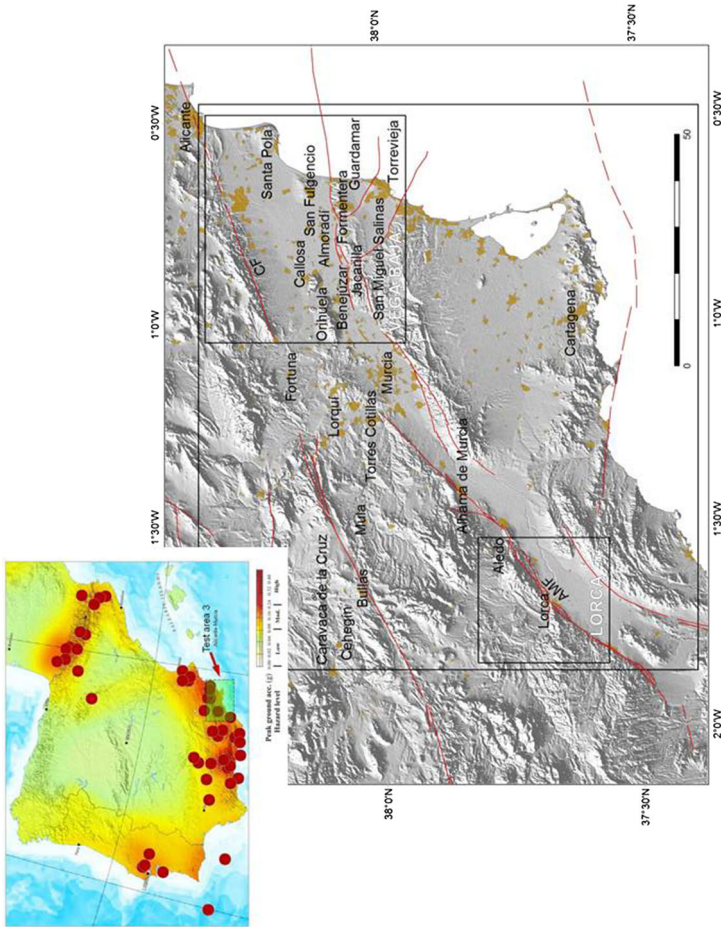


Fig. 1 Shaded relief model of the Alicante-Murcia region in SE Spain, main localities in the Vega Baja and Lorca areas, and main faults traces from the quaternary fault database in IGME (2012). AMF Alhama de Murcia fault, CF Crevillente fault. *Inset* Larger ($I_{max} \geq VIII$) historical earthquakes in the Iberian Peninsula overlaid on the European-Mediterranean Seismic Hazard Map in terms of peak ground acceleration with 10 % probability of exceedance in 50 years (modified from Jiménez et al. 2003). The *rectangle* identifies UPStrat-MAFA Test Area 3 (Alicante-Murcia region)

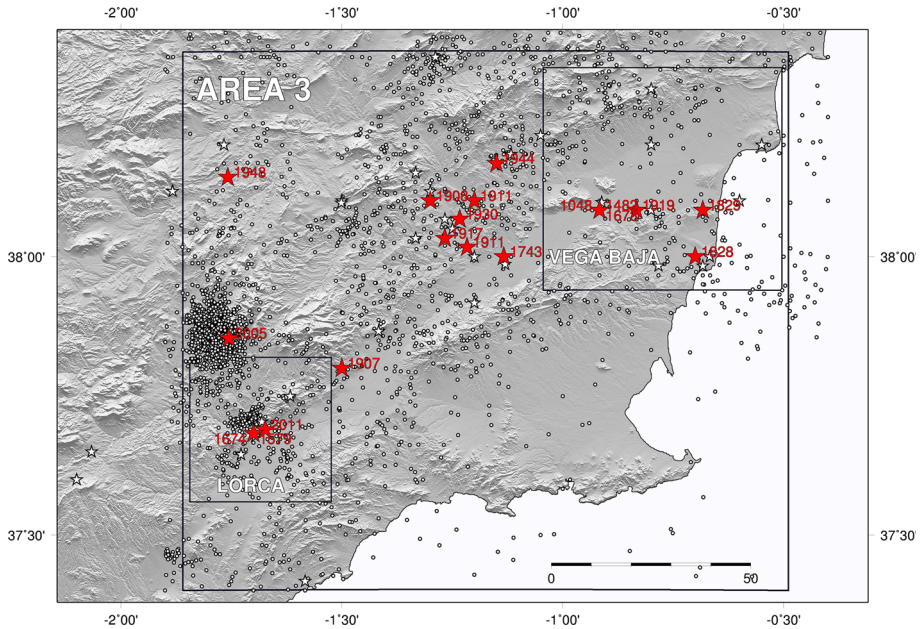


Fig. 2 Seismicity in the Alicante-Murcia region, SE Spain, for the period 1048–2012, from the Spanish earthquake catalogue data base (<http://www.ign.es/ign/layoutIn/sismoFormularioCatalogo.do>). White stars highlight epicentres of the larger earthquakes ($I\text{-EMS98} \geq V\text{--}VI$), while red stars do for the strongest events $I\text{-EMS98} \geq VII$

the bulk of the earthquake database is constituted by macroseismic data, and thus the application of the standard Cornell-McGuire (Cornell 1968; McGuire 1978) methodology for probabilistic seismic hazard assessment (PSHA) requires a “forcing” of macroseismic information into a para-instrumental format.

For the above reasons, a probabilistic procedure was developed to handle macroseismic data to evaluate seismic hazard (Albarelo and Mucciarelli 2002). This procedure, implemented by D’Amico and Albarelo (2008) in the computer code SASHA (Site Approach to Seismic Hazard Assessment), calculates seismic hazard in terms of macroseismic intensity by basically relying on local information concerning effects of past earthquakes at the site where seismic hazard is assessed. This is why it is referred as ‘site approach’. There is no need for any model of seismogenic sources. The approach allows to fully exploiting the macroseismic information available at the site in the frame of a formally coherent and complete treatment of intensity data, by taking into account the relevant uncertainty and the inherently bounded, ordinal and discrete character of intensity values. Like in the standard Cornell-McGuire approach, the seismogenic process is assumed to be stationary, but no seismotectonic constraint is considered. Several PSHA studies were performed in the last decade in Italy and elsewhere using different versions of the site approach (Albarelo et al. 2002; D’Amico and Albarelo 2003, 2008; Galea 2007; Azzaro et al. 2008; Bindi et al. 2012).

Seismic hazard is computed by considering a time series of macroseismic intensities at the site of interest (local seismic history). This time series is built up by combining seismic effects observed at the site during past earthquakes, in terms of intensity, and, when needed, expected intensity values deduced from epicentral data through intensity-based

empirical ground-motion prediction equations (see e.g., Albarello and D’Amico 2004; Rotondi and Zonno 2004; Pasolini et al. 2008; Zonno et al. 2009). Each intensity evaluation is considered as affected by a measurable uncertainty depending on the available information. Completeness and representativity of information locally available is then evaluated along with the relevant uncertainty (local completeness). Seismic recurrence at the site, for each intensity threshold I_s , is parameterized by a fully distribution-free approach not requiring any pre-processing (like e.g., aftershock removal, selection of mainshocks within a seismic sequence, etc.).

SASHA provides two main outputs: hazard curve (probability that at least one event with intensity not less than I_s will occur in the exposure time at the site under study); and reference intensity, I_{ref} , determined from the hazard curve as a function of the considered probability threshold (e.g., 0.1). Furthermore, in the version used for the UPStrat-MAFA project, magnitude/distance pairs more representative for the reference ground motion (disaggregation) are provided along with past earthquakes most important for local hazard (see Albarello 2012 for details).

In the frame of USPtrat-MAFA project, the SASHA code has been significantly improved to make it applicable in different contexts and for different purposes. Major changes concern the reconstruction of the site seismic history. In this implementation, five general forms for ground-motion prediction models are allowed, whose parameters are provided for each earthquake, and it is possible to attribute a different attenuation model to each earthquake in the catalogue. This allows a geographical/seismotectonic differentiation of attenuation patterns and to account for possible propagation anisotropy induced by the source geometry (see e.g., Rotondi and Zonno 2004; Zonno et al. 2009).

3 Data compilation

Table 1 summarizes the 1300–2012 database of macroseismic data points (MDP) compiled from SE Spain region in Jiménez et al. (2015). It incorporates a total number of 64 events for which maximum intensity is equal or greater than V–VI, described by the following parameters: date, location, epicentral intensity and epicentral locality. For all these events the database contains a total number of 887 individual MDP.

The compilation of the MDP was based on the records of earthquake macroseismic intensities in the Spanish catalogue which are heterogeneous. Different periods of time have received different attention and the different intensity scales used through time have not been yet harmonized for the whole time span of the catalogue. A harmonization procedure was carried out of the available and highly heterogeneous MDP. First, a revision and selection of available studies and a collection of MDP for earthquakes above

Table 1 Number of earthquakes and number of macroseismic data points (MDP) gathered for the whole time period (1300–2012) and disaggregated for the two specified periods (1300–1899, 1900–2012)

Macroseismic fields ($I_{max} > = V-VI$)		
Time span	Events	MDP
1300–2012	64	887
1300–1899	25	152
1900–2012	39	735

maximum intensity V–VI in the period 1300–2012 was performed. For the time span 1300–1899 the main source of information was the revised historical catalogue by Martínez Solares and Mézcua (2002) where MDP are mainly referred to the EMS98 scale (Grünthal 1998). Additional sources from recent published studies were considered as well for this time span, to incorporate in the database the most updated results of investigations. The 1900–2012 period was the most incomplete and the most complicated to deal with, as no centralized database with MDP information was available, and information was very dispersed. The intensity observations for this period of time are given in many different forms (analogue tables, digital tables, analogue maps, and in many cases just descriptions of damage, when the original source had to be searched for), and were spread over many different sources and a few recently published studies in the literature on historical earthquakes in the twentieth century (e.g., Buforn et al. 2005). Once compiled, the data were harmonized to EMS98 scale according to Musson et al. (2010). For more details on the compilation and harmonization procedure see Jiménez et al. (2015).

To complement intensity observations at a site, expected effects from the compiled earthquake catalogue are calculated using a probabilistic approach to intensity attenuation, a beta-binomial model as proposed by Rotondi and Zonno (2004), with the aim of capturing the intrinsic uncertainty in the attenuation process. In the frame of the USPTrat-MAFA project a specific isotropic model was developed for SE Spain (Rotondi et al. 2015) from the regional earthquake data of MDP compiled. This model provides the smoothed binomial probability of site intensity, I_s , from an earthquake with epicentral intensity I_0 at a distance d by:

$$P(I_s = i | I_0 = i_0; g(d)) = \binom{i_0}{i} g(d)^i (1 - g(d))^{(i_0 - i)}$$

where

$$g(d) = \left(\frac{c_1}{c_1 + d} \right)^{c_2}$$

is a smoothing inverse power function with parameters c_1 and c_2 , whose values for SE Spain are shown in Table 2 for each epicentral intensity class.

The approach followed assumes intensity as a discrete variable. For those earthquakes in the compiled catalogue with epicentral intensity between two intensity values, I_0 is rounded to the lower integer (Rotondi et al. 2015).

Table 2 Parameters of the smoothing inverse power function for each epicentral intensity class used in the isotropic model of intensity attenuation developed for SE Spain

I_0	c_1	c_2
V	5215.7	92.5
VI	441.4	7.9
VII	171.2	2.9
VIII	200.4	3.2
IX	387.2	4.7
X	31,832.6	330
XI	33,942.3	307.7

4 Hazard calculation

Seismic hazard in terms of reference intensity, I_{ref} , was calculated at the nodes of a 5×5 km grid covering the region for 2 and 10 % probability of exceedance in 50 years; considering both, only catalogued felt data and felt data plus expected intensities from the earthquakes in the compiled catalogue 1300–2012, using the intensity attenuation isotropic model described above.

For each node in the grid, the nearest felt intensity observation, if any, in a radius of 3.5 km around the point is selected to build the site seismic history. If no intensity data is available, expected intensities are obtained from earthquakes in the catalogue within a distance of 100 km. If felt observations are available for the same earthquake within 20 km radius the calculated intensities are corrected. The statistical completeness of site seismic histories is considered when computing hazard (see details in D’Amico and Albarello 2008).

Seismic histories, from both, felt and expected observations, at selected localities in the Vega Baja (Almoradí, Torrevieja and Santa Pola) and Lorca (Aguilas, Lorca and Mula) areas are plotted in Fig. 3. Comparing the seismic histories at the localities with largest felt intensity in the two areas, Lorca and Torrevieja, Lorca shows a more complete history, while Torrevieja seems to lack data before 1800. In fact, Lorca was already inhabited since the Arabs ruled it in s. X–XII, and the Christian castle, with local population, dates back to 1300. Torrevieja did not have a significant population until end of s. XVIII (there were few more than 500 inhabitants in 1789).

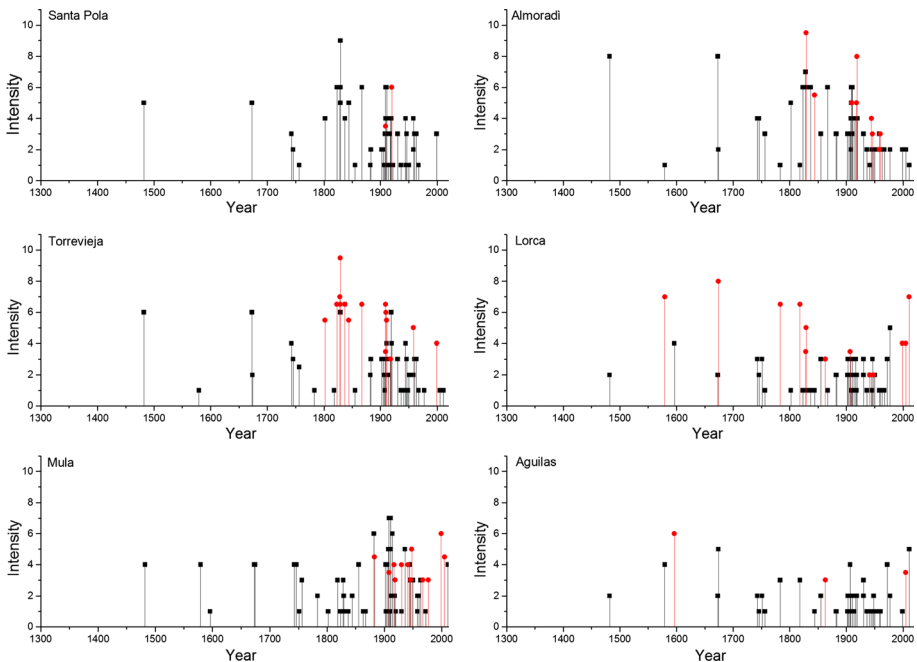


Fig. 3 Seismic histories of the six selected localities in the Alicante-Murcia region. For each earthquake, ‘representative’ intensity value is reported. This value corresponds to the mode of the probability distribution describing uncertainty affecting the relevant information (for details, see Albarello and Mucciarelli 2002; D’Amico and Albarello 2008). *Red dots* indicate that intensity has been deduced from felt effects documented at the site. *Black squares* indicate intensity values deduced from epicentral information via empirical attenuation relationships

Figure 4 shows the hazard maps for I_{ref} with 10 % probability of exceedance in 50 years. When considering only felt data (Fig. 4a) values are below intensity V for most of the region, with largest intensity values (VIII, IX) concentrated in the easternmost Vega Baja. When adding expected intensities (Fig. 4b), the pattern of largest values is similar, but most of the region depicts values of VI and VII.

Maps of I_{ref} with 2 % probability of exceedance in 50 years are shown in Fig. 5. The general pattern using only felt data (Fig. 5a) is similar to that in Fig. 4a; while the use of additional expected intensities (Fig. 5b) increases the regional pattern up to values of VII and greater; with two relatively wide nuclei of VIII in Lorca area and in Vega Baja, where the largest values (IX and X) are obtained.

Comparing the hazard results considering only felt data (Figs. 3a, 4a) with the maximum felt intensities observed in the region in Fig. 6 from the 1300–2012 record, maximum observations in eastern Vega Baja are similar to both hazard values with 10 and 2 % exceedance probability in 50 years. In Lorca area (around Lorca city as well as at the northern and southern ends) maximum observed intensities are closer to hazard values with 2 % exceedance probability in 50 years. Similar comparison is found in the smoothed maps when using both felt data and calculated intensities (Figs. 3b, 4b), but in this case the relative highs are broader.

Specific hazard curves of probability of exceedance in 50-year period are obtained at selected localities in the region. Santa Pola, Almoradí and Torrevieja in the Vega Baja (Fig. 7); and Mula, Lorca and Aguilas in the Lorca area (Fig. 8). As for the hazard maps, two of the curves are computed using only felt data and felt data plus expected intensities. An additional one combining felt data and expected intensities, but rounding epicentral intensities to the upper integer is also plotted, to observe the difference if any with respect to the approach of rounding to the lower integer. In general, rounding epicentral intensity to the upper or lower integer has relatively low influence on the site hazard results.

Several probability levels are identified in the hazard curve plots as a reference. They correspond to 2, 10, 20, 40 and 64 % probability of exceedance in 50 years (equivalent mean return periods of 2475, 475, 225, 98, and 49 years, respectively).

At localities with significant seismic histories, especially for higher intensities, the curve computed using only felt data is close to that adding expected intensity (e.g., Torrevieja and Almoradí in the Vega Baja, and Lorca city). On the contrary, for localities with poor seismic histories (e.g., Santa Pola and Aguilas) the two curves are different, indicating probable incompleteness of low intensity values (e.g., Santa Pola).

Site hazard disaggregation in the applied ‘site approach’ provides first the list of events in the earthquake catalogue contributing to the calculated reference intensity, I_{ref} , with their probability of have been actually felt with intensity not less than I_{ref} . Then, these probabilities are binned in magnitude/distance classes of 0.5 units and 10 km, respectively, giving the normalized relative contribution to the reference intensity. The results obtained for some of the selected localities in the region are shown in Fig. 9. In Lorca (Fig. 9a), the contribution to $I_{\text{ref}} = \text{VII}$, the reference intensity with 10 % probability of exceedance in 50 years, is mainly coming from moderate size events (M_w 5.0–6.0) close to the city (0–10 km); while the reference intensity with 2 % probability of exceedance in 50 years, VIII, is dominated by a single event of M_w 5.5 at 1 km distance, corresponding to the 28/08/1674 event in the catalogue. The reference intensity at Torrevieja (Fig. 9b), for both 10 and 2 % exceedance probability in 50 years, is 100 % dominated by the 1829 earthquake. The specific implementation of the ‘site approach’ allows identifying that, in the first case (10 %—50 years), the probability that the earthquake was felt with intensity not

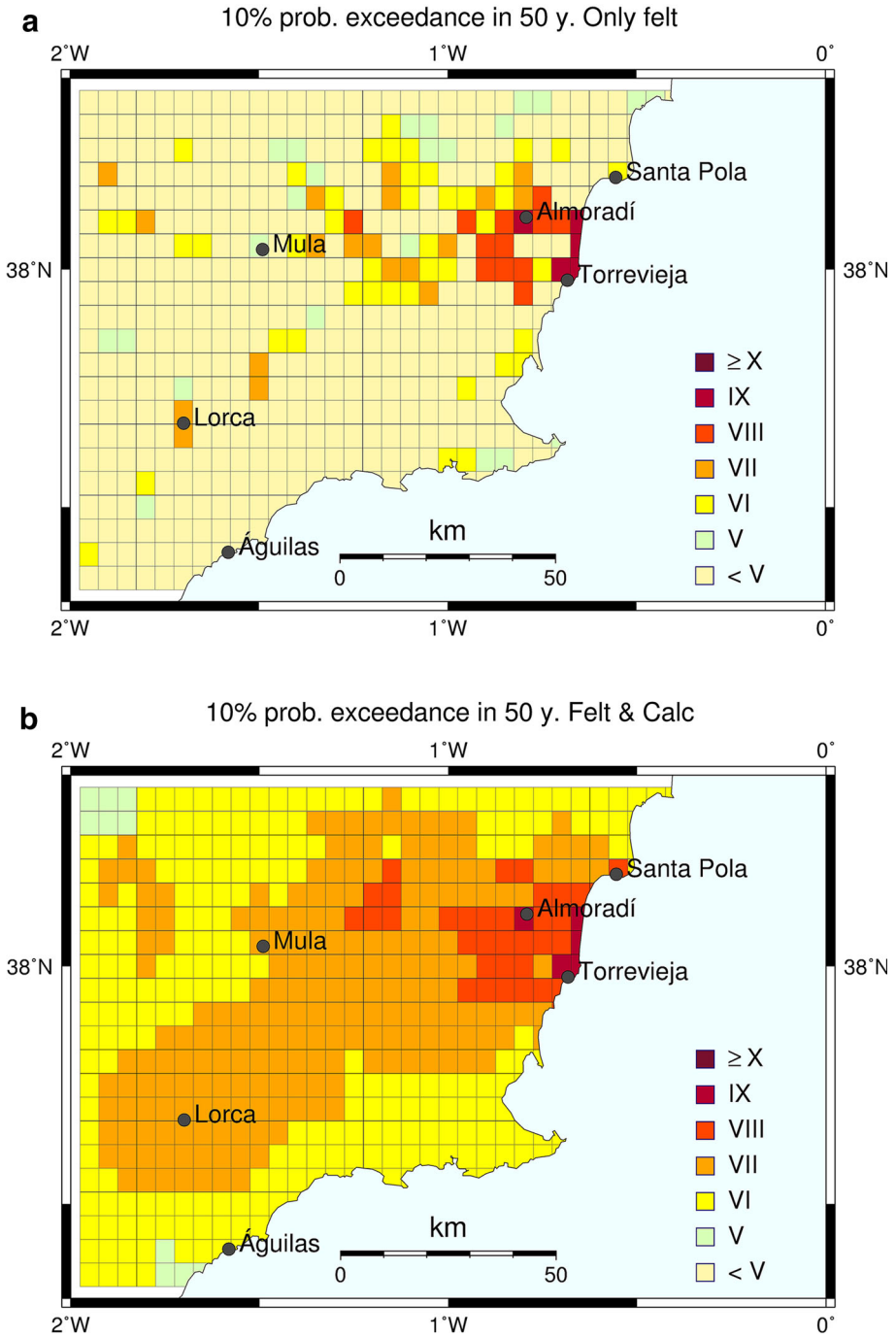


Fig. 4 Hazard values, I_{ref} , with 10 % probability of exceedance in 50 years. **a** Only felt observations, **b** felt observations plus calculated expected intensities

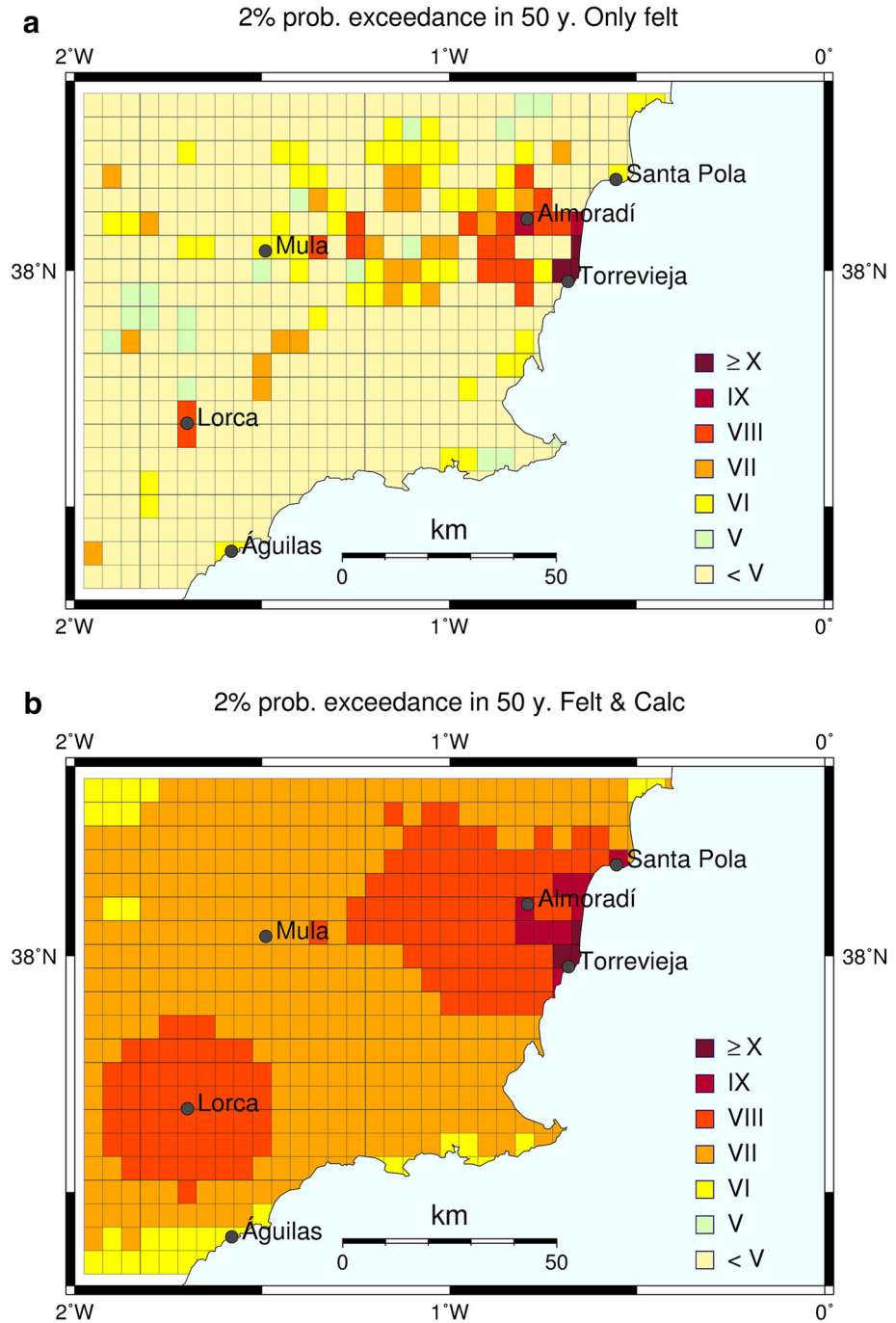


Fig. 5 Hazard values, I_{ref} , with 2 % probability of exceedance in 50 years. **a** Only felt observations, **b** felt observations plus calculated expected intensities

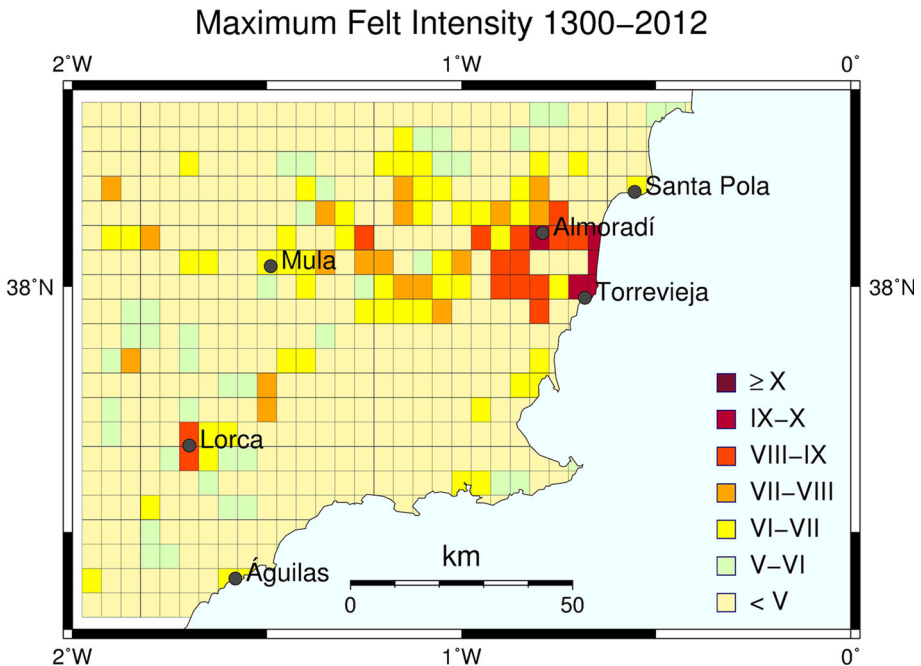


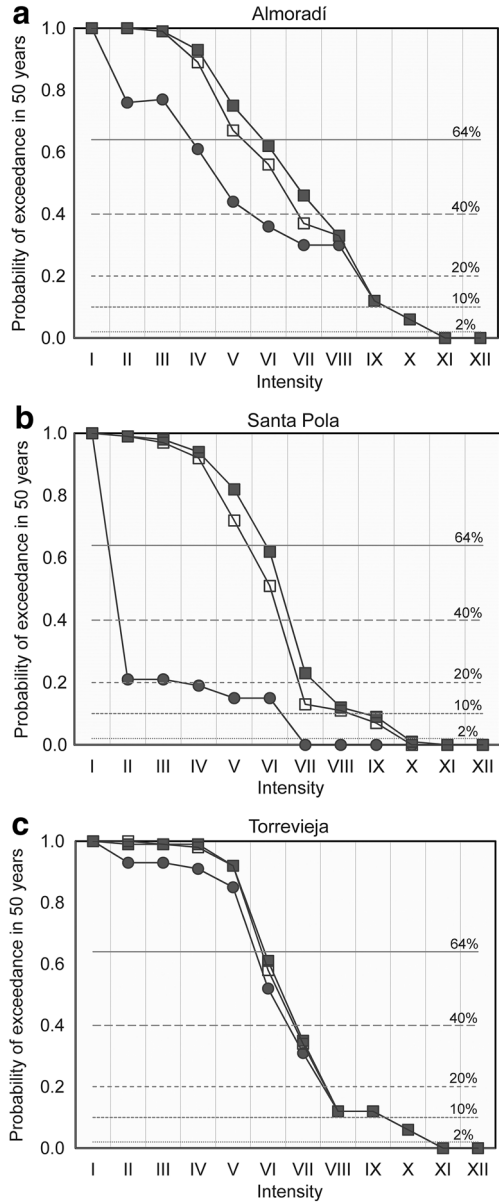
Fig. 6 Maximum observed intensities in the period 1300–2012. Intervals in the legend correspond to intensities equal to the lower value or between both

less than IX is 1, while for 2 % probability of exceedance in 50 years it is 0.5. Figure 9c shows the disaggregation results for two localities, Águilas and Mula, where the reference intensity has the same value for the two hazard probability levels calculated (10 and 2 % in 50 years). In both cases the main contributions show a bimodal distribution. In Águilas, the reference intensity is mostly due to small magnitude (M_w 4.0–4.5) earthquakes close to the site (0–10 km), with a significant contribution from moderate events (M_w 5.5–6.0) relatively distant (30–40 km). In Mula, small (M_w 4.5–5.0) and moderate (M_w 5.5–6.0) earthquakes at relatively short distances, 10–20 and 20–30 km, respectively, are representative of the reference intensity with the same relative contribution.

The maximum felt intensity observed at each locality in 713 years of catalogued data (1300–2012) is summarized in Table 3, together with the reference values, I_{ref} , from the hazard calculations in this work for 10 and 2 % exceedance probability in 50 years, with the values included in the Spanish Building Code in force (NCSE-02 2003), and with the values included in the most recent official update of the Seismic Hazard Map of Spain (IGN2012) by Martínez Solares et al. (2013).

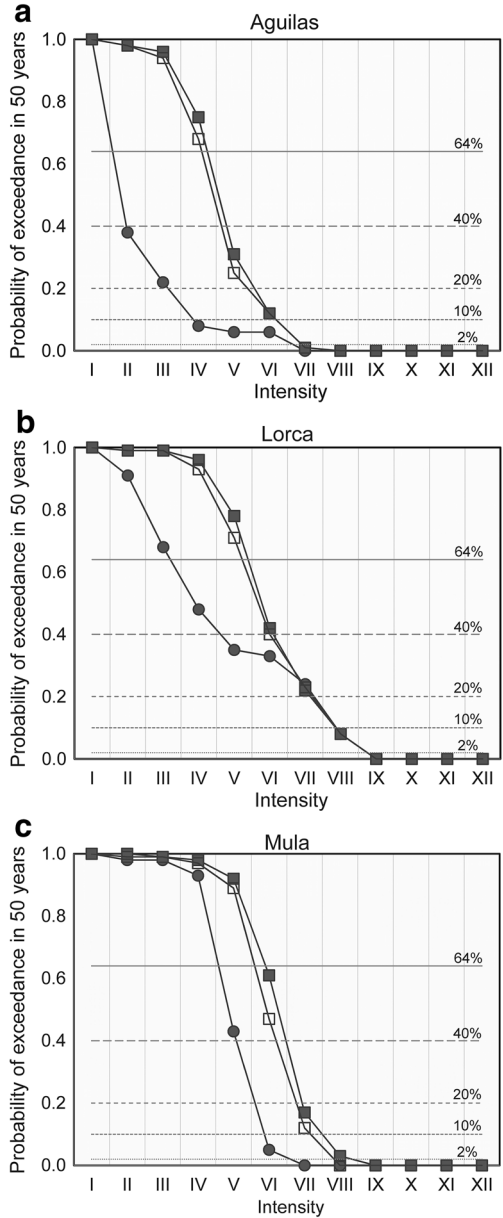
Both, the NCSE-02 Building Code and the updated IGN2012 Hazard Map, provide ground motion values with 10 % probability of exceedance in 50 years, in terms of peak ground acceleration (PGA). Suggested PGA-Intensity empirical correlations by NCSE-02 (2003) and Martínez Solares et al. (2013) give practically the same values when used to obtain the intensities in Table 3. Thus, in what follows we use the NCSE-02 Building Code values as reference.

Fig. 7 Hazard curves of probability of exceedance in 50-year period for selected localities in Vega Baja area: **a** Almoradí, **b** Santa Pola, and **c** Torrevieja. *Filled circle* Only felt data. *Open square* Felt data and calculated felt intensities, rounding I_0 to lower integer. *Filled square* Felt data and calculated felt intensities, rounding I_0 to upper integer



Intensity values in Table 3, except IGN2012, are graphically compared in Fig. 10. In Almoradí and Torrevieja, the maximum observed intensity lies between the hazard values for 10 and 2 % exceedance probability in 50 years, and it is larger than that in NCSE-02. For Santa Pola, Aguilas and Mula (most evident in Santa Pola), the value observed is significantly lower than the Building Code reference, and also lower than the hazard values

Fig. 8 Hazard curves of probability of exceedance in 50-year period for selected localities in Lorca area: **a** Aguilas, **b** Lorca, and **c** Mula. *Filled circle* Only felt data. *Open square* Felt data and calculated felt intensities, rounding I_0 to lower integer. *Filled square* Felt data and calculated felt intensities, rounding I_0 to upper integer



using felt and expected intensity for both, 10 and 2 % exceedance probability in 50 years. In Lorca city, all values are very similar. In general, the observations are closer to the hazard values calculated for 2 % probability of exceedance in 50 years, using felt and expected intensity, in all the localities, but in Santa Pola and Mula.

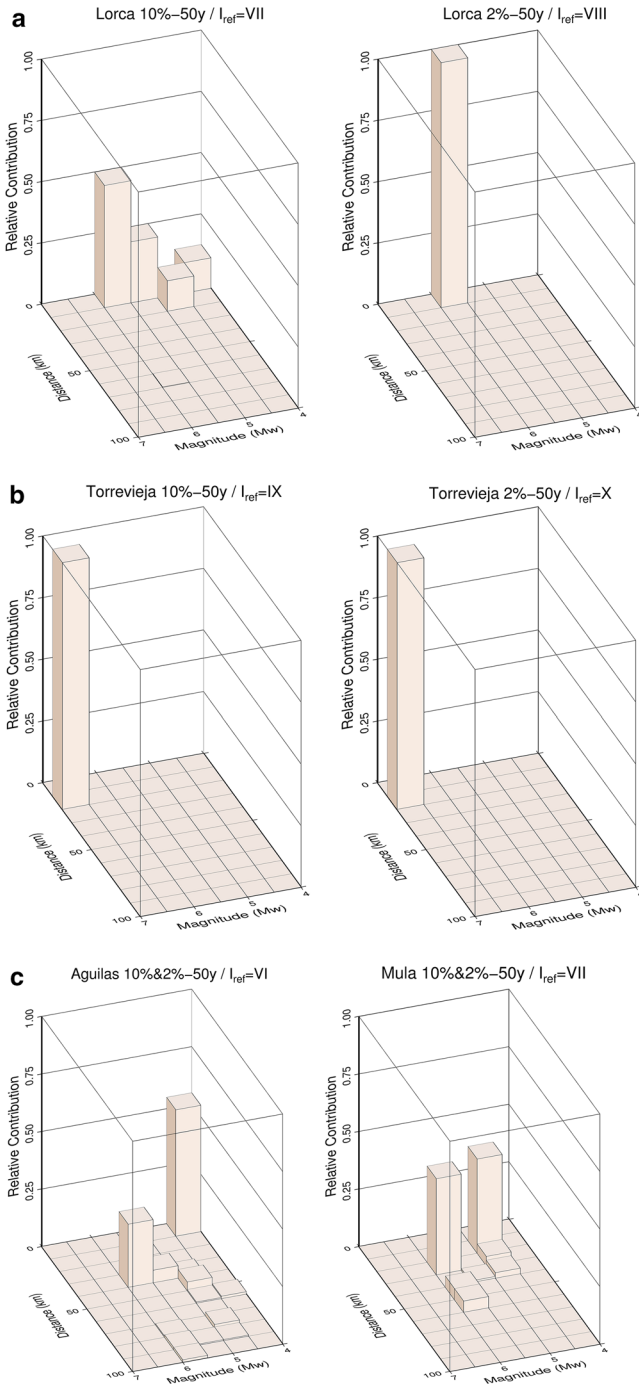


Fig. 9 Binned relative contribution to the reference intensity for 10 and 2 % exceedance probability in 50 years at some of the selected localities in the Alicante-Murcia region. **a** Lorca. **b** Torrevieja. **c** Aguilas and Mula

Table 3 Observed, calculated and reference seismic intensity at selected localities in the Alicante-Murcia region

Locality	MDPs $I \geq I$	I_{max}	I_{ref} 10 % only felt	I_{ref} 10 % felt and calc.	I_{ref} 2 % only felt	I_{ref} 2 % felt and calc.	I_{ref} NCSE-02	I_{ref} IGN2012
Almoradí	9	IX– X	IX	IX	X	X	VIII	VIII
Santa Pola	2	VI	VI	VIII	VI	IX	VIII	VIII
Torrevieja	15	IX– X	IX	IX	X	X	VIII	VII–VIII
Aguilas	4	VI	III	VI	VI	VI	VII–VIII	VII
Lorca	13	VIII	VII	VII	VIII	VIII	VII–VIII	VII–VIII
Mula	13	VI	V	VII	VI	VII	VII	VII

MDPs $I \geq I$: Number of observations with $I \geq I$; I_{max} : Maximum observed intensity; I_{ref} 10 % only felt: hazard value with 10 % probability of exceedance in 50 years using only felt data; I_{ref} 10 % felt & calc.: hazard value with 10 % probability of exceedance in 50 years using felt data plus expected felt intensities; I_{ref} 2 % only felt: hazard value with 2 % probability of exceedance in 50 years using only felt data; I_{ref} 2 % felt & calc.: hazard value with 2 % probability of exceedance in 50 years using felt data plus expected felt intensities; I_{ref} NCSE-02: reference value from the NCSE-02 Building Code (10 % probability of exceedance in 50 years); I_{ref} IGN2012: reference value from the 2012 updated Seismic Hazard Map of Spain (10 % probability of exceedance in 50 years)

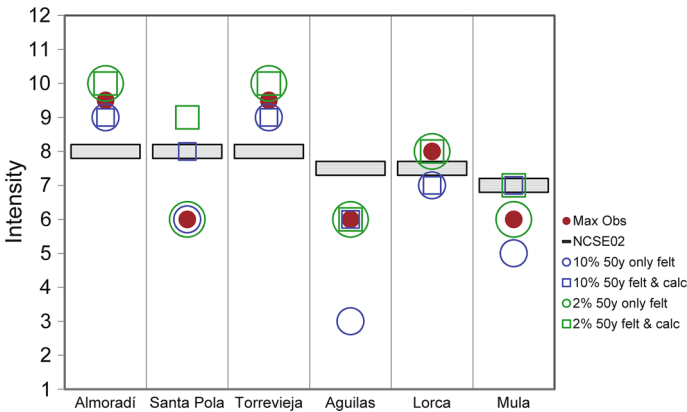


Fig. 10 Observed, calculated and reference seismic intensity at the selected localities in the Alicante-Murcia region from Table 3

5 Conclusions

Intensity-based hazard approaches allow full exploitation of the large amount of macro-seismic data, which constitute the bulk of available earthquake information particularly in regions of moderate to low seismicity and large historical record, like e.g., the Iberian Peninsula. Intensity-based PSHA has been performed in SE Spain following the method developed by D’Amico and Albarello (2008), using the intensity data points and the

earthquake catalogue compiled by Jiménez et al. (2015) for the 1300–2012 period, with a specific isotropic beta-binomial model of intensity attenuation developed for SE Spain (Rotondi et al. 2015). Results include regional hazard mapping as well as single site hazard curves, at different probability levels.

Hazard maps show their largest values in eastern Vega Baja. These are similar for both 10 and 2 % exceedance probability in 50 years and comparable to maximum observed intensities in the historical record. In the Lorca area observed intensities are closer to hazard values with 2 % exceedance probability in 50 years.

Looking at specific localities, those with significant amount of MDP in the compiled regional database, especially for higher intensities, show similar hazard curves regardless of using only felt data or adding expected felt intensity. Localities with poor seismic histories have very different curves most probably evidencing incompleteness—especially in lower intensity values—in the hazard curve based only on observations. When comparing at the same localities the maximum felt intensities in the period 1300–2012, the calculated values with 10 and 2 % probability of exceedance in 50 years, and the reference values from the Building Code in force, the observations are larger than the Building Code reference at sites with relatively more complete seismic history, and lower at sites with poor or more limited seismic history. In general, the maximum felt intensity values in the period 1300–2012 are closer to the hazard values calculated for 2 % probability of exceedance in 50 years, using felt and expected intensity, especially at those places where larger values were observed and are predicted. Seismic intensity values, both observed and calculated, could incorporate site effects and/or vulnerability assessment. Therefore, any conclusion from direct comparison with Building Code reference values should be considered carefully. Building code values normally refer to rock or stiff soil conditions (e.g., NCSE-02 values correspond to a ground type with shear wave velocity between 400 and 750 m/s) and are influenced as well by the uncertainty involved in the PGA-intensity empirical relationships used.

Nevertheless, it is still possible to qualitatively compare the pattern of the hazard map from the Spanish NCSE-02 code (Fig. 11) in SE Spain, and the corresponding map applying the ‘site approach’ (Fig. 4b). NCSE-02 map, either in terms of acceleration (Fig. 11a) or intensity (Fig. 11b), shows a significant smooth pattern in SE Spain affected not only by the application of a general regional attenuation relationship, but also by the use of seismogenic sources with the assumption of uniform distribution of seismicity. This produces a homogeneous regional pattern of hazard values and the lowering of these latter in actual epicentral areas (Albarelo et al. 2002).

The ‘site approach’ is not biased by the effect of seismogenic sources, and the main role played by the available felt intensities resolves hazard mapping with greater lateral heterogeneity. These can be associated with strong local effects present in the region (García-Fernández and Jiménez 2012) which reflect in the observed intensities. The smoothing effect inherent to standard PSHA methods, as those used in building code maps such as the Spanish NCSE-02, or in regional maps like the European-Mediterranean Seismic Hazard Map (Jiménez et al. 2003) depicted in the inset of Fig. 1, could result either in over-estimates or sub-estimates of site hazard values. The comparison with equivalent results based on the ‘site approach’ provides complementary and very valuable information to help identify if such differences exist, and if they are relevant.

The PSHA based on the ‘site approach’, represents a useful tool that can contribute to the strategies on local seismic risk reduction and to future updates and revisions of building code hazard maps.

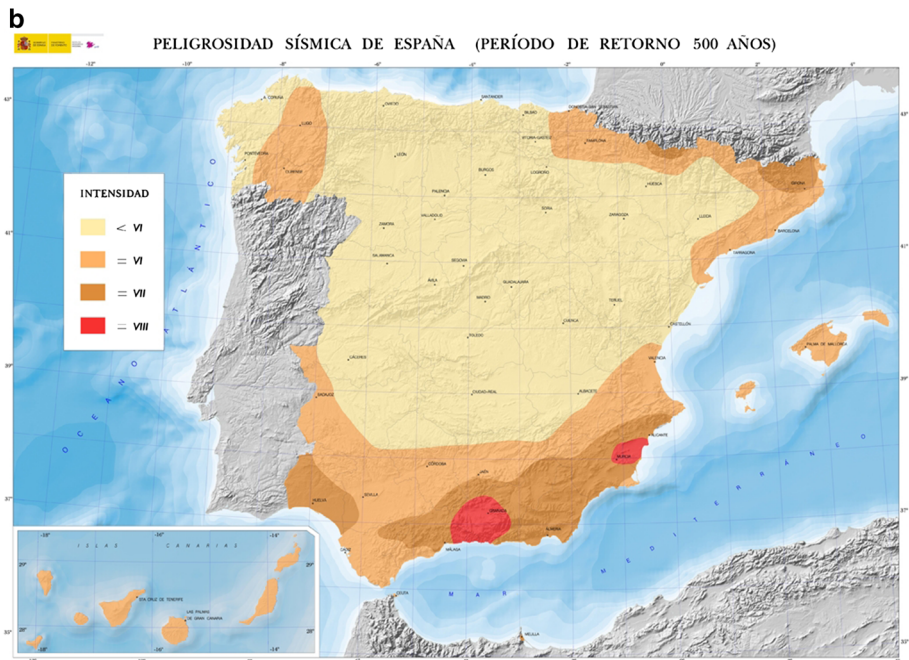
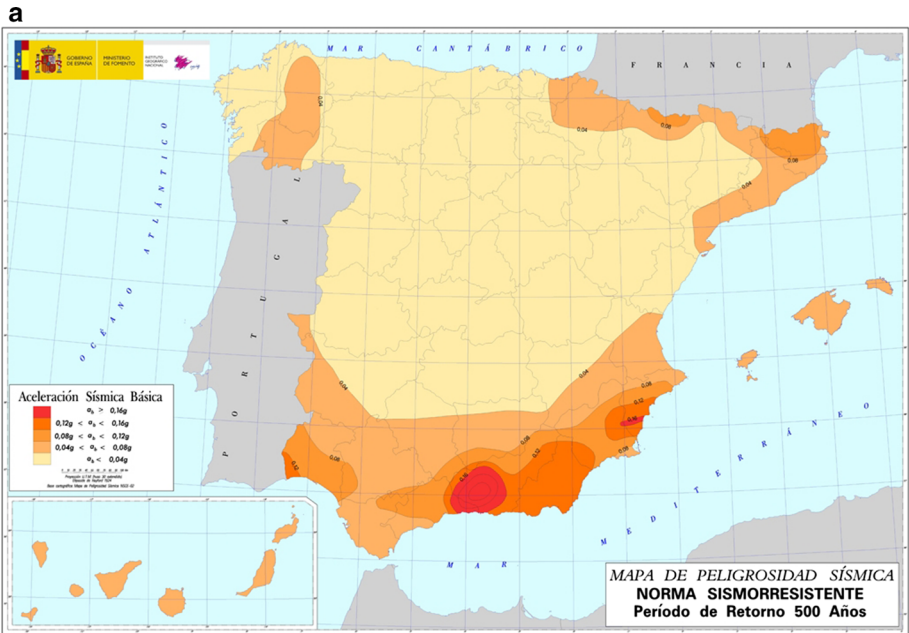


Fig. 11 Hazard map from the Spanish NCSE-02 Building Code (<http://www.ign.es/ign/layoutIn/sismoListadoMapasSismicos.do>. Accessed 15 December 2014). **a** In terms of PGA. **b** In terms of EMS98 intensity

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