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The 1748 Montesa (southeast Spain) earthquake — A singular event

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ABSTRACT

The Montesa earthquake of 23 March 1748 in southeast Spain caused heavy damage and was felt over a wide area. It occurred in a region considered of low seismic hazard where few large earthquakes have happened. The abundant contemporary documentation about the damage caused by the earthquake, especially to the castle of Montesa and the city of Játiva, allows a re-evaluation of the seismic intensity distribution giving a maximum intensity I = IX (EMS-1998). The focal parameters are estimated as: origin time 6 h 30 m local time, epicentre 39.00°N 0.64°W, and magnitude 6. The spatial distribution of ground acceleration derived from intensity values is modelled on a very shallow bilateral rupture of 10 km length with strike 60°, dip 45°, and rake 90°. This source orientation agrees with the faults present in the area.

1. Introduction

The traditionally known as "The Montesa earthquake of 1748" took place in the south-eastern region of Spain, caused heavy damage, and was felt over a wide area (Fig. 1). The name refers to the famous Castle-Convent of Montesa which was totally destroyed by the quakes. The main shock occurred on the 23rd of March and was followed by a series of aftershocks, the largest on the 2nd of April. Despite the many contemporary documents with descriptions about this earthquake, the only detailed seismological study is that by Bisbal Cervelló (1984, 1995) which only analyses the damage it caused. Most earthquakes in the Iberian Peninsula are of moderate magnitude (M < 5), and large shocks (M > 6) occur separated by very long time intervals (Buforn et al., 1988). Studies of historical earthquakes are therefore very important to be able to assess seismic hazard. In southern Spain, the three best studied large historical earthquakes are those of Málaga (1680) (Goded et al., 2008), Torrevieja (1829) (Canales-Martínez, 1999; Muñoz and Udías, 1991), and Arenas del Rey (1884) (Udías and Muñoz, 1979). These earthquakes had maximum intensities of IX or X. They were all located south of the Cádiz-Alicante fault system (Fig. 2a). The Montesa earthquakes occurred outside this system, to the northeast. Today, the area affected by the earthquake has a high level of industrial and tourist development, including the city of Valencia and other important towns such as Alcoy, Gandía, Játiva/Xátiva and Onteniente/Ontinyent (double names correspond to the Spanish and Valencian languages) (Fig. 1a, b).

We consider the Montesa earthquake to be a singular event because it occurred in an area with low seismicity, where in the past very few large earthquakes had occurred. According to the Spanish Seismic Code (Norma, 2002) this area is considered to be of low seismic hazard with a characteristic acceleration of 0.07 *g* for a return period of 500 years. Recently, the Instituto Geográfico Nacional (IGN) has re-evaluated this figure using probabilistic seismic hazard assessment (PSHA), assigning the PGA a value of 0.16 *g* at Montesa, Játiva, and Estubeny, the places suffering the greatest damage in the 1748 earthquake (Martínez Solares et al., 2013). The occurrence of recent damaging earthquakes, such as those of L'Aquila (2009) or Haiti (2010), in regions considered to be of low seismic risk, but where in the past large shocks have occurred, highlights the importance of carrying out detailed studies of historical seismicity in this type of regions. In this paper, we present a re-assessment of the damage caused by the 1748 Montesa earthquake using contemporary documents with a detailed study of the damage caused at the Castle of Montesa and in Játiva, the largest town affected by the quake, and a re-evaluation of the seismic intensities. We estimated the focal parameters from known geological features and the intensity distribution and, using an empirical correlation, the distribution of ground acceleration in the region. Finally, we propose a rupture source model based on the intensity distribution and geological features.

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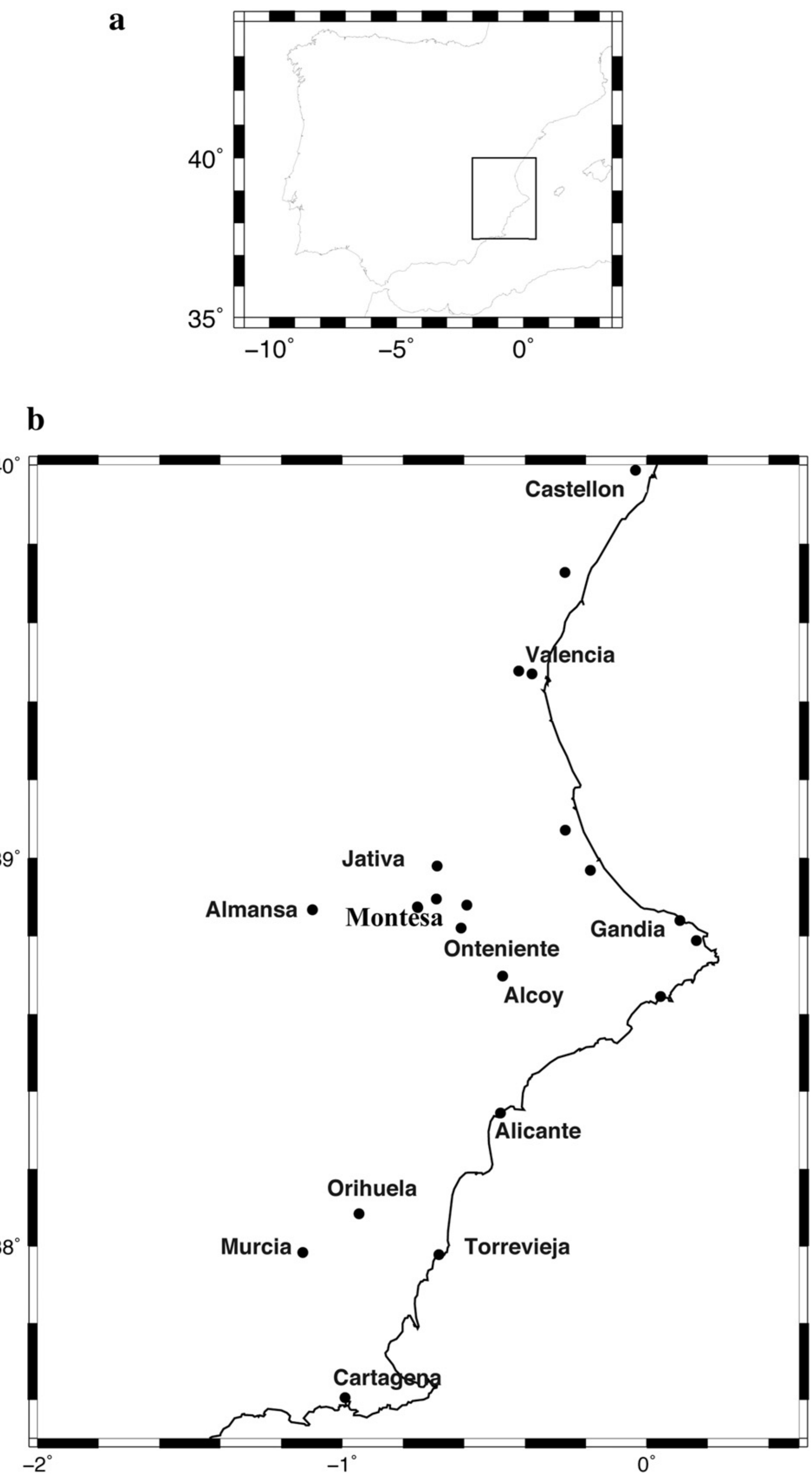


Fig. 1. Map of Spain. The studied region is marked as a square (a). Location of cities, towns and villages affected by the earthquake of 1748 (b).

2. Geological setting

The area affected by the Montesa earthquake is located in the SE part of the Iberian Chain, near the Pre-Betic Domain (External Zone of the Betic Cordillera). For this reason the southern part of the sector presents structures, mainly folds, of NE–SW to ENE–WSW direction, while in the northern part there are folds of predominantly NNW–SSE direction corresponding to the Iberian Chain Domain (Fig. 2a). Besides the cited folds, the area is also affected by NE–SW reverse faults verging to the NW, and by two other sets of faults, one NNW–SSE and the other ESE–WSW, of normal character, although in some cases probably also presenting lateral components of movement (Fig. 2b). These two sets have determined the existence of two bands of tectonic weakness (marked in salmon colour in Fig. 2b), occupied in great part by Triassic sediments. These bands correspond to sectors affected by important faults, some of which are not necessarily visible. This description corresponds well with the geological features of the sedimentary cover directly observable in the field.

The lithological sequences comprise units from the Triassic to the late Cretaceous–Paleogene, and another one ranging from the Miocene to the Quaternary. This cover was deposited over the Paleozoic basement (eastwards continuation of the Iberian Paleozoic Shield; Fig. 2a).

In the area of Estubeny–Enguera–Montesa (Fig. 2b), the basement is located at a depth of about 2.5–3 km depending on the thickness of the cover (De Ruig, 1992; García Mayordomo, 2005). Thus, the question is to elucidate whether or not there is a relationship between the geological features of the cover and the structures (faults) affecting the basement. The area is mainly characterized by thin-skinned tectonics, and probably all or most of the folds and reverse faults existing in the area correspond to this type of tectonics and are independent of the basement. However, the existence of long lines of normal and strike-slip faults in the area suggests the possibility that the basement is also involved. In general, these faults are younger than the folds present in the area (they cut the folds). The existence of faults affecting the basement and in some cases cutting the entire cover is also known in other areas of southern Spain. An example is the Guadalquivir basin (Fig. 2a) (Sanz de Galdeano et al., 2013). This means that thin-skinned tectonics is not necessarily the only type existing in the study area and in other nearby areas.

The relief of this area is formed in the southern part by two mountain ranges (*sierras*) of NE–SW strike with the highest altitudes reaching about 900 m: Tres Mojones–La Plana Sierra to the north and Sierra Gorda to the south. Between the two sierras there is a valley traversed by the Cañoles River on which Játiva, Montesa and many other villages are situated. There is another valley to the north of the Sierra Tres Mojones–La Plana where Enguera, Estubeny, Anna, and Sellent, the places that suffered greatest damage in the Montesa earthquake, are located (Fig. 2b).

3. Seismicity

Fig. 3 shows the large earthquakes that have occurred in the region: historical, before 1900 (triangles) with maximum intensity IX and VIII; and instrumental, from 1900 until 2014 (circles) with magnitudes larger than 4.8 (Instituto Geográfico Nacional (IGN): www.ign.es/ign/layoutIn/sismoFormularioCatalogo.do, last accessed April 2015). Earthquakes to the north of latitude 38.5°N, that of the 1748 earthquake, are concentrated near the coast, and form a group separated from those more frequent to the south. To the west there is a broad region with no seismic activity. The second group of epicentres is located south of latitude 38.2°N extending to the SW. During the instrumental period, no earthquakes with magnitude greater than 5.0 have occurred

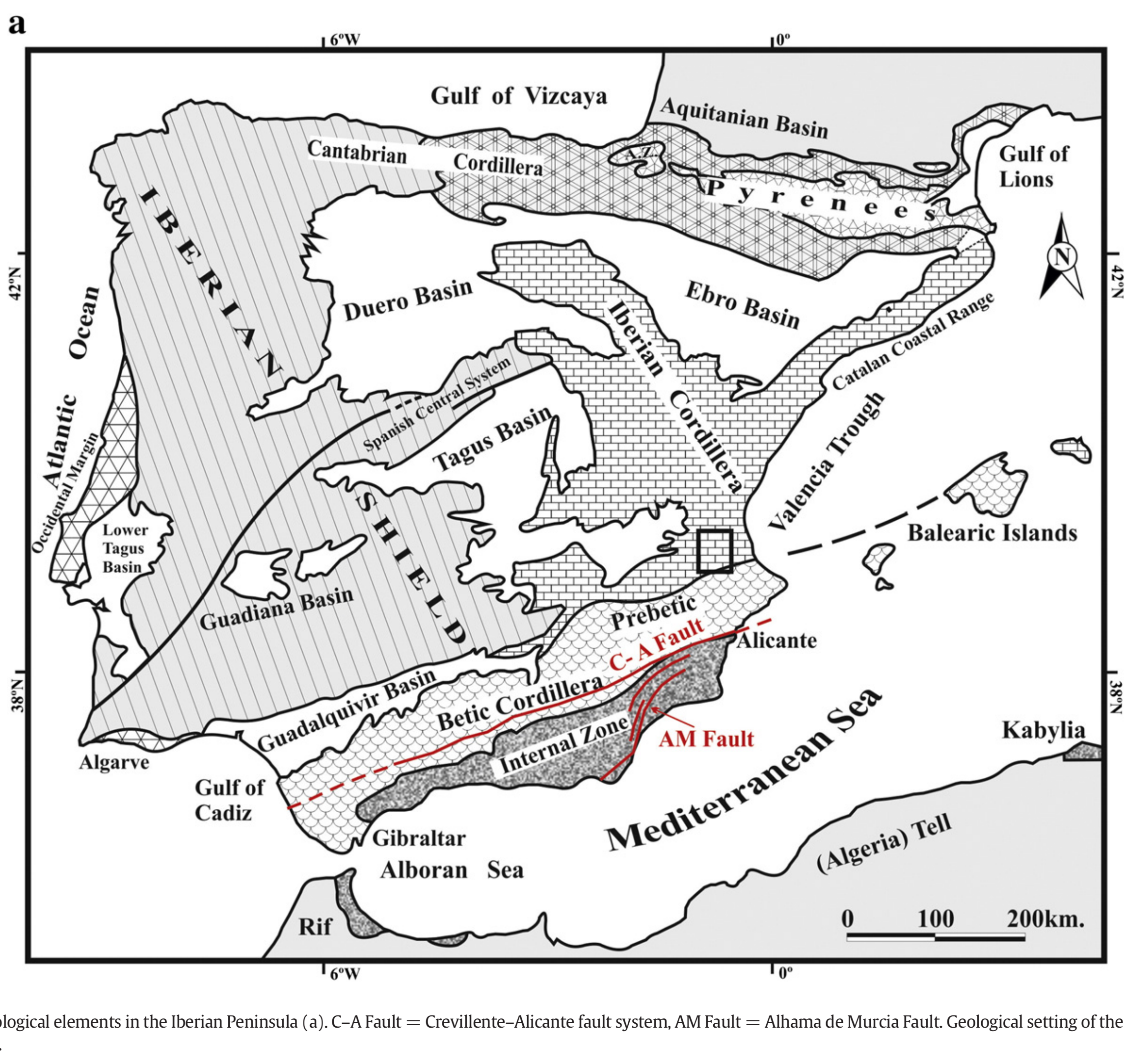


Fig. 2. Main geological elements in the Iberian Peninsula (a). C–A Fault = Crevillente–Alicante fault system, AM Fault = Alhama de Murcia Fault. Geological setting of the area of the 1748 earthquake (b).

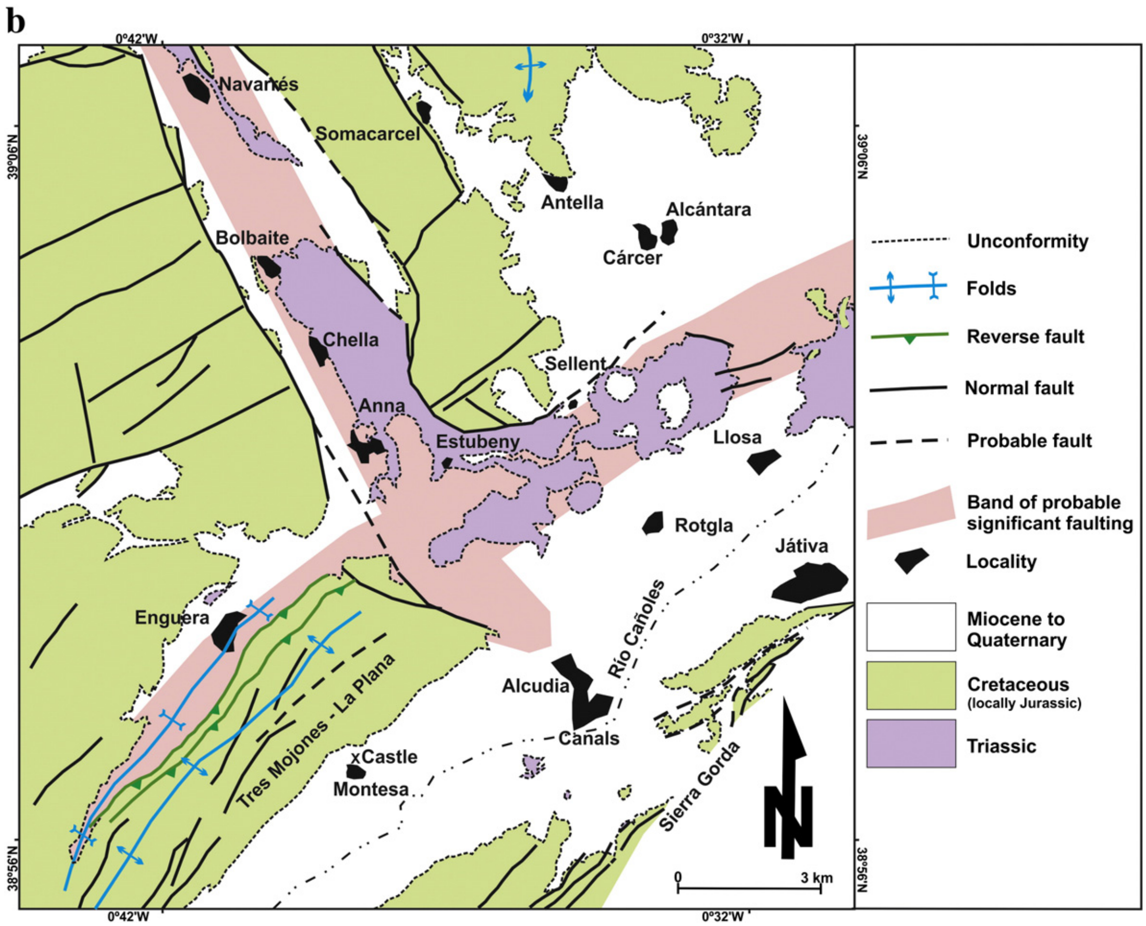


Fig. 2 (*continued*).

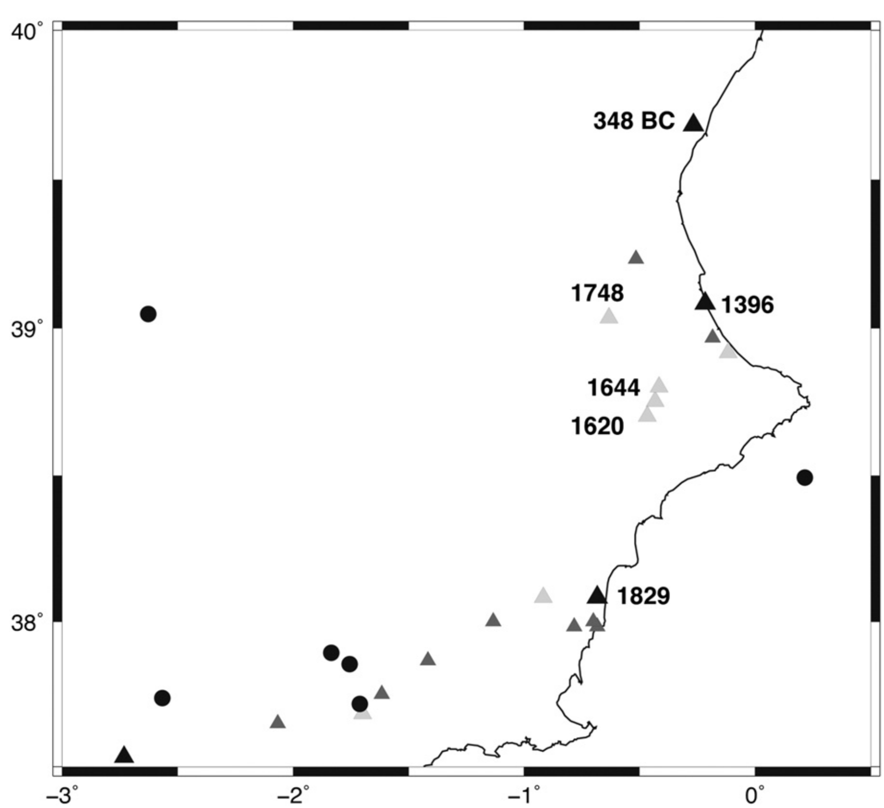


Fig. 3. Largest historical earthquakes taken from the IGN catalogue. Black triangles Imax = IX, light grey triangles Imax = VIII, dark grey triangles Imax = VII, black circles M > 4.8.

to the north of latitude 38.5°N. However, during the historical period, the same number of shocks occurred to the north and south of this latitude. The most notable historical earthquakes of the northern group were the following (Fig. 3): in 348 B.C., an earthquake is reported to have destroyed the prosperous pre-Roman city of Sagunto, as reported by later historians (Udías, 2015); in 1396 an earthquake caused damage to a wide area, including that affected by the 1748 shock, with the destruction of the Monastery of Valldigna (Tavernes de Valldigna) (Fontserè and Iglésies, 1971, 88–94); in 1620 a series of earthquakes took place which caused heavy damage in Alcoy, with the destruction of several churches, and there was a repeat in 1644 (Fonserè and Iglésies, 1971, 248–250, 253–254). Among the earthquakes of the southern group, the most notable was the Torrevieja earthquake of 1829 with maximum intensity X and estimated magnitude 6.9 (Muñoz and Udías, 1991). In this area there has been a continuous activity of earthquakes with maximum intensities greater than VII (historical) and magnitudes greater than 4.5 (instrumental).

Fig. 4 shows the recent low magnitude ($M > 2$) earthquakes for the period 1990–2014 (IGN). The events have been more frequent south of latitude 38.5°N, as also was the case for the larger quakes (Fig. 3). In the northern group, in the north-eastern part of the region shown in Fig. 4, two alignments may be present — one SW–NE and the other NNW–SSE, and these cross precisely in the area of the 1748 earthquake. These shocks are at shallow depth, less than 40 km, and most of them are of very low magnitude (less than $M = 3$). Seismicity continues off-shore but epicentres there do not follow any precise distribution. Between longitudes 1°W and 2.5°W, and north of latitude 38.7°N, there is a region with very low seismic activity; earthquakes reappear to the east of 3°W (Fig. 4). South of latitude 38.5°N the epicentres are distributed following mainly a NE–SW direction, parallel to the coast, and they may be associated with the Alhama de Murcia fault system (AM Fault), the main geological feature in this region (Fig. 2a). The large concentration of epicentres located to the south in Fig. 4 corresponds to the Bullas (Aledo) series of 2002 and 2005 (Buforn et al., 2005; Martínez Solares et al., 2012).

4. Documentary sources

There is abundant contemporary information about the damage caused by the Montesa earthquakes of 1748. We have divided it into three categories: contemporary publications with author, anonymous contemporary publications, and manuscripts.

4.1. Contemporary publications with author

The most important published contemporary document is the report by Esteban Felix Carrasco, an Army Officer and Aide-de-Camp of Claude-Abraham de Tubieres, Marquis of Caylús, Captain General of the Kingdom of Valencia, the highest authority in the region. Carrasco gathered the information from the news and reports about the earthquakes sent to the Marquis of Caylus by the local authorities (*governadores*, *corregidores*, and *justicias*) (Carrasco, 1748a) (Fig. 5). The report contains detailed information about the damage suffered at 36 localities and brief mentions of damage in another 30 in the three districts or provinces (*governaciones*) of Montesa, Játiva, and Alcira. The report was translated into Portuguese and published in Lisbon (Carrasco, 1748b). Two other contemporary published documents are the following: Rafael Lombart, physician at the castle of Montesa, wrote a day-by-day account of what happened at the castle from 23 March to 8 April (Lombart, 1748), and Josep Sarrió, a student of theology in Valencia at that time, wrote a short account of the damage in the town of Anna where he travelled to on 25 March (Sarrió, 1762). Other descriptions of the earthquake are those of Rausell Mompó (1748) and Ximeno (1748).

4.2. Anonymous contemporary publications

There are six anonymous accounts about the earthquake, two published in Valencia (Relación verdadera, 1748; Verdadera relación, 1748), two in Madrid (Relación de los estragos, 1748; Segunda relación, 1748), one in Barcelona (Relación del Terremoto, 1748), and

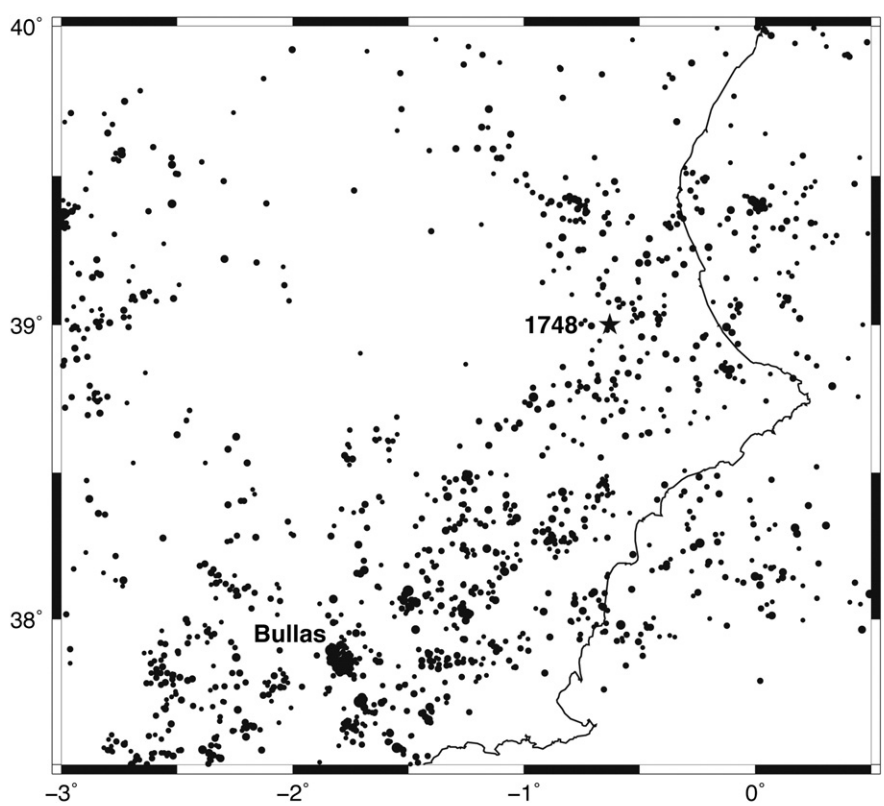
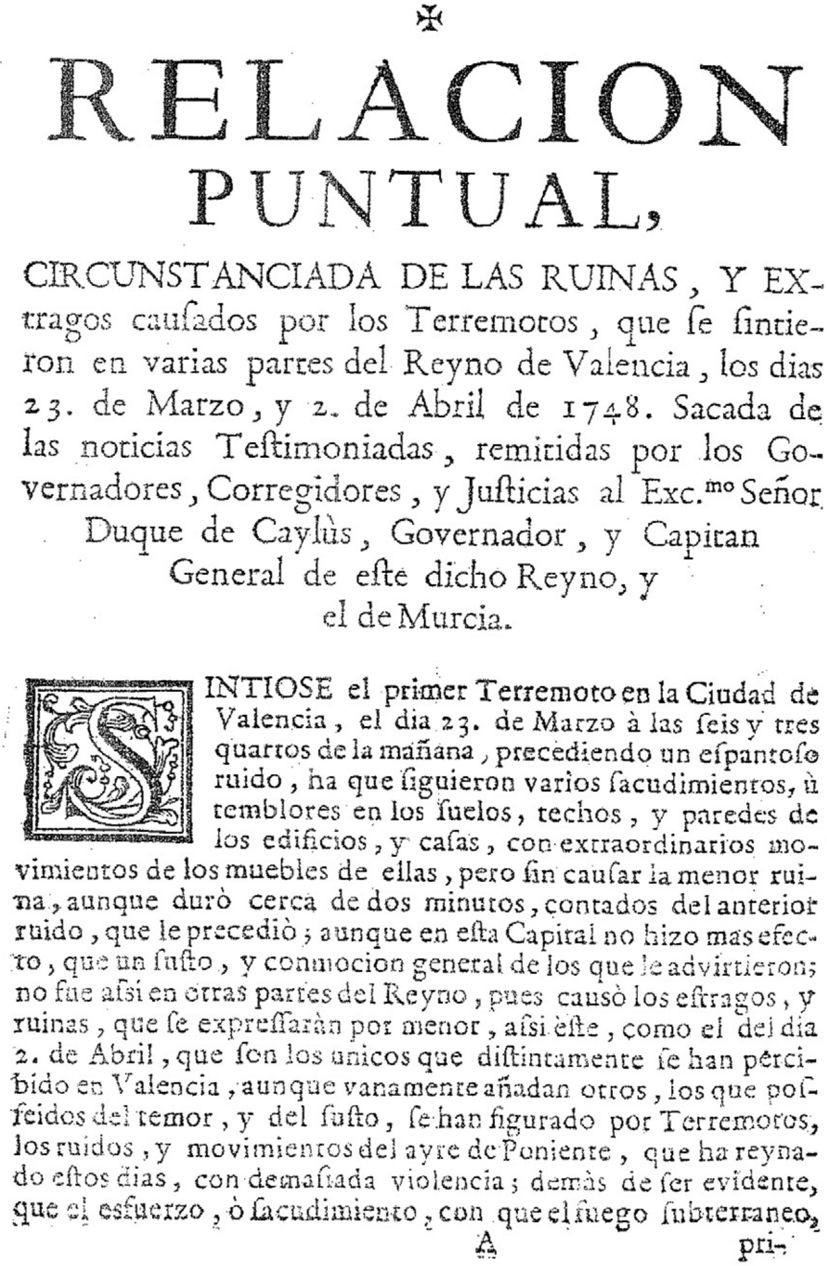


Fig. 4. Seismicity for the period 1990–2014, M > 2.0 taken from IGN catalogue. Star shows the 1748 epicentre. Size of symbols is proportional to the magnitude.



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RELACION

PUNTUAL,

CIRCUNSTANCIADA DE LAS RUINAS, Y EXtragos cauſados por los Terremotos, que ſe ſintieron en varias partes del Reyno de Valencia, los dias 23. de Marzo, y 2. de Abril de 1748. Sacada de las noticias Teſtimoniadas, remitidas por los Governadores, Corregidores, y Juſticias al Exc.^{mo} Señor Duque de Caylùs, Governador, y Capitan General de eſte dicho Reyno, y el de Murcia.

SINTIOSE el primer Terremoto en la Ciudad de Valencia, el dia 23. de Marzo à las ſeis y tres quartos de la mañana, precediendo un eſpantoſo ruido, ha que ſiguieron varios ſacudimientos, ù temblores en los ſuelos, techos, y paredes de los edificios, y caſas, con extraordinarios movimientos de los muebles de ellas, pero ſin cauſar la menor ruina, aunque durò cerca de dos minutos, contados del anterior ruido, que le precediò; aunque en eſta Capital no hizo mas efecto, que un ſuſto, y conmocion general de los que le advirtieron; no fue aſsi en otras partes del Reyno, pues causò los eſtragos, y ruinas, que ſe expreſſaràn por menor, aſsi èſte, como el del dia 2. de Abril, que ſon los unicos que diſtintamente ſe han percibido en Valencia, aunque vanamente añadan otros, los que poſſeidos del temor, y del ſuſto, ſe han figurado por Terremotos, los ruidos, y movimientos del ayre de Poniente, que ha reynado eſtos dias, con demaſiada violencia; demàs de ſer evidente, que el esfuerzo, ò ſacudimiento, con que el fuego ſubterraneo,

A pri-

Fig. 5. Title page of the report by Carrasco (1748a, 1748b).

another in Lisbon (Relaçao do formidavel, 1748). The different places of publication show the general interest aroused by the disaster. All the documents describe the damage suffered by the Castle and Convent of Montesa, which was completely destroyed by the earthquake, especially Relación del terremoto (1748). These accounts complement the information of Carrasco (1748a, 1748b).

4.3. Manuscripts

There are many manuscripts with information about the earthquake. The most important is the official report (*informe*) by the Deputy Mayor of Valencia (*Intendente de Valencia*) Francisco Driget, Marquis of Malespina, to the Secretary of Internal Revenue (*Secretario de Hacienda*), Zenón de Somodevilla, Marquis de la Ensenada, with exhaustive information about the damage and an evaluation of its costs in 58 towns and villages (Extracto, 1748). This report was used to fix the compensation for the damage approved by King Ferdinand VI in August 1748. The total cost of the damage was estimated at 116,377 *libras Valencianas* (the Valencian pound was a unit of account equivalent to 16 *reales*; the 8 *reales* piece or *real de a ocho* was the common Spanish silver coin equivalent to a silver dollar), but compensation was fixed only to a total of 33,017 *libras* (28% of the estimated cost of the damage). For example, the cost of the damage in Játiva was estimated at 8055 *libras*, but only 1688 *libras* were actually assigned (Alberola, 1995). An important manuscript with information about the damage in the town of Játiva is *Autos de Visuras* (Proceedings of Inspections) and *Visuras de los daños* (1748) which presents the results of a visual inspection (*visura*) of the damage suffered by 30 buildings, mostly public buildings, churches, and convents. Another important manuscript (*Relación de lo sucedido*, 1748) gives a short report of the damage in 60 localities of the district of Játiva, in some cases with an evaluation of the cost (Bisbal Cervelló, 1984).

Other important manuscripts that also give information about the earthquake and the damages are: Autos en razón (1748), El

Intendente de Valencia (1748), Informacion dada (1748), Relació del terratrémol (nd), Relación de las desgracias (1748), Relacion de lo sucedido (1748), Relación zircunstanziada de la ruina (1748), Relación del terremoto (1748).

An important secondary source is that contained in the work of local historians. Between 1874 and 1911, Sucias Aparicio wrote a variety of historical notes about the province of Valencia which are preserved in manuscript form. They contain valuable information about the damage caused by the earthquake in many towns and villages (Bisbal Cervelló, 1984; Sucias Aparicio, 1876). In 1883, Vilanova published three articles about the 1748 earthquake in which he reproduces some contemporary documents (Vilanova, 1883). Sarthou Carreres also reproduces some contemporary documents in his history of the town of Xátiva (Sarthou Carreres, 1928; Sarthou Carreres, 1934). The earthquake has also interested recent historians who consider it from the historical and sociological points of view. Faus Prieto (1989) centres his considerations on the ideas about the origin of earthquakes by contemporary authors who wrote about this earthquake. Alberola (1995) gives very detailed historical information about the damage and the actions taken by the local authorities involved, in particular, by Pedro Valdes León, Governor of Játiva, and by Pedro Caro y Fontes, Marquis de la Romana, Governor of Montesa, the Marquis of Caylús, Captain General of the Kingdom of Valencia. They sent their reports to the Marquis de la Ensenada in Madrid who then informed King Ferdinand VI. Alberola (2012) also considers the sociological aspects with the reactions of the people of the towns and villages affected by the earthquake. He gives special attention to the reaction to the earthquake by ordinary people influenced by popular religiosity, and to ecclesiastic interventions presenting the earthquake as God's punishment.

Seismologically, the 1748 Montesa earthquakes can be found in the early catalogues for the Iberian Peninsula (Galbis, 1932; Moreira de Mendonça, 1758; Perrey, 1847; Sánchez Navarro-Neumann, 1921). Fontserè and Iglésies (1971) present a more detailed treatment of these earthquakes in their catalogue of earthquakes of Catalonia. The most comprehensive analysis of the damage caused by the earthquakes is that of Bisbal Cervelló (1984) who reproduces many of the contemporary documents and evaluates the intensities at 78 places. In the most recent catalogue of historical earthquakes in the Iberian Peninsula (Martínez Solares and Mezcua, 2002) there is a re-evaluation of the intensity distribution for this earthquake. Other recent studies centre on detailing the geological ground effects of the earthquakes (Giner-Robles et al., 2014; Silva and Rodriguez Pascua, 2014).

5. Intensity evaluation

The Montesa earthquake occurred in a region with a high density of towns and villages. A 1735 census (*Padrón Demográfico*) gives the size of the towns and villages in terms of the number of family units (*vecinos*) (Camarena Mahiquez, 1966). In total, there is information about the earthquake corresponding to 118 towns and villages, including those where the shocks were only felt but without there being any damage. Among those which suffered damage, there were six towns with more than 2500 inhabitants (multiplying by five the family units given in the census to convert them to population numbers): Onteniente/Ontinyent (6850), Játiva/Xátiva (6010), Alcira (4770), Carcagente/Carcaixent (4475), Algemesí (3905), and Ollería (3060). There are 14 villages with between 500 and 2500 people; 41 villages with between 150 and 500 people; and 26 villages of fewer than 150 people. Of the 87 localities with reported damage, 67 (77%) had fewer than 500 people, so they were fairly small villages.

The building types in the towns were parish churches and convents (larger towns might have several convents), official buildings (town halls), and houses of well-to-do persons, made of dressed or rough stone or of stone and brick masonry, and the ordinary people's houses of weak mortar and rubble masonry. In small villages, buildings are specified as of three types: the parish church, the house of the lord or owner (*casa del señor o dueño del lugar*), of stone masonry, and the people's houses of mortar and rubble masonry. No adobe was used in this part of Spain (Seijo Alonso, 1979). According to the EMS-1998 scale, most of the buildings may be classified as vulnerability classes A or B, and only some churches, convents, and official buildings as class C (Grünthal, 1998).

Contemporary documents do not present the description of damage with any great detail. Houses are said to be, from greater to lesser damage, as: “destroyed” (*asoladas*), “collapsed” (*desplomadas*), “ruined” (*arruinadas*), “shattered” or “broken” (*quebrantadas*), “damaged” (*maltratadas*), “uninhabitable” (*inhabitables*), “threaten ruin” (*amenazar ruina*), or “impaired” (*consentidas*). These descriptions may in some way be comparable with the five grades of the classification of damage to masonry buildings of the EMS-1998. However, this type of description leads to a certain ambiguity in the assignation of intensity degrees. Damage to churches, however, is described more specifically. For example: “part of the vault or dome fallen”, “walls ruined”, “arch fallen”, or “apertures and cracks in vaults and columns”. The number of houses affected is given in an approximate form as “all”, “almost all”, “most”, or “some”. Another problem is that the damage includes also that due to the largest aftershock of the 2nd of April, considered to have been as large as the main shock. Thus, estimated intensities include the damage due to the two shocks. Using the EMS-1998 scale (Grünthal (1998)), in accordance with the type of construction, we assigned a maximum intensity IX for places with all or most houses ruined or devastated and some collapsed, and the so-called house of the owner and the churches and convents with major damage.

Bisbal Cervelló (1984) made a first evaluation of intensities at 78 places extending from X to V, using the MSK-1964 macroseismic scale (Medvedev et al., 1965). Of these, 34 were evaluated directly from the descriptions of damage and 44 calculated from the assigned cost of damage, using as a relation between cost and intensity that obtained for the first 34. Martínez Solares and Mézcua (2002) made a re-evaluation of the intensities using the EMS-1998 scale giving values for 83 places, extending from grade IX to V and for 30 more where it caused slight damage (given as D) or where it was only felt (given as S). We have re-evaluated the intensity at 76 localities directly from the descriptions given in contemporary documents, using the EMS-1998 scale. It should be borne in mind that the descriptions of damage in the documents do not give much detail, so that evaluation of intensities is subject to uncertainties and to the problem of the cumulative damage from the largest aftershocks.

5.1. Places with greatest damage

The localities that are given in contemporary documents with the greatest damage and to which we assign intensity IX are: Estubeny, Sellent, Anna, Chella, and Enguera (Figs. 2b and 6).

Estubeny was a small village of only 50 people and 11 houses, a small church, and the lord's house (Figs. 2b and 6). Everything was devastated including the lord's house and the church. A crack was produced in the ground of 29 m length and 21 cm wide, “so deep its end could not be reached” (Carrasco, 1748a). Sellent of 97 people is 3 km to the NE of Estubeny, and is said to have all houses and church ruined, and one person dead and one injured (Figs. 2b and 6) (Carrasco, 1748a, 1748b). Damage is said to have been equal to that of Estubeny (Segunda relación, 1748). People abandoned both villages. In the *Extracto*, the two villages are the only ones declared as “total ruin” (*ruina total*) (Extracto, 1748). Anna located about 2.5 km to the west of Estubeny was somewhat larger with 370 people (Figs. 2b and 6). Damage is reported in five accounts (Carrasco, 1748a, 1748b; Relación de los estragos, 1748; Relación verdadera, 1748; Sarrió, 1762; Segunda relación, 1748). In the church, the vault collapsed and the tower was ruined, the house of the owner and all the others were heavily damaged, and three persons died in their houses. The shock of the 2nd of April completed the destruction, and the village was abandoned. Chella is

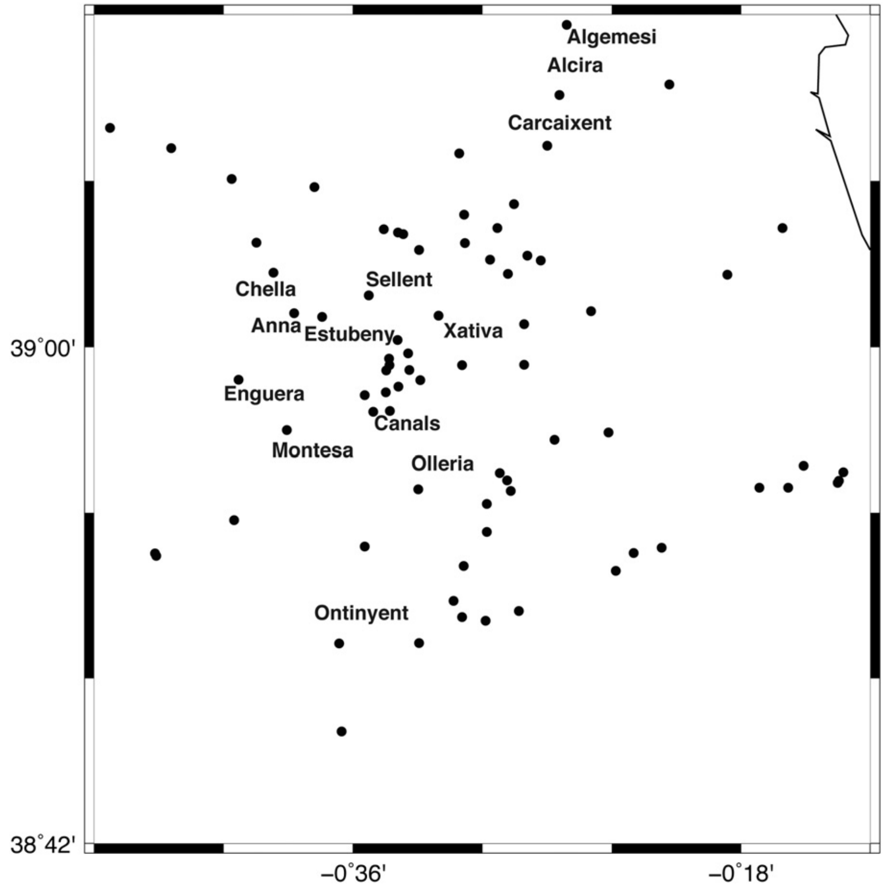

Fig. 6. Localities affected by the earthquake of 1748 and with reported damage.

3 km to the NW of Anna, a village of 264 people (Figs. 2b and 6). The church threatened ruin, four houses collapsed, and the rest with that of the owner were left uninhabitable; the village was abandoned (Carrasco, 1748a, 1748b).

Enguera was the largest town of the heavily damaged area with 1638 people and a flourishing textile industry (Figs. 2b and 6). Carrasco (1748a, 1748b) gives a detailed description of the damage. The church of cut or massive stone suffered ruin of the tower, fall of the vault of the sacristy, and ruin of seven arches which supported the main vault. The Carmelite convent was ruined. A great part of the houses were ruined, and some threatened ruin. The shock of the 2nd of April completed the destruction: some chapels of the church were ruined, as well as the houses damaged by the first shock. Accounts of the damage are also given in Relación de los estragos (1748), Segunda relación (1748), and Relación verdadera (1748).

The Verdadera relacion (1748) states that Sellent, Enguera, Estubeny, and Canals were almost totally ruined. One can thus conclude that the greatest damage extends along a length of about 10 km in a NE–SW direction, from Sellent to Enguera.

A group of 11 villages, namely Cotes, Cárcel, Benegida/Beneixida, Alcudia, Canals, Novele, Rotgla, Granja, Vallés, Torrellá, and Ayacor (each with fewer than 500 people) are located very close together, occupying an area of about 4 km by 3 km southeast of and near to (about 5 km distance) the area of greatest damage (Fig. 6). The damage they suffered is described as the church ruined, the house of the owner partially ruined, and the other houses devastated, ruined, damaged, or threatening ruin. All these villages were abandoned after the earthquake, and people went to live in the fields in huts and tents. We have assigned them intensity VIII.

The total number of casualties was 38, of which 22 were in the castle of Montesa and the rest in different villages.

5.2. Destruction of the Castle-Convent of Montesa

The Castle-Convent of Montesa (Figs. 2b and 6) was built on a rocky hill separated from the nearby sierra. It was originally a thirteenth century Moorish castle, to later come under the occupation of the Knights Templar (Sarthou Carreres, 1951). In 1317, it became the see of the newly created Military Order of Montesa. The church, cloister, chapter-rooms, and other dependencies were built around about 1360 (Fig. 7). At the beginning of the eighteenth century, the Castle-Convent was a very impressive compound of buildings, surrounded by high walls of dressed stone of 3.5 m thickness, occupying an area 500 m long (EW) and 215 m wide (NS). The church of dressed stone in Gothic style with pointed arches had walls of 3.4 m (16 *palmos*) thickness in the lower part and 1.7 m (8 *palmos*) in the upper part, with a square tower to the east with walls of 4.6 m (20 *palmos*). Next to the church were the cloister and the chapter rooms (Fig. 7). All accounts described the total destruction of the convent-castle (especially Carrasco, 1748a, 1748b; Lombart, 1748; and the Relación del terremoto, 1748). The church's southern wall, built on the edge of the hill, collapsed bringing down the vaults and rest of the building. The same occurred to the cloister and the chapter rooms on the same side (Fig. 7). The aftershock of the 2nd of April completed the destruction with the collapse of the still standing walls. In the main shock, 18 people died (most of them in the church), and four

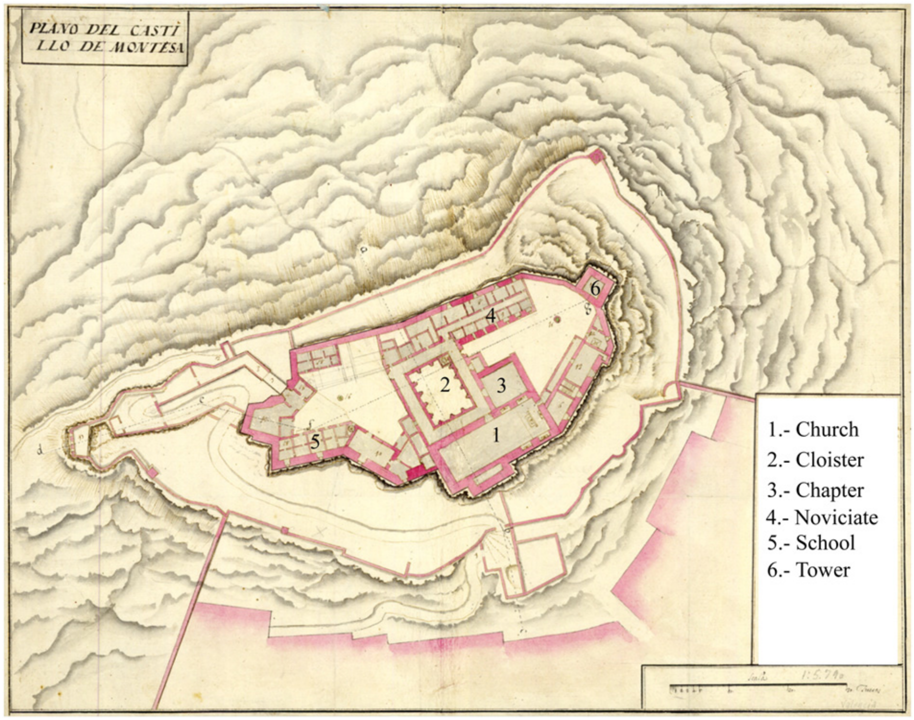

Fig. 7. Drawing of the plan of the Castle of Montesa before the earthquake.
Modified from Plano Castillo de Montesa (1730), Centro Geográfico del Ejército. Archivo Cartográfico y de Estudios Geográficos, Sign. Ar.G-T.3-C.2-235.

more in the 2nd of April aftershock. Thus 22 people died in the castle of Montesa of the total 38 dead in the earthquake. Remains of the castle ruins are still to be seen today (Fig. 8).

Carrasco (1748a, 1748b) assigns the destruction of the castle to its defective construction. He singles out first the inhomogeneous nature of the terrain of the hill with rocky and soil parts of different solidity and the fact that the southern wall of the church which fell completely was set on the edge of the hill. He adds the excessive height of the church walls, the heavy vaults, and the lack of buttresses to sustain the main arches. He writes that had the church had good buttresses it would not have suffered so much adding that the church in Canals (at 5 km) with good arches and buttresses did not suffer any great damage. He assigns the same defects to the other buildings of the castle. We agree with Carrasco because the castle of Montesa is situated on an isolated and prominent hill formed by late Miocene calcarenites, and the site effects were necessarily very important, although the epicentre was as close as it was to Estubeny or Sellent. The village of Montesa itself (550 people) had the church and most houses ruined, with only a few left standing, but nevertheless uninhabitable. There were five people dead and many injured. People abandoned their houses and went to

Fig. 8. Present state of the ruins of the Castle of Montesa.

live in tents and huts in the fields. The collapse of a great part of the castle can be assigned to a combination of the conditions of the terrain and the characteristics of the buildings, especially the church, rather than to very strong ground shaking. Considering also the damage in the village, we assign VIII–IX as the average intensity.

5.3. Damage in the town of Játiva

The town of Játiva/Xátiva with 6010 inhabitants in 1735 was the largest city near the epicentral area (at a distance of about 6 km). Damage due to the earthquake is described in the contemporary reports by Carrasco (1748a, 1748b), Relación de estragos (1748) and Segunda Relación (1748). Sorthou Carreres (1928, 1934), based on contemporary documents of the archives of the town of Játiva, gives a very detailed description of the damage especially to the churches, convents, and public buildings. Carrasco (1748a, 1748b) assigns the damage in part to the poor construction of the houses and to the even poorer materials (*Mala construcción de sus casas y peores materiales*). In 1707 the city had suffered a widespread fire in the siege by the troops of Phillip V in the War of the Spanish Succession. According to Carrasco, in the earthquake 229 houses suffered damage, but only 4 totally collapsed, while 90 needed major repairs and 135 had damage to roofs and walls. He specifies the damage to the Main Church (*Iglesia Colegial*), a late Gothic building of dressed stone, which had cracks in the dome and the walls of the transept and needed repairs to the main door. The same is said of four other churches and convents (Santa Tecla which had to be pulled down, Santa Clara, San Francisco, Santo Domingo, and La Merced) (Fig. 9). Carrasco (1748a, 1748b) assigns the ruin of Santa Tecla to its faulty construction. The City Hall suffered damage to the tower, roof, and walls; the Hospital needed repairs; and the Customs Office needed major repairs. Relacion de estragos (1748) mentions the partial ruin of the castle, and specifies the damage to the Main Church and to the convents of La Merced with the dome ruined, San Francisco, and Santa Clara (Fig. 9). All three convents had to be abandoned, and the Main Church could not be used. The report states that great parts of the houses were abandoned.

Sarthou-Carreres (1934) reports the results of an inspection made after the earthquake by the military engineer Juan Bautista Trench, ordered by the Marquis of Caylús. He gives the damage to four public buildings – the City Hall, Hospital, Customs, and Almudín (the city's granary) – that needed repairs. The Main Church suffered cracks in its dome, front, and walls, especially in the transept. He details the damage to the eight convents of the city. This varied from some cracks in domes and walls to ruin. Some were abandoned. Special attention is given to the convent of Santa Clara, a building of the fourteenth century reformed in the sixteenth and seventeenth centuries, because of the controversy between the nuns who left the convent and the town council about the damage and who would have to pay for the repairs. The reported damage to the buildings of the town shows no particular distribution (Fig. 9). From this description we conclude that there were no observable site effects in Játiva. Only four houses are reported to have totally collapsed, and the differing damage suffered by the buildings may have been due to the construction which Carrasco (1748a, 1748b) considered to generally be very defective. Of the ten churches and convents, only one (Santa Tecla) is described as being in danger, was therefore closed, and a great part would have to be pulled down, or at least reinforced. The damage to the others is limited to cracks of different sizes in domes and walls. Thus the overall intensity for the town is estimated as VIII.

5.4. Lower intensities

The large number of villages with descriptions of damage to the east of the epicentral area (Fig. 1) allows their damage to be evaluated as from intensities VII to IV (felt). We estimate damage at intensity VII for localities at distances between 15 km and 35 km, most of them to the east of the region of greatest damage. Because the region to the west is sparsely inhabited, one has very little data available (Fig. 1).

Fig. 9. Eighteenth century plan of the city of Játiva. Modified from Pérez Ballester (2006).

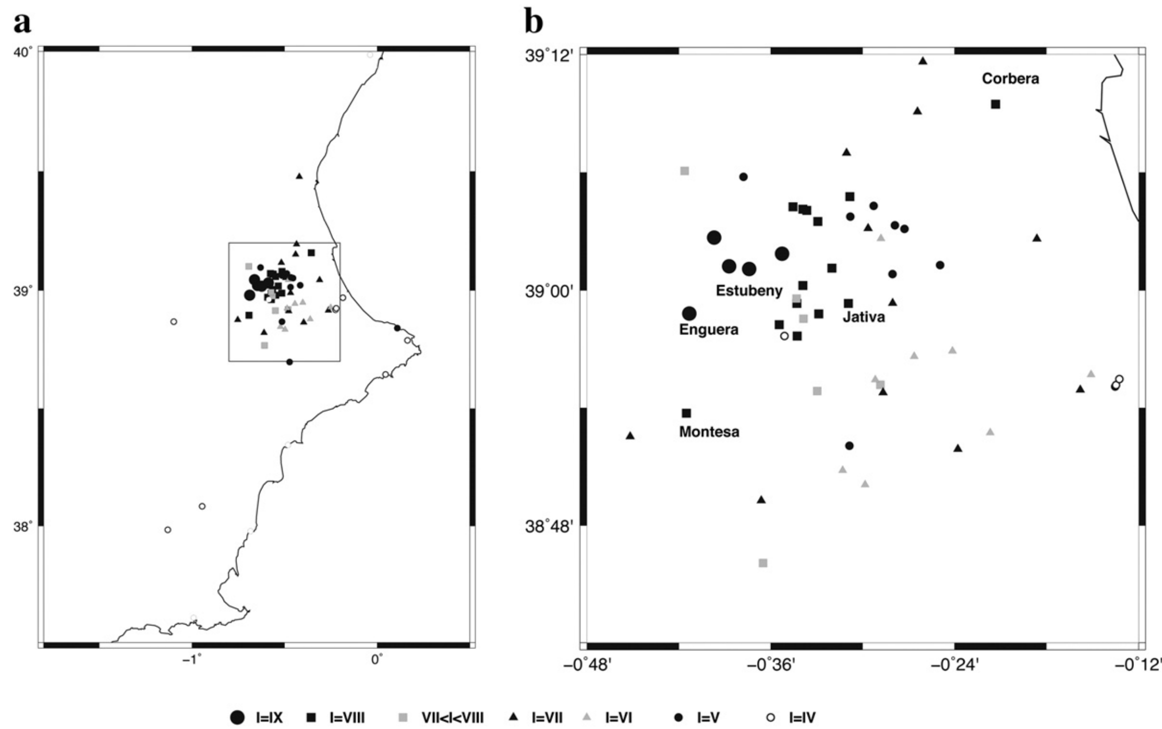

Fig. 10. (a) Intensity map of Montesa 1748 earthquake. (b) Intensity map of the area of the largest damage of the Montesa 1748 earthquake (square on a).

The earthquake was reported to have been felt without causing damage in Valencia, Alicante, Orihuela (Carrasco, 1748a); in Venisa, Xabea, Calpe, Denia, Gandía, Castellón (Relación de Estragos, 1748); and in Valencia, Orihuela, Murcia, Alicante, Xabea (Segunda Relación, 1748). These localities are at distances between 40 km and 115 km from the epicentral area.

5.5. Intensity map

The intensities estimated in this study are plotted in Fig. 10. The map is not very different from that of Martínez-Solares and Mezcua (2002). The main differences are the extension of the intensity IX area to Enguera and the location of the boundary between the areas of intensity VIII and VII (Fig. 10b). Relative to the map of Martínez-Solares and Mezcua (2002), the present map has also been extended to include the area where the shock was only felt (Fig. 10a). The intensity map is better defined towards the region east of the area of greatest damage (Estubeny–Enguera) up to the coast where the population density is greatest. There is very little information with which the intensity map can be constrained to the west due to the almost complete lack of villages. One observes in these maps that places with intensity VIII correspond to a region southeast of an Estubeny–Enguera line. The total area with intensities greater than VI corresponds approximately to a region of 43 km by 33 km. The shock was felt at distances of up to 150 km away (Fig. 10a). Corbera, located 30 km NE of Estubeny (Fig. 10b), was reported to have had major damage: "church and lord's house almost ruined, out of 23 houses 15 are totally ruined, all the rest uninhabitable" (intensity VIII) (Carrasco, 1748a, 1748b). This is an isolated case for that distance, and may have been due to local site effects. Fig. 11 shows the relationship between intensity and distance together with the attenuation laws obtained by Martin (1984) and López Casado et al. (2010) for eastern Spain. For this event, Martín's law (1984) fits the observations better.

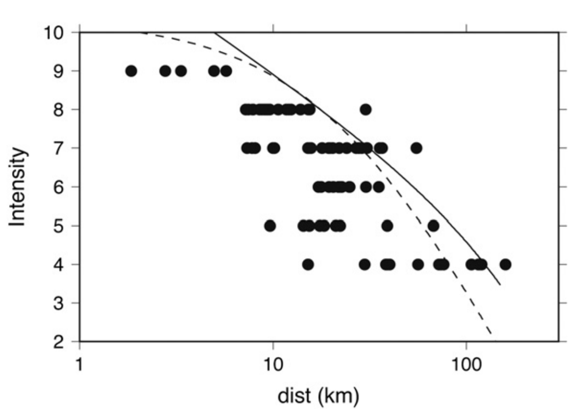

Fig. 11. Relation of attenuation with distance. Continuous line (Lopez Casado et al. 2010), dash-line (Martin, 1984).

Table 1 presents the comparison of the intensities assigned by Bisbal Cervello (1984) (hereafter BC), Martínez-Solares and Mezcua (2002) (hereafter MSM), and the present study for intensities greater than VI, ordered by distance from the area of greater damage. BC assigns Estubeny intensity X because of the observed ground rupture, but this is a secondary effect not contemplated in EMS-1998. MSM assigns Anna, Chella, and Enguera intensity VIII, but contemporary accounts describe the same damage for all five places (Anna, Estubeny, Sellent, Chella, and Enguera). The estimate of the damage in Montesa (castle and town) is better estimated, being VIII–IX considering the destruction of the castle due to its construction and location as explained above. We agree with MSM for localities with intensity VIII, although MSM assigns VII–VIII for some of them. The intensity IX assigned by BC to four locations (Cotes, Navarres, Alcantara, and Beneixida) is an overestimate. And the overestimate is even greater for BC's assignation of intensity IX to Olleria, Guadasquies, Mogente, and Onteniente when compared with MSM and the present study (VI and VII). BC also gives intensity VIII to places where MSM and the present study give VI or VII.

6. Source parameters

The date and time of the main shock are given by most of the contemporary accounts as 23 March 1748, at 06:30 h local time. It is said

Table 1
Estimated intensities for Montesa 1748 earthquake.

Town	B	MSM	This study
Anna	IX	VIII	IX
Estubeny	X	IX	IX
Chella	IX	VIII	IX
Enguera	–	VIII	IX
Sellent	IX	IX	IX
Montesa	IXIX	VIII–IX	
Llanera de R.	–	VIII	VII–VIII
Torella	–	VII–VIII	VIII
Alcudia de C.	IX	VII–VIII	VIII
Cerdá	–	VIII	VII
Canals	–	VII–VIII	VIII
Torre Cerda	–	VII–VIII	VIII
Ayelo de M.	VIII	–	VII
Ayacor	–	VIII	VIII
Granja de la C.	–	VII	VIII
Vallada	VIII	VII–VIII	VIII
Torrente de F.	–	VIII	VIII
Rotgla	–	VII–VIII	VIII
La Losa	–	–	VIII
Cotes	IX	VIII	VIII
Navarrés	IX	VII–VIII	VII–VIII
Anahuir	–	VII–VIII	VII–VIII
Alcantara de X.	IX	VII–VIII	VIII
Beneixida	IX	VII–VIII	VIII
Novele	VIII	–	VIII
Xátiva	VIII	VII–VIII	VIII
Manuel	–	VII	VII
Villanueva de C	–	VII	VIII
Genoves	VIII	–	VII
Olleria	IX	VII	VII–VIII?
Alberique	–	–	VII
Guadasquies	IX	VII	VI
Puebla del D.	–	–	VI–VII
Mogente	IX	VII	VII
Sempere	VIII	VII–VIII	VII–VIII
Benisuera	VIII	VII	VII
Benegida	–	–	VI
Onteniente	IX	VII	VII
Carcagente	VII	VI	VI–VII
Alcira	VII	VII	VII
Bocairente	VIII	VII	VII
Rafol de S	–	VII	VII
Corbera	–	VII–VIII	VIII
Rugat	VIII	–	VI
Simat de V.	VII	VI–VII	VII
Tabernes	VIII	–	VI–VII

B: Bisbal Cervelló (1984).
MSM: Martínez-Solares and Mezcua (2002).

to have been felt in Valencia at 06:45 h (6¾ h, Carrasco, 1748a, 1748b). A more precise time is given for Játiva — 06:33 h (Autos de Visuras, 1748). The duration in Valencia is given by Carrasco (1748a, 1748b) as 2 min. Other accounts give the duration as between one *Credo* and one-and-a-half *Credos* (the time taken to recite the Credo — a Christian recitation of faith known as the Apostles' Creed which is also used as a prayer and takes about 45–50 s to recite), i.e., somewhere between 1 min and one-and-a-half minutes. There is no mention of any foreshock. All accounts refer to aftershocks felt every day after the main shock. One specifies more than 80 felt in Játiva, but without giving the time interval (Segunda relación, 1748), especially one on the 28th of March at 03:00–04:00 h in the morning. The largest aftershock occurred on the 2nd of April at 21:00 h or 21:30 h followed by another on the 3rd of April at 03:00 h. The shock of the 2nd of April is said to have been as large as the main shock but with less duration (Carrasco, 1748a, 1748b), and to have contributed to the damage of the buildings already affected by the main shock (*acabó de derribar lo que aun quedaba en pie*, Lombart, 1748). Aftershocks are reported to have continued up to the 8th of April when another intense shock was felt between 21:00 h and 22:00 h (Relacion verdadera, 1748).

The source area can be defined by that of intensity IX extending from Sellent to Engera (Fig. 10), with a length of 10 km in the NE–SW direction. A macroseismic epicentre could be positioned at a point to the SW of Estubeny of coordinates 39.00°N, 0.64°W. This would imply a bilateral rupture in directions towards Sellent in the NE and Enguera in the SW. This differs a little from the epicentre given by Martinez-Solares and Mezcua (2002) at Estubeny (39°02′N, 0°38′W) using the method of Bakun and Wentworth (1997). Recently Mezcua et al. (2013), using the same method, obtained 38.91°N, 0.58°W, and a depth of 15 km. In our estimate of the epicentral location, we took into account not only the intensity distribution but also the topographic and geological features as will be described in the next section.

The magnitude has been estimated using a relationship between maximum intensity and magnitude (Martinez-Solares and Mezcua, 2002), giving a value of 6.2 using the method of Bakun and Wenthworth (1997) and 5.9 (Mezcua et al., 2013) by the same method. Our estimate takes the maximum intensity IX to correspond to magnitude of about 6 — uncertainties in historical earthquakes do not allow greater precision (Gurdeutsch, Kaiser and Jentzsch, 2002).

7. Acceleration distribution and source model

In order to check the focal parameters that had been obtained and a source model proposed for this earthquake, we determined an approximation to the peak ground horizontal accelerations (PGA) from the intensity values. Among the existing relations we use the correlation given by Murphy and O'Brien (1977) for southern Europe (although that relationship is for Modified Mercalli Intensities, it can be used for EMS-1998) (*PGA* in cm/s^2) (Fig. 12):

$$\log PGA = 0.24I + 0.57.$$

For the area of maximum intensity (I = IX), the acceleration is 5.37 m/s^2 or 0.55 *g*. For our purpose, there is not great difference for values obtained using other empirical relations (for example, using Faenza and Michelini (2010) based on Italy data, for I = IX gives PGA 6.87 m/s^2). This maximum acceleration value is similar to the values of between 4.36 m/s^2 and 10 m/s^2 observed in the L'Aquila earthquake (M = 6.3) for epicentral distances of less than 5 km (Çelebi et al., 2010). Accelerations greater than 3 m/s^2 are concentrated in a small area about 25 km long and 11 km wide (Fig. 12). The area to the west is poorly defined due to the lack of information (Fig. 10). Although we are comparing different types of values, the maximum acceleration obtained for Montesa derived from intensity of 0.55 *g* is a much greater value than the PGA of 0.16 *g* (for a 475 year return period) recently assigned to this area using PSHA methodology by Martínez Solares et al. (2013).

The Montesa earthquake reached its greatest intensity in the area of Sellent, Estubeny, Anna, Chella, and Enguera (Fig. 10b). According to the distribution of these localities, the epicentral area probably was situated in the about 13 km long NE–SW band from Sellent to Enguera. The possible localization of the fracture area located in this NE–SW band leads one to think that this band might really be connected with a fault zone affecting the basement. This would agree with the model based on the distribution of accelerations proposed for this earthquake. The topographic relief in the NE–SW direction (Sierra Tres Mojones–La Plana; Fig. 2b) shows a fault on its northern border that extends from Enguera to Estubeny and Sellent where this structure presents a termination. The main fault rupture in the earthquakes will then be that corresponding to this structure. From Estubeny in a NNW–SSE direction there is another system of faults which is coherent with the damage in Anna and Chella (Fig. 2b). A short segment of this fault could also have been activated during the earthquake.

We first modelled the earthquake using a point source approximation in order to assess its depth and moment release. We fixed the normal fault mechanism to have strike N60°W, dip 45° to the SW, and rake

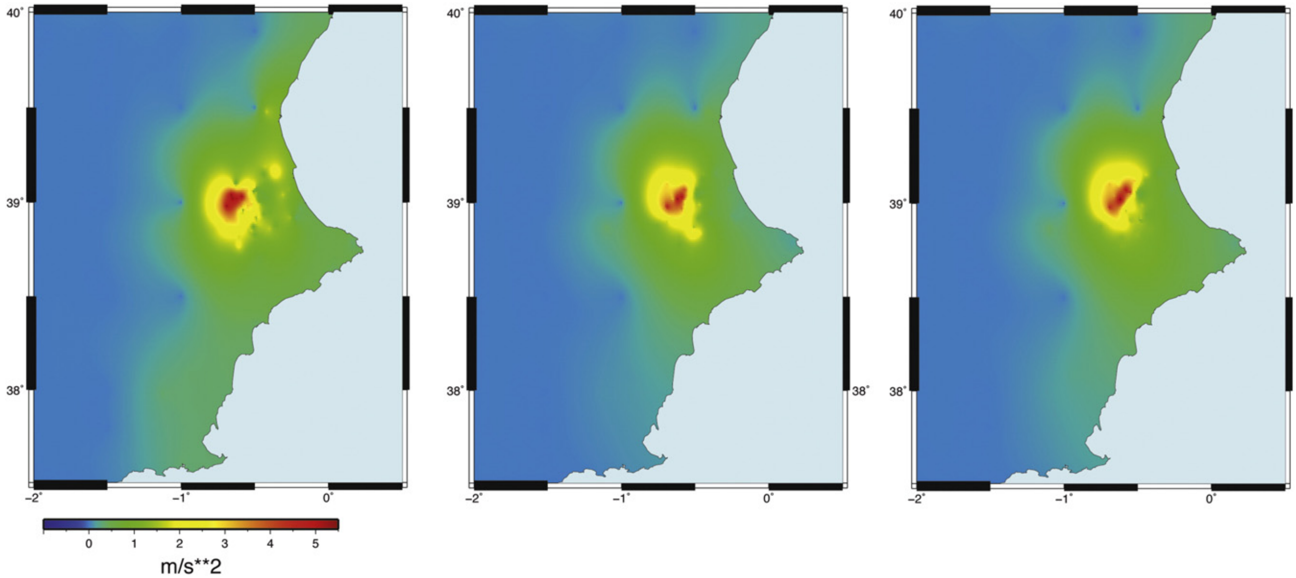

Fig. 12. Spatial distribution of maximal horizontal accelerations derived from intensities (left), synthetic accelerations for a point source model (centre) and from extended source model (right).

90°. Note that the fault and auxiliary planes of these focal mechanisms correspond to the two possible expected rupture scenarios, in which the strike and rake are constrained by the known fault structures and the dip is unknown, with candidate faults in the epicentral region dipping to both NE and SW. We considered source depths from 2 km to 12 km, computing synthetic acceleration seismograms using a crustal velocity model for Southern Spain (Cesca et al., 2006) and the Kiwi tools (Heimann, 2011) with band-pass filters of 0.02 Hz to 10 Hz, extracting the maximal horizontal acceleration.

Since the scalar moment only scales the seismograms and hence the acceleration amplitudes, the best scalar moment can be inferred by minimising the differences between the estimated and the modelled intensities. The resulting misfit (expressed as an L^2 norm) is used to determine the best solution. It is important to mention that our approach uses a one-dimensional (1D) model and cannot account for any site effects since it models the spatial pattern of maximal amplitude only as a consequence of the radiation pattern and source depth. The moment estimate is also affected by the rupture's duration, and hence involves major uncertainties. To model the high-frequency accelerations, which may better reproduce the values estimated from the intensities, we chose a very short duration of 0.5 s.

The best solution was the shallowest one (at 2 km). It predicts a moment magnitude of Mw 5.9 (Fig. 12). This value is most likely a lower bound since it would be greater with a longer duration of the source time function. In order to further improve the fit of the spatial acceleration distribution and to derive other source parameters, we extended the modelling to a finite source (Cesca et al., 2010; Heimann, 2011). We constrained the source model to a single patch of 8 km length and 4 km width, testing two possible dip angles of 45°, one towards the SE and the other towards the NW, and 8 propagation modes, including a bilateral rupture and unilateral and asymmetric unilateral ruptures propagating both laterally and upwards/downwards.

The selected rupture size is consistent with an earthquake of magnitude 6, with a corresponding maximum slip of about 0.5 m (Wells and Coppersmith, 1994). Since the scalar moment is poorly known, we again selected the preferred model by comparing the misfits between the estimated and the modelled accelerations for the best fitting scalar moment. We modelled the source of the earthquake as a bilateral fracture of 10 km length and 3 km width in a normal fault with strike N50°W dipping 45° to the SW (strike 60°, dip 45°, rake 90°). This is the roughly subsurface rupture length and width corresponding to an earthquake of magnitude 6, with a corresponding maximum slip of about 0.5 m (Wells and Coppersmith, 1994). The rupture nucleates slightly below the centre, and propagates laterally with a bilateral rupture propagating towards the NE and SW, and upwards. On the basis of this model, we calculated the expected peak ground accelerations, and compared them with those derived from the intensities (Fig. 12). There was a significant improvement in reproducing the spatial pattern by considering a finite source model. In particular, the finite model better explains the differences between the higher near-field accelerations observed NW of the epicentre and the lower values on the other side of the fault. In our model, this is attributable to the fault dip orientation, with the fault reaching the surface NW of the epicentre and deepening towards the SE. On the other hand, the lack of any strong asymmetry in the peak NE/SW accelerations rules out any concomitant strong lateral directivity effect.

8. Conclusions

The 1748 Montesa earthquake occurred in a region with low seismic activity, but where large earthquakes had indeed occurred in the past. From the contemporary documents, we have estimated a maximum intensity of IX in the region from Sellent to Enguera. We located the macroseismic epicentre at a point to the SW of Estubeny, of coordinates 39°N, 0.64°W, and an Mw magnitude of 6.0, although these values must be taken as an approximation since they were obtained using intensity data estimated from the available contemporary reports which may well be subject to uncertainties. The proposed rupture model obtained from the spatial distribution of accelerations derived from the estimated intensities corresponds to a bilateral fracture of 8 km length propagating towards Sellent in the NE and towards Enguera in the SW. This would be a normal fault striking N50°W with a fault plane dipping 45° to the SE.

Although these are different types of values to be compared, as already mentioned, the acceleration values (0.55 *g*) derived from the reported maximum intensities for this earthquake are greater than the characteristic acceleration of 0.07 *g* for a return period of 500 years of the Spanish Seismic Code (Norma de la Construcción Sismorresistente Española, NCSE-02, 2002) for this area and the PGA value (0.16 *g*) proposed for this region by the recent PSHA study of Martínez Solares et al. (2013). Such a major difference should be taken into consideration in the estimation of the seismic hazard for this region.

Acknowledgements

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