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Geological and Archaeological effects of the AD 1504 Carmona Earthquake (Guadalquivir valley, South Spain): preliminary data on probable seismic sources

Efectos Geológicos y Arqueológicos producidos por el Terremoto de Carmona de 1504 AD (Cuenca del Guadalquivir, Sur España): Datos preliminares sobre las posibles fuentes sísmicas

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Abstract:

Data reported by George Bonsor (1918) about damage in the City of Carmona (Sevilla, South Spain) triggered by the AD 1504 Earthquake (X MSK) constitutes the first archaeoseismological report published in the Spanish scientific literature. This work analyses and updates de Bonsor's data using the ESI-07 Intensity Scale. Most of the described damage at the ancient Arab Castle of Carmona can be attributed to large landslide events in the Late Neogene calcarenites of "Los Alcores Scarp". Large open cracks of hectometric length and metric width, landslides of c. 800,000 m^3 and rockfalls involving individual blocks of 10-500 m^3 indicate a minimum IX ESI-07 intensity at Carmona. Within the macroseismic area of about 1300 km^2, two areas within the Guadalquivir river floodplain around 180-200 km^2 are identified where liquefaction processes and lateral spreading were widely documented between Sevilla-Alcalá del Rio and Cantillana-Palma del Rio. Liquefaction processes occurred at maximum distances of c. 40 km from the macroseismic epicentre. Anomalous waves and permanent flooding of the riverbanks was also documented in the vicinity of Sevilla city. Severely damaged localities within the Guadalquivir river floodplain and related earthquake environmental effects can be attributed to site effects; in this zone, well documented far-field effects were caused by the AD 1755 Lisbon earthquake due to maximum intensities of VIII-IX MSK. The location of the macroseismic epicentre considered in the IGN Catalogue (3 km SE of Carmona) does not match with the documented damage orientation (nearly N-S), but suspect faults within the Guadalquivir valley North of Carmona can account for the documented damage. These structures include the controversial NE-SW Guadalquivir Fault and the prolongation of NW-SE Palaeozoic faults beneath the Neogene and Quaternary sedimentary fill between Tocina and Alcolea del Río, and should both be considered as potential seismic sources for the AD 1504 event.

Key words: Earthquake environmental effects; Archaeoseismology; Guadalquivir Basin; South Spain.

Resumen:

Los datos publicados por Bonsor (1918) sobre los efectos del terremoto de 1504 AD (X MSK) en Carmona (Sevilla, Sur de España) constituye el primer informe arqueosismológico que se publica en una revista científica española. El presente trabajo analiza y revisa los datos aportados por Bonsor a la luz de la escala macrosísmica ESI-07. La mayoría de los daños registrados en el antiguo Alcázar de Carmona pueden ser atribuidos a importantes fenómenos de deslizamientos de las calcarenitas neógenas del escarpe de Los Alcores. Grietas de longitud hectométrica y anchura métrica, deslizamientos de c. 800.000 m^3 y caídas de bloques individuales de dimensiones entre 10-500 m^3 indican intensidades mínimas de VIII-IX ESI-07 en la ciudad de Carmona. El area macrosísmica afectada por efectos ambientales cosísmicos puede evaluarse en unos 1300 km^2, dentro de la cual se identifican dos zonas dentro de la llanura aluvial del Guadalquivir de entre 180-200 km^2 en las que los procesos de liquefacción y subsidencia fueron ampliamente documentados en los sectores de Sevilla-Alcalá del Rio y Cantillana-Palma del Rio. Los procesos de licuefacción se documentaron a distancias epicentrales máximas de unos 40 km. Oleajes anómalos del río y procesos de inundación permanente también se documentan en las proximidades de Sevilla. Los importantes daños documentados en las poblaciones situadas en la llanura de inundación del Guadalquivir y efectos ambientales relacionados pueden ser atribuidos a un claro "efecto sitio" tal y como demuestra la ocurrencia de similares procesos en esta misma zona durante el terremoto de Lisboa de 1755 AD que se sintió con intensidades VIII-IX MSK. La localización del epicentro macrosísmico catalogado por el IGN (3 km SE Carmona) no coincide con las orientaciones de los daños (aprox. N-S) y distribución de los efectos ambientales (NNW de Carmona). Por el contrario algunos de los accidentes tectónicos situados al Norte de Carmona en el valle del Guadalquivir podrían explicarlos mejor. Estas estructuras incluyen la controvertida Falla del Guadalquivir (NE-SW) así como la prolongación bajo el relleno Neógeno-Cuaternario de los accidentes paleozoicos de dirección NW-SE en el entorno de Tocina y Alcoléa del Río.

Palabras Clave: Efectos ambientales de los terremotos; Arqueosismología; Cuenca del Guadalquivir; Sur de España.

1. Introduction

This paper documents the earthquake environmental (EEEs) and archaeological effects (EAEs) that occurred during the Carmona earthquake in AD 1504. Collected data are mainly based on the descriptions made by Bonsor (1918), Hernández Pacheco (1918) and the more recent review of Silva *et al* (2009). The Carmona earthquake is included in several published seismic catalogues (e.g. Hernández Pacheco, 1900; Sánchez Navarro-Newman, 1917; Galbis, 1932), with assigned maximum intensities of X MSK (Mezcua and Martínez Solares, 1983) and VIII-IX EMS (Martínez Solares and Mezcua, 2002; Mezcua *et al.*, 2013). Macroseismic information is available for eleven localities, but there is widely documented information on EEEs and EAEs, based on historic documentation (e.g. Zurita, 1610; Ortíz de Zuñiga, 1667; Bernáldez, 1875) cited by Bonsor (1918) and Galbis (1932). This contribution offers a review of the earthquake environmental effects and the archeoseismological record, using the ESI-07 Intensity Scale (Michetti *et al*., 2007) based on the documentary and field review of the main observations of Bonsor (1918). The review of the aforementioned historical reports and geographical descriptions in relation to available modern geological maps and aerial imagery allows most of the documented EEEs and EAEs in the zone affected by the AD 1504 earthquake around the Guadalquivir valley (Southern Spain) to be located and measurements made. This paper also offers an alternative location of the Macroseismic epicentre, different from those listed in the official catalogues, on the basis of field surveys of suspect faults located at the northern margin of the Guadalquivir Basin.

2. Geological Framework

The Guadalquivir Neogene Basin corresponds to the foreland basin of the Betic Cordillera (Fig. 1) and is filled by a thick sedimentary succession (c. 1.5 km) of Miocene to Pliocene marine deposits and olisthostromic units from the last c. 15.5 Ma (e.g. Sierro *et al.*, 1996; González-Delgado *et al.*, 2004). Neogene olisthostromic units are imbricated and overridden by the proximal tectonic wedges formed by Triassic to Paleogene materials along the Betic thrust-front (García-Castellanos *et al.*, 2002). Proximal tectonic loading along the Betic thrust-front and continuous sedimentation from the Betic Cordillera from 10.5 to 5.5 Ma caused lithospheric overloading triggering isostatic forebulging along the northern margin of the basin and the adjacent Palaeozoic materials of the Iberian massif (García-Castellanos *et al.*, 2002). Following these authors, post-Messinian accelerated isostatic uplift propagated to the North into the Iberian massif giving rise to flexural folding in the paleozoic

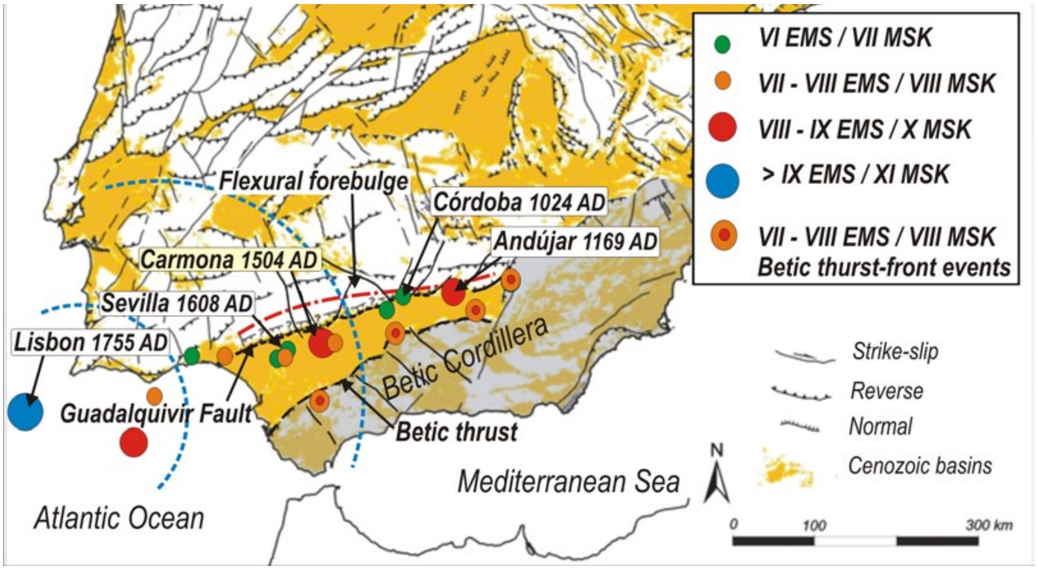


Figure 1. Historical seismicity in the Guadalquivir Basin and Gulf of Cádiz illustrating the more relevant tectonic (black) and isostatic (red) structures related to geology of the zone. Seismic data extracted from the IGN Seismic Catalogue (Mártinez Solares and Mezcua, 2002) and the IGN Seismic data-base (www.ign.es).

Figura 1. Sismicidad histórica en la Depresión del Guadalquivir y Golfo de Cádiz ilustrando las estructuras tectónicas (negro) e isostáticas (rojo) mas relevantes de la zona. Los datos sísmicos se han extraído del Catálogo Sísmico del IGN (Mártinez Solares y Mezcua, 2002) y de la base de datos sísmica on-line del IGN (www.ign.es).

materials and relief generation (i.e. Sierra Morena). Flexural folding along the northern margin of the Guadalquivir Depression might facilitate brittle deformation at upper crustal levels (< 30 km) resulting in NE-SW faulting (e.g. Guadalquivir Fault) and probably the slow differential reactivation of the old NW-SE oriented Palaeozoic faults during Pliocene and Quaternary times (Figs. 1 and 2). The surveyed zone covers the Guadalquivir valley between the localities of Sevilla and Lora del Rio, the adjacent Palaeozoic zone to the north, the Corbones valley to the east and the so-called Los Alcores scarp to the southeast (Fig. 2), and lastly a cuesta-type NE-SW linear structural relief carved in gently dipping Upper Miocene-Pliocene marly and calcarenitic sequences (Baena, 1993) which constitutes the mainland scarp in which the locality of Carmona is seated (Fig. 2).

3. Earthquake data and seismicity of the Guadalquivir valley

Maximum intensities documented for the AD 1504 Carmona earthquake are clearly related to highly vulnerable areas from a geological point of view (Silva *et al.*, 2009). These areas coincide with the floodplain of the Guadalquivir River and the Los Alcores scarp between the localities of Carmona and El Viso where most of the damage occurred (Fig. 2). MSK intensities were VIII to IX MSK within the Guadalquivir floodplain N and NW Carmona, and X MSK in Carmona city (Mezcua and Martínez Solares, 1983). More recent reviews based on the European macroseismic Scale (EMS-98), result in lower intensities of VII for the Guadalquivir valley and VIII-IX for Carmona city (Martínez Solares and Mezcua, 2002; Martínez Solares, 2003). However, since EMS intensity estimations do not consider environmental effects, in this paper we refer to the previously assigned MSK intensities.

The AD 1504 earthquake occurred on 5th April causing 32 deaths and the partial destruction of the medieval city walls along the southern and northern flanks of Carmona. Most of the churches and towers of the city suffered severe damage, and many roofs and walls of houses collapsed. The most relevant documented damage was the partial collapse of the ancient Arab Castle (Alcázar) built on the Los Alcores Scarp in the southeast of the city (Bonsor, 1918). The cities of Sevilla, Alcalá del Rio, Cantillana, Tocina, Lora del Río, Villanueva del Rio, and Palma del Rio, located between 23-45 km away from the macroseismic epicentre, suffered similar severe damage to churches, towers and city walls; furthermore, many village houses collapsed as documented in historical reports cited by Bonsor (1918), Sánchez Navarro-Neuman (1917) and Galbis (1932). However, there is also macroseismic information for other localities such as Cazalla, Puebla de Almadén and Los Palacios in which seismic shaking was felt with EMS intensities of V-VI, or earthquake environmental effects were produced (Mártinez Solares and Mezcua, 2002).

The earthquake was felt in most of the Iberian Peninsula and Northern Africa. At localities as far as Medina del Campo in Valladolid (c. 500 km away) and Murcia (c. 400 km away), the ground motion was widely felt (III-IV MSK) as documented in the History of the Catholic Kings (Bernáldez, 1875). The earthquake was strongly felt in several localities on the North African coast, and in the Spanish cities of Málaga and Granada over a radius of about 200 km (IV-V MSK); it was fairly destructive in El Algarve (SW Portugal) about 180-190 km away (Galbis, 1932), where a minimum intensity of VI MSK can be assumed (Silva *et al.*, 2009). The area of maximum damage within the Guadalquivir valley was around 1300 km^2 (Fig. 2), where localities as far as 43 km to the North (Palma del Rio) and 23 km to the south (Sevilla) underwent seismic shaking intensities of ≥ VII MSK. Due to this large area where the earthquake was felt, it can be assumed that the earthquake was an intermediate depth event (< 20 km) of moderate magnitude. Different empirical approaches assign this earthquake an estimated magnitude of 6.2 - 6.8 Mw (FAUST Project, 2008; Martínez Solares, 2003), locating the epicentre about 9 km SE of

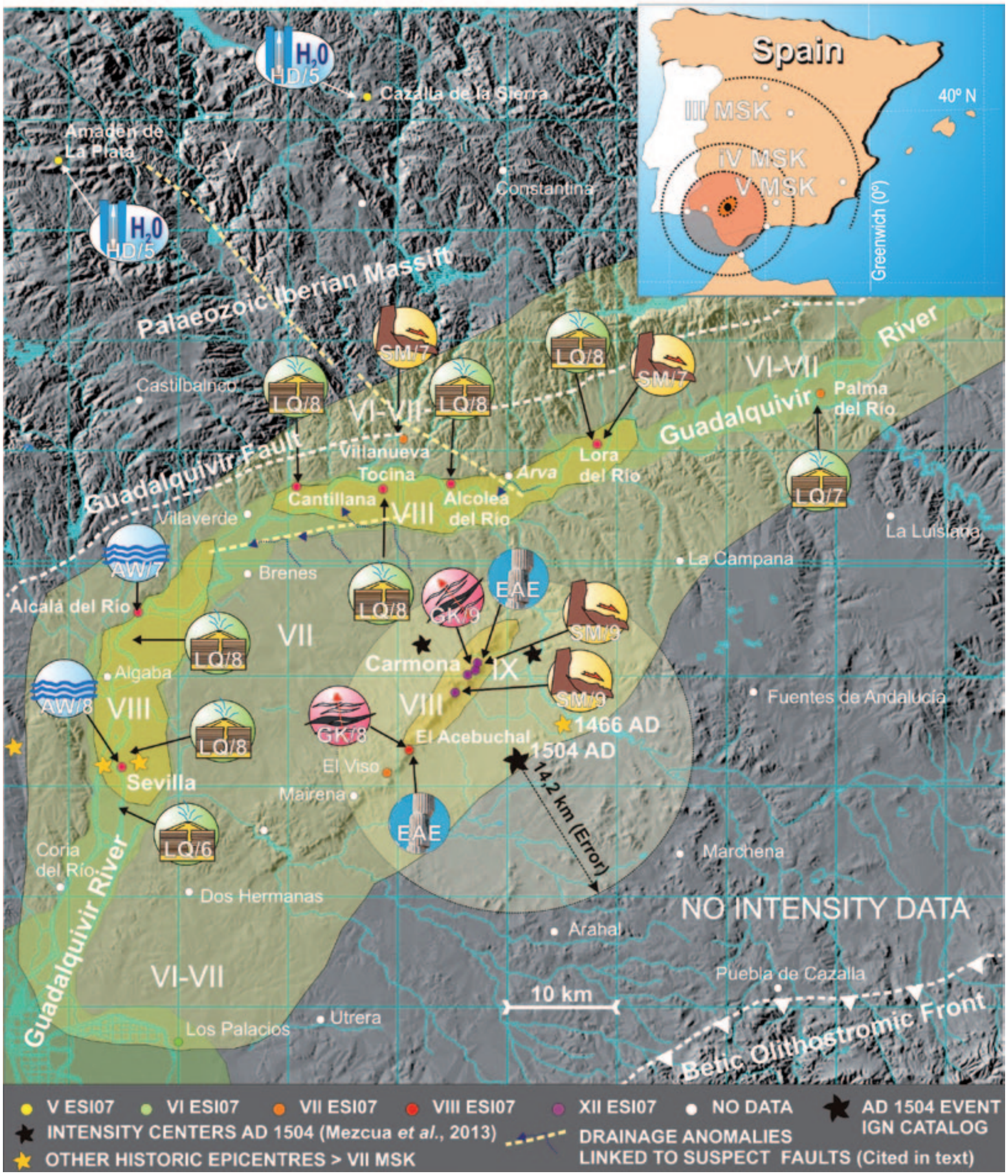


Figure 2. Isoseismal Map (ESI-MSK) of the AD 1504 Carmona Earthquake based on historical descriptions and earthquake environmental effects (EEE) illustrating different categories of secondary effects considered in the ESI-07 Scale: ground cracks (GK), slope movements (SM), liquefaction processes (LQ), anomalous waves (AW) and flooding in rivers and temporary turbidity changes in wells (HD), as well as sites with documented archaeoseismological damage (IGCP-567 Logo). Decimal notations in the documented EEE sites (e.g. GK/8) indicate the evaluated ESI-07 Intensity. Epicentral location parameters (IGN; red star) and error radius are from FAUST PROJECT: http://faustproject.com. The delineation of isoseismal lines SE of Carmona is tentative (no data available for this zone).

Figura 2. Mapa de isosistas (ESI-MSK) del terremoto de Carmona de 1504 AD basado en descripciones históricas y efectos ambientales de los terremotos (EEE) pertenecientes a la categoría de efectos secundarios considerados en la Escala ESI-07: Grietas del terreno (GK); Movimientos de ladera (SM), procesos de liquefacción (LQ), Oleaje anómalo en ríos (AW) y cambios temporales en la turbidez de pozos y Fuentes (HD), así como el conjunto de efectos arqueoseismológicos documentados (IGCP-567 Logo). Las notaciones decimals en los efectos documentasdos (e.g. GK/8) indican las intensidades estimadas. Los parametros de localización epicentral proceden de los datos del IGN y del Projecto FAUST: http://faustproject.com. El digujo de las isosistas al SE de Carmona es tentativo ya que no existen datos para esa zona.

Carmona City, with a radius of confidence (epicentral error) of 14.2 km, where no known Quaternary fault occur (Fig. 2). More recent approaches re-evaluate the epicentral location giving intensity centres (i.e. epicentral locations) in the vicinity of Carmona, 5 km away, within the Guadalquivir valley (Mezcua *et al.,* 2013). These last locations are more consistent with the geological data reported by Silva *et al.* (2009). Some relevant tectonic structures occur north and northwest of the city relating to the most damaged zones within the Guadalquivir valley (Fig. 2). The main one is the controversial Guadalquivir Fault, a suspect NE-SW fault zone separating the Palaeozoic metamorphic materials of the Iberian massif from the Neogene materials of the Guadalquivir Basin which runs along the northern border of the Guadalquivir river valley (Hernández-Pacheco, 1918; Goy *et al*., 1994), about 35 - 40 km North of Carmona (Figs. 1 and 2). However, the occurrence of buried faults in this northern zone must be taken into account, especially those corresponding to the prolongation of the NW-SE old Palaeozoic faults buried under the Neogene sedimentary cover of the Guadalquivir Depression, which is at least 1000 m thick in the vicinity of Carmona as documented in regional geophysical and Geological surveys (e.g. IGME, 1983; García-Castellanos *et al*., 2002; González-Delgado *et al*., 2004). The prolongation of the old NW-SE faults under the sediments of the basin is not only a better fit using the new epicentral location provided by Mezcua *et al.,* (2013), but also with the location of a recent earthquake on 30th October 2013 located in the Guadalquivir valley 4 km WSW of Carmona. Preliminary data reported by the IGN (2013) indicate that this was a small magnitude event (3.4 mb), at a depth of 15.6 km and felt with intensity II-III EMS in the area of interest for this study.

The AD 1504 Carmona Event occurred during a suspected seismic sequence which lasted almost 40 days, when a main aftershock (VI MSK / V EMS) occurred on 21st June AD 1504 and caused minor damage in the previously affected area Gentil Govantes, 1985; Martínez Solares and Mezcua, 2002). In AD 1466 a previous strong event (VIII MSK / VIII EMS) caused significant damage around the same area of the Guadalquivir valley (Fig. 2), but especially in the cities of Carmona and Sevilla (Galbis, 1932). This previous earthquake mainly affected the northern part of Carmona damaging the ancient Alcázar de la Reina (Puerta de Córdoba site), which was in ruins and was eventually demolished few years before (AD 1501) the event studied here (Galbis, 1932). The seismicity of the zone records about 30 historical seismic events for the period AD 900 – 1900 along the Guadalquivir Valley following the suspect Guadalquivir Fault (Martínez Solares and Mezcua, 2002). Other than Carmona (AD 1504; X MSK), only threemacroseismic areas record strong earthquakes (Fig. 1) around the localities of Córdoba (AD 1024; VII-VIII MSK), Andújar (AD 1169; X MSK) and Sevilla (AD 1608; VIII MSK). However, the area suffered relevant far-field effects (VII – VIII MSK) linked to strong earthquakes which occurred in the Gulf of Cadiz (> 500 km away; Atlantic Ocean), such as the well-known Lisbon earthquake in AD 1755 (Fig. 1). This far-field event affected the Guadalquivir valley south of the locality of Córdoba with intensities VII to VIII MSK causing severe damage and noticeable earthquake environmental effects in all the localities also affected by the AD 1504 event. EEEs were especially documented in Sevilla and Carmona (Galbis, 1932; Martínez Solares, 2001).

Besides these local and far-field seismic events, the Guadalquivir basin only has records of a few relatively strong earthquakes having occurred in the southern margin of the depression along the thrust-front of the Betic Cordillera (Fig. 1); documented earthquakes are the AD 1862 Villanueva de San Juan (Sevilla) and the AD 1930 Montilla (Córdoba) VIII MSK intensity events (Gentil Govantes, 1985). This Betic thrust-front, about 60-80 km away from the studied zone, records most of the current instrumental seismic activity of the Guadalquivir Basin, which is commonly scarce, shallow (10-20 km) and of small magnitude (< 4.0 mb). On the contrary, in the northern margin of the basin instrumental records are very rare and of smaller magnitude. Only the abovementioned recent earthquake (3.4 mb) of October 2013 is noticeable because it was located in the vicinity of Carmona.

4. Earthquake environmental effects (EEE) triggered by the AD 1504 Event

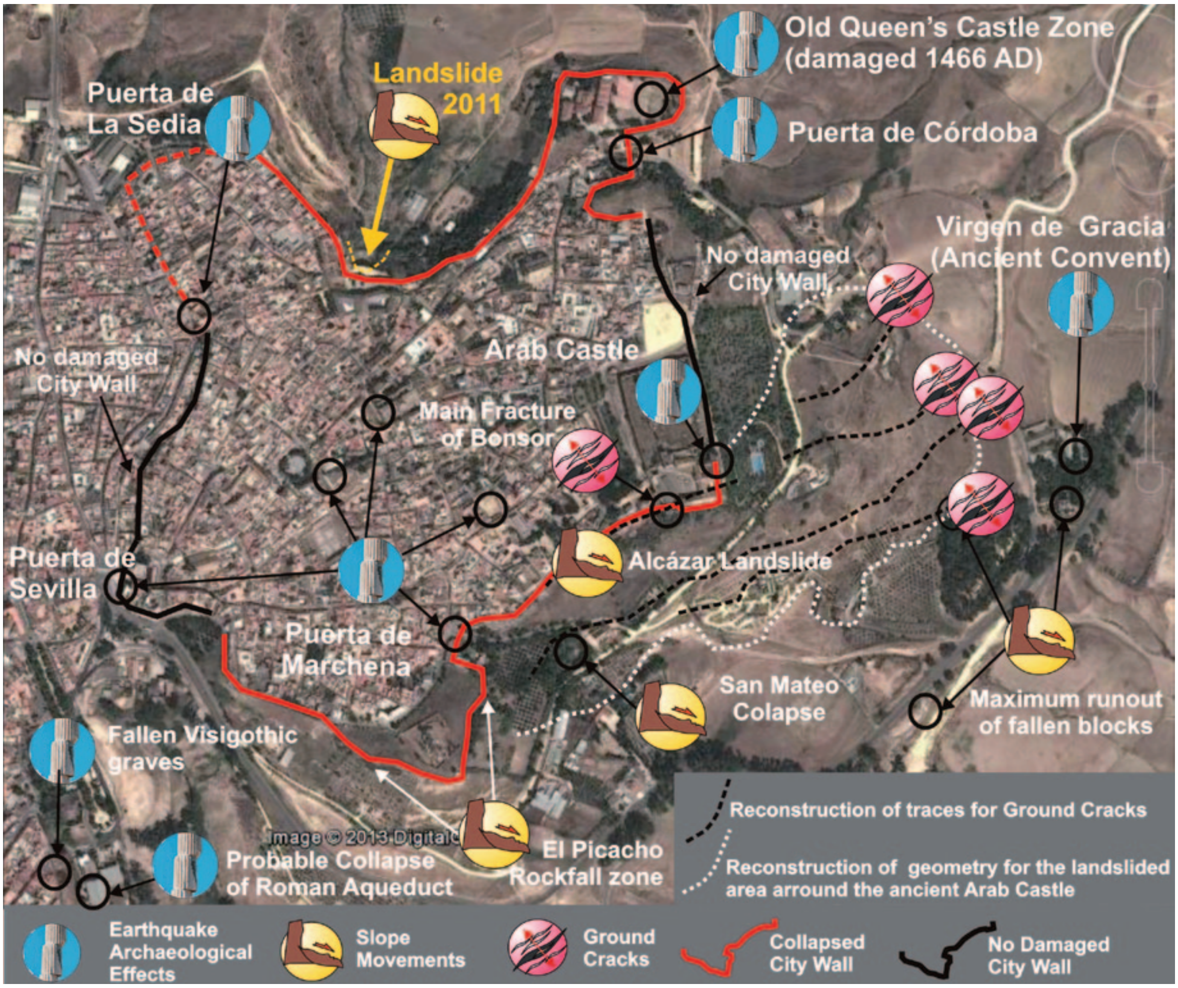
Coseismic ground effects produced by the AD 1504 earthquake can be classified as secondary environmental effects of the ESI-07 Scale (Michetti *et al*., 2007) including the categories of slope movements and large ground cracks (Los Alcores Scarp and Carmona City) about 3 to 10 km away from the macroseismic epicentre (Fig. 2). Liquefactions were widely reported within the Guadalquivir flood plain between Sevilla and Palma del Rio at a maximum distance of 45 km from the macroseismic epicentre (Fig. 2). Anomalous waves in the Guadalquivir River were only reported in Sevilla, 23 km away from the epicentre (Fig. 2). Within the category of hydrological anomalies, temporal variations in the turbidity of wells were reported at two distant localities (Amadén de la Plata y Cazalla), both in the palaeozoic basement on the NW margin of the Guadalquivir Depression, about 60 to 70 km away from the epicentral area (Fig. 2). There are no reports on the occurrence of surface faulting linked to the earthquake. The isoseismal map of figure 2 is not a conventional one due to the scarcity of the macroseismic data. This map only illustrates theoretical ESI-07/MSK intensity zones in the affected area in relation to the geomorphology (scarps), geology (Guadalquivir flood plain) and tectonic structures of the area where the main ground coseismic effects were recorded.

4.1. Slope movements and rockfalls

These ground failures are mainly related with Los Alcores Scarp where the Carmona City is founded. This escarpment is a NE-SW trending active geomorphological feature within the southern margin of the Guadalquivir river valley, subject to rockfalls and large landslides that have differential settlement of buildings (IGME; 1988; Baena, 1993; Da Casa *et al*., 2006; MOPU, 2011). The free face of the scarp develops in a 30 to 70 m thick calcarenitic unit, resting upon a thicker marly Messinian sequence which overlies plastic olisthostromic units coming from the Betic Cordillera front located to the SE. The Palaeozoic substratum is at around 1000 metres depth beneath the City of Carmona, whilst in the opposite margin of the Guadalquivir valley, about 30 km NW, the metamorphic Palaeozoic materials outcrop at the surface (Fig. 2).

Los Alcores Scarp ranges in altitude from 140 m in Carmona to about 40 m in Alcalá de Guadaira which is located 25 km southeast and is where the scarp progressively dies-out under the Pleistocene fluvial deposits of the Gudalquivir valley (Fig. 2). The scarp is a linear geomorphological feature stepped by orthogonal NW-SE and NNE-SSW faults affecting the Late Neogene calcarenites (IGME, 1988; Baena, 1993). This set of faults generates changes in scarp altitude of 5 to 10 m and is also linked to the location of the larger landslides documented along the scarp (IGME, 1988; MOPU, 2011). These faults can, therefore, can be considered gravitational faults. In detail, Los Alcores scarp has a high susceptibility to mass movements; the geotechnical report undertaken for the construction of the Sevilla-Córdoba motorway documents more than 20 large complex landslides in the vicinity of the Carmona (MOPU, 2011), including the one that affected the ancient Medieval Arab Castle (Alcázar) during the AD 1504 earthquake (Da Casa *et al*., 2006).

The largest landslide event that affected the Alcázar of Carmona is nicely documented by Bonsor (1918). The maximum vertical displacement of the slide was 1.8 m with associated maximum left lateral displacements of 1.4 m. The larger fracture affecting the Alcázar was about 500 m long, 6.6 m wide, seated to a depth of 8 m, where it is about 3.5 m wide (Fig. 3). The main fracture had an E-W orientation in the Arab Castle walls, but its downslope prolongation displayed a NE-SW orientation over a length of almost 1,200 m reaching the ancient Convent of Los Jeronimos (presently Santa María de Gracia Church). As a consequence this building partially collapsed during the earthquake causing the death of two people. The total mobilised material for this individual landslide, evaluated from field mapping, exceed 800,000 m^3 (Fig. 3) indicating a minimum ESI-2007 intensity of VIII. Additionally, large calcarenite blocks between 10 and 500 m^3 rolled downslope for a maximum distance of about 1-1.2 km (Figs. 3 and 4) traversing several metres past the present Carmona – Marchena road.



Fiigure 3. Aerial plan-view (Goggle Earth) of the Carmona city displaying the ground cracks documented by Bonsor (1918) affecting the ancient Arab Castle (Alcázar) walls and the Virgen de Gracia Church (Ancient Los Jerónimos Convent) in the context of the area that underwent landsliding. The sector of the ancient city walls (north and south) damaged by the earthquake are highlighted in red, as well as different documented archaeoseismological effects cited by Bonsor (1918) around Carmona. The recent building constructed on the ancient damaged ruins of the Castle is the Parador Nacional de Turismo of Carmona (1976).

Figura 3. Imagen aérea (Google Earth) de la ciudad de Carmona mostrando las grietas del terreno y deslizamientos que afectaron al antiguo Alcázar de Carmona y la Iglesia de la Virgen de Gracia (antiguo Convento de Los Jerónimos) documentados por Bonsor (1918). El sector de las antiguas murallas de la ciudad dañadas por el terremoto (norte y sur de la ciudad) se resalta en rojo, así como otros efectos arqueosismológicos citados por Bonsor (1918) en el entrono de Carmona. El edificiio modern construido sobre las ruinas del Castillo árabe es el Parador Nacional de Turismo de Carmona (1976).

Several similar large blocks rolled downslope along the southern segment of the scarp (e.g. El Picacho; Fig. 4) destroying the city's entire medieval wall over a distance of about 900 m (Bonsor, 1918). In the northern segment of the scarp, the zone of the ancient Quenn`s Castle, damaged by the AD 1466 event (VIII MSK), it is also possible to observe large fallen calcarenite blocks (> 10 m^3), but impossible to assign them to the AD 1504 event with confidence (Fig. 3). Taking into account the extension of the damaged segment of the mainland scarp of the city and the assumed size of landslides and rockfalls presently observed in the area (Fig. 3), the estimated total mobilized volume of materials by the AD 1504 event in Carmona will significantly surpass 10^6 m^3 over an area of about 11 km^2 indicating an ESI intensity of IX (Michetti *et al*., 2007).

1 km SE of the damaged Arab Castle of Carmona Bonsor (1918), several rockfalls are documented affecting the ancient Visigoth graves (Century 5th – 7th AD) carved in the calcarenites at the top of the cliff in the necropolis of Cuesta del Chorrillo (Fig. 3). Large blocks with inset Visigoth graves became detached from the cliff and rolled downslope. In this case, rockfall events are older than the 8th Century AD (Muslim Conquest of Iberia) but may reasonably be assigned to the AD 1504 event, since besides the AD 1466 VIII MSK event, there are no documented strong event in the Carmona zone during this time-period.

Similar fractures and scattered rockfalls where also documented along a 14 km zone between the localities of Carmona and Mairena del Alcor (Bonsor, 1918) along Los Alcores scarp; however, these mainly affected the 8 km separating the localities of Carmona and El Viso del Alcor, where the ancient Tartessic necropolis of "El Acebuchal (Century 8-6th BC) is located (Fig. 2). In this archaeological site, some of the individual fallen blocks exceed 300 m^3, as is the case of the Tartessic "Peña de los Sacrificios" (Gentil Govantes, 1985). For this case, it is also difficult to assign the observed rockfalls to the AD 1504 event, since the related ground failures might be caused by previous "non-documented" ancient earthquakes occurred after the 8th Century BC.

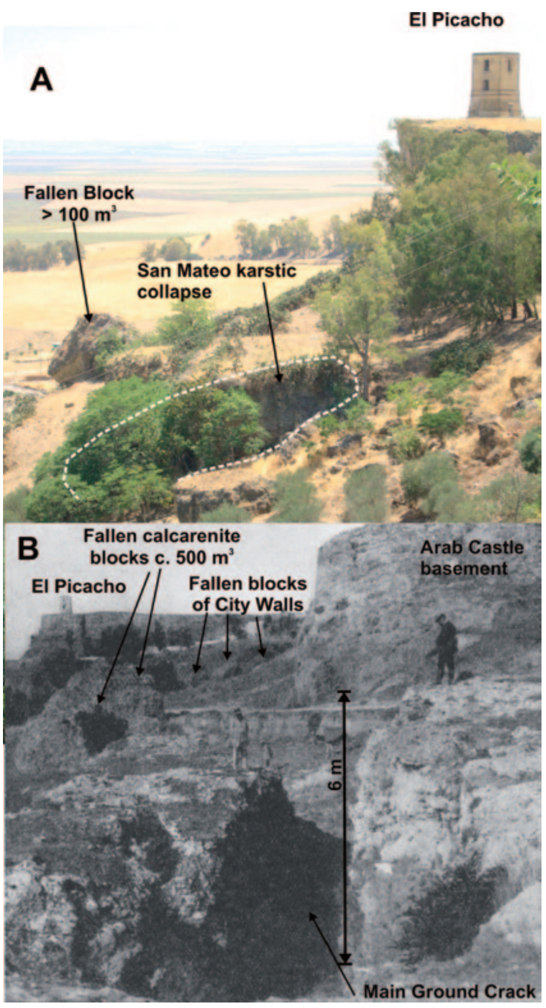


Figure 4. A: View from the ancient Arab Castle of the Picaho rockfall zone. Note the ancient fallen blocks of dimensions up to 100 m^3 and karstic vault collapses exceeding 50 m^2 (close to the San Mateo Church). B: Historical photograph of large blocks of the Landslide triggered by the AD 1504 Earthquake affecting to the ancient Arab Castle, view to the west (from Hernández-Pacheco, 1956).

Figura 4. A: Vista desde el antiguo Alcázar de la zona de desprendimientos de El Pichacho. Notesé las grandes dimensiones de los antiguos bloques caídos de algo más de 100 m3, así como el colapso kárstico de alrededor de 50 m2 en las cercanias de la Ermita de San Mateo. B: Fotografía histórica de los grandes bloques caidos durante el terremoto de 1504 AD que afectó al antiguo Alc´zar, vista hacia el Oeste (tomada de Hernández-Pacheco, 1956).

4.2. Fractures and ground cracks

Main fractures and cracks occurred in relation to the aforementioned landslide event affecting the ancient Arab Castle (Fig. 5A). The main open crack in the hard-rock calcarenitic substratum was about 700 m long and had a variable width from 2 to 6.6 m. The maximum width (6.6 m) was recorded downslope close to the ancient Convent of "Los Jerónimos" where the open crack reached a maximum depth of 8 m and an opening of 3.5 m (Bonsor, 1918). Upslope in the castle walls the open crack was only 2 m wide and 3-4 m deep (Fig. 5A). Two more large cracks where documented by Bonsor (1918) 200 m south of the main one, but in this case with a variable opening between 2 and 0.85 m, hectometric length and non determined depth (artificially filled). All these fractures had a broad orientation of E-W at the cliff, but turned to a NE-SW orientation downslope (Fig. 3). Similar ground cracks occurred at a distance of 8 km SW of Carmona at the ancient Necropolis of "El Acebuchal". Bonsor (1918) documented an open fracture of at least 500 m length affecting both, a post-neolithic settlement and ancient tartessic graves (8-6th Century BC) carved in the calcarenites (Fig. 2). At the zone of the tartessic graves the open crack had a length of about 200 m, an opening of 0.5-1.5 m and a depth of 3-4 m, with a broad NW-SE orientation (Gentil Govantes, 1985). However, as in the case of the rockfall documented in this zone, is difficult to attribute these ground failures to the AD 1504 event.

Features and dimensions of the aforementioned open cracks in competent rocks point to a minimum IX ESI-07 intensity (Michetti *et al.,* 2007) over Los Alcores escarpment. The application of the ESI-2007 intensity scale must, however, be carefully observed as most of the documented ground cracks are linked to landslide or rockfall processes . This is not the case for the set of ground cracks documented at the ancient roman necropolis of Carmona (2nd Century AD) in a flat terrain about 1.8 km east of the damaged Arab Castle (Bonsor, 1918). These cracks affected large cave-graves carved in the calcarenites. They had centimetric widths affecting both the floors and the roofs of the graves, and in some cases the roof was partially collapsed as was the case of "La Cantera Grave". These cracks were also oriented NE-SW and propagated outside of the Roman necropolis reaching hectometric lengths in the surrounding flat terrains (Bonsor, 1918). These cracks are not related to mass movements and their dimensions point to a minimum VIII ESI-07 intensity (Michetti *et al.,* 2007).

4.3. Liquefaction and lateral spreading processes

Localized liquefaction about 25 to 43 km away from the epicentre was reported in the Guadlaquivir floodplain affecting the localities of Sevilla, Alcalá del Rio, Cantillana, and Tocina y Palma del Rio covering an area of about 450 km^2. Historical descriptions cited by Bonsor (1918) indicate the opening of ground fissures and big craterlets in the soft-sedimentary filling of the floodplain accompanied by ejection of muddy water. Historical descriptions indicate that water ejection ceased immediately after the ground shaking, and fissures and craterlets were sealed. Linked to these environmental effects, historical descriptions indicate the occurrence of land subsidence along the former river banks of the Guadalquivir around the localities of Sevilla and Alcalá del Río, where some areas became permanently inundated. These phenomena can be reasonably attributed to the occurrence of lateral spreading along some sectors of the river banks which accompanied liquefaction processes.

The precise location of these effects is today impossible to envisage due to the short-term preservation of these kinds of earthquake environmental effects in the geomorphological record. However, through the inspection of aerial imagery and ongoing field research, several areas where lateral spreading is still today an active process along the Guadalquivir River can be identified. Figure 2 shows the location of these areas: (a) 1 km downstream from Sevilla, between this city and the locality of Coria del Rio over a length of 2 km (35 km away from the macroseismic epicentre); (b) the external side of the "La Rinconada Meander" over a distance of 800 m close to Alcala del Rio (32 km away); (c) the external banks of the abandoned Meander of Cantillana over a length of 1.8 km (30 km away); and (d) the zone of the ancient medieval castle of Lora del Rio adjacent to the old river path (28 km away). All the collected data indicate a minimum VIII ESI-07 intensity for the Guadalquivir floodplain, with two main zones, each with around 180-200 km^2, where liquefaction and lateral spreading widely occurred at Sevilla-Alcalá and Cantillana-Palma del Río (Fig. 2).

4.4. Anomalous waves and overflow of river courses

This secondary effect is only reported for the cities of Alcalá del Río and Sevilla with Sevilla being mainly affected (Fig. 2). Significant anomalous waves were observed surpassing the metre scale. The water level was elevated by around three-four times its normal level causing shoaling and destruction of boats, fish mortality and overflow in Sevilla (Bonsor, 1918). Data from Sevilla allow us to evaluate the river overflow to be a minimum of 4 m high causing the partial inundation of the ancient harbour around Torre del Loro. Here, the base would have been inundated since it is presently standing about at 2.5 m above the normal water-level. These data indicate intensities of VIII ESI around Sevilla, as at this intensity violently overflowing water from small basins or watercourses occurs (Michetti *et al.,* 2007).

4.5. Hydrological anomalies in springs and wells

The increase in turbidity of water in springs is only clearly cited for the localities of Almadén de la Plata and Cazalla de la Sierra located 67 and 60 km away from the macroseismic epicentre on the Palaeozoic basement at the northern margin of the Guadalquivir Basin (Fig. 2). However, historical descriptions indicate that this phenomenon also affected many wells and springs of all the destroyed cities around the Guadalquivir Valley (e.g. Bonsor, 1918). These descriptions indicate that minimum intensities of about V-IV ESI-07 affected all the localities in a radius of c. 60-70 km from the epicentre. Since IV-V MSK intensities also affected an area of about 200 km minimum radii (see Section 2), it is logical to assume that these localities experienced ground shaking of V ESI intensity (Fig. 2).

4.6. Other Environmental effects: Cave collapses

Among the set of effects not considered in the ESI-07 scale (Michetti *et al*., 2007) are cave-vault collapses. Natural and man-made large caves carved at the toe of the free-face of the calcarenitic scarp of Los Alcores collapsed during the event causing relevant ground failures (Bonsor, 1918). Analysis of the scarp, in some cases, revealed sinkhole-type collapses presently preserved between the zone of the Ancient Arab Castle and el Picacho (Fig.4A). These collapses have decametric dimensions and multiple blocks are still preserved in the floor of the ancient sinkholes and surroundings. This type of effect and dimensions match with a minimum VIII ESI-07 intensity; however this type of phenomena (cave collapse) commonly occurs in the zone during or immediately after intense rainfall events (Völlmert *et al*., in press).

5. Earthquake Archaeoseismological Effects

Archaeoseismological damage documented in Carmona site is mainly restricted to the damage of the ancient Arab Castle carefully mapped by Bonsor in 1918 (Figs. 3 and 5). As described in previous sections, archaeoseismological damage is mainly related to secondary coseismic effects such as landsliding, rockfalls and fractures. The rest of the damage within the city, which mainly affected convents, churches and related towers, is presently impossible to document at the reported buildings. Some of the preserved archaeoseismological evidence (e.g. tilted towers; dropped keystones in arches, etc.) belong to the far field effects of the well-known AD 1755 Lisbon Earthquake. Most of the church towers were severely damaged during the AD 1755 event, felt with intensity VIII MSK/VII EMS in Carmona and IX MSK / VIII EMS (Martínez Solares, 2001) within the Guadalquivir Valley affecting the same localities than in the AD 1504 event. In Carmona most of the Church-towers were severely affected, some of them collapsed and most of them were demolished or rebuilt. Damage orientation in the Arab Castle is a consequence of the southwards directed complex landslide with a maximum throw of 1.8 m (Bonsor, 1918). The gravitational fault documented by Bonsor (1918) is still active and affects to the present "Parador de Turismo de Carmona" built in 1976 in the zone of the Castle damaged by the AD 1504 event (Da Casa *et al*., 2006). This gravitational fault penetrates to a depth of about 50 m in the plastic marly substratum beneath the calcarenites, displaying a maximum accumulated throw of about 6 m (Da Casa *et al*., 206; 2012). Data from these authors indicate that the E-W slide of the Arab Castle underwent previous movements with pre- AD 1504 accumulated throws of c. 4 m. Post-AD 1504 movements have been also documented in relation to heavy rain episodes during the years 1979, 1987 and 1997 (Da Casa *et al*., 2006). After the heavy rains of 1997 the ancient landslide experienced a downslope movement of 2.4 cm in three months and the new building of the Parador de Turismo was subject to reinforcement works for its stabilisation (Da Casa *et al*., 2012).

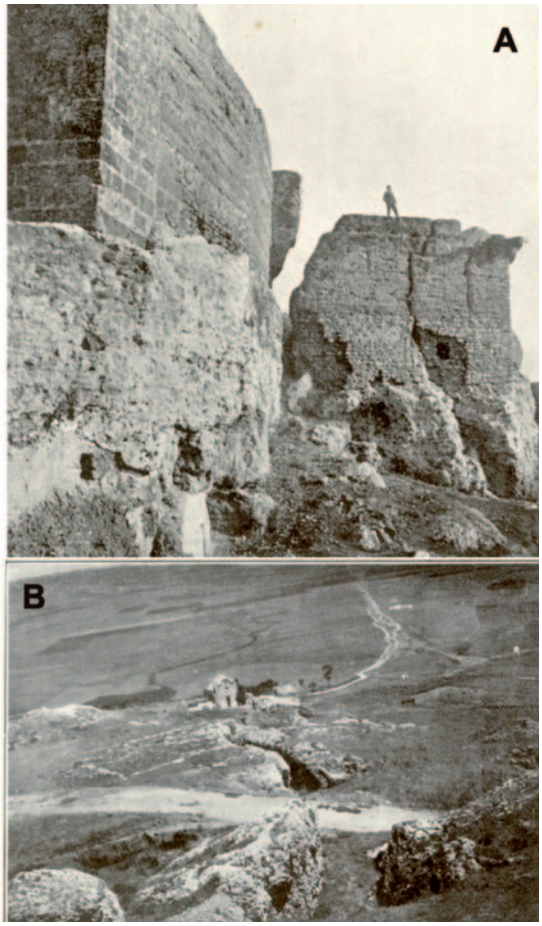


Figure 5. A: historical photograph (P. Castro Barea) of the effects documented by Bonsor, previous to the construction of the present "Parador Nacional de Turismo" (from Bonsor, 1918).B: Historical photograph (P. Bosch Gimpera) of the main ground crack documented by Bonsor running downslope from the Castle to the ancient Convent of Santa María de Gracia over more than 300 m, view to the East (from Bonsor, 1918).

Figura 5. A: Fotografía histórica (P.Castro Barea) the los efectos documentados por Bonsor en el antiguo Alcázar de Carmona previo a la construcción del actual "Parador nacional de Turismo (tomada de Bonsor, 1918). B: Fotografía histórica (P.Bosch Guimpera) de la fractura principal que afectó al Alcázar, en su prolongación SE lader aabajo hasta el antiguo Convento de Santa María de Gracia a lo largo the más de 300 m, vista hacia el Este (tomada de Bonsor, 1918).

Regarding the other documented archaeoseismological effects triggered by the AD 1504 event, it can be said that most of the perimeter of the city wall south (c. 850 m) and north (c. 900 m) of the Arab Castle, was destroyed by the earthquake (Bonsor 1918; Galbis, 1932). In spite of the damage documented in the Castle by the southwards directed landslide, the entire eastern portion of the city wall between the castle and the

Cordoba Gate (c. 350 m) suffered minor damage and still are partially standing in an overall N-S orientation. Also the N-S orientated western segment of the wall is partially preserved today. Three of the five ancient gates of the city wall, La Sedia (NW), Morón (E) and Marchena (SE) gates were totally destroyed (Bonsor, 1918). The Córdoba Gate (NE) and its fortification (Queen`s Castle), damaged during the VIII MSK AD 1466 earthquake, suffered severe damage and was only reconstructed after the AD 1755 Lisbon Earthquake. The only city-gate which suffered only moderate damage was the Sevilla Gate (SW), where one of the three ancient roman arches, oriented N10E, collapsed (Bonsor, 1918). The locations of all these archaeoseismological effects are showed in figure 3. According to the guidelines offered by Giner *et al*. (2012) on oriented archaeoseismological damage, the reported overall damage orientation in the Carmona city walls (North and South segments destroyed) and gates (Fig. 3) indicates a predominant N-S directed ground motion, which is inconsistent with the locations of the macroseismic epicentre provided by Mártinez Solares and Mezcua (2002) and Mezcua *et al*. (2013) illustrated in figure 2.

Additionally, the documentation of Bonsor (1918) and Galbis (1932) indicate probable archaeoseismological damage caused by pre-AD 1504 ancient earthquakes affecting the ancient remains of Tartesian, Phoenician, Roman and Visigothic age around Carmona between the Centuries 8th BC and 8th AD. Archaeoseismological analyses in these historic remains is necessary to assess (or identify) the occurrence of proto-historic seismic events. As previously mentioned, the only documented historic earthquake in the zone before AD 1504 is the AD 1466 Carmona event (Galbis, 1932) of intensity VIII EMS (Martínez Solares and Mezcua, 2002). Galbis (1932) described severe damage in Carmona around the ancient Queen's Castle (northern zone of Carmona), eventually demolished in AD 1501 before the studied event and in the so-called "Caños de Carmona" a large roman aqueduct in the Sevilla City.

6. Conclusions

A preliminary macroseismic analysis of the AD 1504 earthquake through the study of palaeoseismological and archaeoseismological damage around Carmona, first documented by Bonsor (1918), has been undertaken. All the documented effects can be catalogued as secondary earthquake environmental effects on the ESI-07 Scale. Minimum VIII ESI-07 intensities can be preliminary assessed for Carmona City using documented dimensions of individual landslide events (800.000 m^3), fallen blocks (10-500 m^3) and metre scale wide ground cracks of hectometric length affecting the eastern slopes of Carmona city. VII-VIII ESI-07 intensity can be proposed for the floodplain zone of the Guadalquivir River affected by this event based on a variety of documented coseismic liquefaction features and lateral spreading processes affecting large areas over 180-200 km^2. Far field effects of the AD 1755 Lisbon Earthquake in this zone of the valley (VII EMS; Martínez Solares, 2001) clearly illustrate the high seismic vulnerability of the area indicating the unfavourable geological site conditions causing high amplification that was recorded in the intensity distribution of the macroseismic zone of the AD 1504 event. In detail, the locality of Brenes, near Tocina (Fig. 2), was totally destroyed by the AD 1755 Lisbon Earthquake, reaching local intensities of IX EMS (Martinez Solares, 2001) as a consequence of site effect.

High susceptibility to landslides (MOPU, 2011) and unfavourable geotechnical parameters (Völlmert *et al*., in press) of the weathered calcarenites of Los Alcores scarp, helped induce the widespread occurrence of slope movements during the AD 1504 Earthquake. In fact, multiple landslide events commonly occur around Carmona as documented during recent intense regional precipitation events in the years 1979, 1989, 1997 and 2010. During the 2010 rain episode (max. 66 mm/hr) a large landslide of c. 120.000 m^3 occurred affected the parking area of one of the main hotels of Carmona (Alcazar de La Reina) founded on the calcarenite scarp north of the Ancient Arab Castle (Völlmert *et al*., in press). During the 1979 and 1997 rains, the ancient landslide scar produced during the AD 1504 event was reactivated, causing structural damage on the modern Parador Nacional de Turismo founded in the same site (Da Casa *et al*., 2006; 2012). Data from these authors reveal that the maximum accumulated throw on the main gravity fault is of c. 6 m. Therefore, since the documented vertical throw for the AD 1504 event is of 1.8 m (Bonsor, 1918), the landslide was previously activated with a pre- AD 1504 throw of c. 4.2 m suggesting the occurrence of large similar ancient events previous to the reinforcement of the ancient Arab Castle in AD 1350-1360. Considering landslide susceptibility in the Carmona area, ground water saturation during (or soon after) intense rainfall events offers the most hazardous picture (Völlmert *et al*., in press). In fact, historical records for the Guadlaquivir valley (Font Tullot, 1988) indicate that in the study area in AD 1504, there were particularly heavy rains throughout winter-spring time. On 6th January AD 1504, three months before the intervening earthquake, the Guadalquivir valley was subject to flooding in Sevilla and also other nearby upstream localities also affected by the earthquake. Therefore, expected nearly-water saturated conditions favoured the occurrence of landslide events and liquefaction processes during the earthquake.

The conjugate analysis of paleoseismological and archaeoseismological field data reported here indicate a main N-S component in ground shaking facilitating the destruction of the northern and southern segments of the old city walls and favouring southwards directed large landslides. Damage distribution and orientations are not consistent with the location of the macroseismic epicentre provided in macroseismic catalogues (Martínez solares and Mezcua, 2002; Mezcua *et al*., 2013). The spatial distribution of archaeoseismic damage and earthquake environmental effects is mainly restricted to the W and NW geographical quadrants of Carmona within the Guadalquivir valley (Fig. 6). There is no documented damage in the localities located South and SE Carmona, where the earthquake's supposed epicentre is located (Fig. 6). Additionally, as illustrated in figure 6, no known Quaternary faults are located in this zone. However, N and NW Carmona, where most of the documented environmental damage occurred, there are some faults, that can be considered probable seismic-sources.

The Guadalquivir Fault and significant old NW-SE Palaeozoic faults are located in the NW quadrant of the city less than 20 km away. The main Palaeozoic fault crosses the Guadalquivir watercourse a few kilometres upstream of Alcolea del Rio, exposing the contact between the Palaeozoic metamorphic materials and the Holocene sedimentary fill within the present river bed, and gives place to the occurrence of white-waters and rapids of submetric scale (Fig. 2). This is a relevant anomaly since several hundred metres upstream of the rapids the ancient roman fluvial harbour of "Arva" (Bonsor, 1902; 1932; Clark-Maxwell, 1896) is located. Following these authors, the Guadalquivir was navigable for 20-25 km upstream form this point and consequently the rapids generated on the Palaeozoic fault would not have been present in roman times (2nd – 3rd Century AD). The analysis of this river anomaly and others related to relevant deflections and apparent offsets of the drainage between the localities of Cantillana and Tocina (Figs. 2 and 6) will help to indentify suspect seismogenic faults and ancient earthquakes in this zone of the Guadalquivir Basin. Additionally, a wide variety of archaeoseismological information is available for this sector of the Guadalquivir valley, ranging from the 8th Century BC to the 7th Century AD. The further detailed field-analysis of the preliminary data-set presented in this paper will help to understand the seismic cycles and recurrence intervals of this zone of the Guadalquivir valley placed in a relevant crustal boundary between the Iberian Palaeozoic massif (NW) and the foreland basin of the Betic Cordillera (SE) subject to relevant isostatic processes of forebulging.

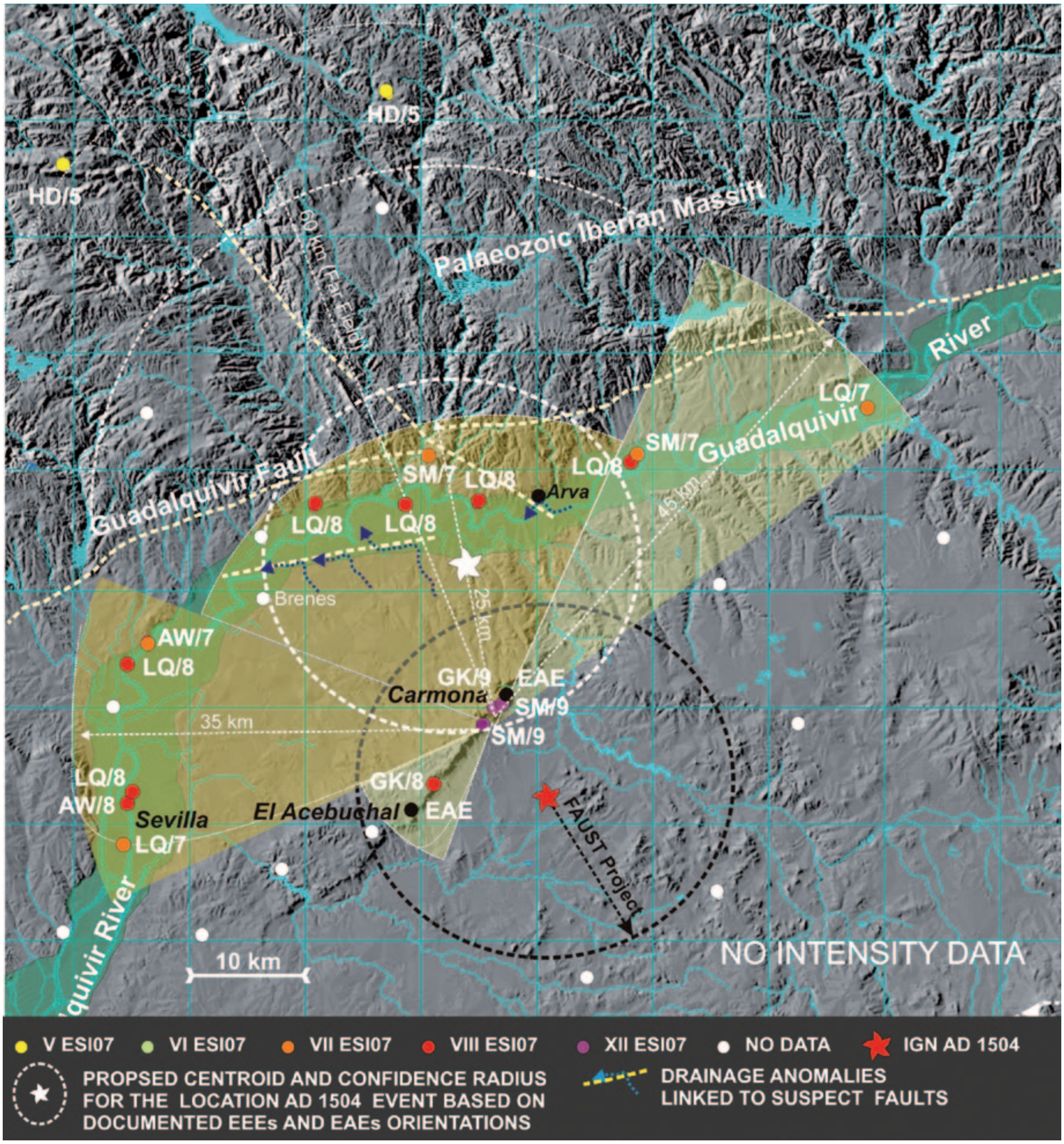


Figure 6. Orientation of documented EEE during the AD 1504 Earthquake in relation to the Carmona city displaying distances and maximum damage W, NW and N of the city. The geographical location of the macroseismic epicentre is tentative. It is based on the geographical distribution of damage, EEEs and dominant archaeoseismological damage orientations in Carmona. The proposed zone coincides with the occurrence of suspect faults identified by field survey on the basis of drainage anomalies. Symbols for EEEs and EAEs are the same than in figure 2.

Figura 6. Orientaciones respecto a la ciudad de Carmona de los EEE documentados durante el terremoto de 1504 AD indicando las distancias y daños más relevantes al Oeste, Noroeste y Norte de la ciudad. La localización del epicentro macrosísmico propuesto es tentativa. Se basa en la distribución geográfica de los daños, EEEs, y orientaciones preferentes de efectos arqueosismológicos (EAEs) en la ciudad de Carmona. Su localización coincide con la zona de fallas identificadas en el campo en base a anomalías del drenaje. Los símbolos y acrónimos de EEEs y EAEs son los mismos que en la figura 2.

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