PALEOGEOGRAPHY AND PALEOSEISMICITY: THE AD 1048 ORIHUELA EARTHQUAKE CASE STUDY (LOWER SEGURA DEPRESSION, SE SPAIN)

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Resumen (Paleogeografía y Paleosismicidad: El caso de estudio del Terremoto de Orihuela de1048 AD. Depresión del Bajo Segura, SE España): *El presente trabajo aborda el análisis paleogeográfico de la Depresión del Bajo Segura donde se ubicaba la antigua bahía Ibero-Romana del Sinus ilicitanus. Se confrontan datos de reconstrucciones paleogeográficas, documentos históricos con el análisis geomorfológico del sistema de acequias, azudes y canales de la zona y su desarrollo en diferentes periodos. Se concluye que durante la época musulmana la zona afectada por el terremoto en las inmediaciones de Orihuela era un sistema deltáico palmeado progradando sobre una zona pantanosa. Los efectos ambientales del terremoto de 1048 AD se relacionan con fracturación del terreno y procesos de licuefacción, así como un relevante cambio del curso del río Segura y abandono del sistema deltaico. Se discuten otras implicaciones respecto a la sismicidad y riesgo sísmico de la zona.*

Palabras clave: *Paleosismología, Paleogeografía, Terremotos antiguos, zonas litorales, SE España*
Key words*: Paleoseismology, Paleogeography, Ancient earthquakes, littoral zones, SE Spain*

INTRODUCTION.

The AD 1048 Orihuela earthquake represents an example of the role of palaeogeographic evolution of estuarine environments in the understanding of poorly documented historic earthquakes. This earthquake is only documented by the historical description of the Arab geographer *al-Urdi* (Espinar Moreno, 1994) in reference to the ancient *"Muslim kingdom of Tudmir"* (Alicante and Murcia Regions).

The original description by *al-Udri* (11^{th} Century AD) of the earthquake is as follows: *"There was a series of earthquakes followed one another in the fertile plains of Tudmir, in the cities of Orihuela, Murcia and in the area between them (Segura Valley). That occurred after the year 440 of the Hijra (AD 1048). Tremors repeated continuously during a year, occurring several times every day and every night. Houses were destroyed, minarets and all high buildings collapsed. In Orihuela the main Mosque (Aljama) and its minaret were completely destroyed. The ground cracked over the entire agricultural area (nahiya) of the valley (hawma). Many wells and springs dried up and fetid water ejections occurred".*

Nevertheless, regarding to the earthquake environmental effects, other translations say that *"many springs disappeared under the ground and other ones emerged welling up stinking waters"* (Sánchez-Pérez and Alonso, 2004; Franco Sánchez, 2014) suggesting the occurrence of widespread liquefaction processes as occurred in this area during the AD 1829 Torrevieja event affecting the whole Lower Segura Depression (Alfaro et al., 2012). The original Arab text of al-Udri also mentioned the *"littoral zone of Tudmir",* as well as the cities of Lorca, Cartagena, Elche, Santa Pola and Alicante. Espinar Moreno (1994) interpreted that all these localities were out of the macroseismic area, but the location of the *"ancient littoral zone of Tudmir"* has to be construed under the light of the palaeogeography of the zone in the 11th century AD (Fig. 1).

MACROSEISMIC DATA.

Espinar Moreno (1994) locate the earthquake between Murcia and Orihuela because those were the only cited by al-Urdi. The Spanish IGN Catalogue, place the macroseismic epicenter in Orihuela with an intensity of VIII EMS (Martínez Solares and Mezcua, 2002). No macroseismic data are available for other localities east of Orihuela. This is an anomaly, since some authors indicate that the earthquake was similar to the well-known AD 1829 Torrevieja event (Alfaro et al, 2012), in which Orihuela recorded a similar VIII EMS intensity, but the strongest damage (IX-X EMS) was recorded in the eastern zone of the Lower Segura Depression.

Recent data indicate that the "Rábitas Califales" (little mosques) of Guardamar del Segura (10^{th} Century AD), about 18 km east of Orihuela (Fig. 2), were partially destroyed by this earthquake (Franco Sánchez, 2014). This author documents the southwards collapse of the mirháb and the southern wall of the mosque M-II of this archaeological site, relating its final abandonment to seismic damage. This is a newly reported earthquake archaeological effect (EAE) for this seismic event, and the unique one in the eastern zone of the Lower Segura Depression (Fig. 2). The location of the site, about 2 km north of the Lower Segura Fault-trace, and the southwards collapse of the walls fit well with the earthquake secondary effects on building fabrics listed by Rodríguez-Pascua et al. (2011). In fact, most authors identify the Lower Segura Blind Fault as the most probable seismic source for the AD 1829 and AD 1048 earthquakes (Alfaro et al., 2012).

PALAEOGEOGRAPHICAL EVOLUTION OF THE LOWER SEGURA DEPRESSION.

Recent palaeogeographic reconstructions (Tent Manclús, 2013) indicate that the Lower Segura Depression was occupied by a large bay, between Elche and Orihuela, subject to progressive sedimentary filling by the old prograding deltas of the Vinalopó (North) and Segura (South) rivers since c. 6,000 BP (Fig. 1). This large bay corresponds to the Ibero-Roman *"Sinus Ilicitanus"* described by the Roman geographers (i.e. Gagnaison et al., 2007). These old descriptions indicate the occurrence of a large shallow-marine embayment with three main islands (Fig. 1), corresponding to the Tabarca Island, El Molar island and the San Isidro rocky islet (Tent Manclús, 2013). Some of the palaeogeographic reconstructions indicate the occurrence of littoral sand-bars North (La Marina spit-bar) and South (Guardamar spit-bar) of El Molar Island giving place to the generation of a variety of marshlands, salt marshes and lagoon areas (Blázquez and Usera, 2004; Giménez Font, 2009).

The old embayment of the Lower Segura Depression (*Sinus ilicitanus*) was featured by the occurrence of shallow marshlands, which were progressively filled from Roman times (Fig. 1; Pocklington, 1989). Eventually, in the early 18th century, the zone was subjected to large artificial drainage works in order to reclaim the existing swampy littoral areas for agriculture (Bernabé Gil, 1999). The last artificial drainage works of the ancient marshlands were carried out during the second half of the 20th century (1950 – 1956; Delgado et al., 1988).

Following the work of Tent-Manclús (2013) from pre-Roman to Roman times (c. 1st century AD) the Segura river-delta front was located in the vicinity of Callosa south of the San Isidro rocky islet, (Figs. 1 and 2). The Roman delta consisted of a main lobe with the Segura River main channel running towards the NNE and flowing into the *Sinus ilicitanus* in the vicinity of the present locality of Catral. The old Roman coastline bordered the present localities of Catral, Rafal and Benejuzar about 11 km ENE from Orihuela (Fig. 2). Tent-Manclús (2013) identifies an anomalous subsidence event during Roman times (AD 1 - AD 200), which triggered the abandonment of the old NNE Roman delta-channel that shifted to a southern position, flowing E-W along the present localities of Almoradí, La Daya and S. Fulgencio (Fig. 1). The new delta prograded into the marshlands and generated several small delta-lobes south of the El Molar Island. This palaeogeographical conditions remained until the 10th century, when the first Muslim settlements occurred in this area (Gutiérrez Lloret, 1995; Azuar Ruiz, 1999) and persisted at least until the early 14th century (Azuar Ruíz, 1999).

Descriptions of the zone made by *al-Udri* in the 11thcentury (Sánchez-Pérez and Alonso, 2004) suggest the occurrence of two main channels of the Segura river during the Muslin period. The first one flowing to the NE towards Callosa and Catral (ancient Roman river-course converted into an irrigation canal) and the main one flowing to the towards the East by the Almoradí –Algorfa area (Fig. 1; Silva et al., 2015). Historical landscape reconstructions for Muslim times (Gutiérrez Lloret, 1995; Azuar-Ruíz, 1999; Giménez Font, 2009) clearly indicate that the inner coastline of the *Sinus ilicitanus* was bordering

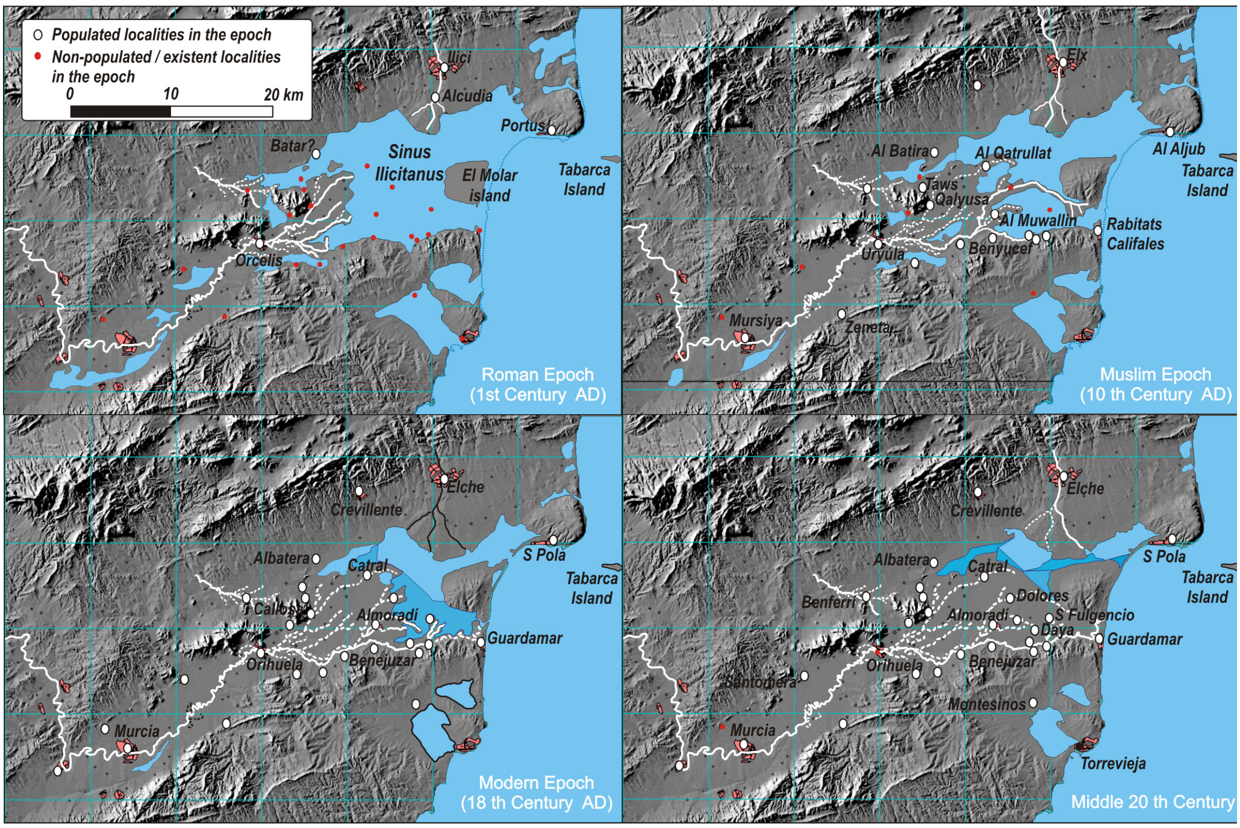

Fig. 1: Palaeogeographical reconstruction of the Lower Segura Depression and Segura valley based on the proposals of Tent-Manclús (2013), reconstructions of ancient acequia systems (irrigation cannals), historical data on reclaimed lands of the ancient Sinus Ilicitanus and palaeogeographical descriptions from roman to muslin times by Pocklington (1989), Azuar Ruiz (1999), Gutierrez Lloret et al. (1995); Sánchez-Pérez and Alonso (2004) and Parra Villaescusa (2013). Base map 25 m resolution DEM Instituto Geográfico del Ejército.

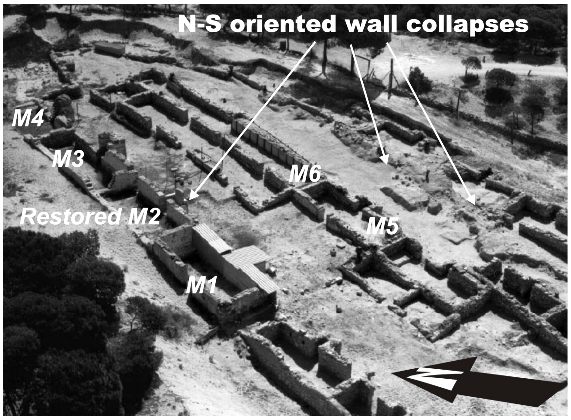

Fig. 2: N-S oriented wall collapses in the Rábitas Califales (Guardamar del Segura) linked to damage during the AD 1048 Orihuela earthquake. Mosque M2 (presently restored) displayed the major damage. Modified from Azuar-Ruíz (2010).

the localities of Almoradi - La Daya – Algorfa in the South and Catral in the North, presently at about 14 km from the shoreline (Fig. 2).

THE ANCIENT SEGURA RIVER DELTA DURING THE 10th - 11th CENTURIES.

Reconstructions of the irrigation systems during the Muslim period in the zone (Azuar Ruiz, 1999; Parra Villaescusa, 2013) evidence how the early Muslim settlers took advantage of the distributary pattern of the ancient Segura River delta system to develop the irrigation system along the western zone of the Lower Segura Depression (Silva et al, 2015). The projection of the ancient irrigation systems and old tracks-ways with significant meandering geometry on digital terrain models of the zone resulted in channel fingered patterns, resembling the "foot-bird patterns" of river-dominated deltas (Fig. 3) consistent with the micro-tidal nature of this Mediterranean coast. The major irrigation canals (Acequias) and some of the largest tracks in the studied zone, constituted the main ancient delta-channels. These are presently about 3-4 m above the adjacent plains, suggesting the occurrence of channel-levee systems (probably enlarged and fixed during the Muslim period). On the contrary, minor canals used by the evacuation of leftover waters (Azarbes) are commonly at the ground level and display frequent rectilinear geometries and clear cross-cutting relationships with the main canals (acequias) indicating their man-made nature.

These analyses highlight the occurrence of two main delta lobes prograding in the ancient marshlands (remains of the *Sinus Ilicitanus*). These deltaic bodies occupied the central area of the Lower Segura Depression west of Almoradí (Fig. 2). Several delta-channels protruded into the ancient marshlands separated from the sea by emergent spit-bar systems (Fig. 2), fitting well with historical landscape reconstructions (Gutiérrez Lloret , 1995; Azuar-Ruiz, 1999).

Fig. 3 illustrates the most probable geometry and features of the Segura river-delta protruding into the old estuarine zone during Muslim times. The oldest delta-lobe NE Orihuela (A1) corresponds to the old Roman delta drained by the "Acequia Mayor de Orihuela-Callosa" described by *al-Udrí* (main Roman river channel) and five main distribu-taries (acequias of Albatera, Moncada, Algimet, Benimancox and Bemira). The second delta-lobe (A2), corresponds to the active delta lobe during early Muslim times (9th century) drained by the "Acequia Vieja de Almoradí" (main Muslim river channel) with four main distributaries (acequias of Aceyt, Teyl, Almisgram and Mayayo; Fig.3). The paleogeographical model also includes the main channel of the Segura River identified by Tent-Manclús (2013), flowing close to the southern flank of the Molar island, where developed a small delta lobe (B3; Fig. 3). This ancient river channel, already converted into an irrigation canal (Acequia Vieja de Almoradí), is still

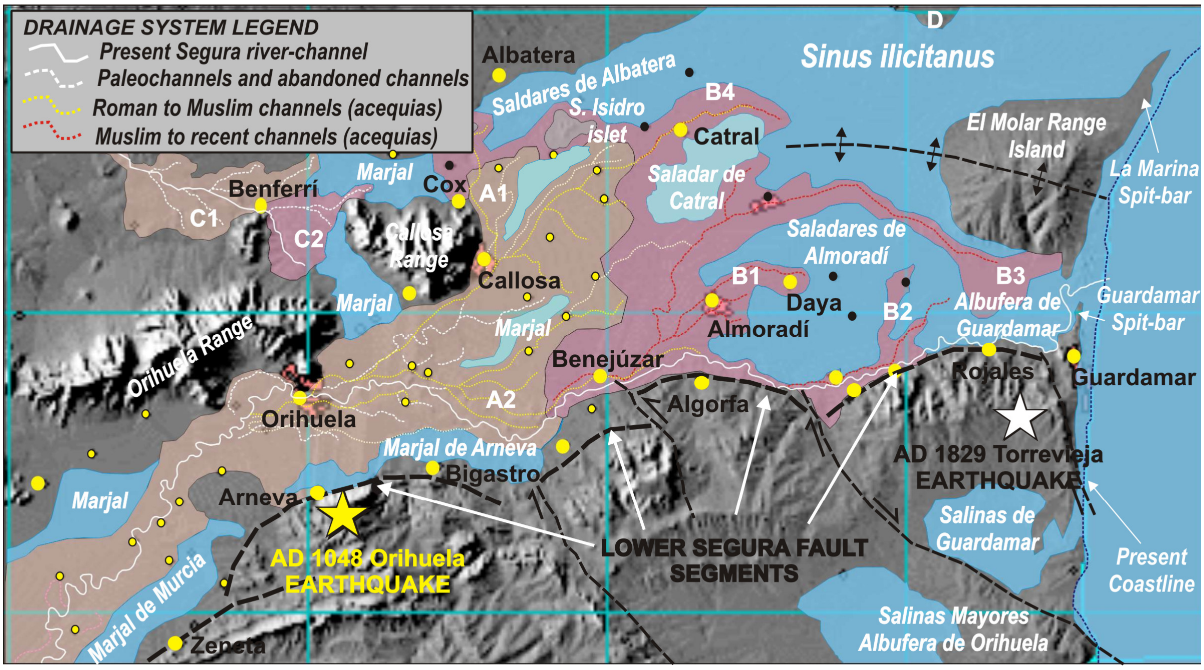

Fig. 3: Theoretical reconstruction of active delta lobes and channel systems of the Segura River during Roman (A) and Muslim (B) times protruding in the ancient marshlands of the Sinus Ilicitanus. Giving place to foot-bird distributary patterns and minor delta lobes at Almoradi (B1), S. Fulgencio (B2) Albuferra de Guardamar (B3) and Catral (B4). Also is illustrated the evolution of the rambla-delta of Benferrí (C) during both periods. To the north the (D) is the Vinalopó Delta. Tthe location of the main segments of the Lower Segura blind-fault and El Molar Range Anticline are displayed in black.

documented in the early 14th century maps (Azuar-Ruíz, 1999). From the 10th century the eastern delta lobe (A2) prograded into the eastern marshlands generating a "bird-foot delta" and different minor delta lobes (B1 to B4; Fig.3). The palaeogeographical models of Tent-Manclús (2013) indicate that the present E-W river-course of the Segura, adjacent to the Lower Segura blind fault, was firstly outlined in the late 11th century. From this period the old "foot-bird" distributary system of the Segura river was progressively converted into irrigation canals.

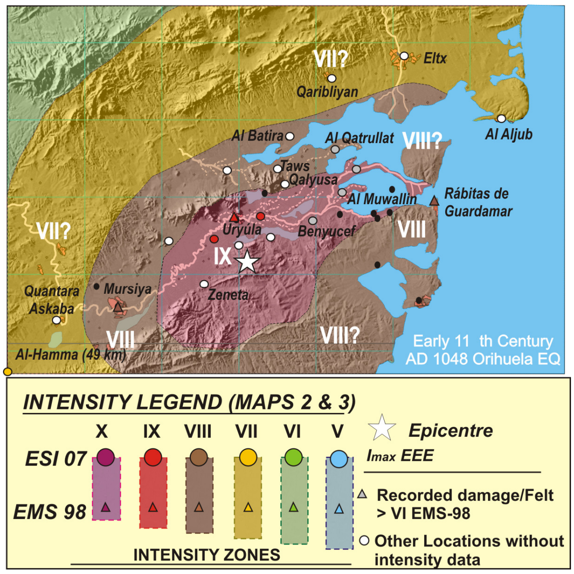

Fig. 4: Theoretical reconstruction of ESI-07 intensity zones during the AD 1048 Orihuela earthquake based on the theoretical ground-susceptibility induced by the location of inactive Roman and active Muslim delta lobes and marshlands.

Finally, the paleogeographical reconstruction presented in this works helps to understand damage distribution occurred in the area during more recent earthquakes. This is the case of the well-known AD 1829 Torrevieja earthquake (Mw 6.6; IX-X EMS; Martínez Solares and Mezcua, 2002). During this historical earthquake, extensive liquefaction and building damage were concentrated in the eastern zone of the ancient *"Sinus ilicitanus"* (Silva and Rodríguez-Pascua, 2014; Fig. 1). In fact, comparing the ancient paleogeography and damage distribution, most affected sites were those located on the old Muslim delta channels and lobes. The Torrevieja earthquake was characterized by widespread occurrence of liquefaction in this area with massive ejection of sand and salt-waters, mainly affecting the localities of Dolores, Daya vieja, San Fulgencio, Benijofar, Rafal, Formentera, Benejuzar and Almoradí (Larramendi, 1829; Alfaro et al., 2012). As illustrated in Fig. 1 these localities are placed on ancient delta-channels of Muslim epoch (Silva et al., 2015), some of them (Almoradí and Benejúzar), were totally destroyed and rebuilt.

A similar seismic scenario occurred during the recent Emilia-Romagna earthquake (Mw 6.2) in the Pianura Padanna (Southern Po Plain, Italy; Emergeo, 2013), where localities located on old river palaeochannels underwent strong seismic damage induced by liquefaction, widespread ejection of sand and water, repeated ground waving and sloshing (Rodríguez-Pascua et al., 2015).

CONCLUSIONS

The progressive growth of the Segura river-delta and palaeogeographical reconstructions provided in this work has a relevant impact in the interpretation of seismic damage records in the zone.

(1) During the AD 1048 Orihuela event (VIII EMS) the main localities in the zone were Murcia, Orihuela and Callosa as described by al-Udri (11th century AD). Other mentioned locations in the muslin texts, such as Catral, Almoradí and Algorfa were merely early agricultural farmsteads bordering the estuarine non-productive swampy areas. Therefore, the description of the AD 1048 earthquake only mentioned these two main localities in which urban development were already important to report seismic building damage. In contrast, in the surrounding agricultural areas only generalized ground cracking, hydrogeological anomalies and liquefaction processes are mentioned, which is consistent with the swampy nature of these zones in the Muslim period.

(2) The presumable destruction of the *"Rábitas Califales"* in Guardamar del Segura built on the emergent spit-bar of Guardamar (Fig. 3) constitutes a newly reported seismic damage data (Franco-Sánchez,2014). Damage in the eastern end of the Lower Segura Depression allow to ensure that the entire Depression from Orihuela (West) to Guardamar (East) underwent significant ground shaking of intensities VIII to IX ESI-07. Fig.4 depicts the hypothetical intensities zones.

(3) Repeated southward shifting of the main Segura river-channel occurred in Roman (1st – 2nd c. AD) and Muslim times (11th -12th c. AD) proposed by Tent-Manclús (2013) can be linked to the activity of the Lower Segura fault. In the second case can be preliminary interpreted as a significant earthquake environmental effect (EEE)of the AD 1048 event of minimum intensity IX (Michetti et al., 2007). If this is the case the previous shifting of the river during Roman times could be also related with an unknown ancient earthquake affecting a nearly depopulated area occupied by the old embayment of the *Sinus ilicitanus* (Fig. 1). If proved, this will imply recurrence periods for Torrevieja-type events of c. 800 - 1000 years in the area.

(4) Paleogeographical reconstructions indicate that most affected localities in the AD 1829 Torrevieja earthquake was placed on ancient channels of the old Muslim delta-lobe. Further studies are necessary to relate probable site-effect and amplification of liquefaction processes in these on-channel localities.

The development of ancient paleogeography helps to improve the knowledge on ancient seismic scenarios (AD 1048), but also identify ground susceptibility data critical for the understanding of damage distribution on historic (AD 1829) and future earthquakes. In detail the relationships of environmental earthquake effects and geological site effect during ancient or poorly documented earthquakes are difficult to understand without a well constrained paleogeographical scenario. This is of especial relevance in ancient littoral zones, as is the case of the deltaic system of the Segura river in the vicinity of Orihuela during Roman and Muslim times. To the present this area has been conventionally considered as a largely homogeneous alluvial plain.

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