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ORIGINAL ARTICLE

Seismic hazard assessment of the Province of Murcia (SE Spain): analysis of source contribution to hazard

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Abstract A probabilistic seismic hazard assessment of the Province of Murcia in terms of peak ground acceleration (PGA) and spectral accelerations [SA(*T*)] is presented in this paper. In contrast to most of the previous studies in the region, which were performed for PGA making use of intensity-to-PGA relationships, hazard is here calculated in terms of magnitude and using European spectral ground-motion models. Moreover, we have considered the most important faults in the region as specific seismic sources, and also comprehensively reviewed the earthquake catalogue. Hazard calculations are performed following the Probabilistic Seismic Hazard Assessment (PSHA) methodology using a logic tree, which accounts for three different seismic source zonings and three different ground-motion models. Hazard maps in terms of PGA and SA(0.1, 0.2, 0.5, 1.0 and 2.0 s) and coefficient of variation (COV) for the 475-year return period are shown. Subsequent analysis is focused on three sites of the province, namely, the cities of Murcia, Lorca and Cartagena, which are important industrial and tourism centres. Results at these sites have been analysed to evaluate the influence of the different input options. The most important factor affecting the results is the choice of the attenuation relationship, whereas the influence of the selected seismic source zonings appears strongly site dependant. Finally, we have performed an analysis of source contribution to hazard at each of these cities to provide preliminary guidance in devising specific risk scenarios. We have found that local source zones control the hazard for PGA and SA($T \leq 1.0$ s), although contribution from specific fault sources and long-distance north Algerian sources becomes significant from SA(0.5 s) onwards.

Keywords PSHA · Logic tree · Active faults · Spectral acceleration · Spain

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1 Introduction

The Province of Murcia (11,313 km^2) is located in southeast Spain. It represents one of the most important seismic areas in the Iberian Peninsula, although it should be defined as a moderate seismic area in a worldwide context. Earthquake occurrence in the province and neighbouring areas is known since historical time, and there is also clear evidence of active faulting in recent geologic time (last 125,000 years).

Damaging earthquakes have struck the Province of Murcia several times in the last 500 years. Recently, three significant events have taken place in a period of just 6 years – 1999, Mula (m_{bLg}=4.8, I_{EMS}=VI); 2002, Bullas (m_{bLg}=5.0, I_{EMS}=V); and 2005, La Paca (m_{bLg}=4.7, I_{EMS}=VI–VII) – producing widespread damage within the villages of La Paca and Zarcilla de Ramos and a very important social concern. Consequently, local authorities have promoted a seismic risk assessment of the province, which has been named the RISMUR project (Benito et al. 2006a). In this paper, we present the main results and conclusions of the first part of this major project, aimed at estimating the expected motion with 10% of exceedance probability in 50 years on rock.

Seismic hazard assessment of moderate seismic areas is flawed by many factors. The scarceness of instrumental records of significant seismic sequences is one of the most crucial ones, from which other important issues in seismic hazard analysis are dependant on. Particularly important are the difficulties in characterising seismic sources and the unavailability of strong-motion models covering magnitude ranges of engineering significance (M_w>5.0; e.g., Benito and Gaspar-Escribano 2007).

To overcome these shortcomings, different authors have performed their studies based strongly on the historical seismic record of southeast Spain. A great number of studies have been devoted to assigning macroseismic intensity to historical events, to drawing isoseismal maps and to locating the epicentres. A compilation of these works can be found in Mezcua (1982), Muñoz and Udías (1982), Martínez-Solares and Mezcua (2002), Buforn et al. (2005) and Benito et al. (2006b). This information served to construct attenuation "laws" in terms of intensity, as well as to delineate seismic zones, to be used eventually in seismic hazard calculations.

Hence, most of the seismic hazard studies of the Murcia Province have been presented in terms of macroseismic intensity, eventually converted into peak ground acceleration (PGA) through equations derived from data of other parts of the world (e.g., Martín 1984; Muñoz et al. 1984; IGN 1991a; Molina 1998; Giner et al. 2002; Peláez Montilla and López Casado 2002; Buforn et al. 2005; Fig. 1). As a consequence of the large dispersion inherent to intensity-PGA relationships, hazard estimations vary largely from one author to another. As an example, PGA estimates at the City of Murcia for a 475-year return period span from 0.07 to 0.24 g. None of these studies assessed seismic hazard in terms of spectral acceleration [SA(T)].

Recently, a new seismic hazard study of southeast Spain has been developed (García-Mayordomo 2005). In this work, a hybrid seismic zoning model, composed by source zones and fault sources, was proposed. The former were defined based on relations found between the rheology of the upper crust and seismicity and the latter on updated geological information of specific major active faults in the region. Seismic hazard was finally calculated in terms of PGA and SA(T) using one ground–motion attenuation relationship. The main aim of that study was the use of geological data in seismogenic source characterisation, and no consideration was given to the use of modern techniques for capturing epistemic uncertainty.

This paper presents a probabilistic seismic hazard assessment of the Province of Murcia in terms of both PGA and SA, and accounting for epistemic uncertainty in seismic source definition, and ground–motion attenuation, by means of a logic tree. The main objective of this hazard assessment is twofold: (a) to develop hazard maps for rock conditions for the 475-year return

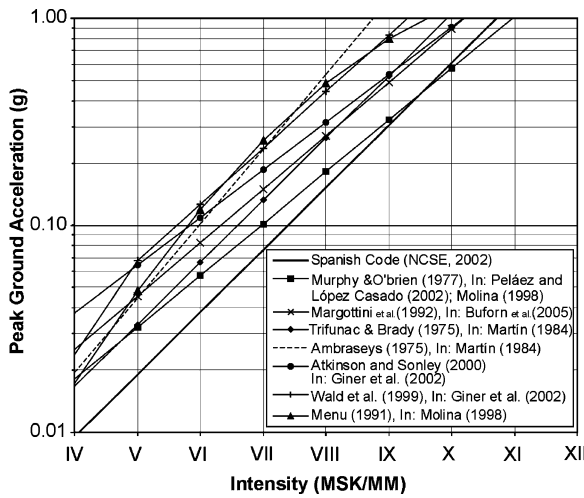


Fig. 1 Comparison among different Intensity-to-PGA conversion equations used in previous seismic hazard studies of the Province of Murcia or areas enclosing it

period in a wide range of spectral ordinates to be used in subsequent phases of the RISMUR project, and (b) to analyse source contribution to hazard to provide preliminary guidance in devising risk scenarios for the Murcia Province. We focus the analysis of our hazard results and source contribution on three of the most important cities of the province: Murcia, Lorca and Cartagena. These are highly populated areas and represent important trade and industrial centres. Cartagena area is also of great significance for holding a rapidly expanding tourism industry.

2 Seismotectonic frame and active faulting in the Province of Murcia

The Province of Murcia is located in the Betic Cordillera (southern Spain), which comprises the Iberian part of the contact zone between the African and European tectonic plates. This contact zone is regarded as a diffuse plate boundary, where convergence between plates is absorbed largely by a dense network of secondary faults rather than by a major contact fault. Consequently, seismicity spreads over a wide area, and earthquakes of small magnitude are predominant (Buforn et al. 1995). Nevertheless, the existence of large faults with late Quaternary activity indicates that the occurrence of major earthquakes ($M_w \geq 6.0$) cannot be dismissed.

The study region is crossed by some of the most important faults in the eastern Betic Cordillera (Fig. 2). The Quaternary activity of many of these faults has been evidenced in many studies (e.g., Bousquet 1979; Goy and Zazo 1989; Baena et al. 1993; Silva et al. 1993, 2003; Alfaro et al. 2002; Martínez-Díaz and Hernández-Enrile 2001; Martínez-Díaz et al. 2001;

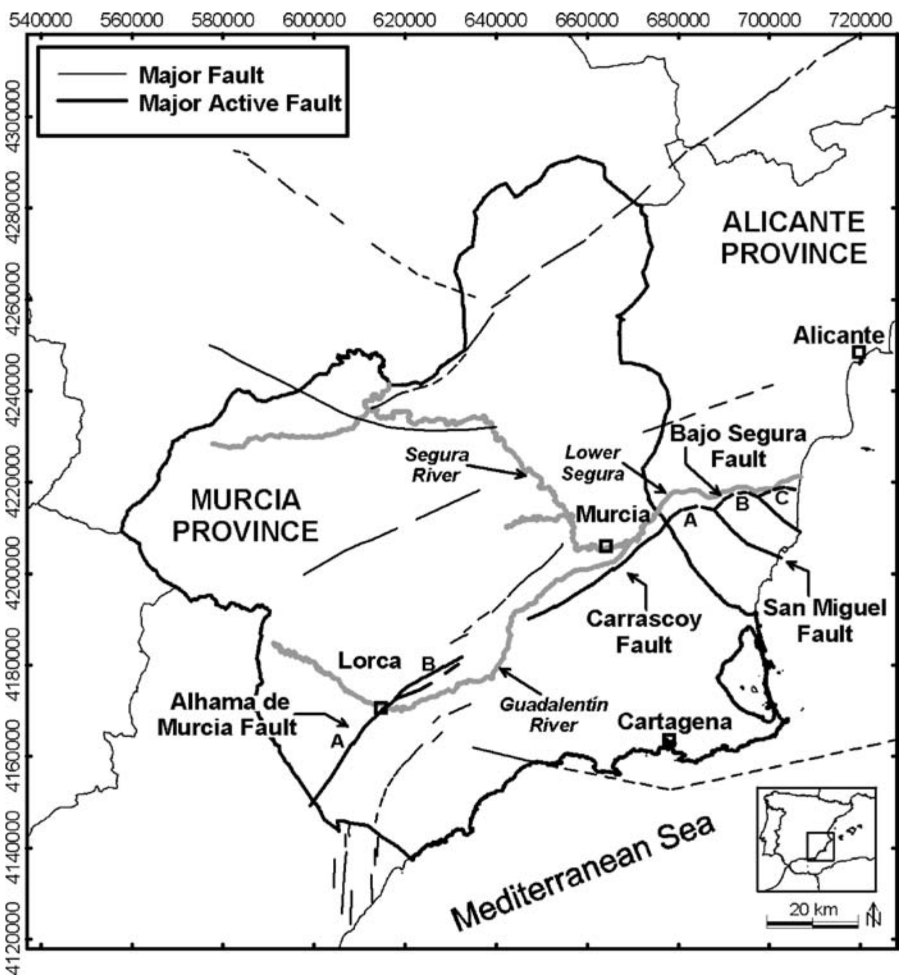


Fig. 2 Major faults of the Province of Murcia and neighbouring areas. The most active faults are highlighted and named. See text for explanation. Capital letters refer to particular fault segments. Alhama de Murcia Fault: A. Puerto Lumbreras–Lorca, B. Lorca–Totana; Bajo Segura Fault: A. Benejúzar, B. Hurchillos, C. Guardamar. See also Table 1

Masana et al. 2004 among others). In a recent work, all the geological information available has been synthesised and prepared to be used in seismic hazard calculations (García-Mayordomo 2005). This author analysed the seismogenic potential of the main faults of southeast Spain and classified them according to their degree of Quaternary activity. For each main fault, the maximum potential earthquake and its mean recurrence time were estimated based on the surface and deep structure of the fault, the age of the Quaternary deformations and the slip rate.

According to García-Mayordomo (2005), the most important faults of the Province of Murcia and neighbouring areas with highest incidence in probabilistic hazard assessment are the Alhama de Murcia, Carrascoy, Bajo Segura and San Miguel de Salinas faults (Fig. 2). These faults display deformations on deposits at least Upper Pleistocene in age (less than 125,000 years old) and show slip rates higher than 0.10 m/ka. Maximum moment magnitudes on each of the segments in which each main fault can be divided range from 6.1 to 6.7 (Table 1). The mean recurrence period (MRP) of such maximum events has been estimated in every case in less than 10,000 years. The seismogenic characteristics of these faults are sufficiently prominent to be considered as specific fault sources in probabilistic hazard calculations. Nevertheless, more research is needed to constraint better the MRP on these faults, as well as in other main faults of southeast Spain (e.g., Carboneras, Crevillente) in which ongoing paleoseismic studies may evidence more activity than currently acknowledged.

3 Seismicity of the Province of Murcia

The seismic catalogue in Spain can be divided into two major periods: Historical and Instrumental. Numerous researchers have studied the historical damage reports available in the region, eventually evaluating macroseismic intensities and epicentre location of singular events (e.g., López Marinas 1978; Bisbal Cervelló 1984; Rodríguez de la Torre 1990; Buforn et al. 2005 among others). Recently, the Instituto Geográfico Nacional (IGN) has performed a new revision of the available data from 800 B.C. until year 1900, which has led to an updated Historical Seismic Catalogue (Martínez-Solares and Mezcua 2002). This revision has greatly increased the number of earthquakes with assigned intensity and has re-assessed the intensity of many others. The MSK scale, commonly used in Spain, was also updated to the modern European Macroseismic Scale (EMS).

The Historical period in the Province of Murcia starts with the first known reference of the occurrence of an earthquake in Lorca, 1579 (I_{EMS}=VII) – although in neighbouring Alicante Province, seismic chronicles stretch back to year 1048. From 1579 to 1920, only 11 earthquakes with EMS intensity VII to VIII have

Table 1 Seismic parameters of the most important faults in the Province of Murcia and neighbouring areas (García-Mayordomo and Álvarez-Gómez 2006; García-Mayordomo and Martínez-Díaz 2006)

Fault (segment)	SL[a] (km)	M_{max}[b] (Mw)	SR[c] (m/ka)	MRP[d] LB (years)	MRP[d] UB (years)
Alhama de Murcia (Lorca–Totana)	23	6.7	0.30	2,000	5,000
Alhama de Murcia (Pto. Lumbreras–Lorca)	28	6.8	0.41	7,000	10,000
Carrascoy	32	6.8	0.54	6,000	10,000
San Miguel de Salinas	17	6.5	0.30	8,000	10,000
Bajo Segura (Hurchillo)	12	6.3	0.35	1,700	6,000
Bajo Segura (Benejúzar)	10	6.2	0.23	2,000	9,000
Bajo Segura (Guardamar)	8	6.1	0.12	3,000	10,000

The MRP range of the Lorca–Totana segment of the Alhama de Murcia fault was estimated from paleoseismic findings described in Martínez-Díaz and Hernández-Enrile (2001) and Masana et al. (2004).

LB lower bound, *UB* upper bound.

[a] Surface length

[b] Maximum moment magnitude

[c] Slip rate in meters per kiloyear (m/ka); slip rates are net apart from San Miguel de Salinas Fault, which is vertical

[d] Estimated mean recurrence period of maximum earthquake

been reported (Fig. 3). The macroseismic epicentres of these earthquakes are located along the main valleys of the province, coinciding with the location of the most populated areas. These towns are founded on thick alluvium deposits, so it is very likely that local amplification effects controlled the distribution of damage. That is the case of the most important event in the region, the 1829 Torrevieja (Alicante) earthquake (I_{EMS}=IX–X). Although the macro-seismic epicentre of this event is located 40 km northeast of Murcia City, it caused liquefaction and widespread damage along the Valley of the Lower Segura River and was felt with intensity VII at the City of Murcia. Intensity VIII has been reached four times within the Province of Murcia: Lorca, 1674; Las Torres de Cotillas, 1911; Lorquí, 1911; and Cehegín, 1948.

The Instrumental Period started with the creation of the first National Seismic Network around 1920, which is operated by the IGN. The size of the network, and its instrumental stock, has underwent several extensions and updates, the most important ones during the middle 1980s (IGN 1991b). During that time, methods for calculating the magnitude of earthquakes experienced important changes (cf. Mezcua and Martínez-Solares 1983; López and Muñoz 2003). Magnitude of records older than 1962 was calculated based on the duration of signal (m_{D}). From 1962 to 1997, magnitudes were calculated based on the period and maximum amplitude of the phase Lg and following a correlation obtained with selected earthquakes, also recorded by the US National Earthquake Information Center (NEIC). For those earthquakes that produced saturation of the signal, magnitude was adopted straight from the NEIC (m_{b}). After subsequent improvements of the network, local equations for magnitude were developed; all of

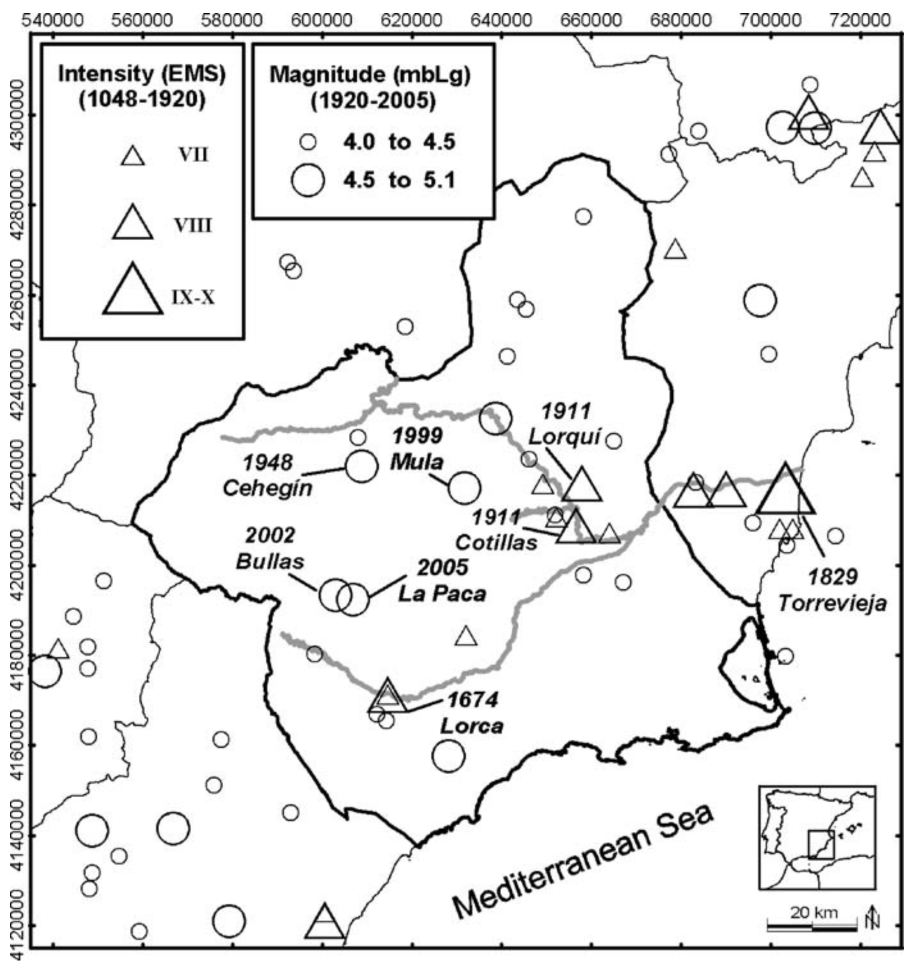


Fig. 3 Epicentre distribution of historical (*triangles*) and instrumental (*circles*) seismicity in the Province of Murcia and neighbouring areas. Only main events are plotted

them based on the amplitude and period of the Lg phase (m_{bLg}; López and Muñoz 2003).

Since 1920 until present, 19 main events with magnitude equal to or larger than 4.0 have occurred within the Province of Murcia (Fig. 3). The most common intensity levels associated to these earthquakes are I_{EMS} VI to VII, apart from the 1948 Cehegín event, which reached I_{EMS} VIII. Instrumental epicentres are not confined to the main valleys of Segura and Guadalentín rivers, contrasting with the preferential location of macro-seismic epicentres during the Historical Period. This is the case of the last three damaging earthquakes that occurred in the province: 1999, Mula (m_{bLg}=4.8, I_{EMS}=VI); 2002, Bullas (m_{bLg} =5.0, I_{EMS}=V); and 2005, La Paca (m_{bLg}=4.7, I_{EMS}= VI–VII). These earthquakes have received the attention of many researches because they produced significant damage in the Spanish context; a full description can be found elsewhere (e.g., IGN 1999; Martínez-Díaz et al. 2002; Buforn et al. 2005; Benito et al. 2006b; Gaspar-Escribano and Benito 2007).

4 Hazard assessment

The study presented in this paper follows the Probabilistic Seismic Hazard Assessment (PSHA) methodology, including a logic tree with two nodes for capturing epistemic uncertainty related to seismic zoning and ground-motion models. The next sections deal with the criteria followed to select and weight the different seismic zonings and ground-motion models that configure the branches of the logic tree. Special consideration is given to the processing of the seismic database before the calculation of seismic parameters.

4.1 Selection of seismic zonings

We have considered three different seismic zonings: the one adopted in the Spanish seismic Building Code (NCSE-02), the model of López Casado et al. (1995; LC-95), and the one of García-Mayordomo (2005; GM-05; Fig. 4). NCSE-02 model is composed of wide zones, which were defined based largely on epicentre distribution and main regional geological features on a peninsula scale. LC-95 is composed by much smaller zones, which were defined based on relations found by the authors between the distribution of epicentres and fracture systems of the Betic Cordillera. Finally, GM-05 is a hybrid model composed by zones and faults, specifically developed for southeast Spain. Zones were defined after a comprehensive analysis on the relations among the strength and geothermal gradient of the crust in the eastern Betic Cordillera and seismicity (García-Mayordomo and Giner-Robles 2006). Fault sources are major active faults in which the recurrence period of maximum magnitude events has been estimated in equal or less than 10,000 years based on available geological information (see Table 1).

We consider that the joint use of these three seismic zonings effectively captures the epistemic uncertainty in seismogenic source characterisation. As a consequence of the different criteria followed by each author, the sizes and geometries of the seismic zones vary greatly from one model to another. An issue of using the seismic zoning of LC-95 is that because of the small size of the zones, the earthquake sample used to derive seismic parameters may lack statistical representivity. In contrast, the use of the NCSE-02 model, composed by much larger zones, permits to obtain larger samples, but then the issue is that so large zones may comprise several distinct seismotectonic domains. On the other hand, the size of the zones in GM-05 model represents a mean term between LC-95 and NCSE-02 zonings, and besides, the occurrence of maximum earthquakes is restricted to specific major faults rather than to broad zones.

Finally, to obtain a first estimation of the impact that long-distance sources may have at long periods ($T\geq 1.0$ s) SAs, we have supplemented the NCSE-02, LC-95 and GM-05 models with the addition of three large zones delineated along the northern margin of Algeria. This matter has been neglected so far in seismic hazard studies of southeast Spain, although northern Algeria has been the source of numerous large earthquakes (I_{MSK}=IX–X; M_w>6.5) since historical to present time (e.g., 1716 Algiers; 1790 Oran; 1825 Blida; 1887 El Kalaâ; 1910 Masqueray; 1954 Orléansville; 1980 El Asnam; 2003 Algiers; cf. Harbi et al. 2003a,b). Several authors have proposed specific zoning models for Algeria (e.g., Hamdache 1988; Aoudia et al. 2000). However, they seem too detailed for our case and could obscure the interpretation of our final results. Hence, for the purpose of our study, we opted for considering a simple zoning composed by three broad, simple zones embracing main epicentre clusters.

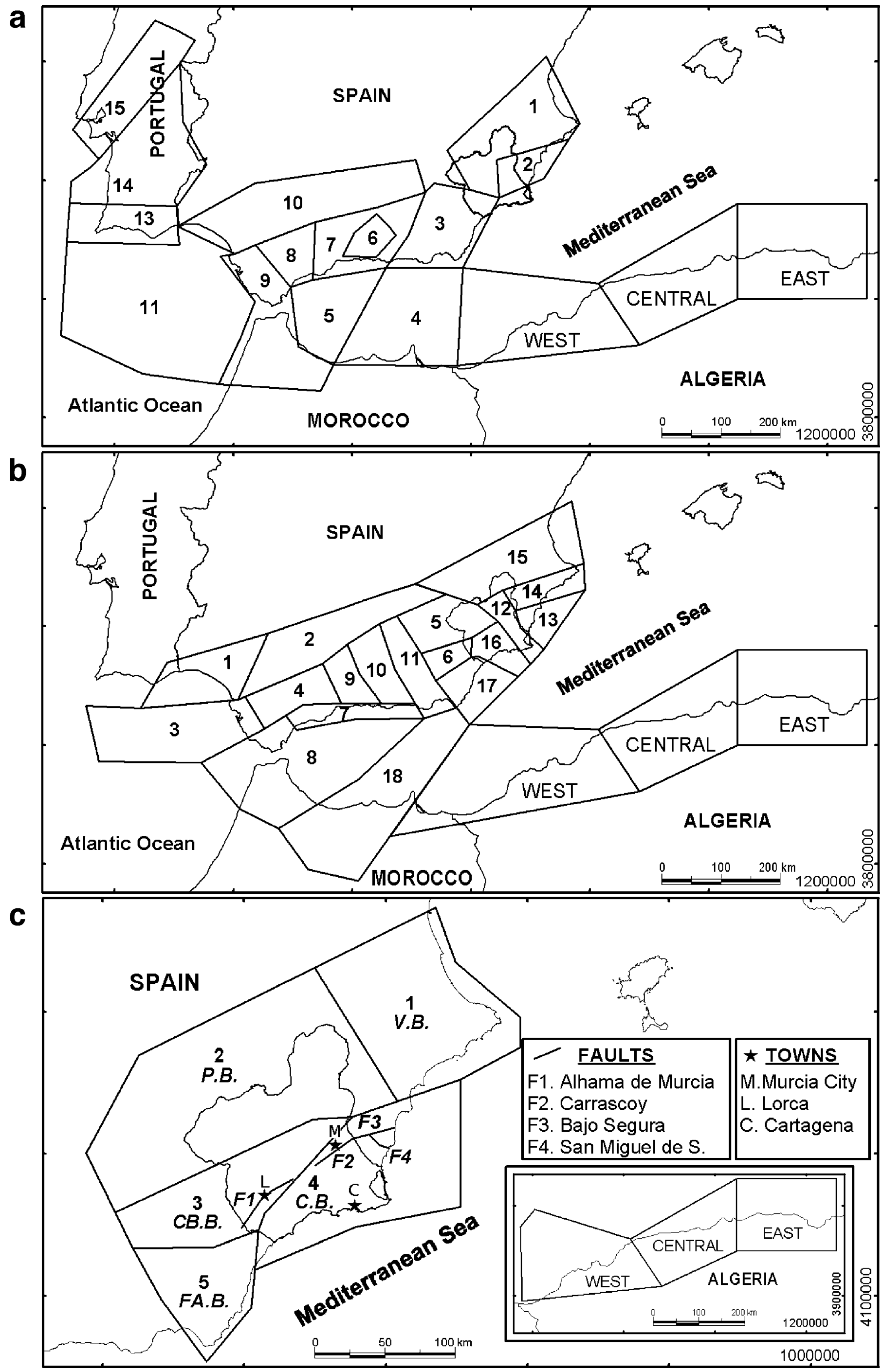


Fig. 4 Seismic zonings considered for the construction of the logic tree. **a** NCSE-02 model; **b** LC-95 model (López Casado et al. 1995); **c** GM-05 model (García-Mayordomo 2005): *B.P.* Prebetic Block; *V.B.* Valencian Block; *CB.B.* Central Betic Block; *C.B.* Cartagena Block; *FA.B.* Filabres–Almeria Block. North Algerian zones have been defined ad hoc for the purpose of this study. See text for details

4.2 Processing of the seismic database and zone parameter calculation

The seismic database used in this work has been extracted from the National Seismic Catalogue of IGN updated until May 2005. Our database comprises records from both the Historical and Instrumental Periods. A number of parameters are provided for each record (e.g., location coordinates, date, depth, etc.), as well as a classification into aftershock or premonitory for earthquakes related to important series. Earthquake size, when available, is given in the MSK or EMS intensity scale and/or in magnitude m_D, m_b or m_{bLg}, as explained above. Hence, before calculating the recurrence parameters of each zone on every seismic zoning model, it was necessary to: (a) decluster the database, (b) homogenise the size parameter and (c) correct the temporal incompleteness of the catalogue.

Declustering the database consisted in eliminating: (1) records without intensity neither magnitude data, (2) sub-crustal events (h>33 km), and (3) fore and aftershocks. The first two actions removed 10% of the records. The third action was performed filtering the database for events occurring both in time and distance intervals of 10 days and 10 km, respectively (Álvarez-Gómez et al. 2005). This filter provided a convenient way to identify swarms and seismic sequences. For larger sequences – all of them located on the North African margin – the classification into aftershock or premonitory provided in the IGN catalogue was followed.

The homogenisation procedure consisted in converting m_b and m_{bLg} scales into the moment magnitude scale (M_w), as well as MSK/EMS intensities into M_w when magnitude data was not available. In the case of old instrumental records (pre-1962), there are no local m_D–M_w conversion relationships available. As the uncertainty on m_D values can be around ±0.4 (Mezcua and Martínez-Solares 1983), differences in magnitude estimates using m_{bLg} and m_D scales are contained in this uncertainty interval. Hence, compatibility between both magnitude scales was assumed. Converting m_b to M_w was performed using Nuttli (1985) m_b to M_o relationships, and then M_o to M_w through Hanks and Kanamori (1979) equation. To convert m_{bLg} to M_w, we used the expression of Rueda and Mezcua (2002). For historical events, we have assumed M_w values given in specific studies whenever available (e.g., Mezcua et al. 2004; Rueda and Mezcua 2005), for the rest, we used the intensity to M_w relationship of Rueda and Mezcua (2001).

Finally, the completeness of the seismic catalogue was assessed plotting the cumulative number of events of particular magnitude ranges through time (Fig. 5). Abrupt increases of slope are associated with the reference year of completeness for that particular magnitude range (Tinti and Mulargia 1985). Two

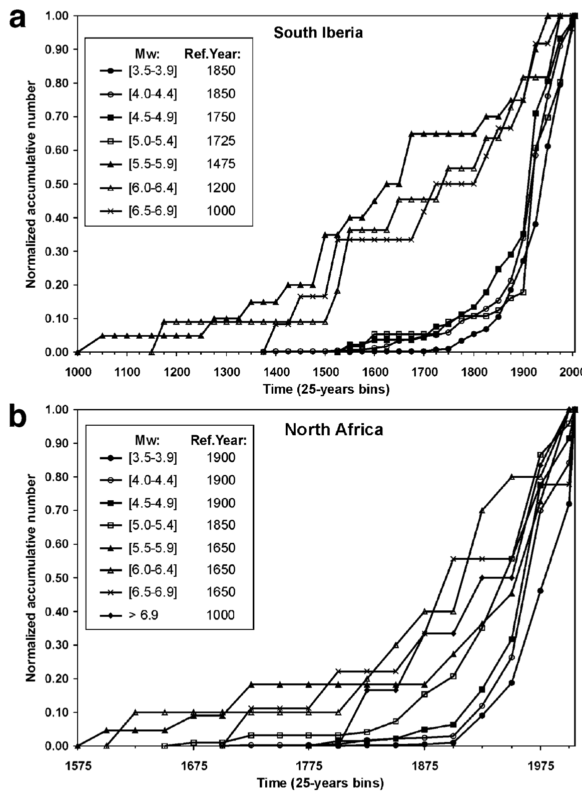


Fig. 5 Cumulative number of events versus time for the South Iberian **a** and North Africa **b** regions. The estimated reference year of completeness for each magnitude range is also shown. The completeness analysis was performed on the homogenized catalogue. See text for details

different regions were considered depending on the historical development and coverage of the seismic network: South Iberian Peninsula and North Africa.

After processing the database, we calculated the Gutenberg–Richter parameters of each zone considered in the NCSE-02, LC-95 and GM-05 models by fitting a log-linear law to the cumulative number of earthquakes with magnitude equal or larger than 3.5 (Table 2). To complete source characterisation, we estimated the upper threshold of the magnitude distribution in each zone – i.e., the maximum earthquake that a zone is potentially capable to generate. This procedure was based on increasing either 0.3 or 0.6 magnitude units the maximum recorded earthquake in each zone, the former being done when a single maximum event outstands from the earthquake sample, and the latter when few maximum events are identified. Additionally, a criteria based on the size of the faults was also used

Table 2 Parameters of the seismic zones in the NCSE-02, LC-95 (López Casado et al. 1995) and GM-05 (García-Mayordomo 2005) models

NCSE-02					LC-95					GM-05				
Zone	λ_0	β	M_{max}	R^2	Zone	λ_0	β	M_{max}	R^2	Zone	λ_0	β	M_{max}	R^2
1	0.7134	2.167	6.8	0.998	1	0.2643	2.208	6.4	0.963	1 (P.B.)	0.3731	2.395	6.2	0.998
2	0.7557	2.227	6.8	0.994	2	0.2013	1.852	7.2	0.983	2 (V.B.)	0.3368	1.913	7.0	0.991
3	0.7300	1.978	6.8	0.998	3	0.2462	1.702	7.2	0.985	3 (CB.B.)	0.4873	2.220	6.2	0.988
4	0.8005	2.107	7.0	0.997	4	0.2417	1.877	7.1	0.996	4 (C.B.)	0.4790	2.121	6.2	0.992
5	0.2008	2.745	6.0	0.999	5	0.1769	1.875	6.2	1.000	5 (FA.B.)	0.2162	2.178	6.4	0.982
6	0.6009	2.040	6.9	0.988	6	0.1910	2.047	6.2	0.994	West Algeria	1.2213	1.796	6.9	0.995
7	0.2454	2.017	7.1	0.978	7	0.1435	1.759	7.0	0.992	Central Algeria	4.3485	2.019	8.0	0.992
8	0.2303	2.056	5.8	0.996	8	0.3563	2.003	7.0	0.998	East Algeria	2.4937	2.551	7.5	0.986
9	0.1830	1.996	6.6	0.999	9	0.2678	1.953	6.9	0.982					
10	0.2376	1.897	7.2	0.987	10	0.5846	2.183	6.9	0.997					
11	0.4264	1.934	7.2	0.989	11	0.2638	1.886	6.8	0.996					
13	0.1821	2.618	5.5	0.990	12	0.3655	2.455	6.8	0.987					
14	0.3128	1.766	5.9	0.967	13	0.3194	1.955	6.8	0.991					
15	0.4697	2.003	6.9	0.984	14	0.2974	2.812	6.8	0.982					
West Algeria	1.1597	1.775	6.9	0.995	15	0.3543	1.923	6.8	0.993					
Central Algeria	4.3485	2.019	8.0	0.992	16	0.1364	2.141	6.8	0.989					
East Algeria	2.9808	2.171	7.5	0.990	17	0.2991	2.375	6.4	0.953					
					18	0.9623	2.383	6.8	0.997					
					West Algeria	1.4583	1.943	6.9	0.984					
					Central Algeria	4.3485	2.019	8.0	0.992					
					East Algeria	2.9808	2.171	7.5	0.990					

Specific fault sources in GM-05 model are listed in Table 1 and depicted in Fig. 4.

in zones where relevant geological data were available (e.g., Sanz de Galdeano et al. 2003; García-Mayordomo 2007).

Fault sources in model GM-05 have been modelled after the Characteristic Earthquake Model (Schwartz and Coppersmith 1984). Table 1 shows maximum magnitudes and corresponding MRPs for each fault segment. Following a conservative approach, only the lower bound of the MRP was considered in the calculations. No consideration has been given to the elapsed time from the last maximum event – Slip Predictable Model – or to the size of the last maximum event – Time Predictable Model – as there is not yet information available in the region to perform a reliable estimation of such parameters (García-Mayordomo 2005).

4.3 Selection of ground motion models

The Spanish Strong Motion Network started operating in the 1980s (cf. Carreño et al. 1999). To date, few studies have been done to provide local strong ground–motion relationships using these data (e.g., Martín et al. 1996; Cabañas et al. 1999; Cantavella et al. 2004). However, these studies are based on a very limited data set – only eight events of magnitude between 4.5 and 5.1 have been recorded in southern Spain since 1989 – and hence, cannot be considered representative for deriving strong motion models. Therefore, it is necessary to select from the literature other attenuation equations drawn from statistically significant data sets and comprising wider magnitude and distance ranges.

Three main criteria have been considered for selecting ground-motion models: (1) that they are derived from extensive databases, and also widely used in European countries located in a similar seismotectonic context (the European–African plate boundary); (2) that the independent variable is given in terms of PGA and spectral ordinates for a wide range of vibration periods (e.g., from 0.1 to 2.0 s) and (3) that they are statistically reliable for small magnitude earthquakes (M_w<5.0). The latter takes into account the importance of small magnitude earthquakes in moderate seismicity areas. It is common in seismic hazard analysis to admit that structural damage starts from magnitude 5.0 or more, but in the Province of Murcia it has been shown that smaller magnitudes produce significant damage referred to the Spanish context. This fact has been observed recently in La Paca 2005, Bullas 2002, and Mula 1999 earthquakes (Benito et al. 2007), all of them having magnitudes around 4.8. In addition, seismic hazard for the 475-year return period would be underestimated if the occurrence rate of earthquakes between magnitudes 4.0 and 5.0 were not included in hazard computations. Considering the aforementioned criteria, we have finally selected the attenuation equations of: Ambraseys et al. (1996; AM-96), Sabetta and Pugliese (1996; SP-96), and Berge-Thierry et al. (2003; BT-03) for rock conditions (Fig. 6).

4.4 Formulation of the logic tree

We set up a logic tree consisting of two nodes: seismic source zoning and ground–motion attenuation model (Fig. 7). The former node splits into three branches that stand for the NCSE-02, LC-95 and GM-05 models, with weights of 0.3, 0.3 and 0.4, respectively. A higher weight was assigned to the GM-05 model because it was specifically derived for southeast Spain and incorporates the most active faults in the Province of Murcia and neighbouring areas.

The attenuation model node consists also of three branches accounting for AM-96, SP-96 and BT-03 equations. Commonly, weighting of the selected ground-motion models is the factor exerting more influence on seismic hazard results. Our criteria to assign weights were based on both intrinsic and application-specific factors (Bommer et al. 2005). We analysed two basic intrinsic factors: the number of records considered in each of the models and the ground-motion parameter predicted. Both AM-96 and BT-03 equations were derived from extended databases of more than 400 and 900 records, respectively; whereas SP-96 was derived from just 195 Italian records. On the other hand, the SP-96 model predicts pseudo-velocity, whereas AM-96 and BT-03 estimate actual SAs. Regarding to application-specific factors, we focused on the magnitude and distance ranges that

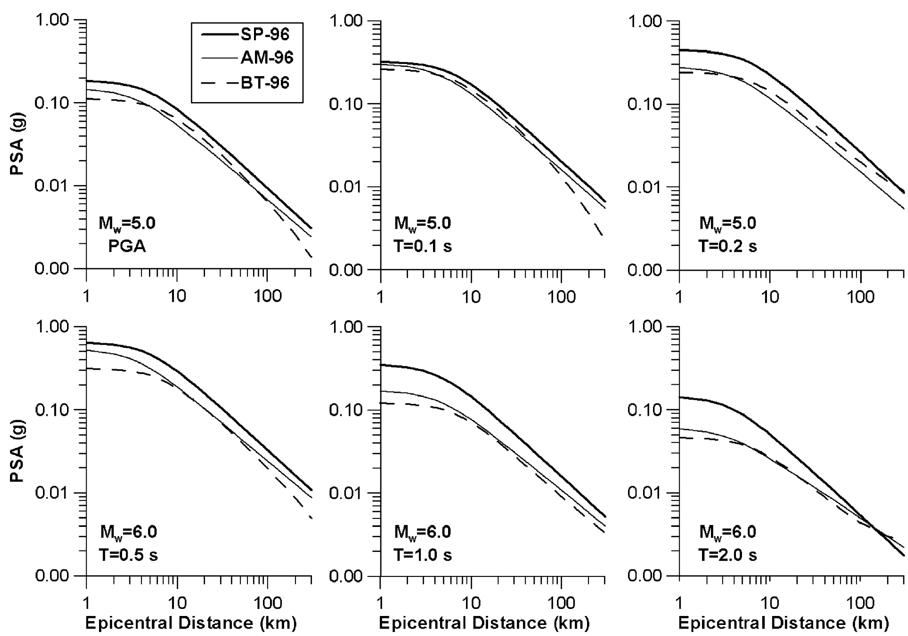


Fig. 6 Comparison among Sabetta and Pugliese (1996; SP-96), Ambraseys et al. (1996; AM-96), and Berge-Thierry et al. (2003; BT-03) ground motion attenuation relationships on rock conditions, for two different magnitudes and for all the vibration periods considered in the hazard calculations. Magnitude scales and distance parameters were converted to moment magnitude and epicentral distance, respectively

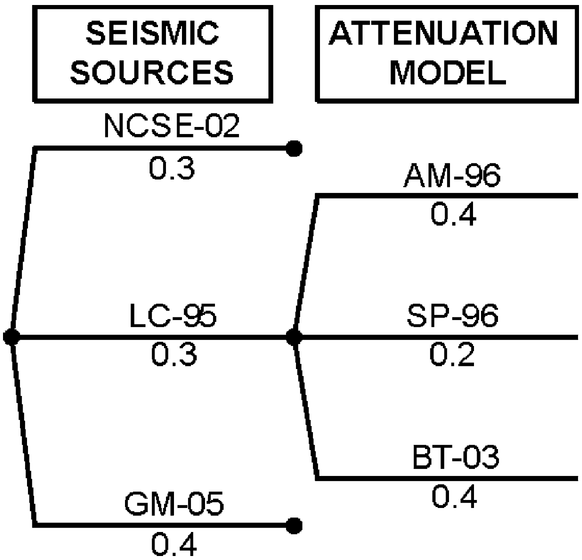


Fig. 7 Structure of the logic-tree considered in this study. Note the different weights on each of the branches. See text for the meaning of abbreviations

are statistically significant in the models. The frequent occurrence of low-magnitude but damaging earthquakes in southeast Spain forces us to pay special attention to the lower bound magnitude from which the equations are statistically reliable. This bound is 4.0 both in AM-96 and BT-03, and 4.6 in SP-96. Regarding the distance range, we favoured equations suitable for distances as longest as possible, which are 200, 100 and 300 km for AM-96, SP-96 and BT-03 models, respectively. Taking into account all that information, we have finally assigned a weight of 0.4 both to AM-96 and BT-03 and 0.2 to SP-96.

A critical issue on the use of ground-motion models in a logic tree is to achieve compatibility among different magnitude scales and/or type of distance-to-source (Bommer et al. 2005). In our case, we converted the surface wave scale (M_S) used in the attenuation models of AM-96 and BT-03 to M_w using the equations of Nuttli (1985). No conversion was performed for the SP-96 model, as it is assumed to be compatible with the M_w scale (cf. Sabetta et al. 2005). On the other hand, AM-96 and SP-96 models measure distance as "fault-distance" – shortest distance to the surface projection of the fault rupture, and as epicentral distance, respectively; whereas BT-03 uses hypocentral distance. To overcome this incompatibility, we considered the seismogenic sources located at a depth of 7 km when using the BT-03 model, which is a representative figure to account for the occurrence of seismicity inside the seismogenic crust of the eastern Betics (García-Mayordomo and Giner-Robles 2006). Finally, we assumed compatibility between fault-distance and epicentral-distance, which is reasonable for regional hazard calculations in areas where the frequency of large earthquakes (M_w>6.0) is very low.

4.5 Hazard maps and COV maps

Hazard calculations were carried out using the CRISIS code (Ordaz et al. 2001). The EXPEL tool (Benito et al. 2004) was used to visualise and manage the different nine solutions stemming from the logic tree.

A total of 12 hazard maps, corresponding to PGA and five SAs (0.1, 0.2, 0.5, 1.0 and 2.0 s) for rock conditions, were developed from a 0.1×0.1° grid, which at this latitude is 10×10 km approximately (Fig. 8). Hazard maps show weighted-mean acceleration values for the 475-year return period. This return period is the hazard level usually considered in seismic design of conventional buildings (e.g., Eurocode-8, NCSE-02), and it has also been the one considered in the RISMUR regional risk assessment of the Province of Murcia (Benito et al. 2006c). We shall focus our subsequent analysis on this return period and on three of the most important cities of the Province: Murcia, Lorca and Cartagena.

5 Analysis of results

Seismic hazard in the Province of Murcia for generic rock conditions is highest along the southwest–northeast trending central part of the region, and rapidly decreases to the northwest and southeast. This general picture is observed on all maps, although hazard gradient differs greatly from one map to another, being maximum at T=0.2 s and minimum at T=1.0 s. Murcia City and Lorca are located in the most hazardous areas of the province, whereas Cartagena is in an area of moderate hazard. In general terms, our seismic hazard results for PGA are intermediate compared to previous studies and similar to the ones provided in the Spanish seismic code for rock conditions, except for Cartagena where we obtain higher seismic hazard.

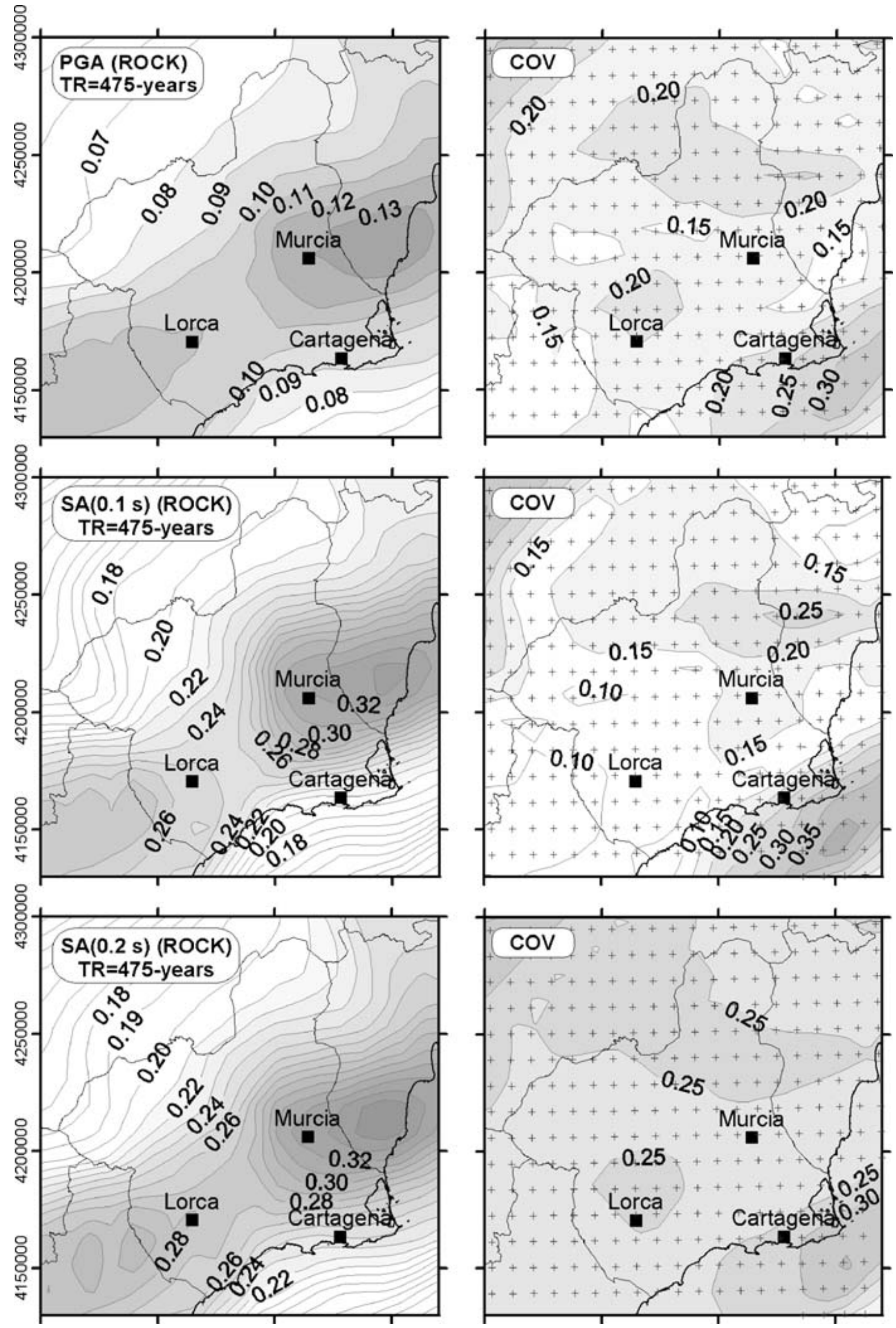
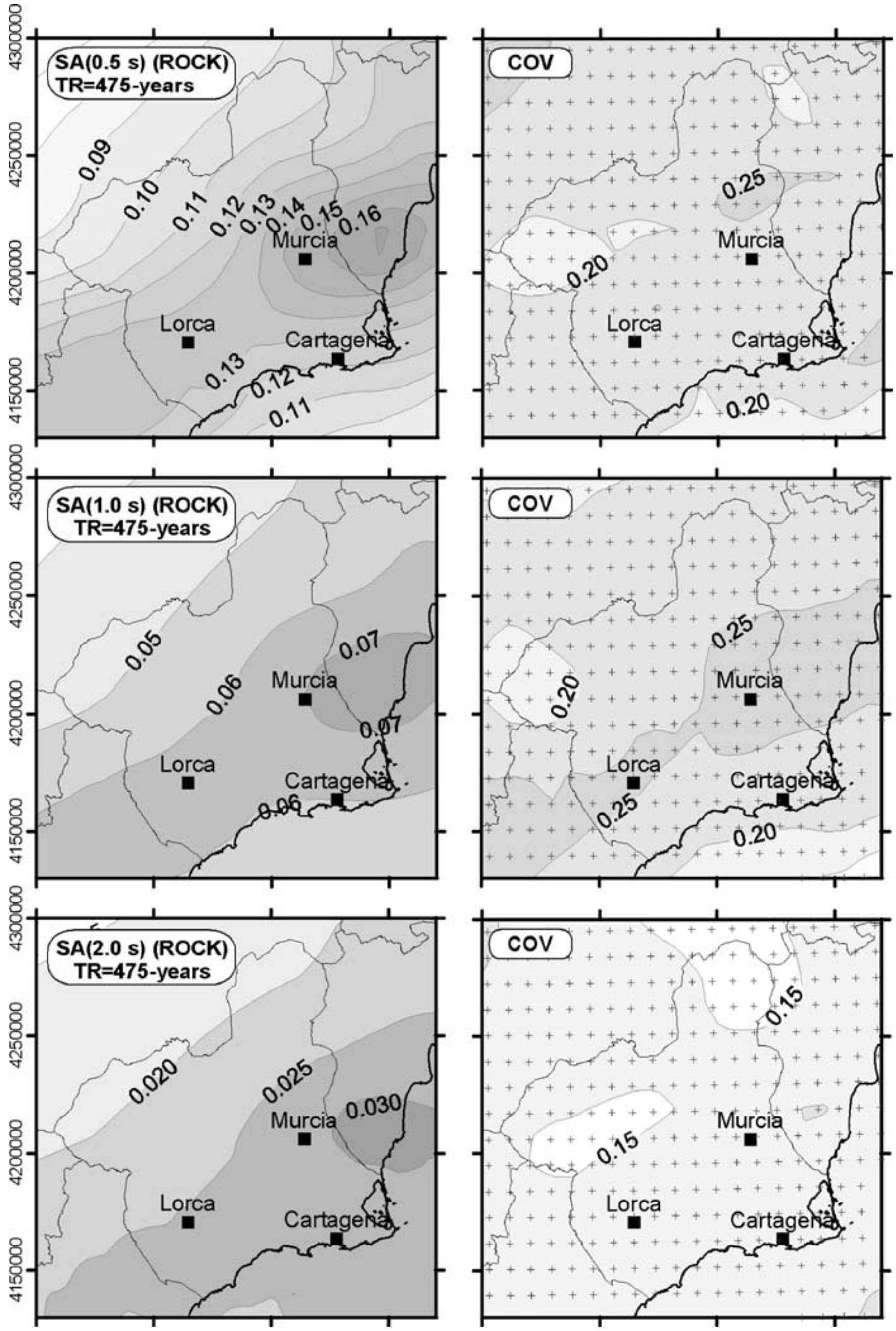


Fig. 8 Seismic hazard maps of the Province of Murcia in terms of PGA and SA(0.1, 0.2, 0.5, 1.0 and 2.0 s) for the 475-year return period (*left*) and corresponding COV maps (*right*). Accelerations are in *g* units

In addition, for each hazard map a coefficient of variation (COV) map – the ratio of the standard deviation divided by the mean – was also calculated (see Fig. 8). High and low COV values indicate relatively high and low variability of results, respectively. COV values in the Province of Murcia range between 0.20 and 0.30, except for SA(0.1 s) where COV values are the lowest (0.1–0.2). Estimates for SA(0.1 s) from SP-96, AMB-96 and BT-03 ground–motion attenuation relationships show lower variability than for other SAs (see Fig. 6).

The areas showing more variability in the Province of Murcia are located around Lorca and particularly around Cartagena and offshore Cartagena. In contrast,

Fig. 8 (continued)



Murcia City shows relatively low variability. The higher variability shown in the Cartagena area is a result of the NCSE-02 seismic zoning, which in contrast to LC-95 and GM-05 models does not define any source zone enclosing this site. This significant difference between models highlights the importance of focussing more research efforts in seismic source characterization in the Cartagena area.

Figure 9 shows the weighted-mean uniform hazard spectra (UHS) obtained at Murcia City, Lorca and Cartagena and compares them to maximum and minimum UHS arising from individual branches of

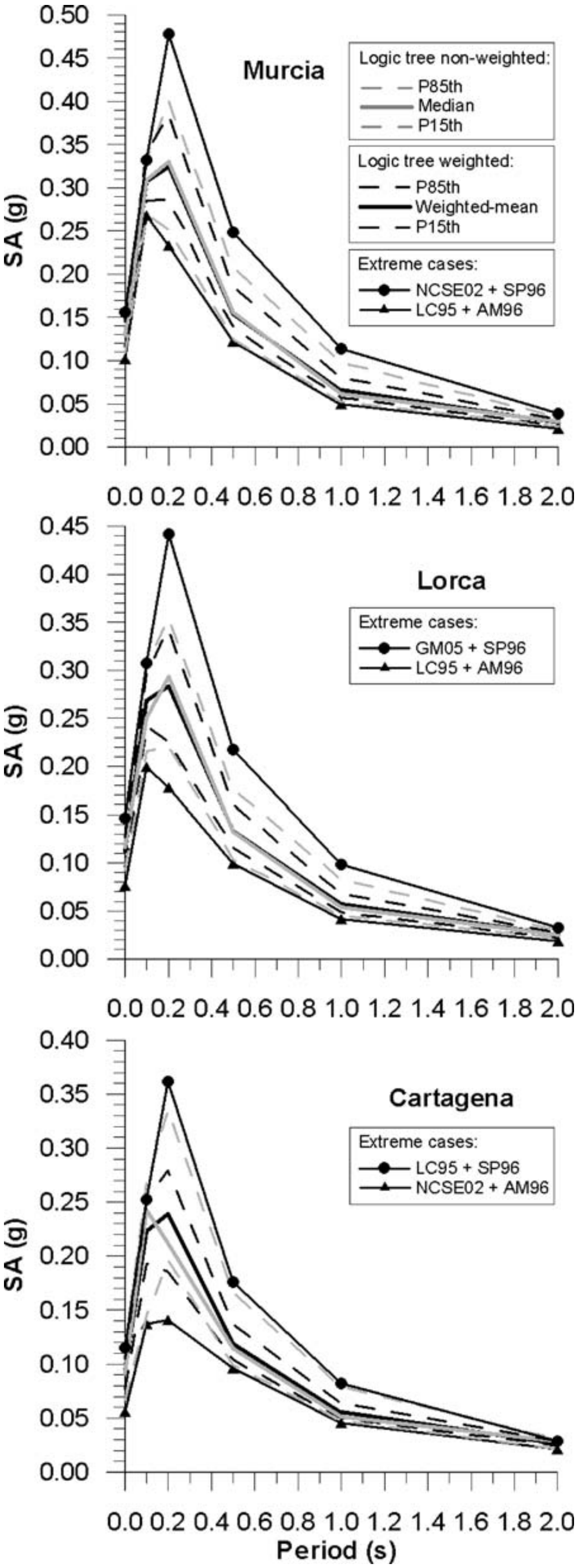


Fig. 9 Comparison among the resulting UHS from non-weighted and weighted solutions of the logic tree at Murcia, Lorca and Cartagena. Maximum and minimum spectra arising from specific choices of seismic source zonings and ground motion attenuation models (extreme cases) are also shown at each city

the logic tree – i.e., single combinations of seismic zoning model and ground–motion attenuation relationship, at each site. Maximum UHS at any site are always caused by branches considering SP-96 attenuation relationship, particularly at T=0.2 s, where the difference can be around 50% higher. Minimum UHS are always caused by the use of AM-96 relationship. In contrast, the impact of selecting specific seismic zoning models is clearly site dependant. NCSE-02, GM-05 and LC-95 models produce maximum SAs at Murcia City, Lorca and Cartagena, respectively.

Finally, we have compared our weighted-mean UHS to the median UHS resulting if a non-weighted logic tree were considered in hazard computations (Fig. 9). Both weighted-mean and median UHS are very similar at each city. However, dispersion of our weighted-mean UHS – shown by the inter-percentile range (15th–85th) – is lower than that of median UHS. Cartagena weighted-mean UHS shows the largest differences to median UHS but also the highest reduction in dispersion at the short-period range. For example, weighted-mean and median values for SA (0.2 s) at Cartagena are 0.24 and 0.21 g, respectively; whereas 85th percentile values are 0.28 and 0.34 g, respectively.

6 Analysis of source contribution to Hazard

With the aim of providing preliminary guidance for devising seismic risk scenarios for the RISMUR project at the 475-year return period, we have performed an analysis of source contribution to total hazard for all spectral ordinates. To simplify the analysis, we focused on the GM-05 source model and the BT-03 attenuation relationship. Figure 10 shows partial contributions to total hazard at Murcia, Lorca and Cartagena from: local source zones, specific fault sources, North Algerian source zones and the remaining sources. Hereafter, local source zones are in every case the so-called Central Betic and Cartagena blocks, the specific fault sources are those listed in Table 1 (see Figs. 2 and 4c), and the remaining source zones

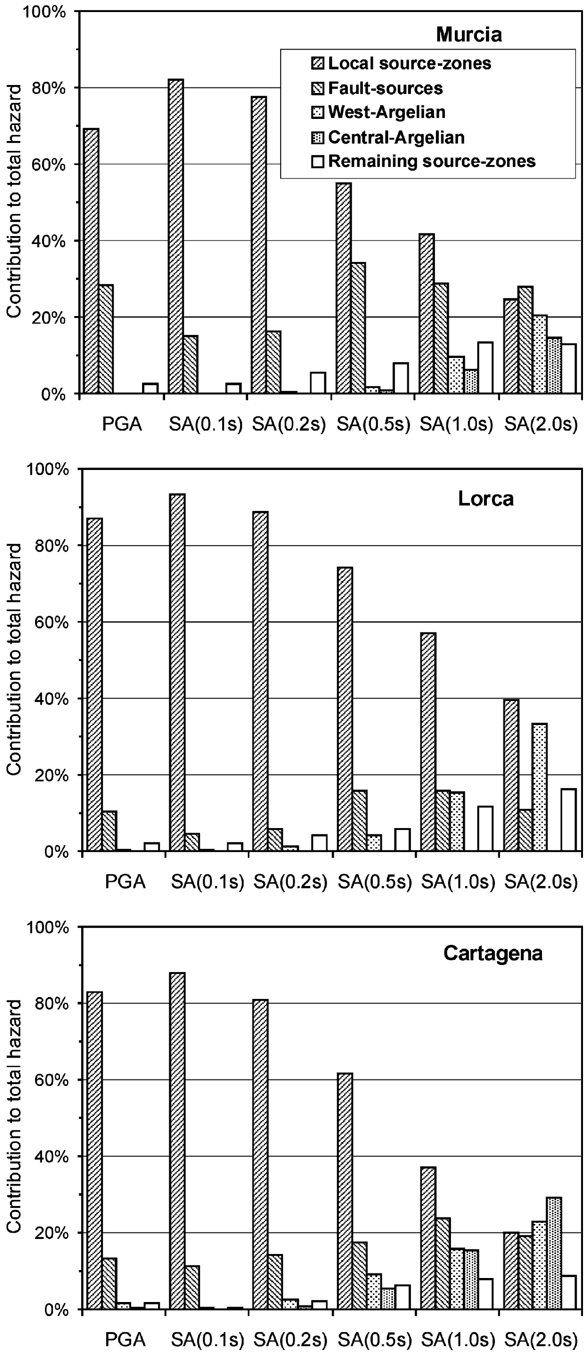


Fig. 10 Contribution of seismic sources to total hazard at Murcia City, Lorca and Cartagena for the 475-year return period. See text for explanation

are in all cases the Valencian, Prebetic and Almería-Filabres blocks.

Local source zones represent the major contribution to hazard at every city from PGA to SA(1.0 s), this being particularly outstanding for the short period range: PGA, SA(0.1 s) and SA(0.2 s). Seismicity in the Cartagena and Central Betic crustal blocks has been related to movements on small faults – maximum estimated rupture area between 90 and 130 km^2 – densely distributed within the upper 10 km of the crust (García-Mayordomo 2005). Therefore, devising seismic scenarios for PGA and SA (0.1 and 0.2 s) for the 475-year return period, do not necessarily have to relate to specific mapped faults.

The contribution from specific fault sources and North Algerian source zones becomes significant from SA(0.5 s) onwards. Fault source contribution is particularly significant in the case of Murcia City. This fact is due to the location of most of the active faults at distances shorter than 35 km. The faults that contribute the most at any SA are the Hurchillo and Benejúzar segments of the Bajo Segura Fault, and the Lorca-Totana segment of the Alhama de Murcia Fault. The Carrascoy Fault, although located at less than 10 km from Murcia City, contributes very little to the 475-year return period because of the long recurrence period of its characteristic earthquake. Actually, single-fault contributions never overpass the contribution from the rest of the sources, apart from the case of the Lorca-Totana segment at Lorca (Fig. 11). This segment of the Alhama de Murcia fault

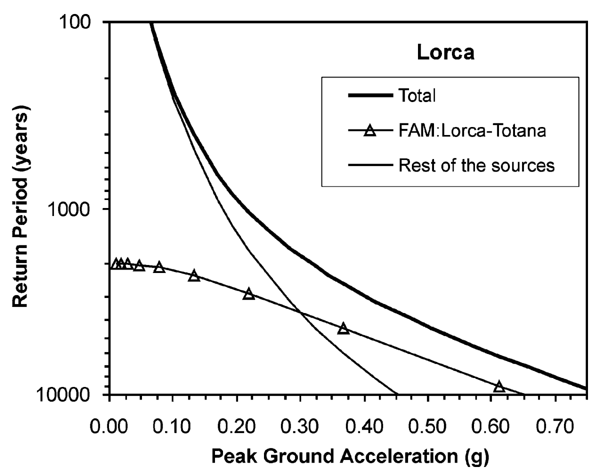


Fig. 11 Comparison of hazard curves at Lorca considering the contribution of all seismic sources (*Total*), the Lorca–Totana segment of the Alhama de Murcia Fault (*FAM*), and the remaining sources. Note that hazard due to FAM overpass the contribution from the rest of the seismic sources at approximately the 3,500-year return period. The same results were obtained for SA(0.5, 1.0 and 2.0 s)

represents the most hazardous seismogenic source at Lorca in terms of PGA and SA(0.5, 1.0 and 2.0 s.) for return periods longer than 3,500-year. On the other hand, North Algerian source zones represent a major fraction of the total hazard – or even the highest contribution – for SA(1.0 and 2.0 s), this fact being particularly outstanding at Cartagena. However, these results have to be taken with caution due to the simple zoning model used for Algeria.

The devise of seismic scenarios for conventional structures in the intermediate- (T=0.5 s) and long-period range (T≥1.0 s) should be based on the analysis of local, fault and North Algerian sources. Specific scenarios for hazard levels much higher than the 475-year return period, and particularly for critical structures, should always pay careful consideration to specific major active faults. According to our first results on the influence of North Algerian sources on seismic hazard at long periods, it is also recommended to distinctly consider these sources in the case of coastal towns, where resorts comprising a large number of tall buildings are widespread. This issue may be extendable to other coastal towns in neighbouring provinces (e.g., Alicante Province) and to the Balearic Archipelago. The significance of local and distant sources for target motions associated to return periods usually considered in seismic design of conventional structures is further studied in Gaspar-Escribano et al. (2007).

7 Conclusions

The seismic hazard assessment of the Province of Murcia presented in this paper follows the PSHA methodology and has been performed in terms of PGA and SA(T) for rock conditions, avoiding the use of intensity–acceleration relationships used in most of the previous studies in the region. Furthermore, we have considered the most updated geological and seismic information available. Special attention has been paid to the process of declustering and homogenising to a common M_w the IGN earthquake catalogue, and to assess its temporal completeness for South Spain and North Africa regions. Hazard results are presented as the weighted mean of all possible solutions stemming from a logic tree, which accounted for three different seismic source zonings and three different ground–motion attenuation relationships. Hazard and COV maps for the 475-year return period for PGA and SA(0.1, 0.2, 0.5, 1.0 and 2.0 s) are presented in the paper, showing maximum expected accelerations along a NE–SW trending area embracing Murcia City and Lorca.

We focussed the analysis of our results on three representative sites of the Province of Murcia, the cities of Murcia, Lorca, and Cartagena, which are also sites of prime interest for risk assessment in the frame of the RISMUR project. Murcia and Lorca areas show the highest seismic hazard in the province, whereas the Cartagena area shows an intermediate seismic hazard, although higher than stated in the Spanish seismic provisions. Cartagena area also shows the highest COV values, which highlights the interest of focusing more research in the area, particularly in characterising the seismic potential of offshore faults.

The most important factor affecting hazard results is the selection of the ground–motion attenuation relationship. SP-96 relationship leads to the highest results for every SA at every city, whereas AM-96 provides the lowest. The impact exerted by the seismic zoning models is site dependant. It is worthy to note the case of Cartagena, where the use of the NCSE-02 zoning draws very low results as compared to LC-95 and GM-05 zonings, because that city is actually outside any source zone in NCSE-02 model. In addition, we compared our weighted-mean UHS to the median UHS from a calculation considering a non-weighted logic tree at these cities, and found that both UHS are very similar. The main effect of our adopted weight scheme is that dispersion is reduced.

Source contribution to total hazard for the 475-year return period at Murcia, Lorca and Cartagena was analysed considering the GM-05 seismic source hybrid model and the BT-03 ground motion attenuation relationship only. Local source zones control the hazard for PGA and SA(T≤1.0 s), although from SA (0.5 s) to SA(2.0 s), the contribution from specific fault sources and North-Algerian source zones becomes significant. The latter is very apparent in the case of Cartagena for SA(1.0 s) and SA(2.0 s). These results highlight the importance of future research in considering long-distance seismic sources from North Algeria in seismic risk assessment in southeast Spain, particularly in the coast, where beach resorts comprise a large number of high-rise buildings. For short-period structures (T<0.5 s), it is recommended to devise scenarios derived from local source zones, whereas for intermediate- and long-period structures ($T \geq 0.5$ s) specific fault sources and North Algerian sources should also be considered. Finally, we regard that the use of hybrid source models – i.e., composed of source zones and specific fault sources, seems the best to account both for small-to-moderate diffuse seismicity and maximum magnitude events, respectively, for future seismic hazard and risk assessments studies in southeast Spain. However, more research on specific major active faults is needed.

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