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Seismic palaeogeography of coastal zones in the Iberian Peninsula: Understanding ancient and historic earthquakes in Spain

Paleogeografía sísmica de zonas costeras en la Península Ibérica: su impacto en el análisis de terremotos antiguos e históricos en España

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Abstract

This paper presents three examples of ancient earthquakes occurring in coastal areas of the S and SE of the Iberian Peninsula (218 BC, AD 40-60 and AD 1048) with the aim of illustrating the use of geological and archaeological data in their macroseismic characterization. Historical information for ancient earthquakes that occurred in Spain prior to the 10th century is scarce or non-existent. This paper shows that the current state of knowledge on palaeoseismology and archaeoseismology on these ancient events clearly exceeds the existing historical information allowing the increase of macroseismic information points by using the ESI-07 scale (Environmental Seismic Intensity). Consequently, the geologic analyses of ancient earthquakes contribute to their understanding and parametric evaluations, and improve further advances in seismic hazard assessments. The most significant issue outlined in the present paper is the analysis of the ancient palaeogeography of the affected areas. The studied examples analysed were located in open estuarine areas that have been filled by fluvial sediments or anthropogenic fills over time. The effects of the 218 BC earthquake-tsunami event in the Gulf of Cadiz are analysed in estuarine areas, and especially in the ancient Roman *Lagus Ligustinus* (Guadalquivir Depression marshes); the effects of the earthquake in AD 40-60 is analysed in the old

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Roman city of *Baelo Claudia* located in the Bolonia Bay (Strait of Gibraltar); and the effects of the earthquake of AD 1048on the ancient *Sinus Ilicitanus* (Bajo Segura Depression) during Muslim times. Descriptions from Roman and Arabic geographers are cross-checked with existing palaeogeographic models based on geological data. This type of analysis results in ancient macroseismic scenarios for the interpretation of theoretical distributions of intensities and environmental effects supporting the concept of "seismic palaeogeography" proposed in this paper.

Keywords: Palaeoseismology, Archaeosismology, Palaeogeography, ancient earthquake, littoral zone, South Spain.

Resumen

El presente trabajo recoge tres ejemplos de terremotos antiguos (218 AC, 40-60 AD y 1048 AD) ocurridos en zonas litorales del S y SO de la Península Ibérica con la intención de ilustrar el uso de datos geológicos y arqueológicos en la caracterización macrosísmica de los mismos. En la mayor parte de los sísmos ocurridos con anterioridad al siglo X d.C. la información documental histórica que se posee es muy escasa o inexistente. El presente trabajo muestra que el actual estado de conocimiento en paleosismología y arqueosismologia sobre este tipo de terremotos sobrepasa con creces la información documental histórica, permitiendo la multiplicación de los puntos de información macrosísmica mediante el uso de la escala ESI-07 (*Environmental Seismic Intensity*). Consecuentemente, el análisis geológico de los terremotos antiguos mejora su conocimiento y análisis paramétrico, permitiendo avanzar la evaluación de la peligrosidad sísmica de las zonas afectadas. El aspecto que se pone de especial relieve en este trabajo es el análisis de la paleogeografía existente en la antigüedad, ya que todas las zonas (afectadas) analizadas en este trabajo corresponden a zonas estuarinas abiertas que se han ido rellenado por aportes fluviales o de forma artificial con el tiempo. Se analizan los efectos del terremoto de 218 AC en las zonas estuarinas del Golfo de Cádiz y muy especialmente en el antiguo *Lacus Ligustinus* (marismas del Guadalquivir) durante época romana; los efectos del terremoto de 40-60 AD en la antigua Bahía de *Baelo Claudia* (Estrecho de Gibraltar); y los efectos del terremoto de 1048 AD en el antiguo *Sinus ilicitanus* (Depresión del Bajo Segura) durante época musulmana. Se han cotejado descripciones de geógrafos romanos y árabes con modelos basados en datos geológicos. Este tipo de análisis ha permitido generar antiguos escenarios macrosísmicos basados en la paleogeografía y reinterpretar las distribuciones teóricas de intensidades y los efectos ambientales de los terremotos estudiados que es a lo que se refiere el concepto de "paleogeografía sísmica" propuesto en este trabajo.

Palabras clave: Paleosismología, Arqueosismología, Paleogeografía, terremotos antiguos, zonas litorales, Sur España

1. Introduction

Data on ancient and historic earthquakes in Spain previous to the 10th century are very scarce. In most cases only strong seismic events with intensities ≥VIII, are historically documented in old chronicles covering wide areas. Commonly, these historical data are very general and provide vague descriptions on the events, with extremely poor geographical data on the affected localities or geographical zones. Descriptions such as *"the island of Cadiz, but also all the littoral zone of Andalucía underwent strong earthquakes and tremors, producing the collapse of buildings, many fatalities, injuries and terrible disasters everywhere; the sea flooded many places that were first uncovered by the waters, throwing out a multitude of fishes, some of them familiar but others never seen before"* are common, enough to identify an old earthquake-tsunami event. This corresponds to the description of the historic chronicles of Florian de Ocampo in AD 1553 (Galbis, 1932) in reference to one of the oldest historically documented events in Spain affecting the Gulf of Cádiz in 218 BC.

The Spanish catalogue on historical earthquakes (Martínez Solares and Mezcua, 2002) only records 34 seismic events previous to AD 1100. Most of them (60%) occurred offshore in the Gulf of Cádiz and SW Portugal, affecting the Atlantic littoral zones of the western Iberian Peninsula, Andalucía, the old Emirate of Cordoba or the Islamic zone of al-Andalus (Fig. 1). Half of these ancient, historically documented, events occurred during the Muslim epoch (> AD 711), but curiously, no seismic events are catalogued in the Spanish territory during the Roman epoch (c. 3rd BC to 5th AD centuries). However, recent geological, palaeoseismological and archaeoseismological studies have thrown light on these poorly documented periods and several "lost ancient earthquakes" have been revealed from geological and geo-archaeological records. Some examples are the aforementioned 218 BC seismic event recorded in the Doñana area (Luque *et al*., 2001, 2002; Lario *et al*., 2001, 2011; Rodríguez-Vidal *et al*., 2011), the roman earthquakes affecting "*Baelo Claudia"* (Cádiz) in the 1st century AD and especially in the 3rd century AD (Silva *et al*., 2005, 2009) and the late roman event affecting the old city of "*Ilunum"* (Tolmo de Minateda; Albacete) in the 4th-5th centuries AD (Rodríguez-Pascua *et al*., 2013).

The recent development of the Spanish Catalogue of Earthquake Environmental effects edited by IGME-AEQUA (Silva and Rodríguez-Pascua, 2014) allowed the identification and classification of multiple geological and archaeological records from ancient events. The compilation revealed that in most cases palaeogeography was completely different than the present sedimentary environment, especially in ancient estuarine zones.

Littoral palaeogeography and its historical evolution condition the evidence of past seismic events in the ancient emerged areas, but also the intensity distribution in the presently emerged ones. This paper analyses old seismic events in littoral areas and the role played by the palaeogeography in their understanding, substantiating the concept of *"seismic palaeogeography"* as the *"palaeogeographical analysis of ancient macroseismic scenarios, of special relevance in coastal zones where significant changes have been produced during the last 6000 years"*. Three main events are used in this paper as type-examples: the 218 BC earthquake in the ancient *"Lacus Ligustinus"* (Huelva) and *"Sinus Tartesicus"* (Cádiz); the AD 40-60 *"Baelo Claudia"* earthquake in the old Bolonia Bay (Cádiz) and the AD 1048 Orihuela earthquake in the ancient littoral area of the Muslim Kingdom of Tudmir, adjacent to the past Ibero-Roman *"Sinus Ilicitanus"* (Lower Segura Depression, Alicante).

2. Methodology

This study is based on the cataloguing of earthquake environmental effects (EEEs) following the ESI-07 intensity scale (Michetti *et al*., 2007) and the identification of earthquake archaeological effects (EAEs) from the classification of Rodríguez-Pascua *et al*. (2011), developed for the edition of the "Spanish Catalogue of Earthquake Environmental Effects" (Silva and Rodríguez-Pascua, 2014). All the data presented here come from the compilation, cross-checking, re-interpretation and synthesis of geological information provided in recent scientific publications and old historic documents. The more relevant earthquakes are displayed in figure 1, including the three ones studied in this paper.

Compiled and synthesized seismic data-sets have been projected on palaeogeographical models developed from old descriptions of Greek, Roman or Muslim geographers such as, *Strabo* (1st BC to 1st AD centuries), *Pomponius Mela* (1st century AD), *Pliny the Elder* (1st century AD), *al-Urdí* (11th century AD) and *al-Idrisi* (12th Century AD). Older references to the ancient littoral geography of south Spain has been obtained from translations of the *"Ora maritima"* (Sea Coasts) of Avienus (4th century

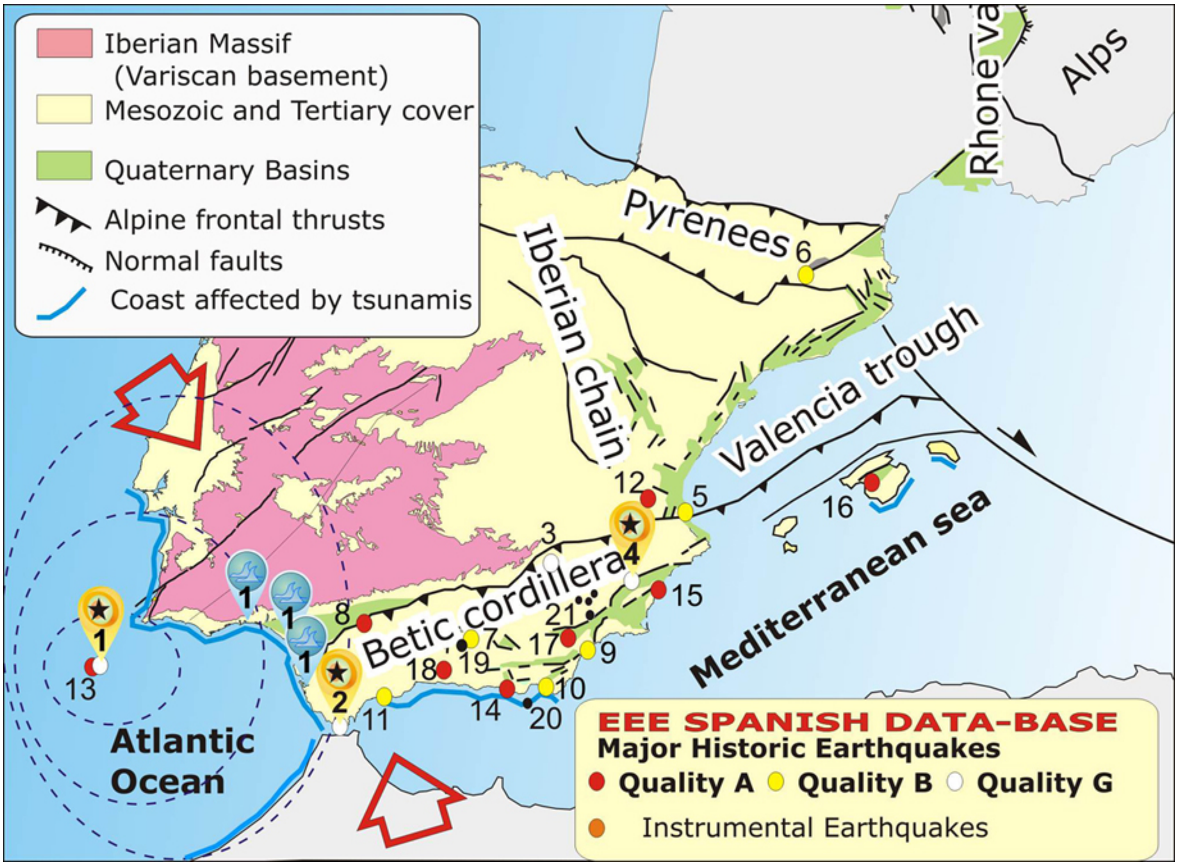

Figure 1. Data base of ancient, historical and instrumental earthquakes with well-documented Earthquake Environmental Effects (EEE) **1: 218 BC (Gorringe Bank)**; **2: AD 40-60** and AD 260-290 **(Baelo Claudia)**; 3: AD 300-400 (Tobarra); **4: AD 1048 (Orihuela)**; 5: AD 1396 (Tavernes); 6: AD 1427 and AD 1428 (Olot and Queralbs); 7: AD 1431 (Sur Granada); 8: AD 1504 (Carmona); 9: AD 1518 (Vera); 10: AD 1522 Alhama de Almería); 11: AD 1680 (Málaga); 12: AD 1748 (Estubeny); 13: AD 1755 (Lisbon Earthquake-Tsunami); 14: AD 1804 (Dalías); 15: AD 1829 (Torrevieja); 16: AD 1851 (Palma de Mallorca); 17: AD 1863 (Huércal-Overa); 18: AD 1884 (Arenas del Rey); 19: AD 1956 (Albolote); 20: AD 1993 (Adra); 21: AD 2011 (Lorca) and earthquakes of Mula (AD 1999), Bullas (AD 2002) and La Paca (AD 2005). Globes with stars illustrate the location of macroseismic epicentres of the **studied ancient earthquakes (1, 2 and 4)**. Blue globes with waves illustrate the main sites in which the **218 BC earthquake-tsunami event (1)** is geologically documented. Data summarized from Silva and Rodríguez-Pascua (2014).

Figura 1. Base de datos de terremotos antiguos, históricos e instrumentales con efectos geológicos y ambientales (EEE) bien documentados en la Península Ibérica. ***1: 218 BC (Gorringe Bank)****;* ***2: 40-60 AD*** *and 260-290 AD* ***(Baelo Claudia)****; 3: 300-400 AD (Tobarra);* ***4: 1048 AD (Orihuela)****; 5: 1396 AD (Tavernes); 6: 1427 AD y 1428 AD (Olot y Queralbs); 7: 1431 AD (Sur de Granada); 8: 1504 AD (Carmona); 9: 1518 AD (Vera); 10: 1522 AD (Alhama de Almería); 11: 1680 AD (Málaga); 12: 1748 AD (Estubeny); 13: 1755 AD (terremoto-tsunami de Lisboa); 14: 1804 AD (Dalías); 15: 1829 AD (Torrevieja); 16: 1851 AD (Palma de Mallorca); 17: 1863 AD (Huércal-Overa); 18: 1884 AD (Arenas del Rey); 19: 1956 AD (Albolote); 20: 1993 AD (Adra); 21: 2011 AD (Lorca) y sismos de Mula (1999 AD), Bullas (2002 AD) y La Paca (2005 AD).Los globos con estrella identifican la localización de los epicentros macrosísmicos de los* ***terremotos antiguos estudiados (1, 2 and 4)****. Los globos azules con olas indican la localización de las principales áreas de registro geológico del* ***terremoto-tsunami de 218 BC (1).*** *Datos recopilados de Silva y Rodríguez-Pascua (2014).*

AD), which described the old coastal landscapes of south Spain from ancient Greek texts of the 4th – 5th centuries BC (i.e. Gavala, 1959; González Ponce, 2008). These ancient descriptions have been compared with palaeogeographical models developed by several authors in the studied zones, based on sea-level reconstructions (i.e. Rodríguez-Ramirez *et* *al*., 1996; Tent-Manclús, 2013); ancient drainage and/or irrigation development models (i.e. Bernabé Gil, 1999; Giménez Font, 2009; Parra Villaescusa, 2013); palaeogeographical proposals based on old descriptions and landscape archaeology (i.e. Gutiérrrez Lloret, 1995; Azuar Ruiz, 1999; Alonso-Villalobos *et al*., 2003; Sánchez Pérez and Alonso, 2004; Barragán de La Rosa, 2012; Ferrer Albelda *et al*., 2008); and archaeological data (i.e., Prados Martínez, 2011). The obtained information has been incorporated into digital elevation models and cross-checked with the available macroseismic data for each event in order to illustrate the ancient palaeoseismic scenarios preliminarily explored in this paper.

3. Palaeoseismic analyses of the littoral Atlantic zones from SW Iberian Peninsula

The littoral zones most affected by ancient earthquake-tsunamis are located in the Gulf of Cádiz and the western sector of the Gibraltar Arc. Four of these events are included in the existing tsunami catalogues (Campos, 1991; IGN, 2014), and seems to be similar (in terms of damage) to the well-known AD 1755 Lisbon event. Descriptions for these events are very poor, insufficient to infer earthquake size and location parameters (Martínez Solares and Mezcua, 2002). In this section we analyse the ancient earthquakes that occurred in 218 BC in the Gulf of Cádiz and the AD 40-60eventaffecting the Roman city of *Baelo Claudia* in the Gibraltar Strait area. The first one is documented both by historic and geologic data, and it is included in the IGN Catalogue of Historic Earthquakes (Martínez Solares and Mezcua, 2002). Despite the recent geoarchaeological review by Rodríguez-Vidal *et al*. (2011) proving the occurrence of a tsunami event comparable to that induced by the AD 1755 Lisbon event, the 218 BC event still remains labeled as an “unlikely tsunami event” in the IGN Tsunami catalogue (IGN, 2014). This ancient earthquake constitutes a good example for crosschecking the quality of geoarchaeological data *versus* the historical information commonly used in standard macroseismic analyses. The second event partially destroyed the old Roman city of *Baelo Claudia* during the 1st century AD, leading to the entire rebuilding of the lower sector of the city (Sillières, 1997). This event is not catalogued in the seismic data-bases of the IGN (i.e. no historically documented) and illustrates how archaeoseismology can help to find “lost ancient earthquakes” just from geoarchaeological data (Silva *et al*., 2005, 2009).

3.1. 218 BC earthquake in the Gulf of Cádiz

Historical data from Florian de Ocampo (Galbis, 1932) are transcribed in the narrative of the beginning of the Second Punic War (218 – 203 BC) and the overland journey of *Hannibal Barca* to Italy. The historical descriptions indicate the occurrence of an earthquake-tsunami event, which severely affected the littoral zone in the Gulf of Cádiz, and especially the old insular emporium of Gades (Cádiz), which is the only locality cited in the short historical tale documenting the seismic event (see section 1). In contrast, tsunami research in the zone resulted in the recognition and radiocarbon dating of different tsunami deposits and geomorphological anomalies associated with this event in the coastal estuarine zones of the Tinto-Odiel (Huelva), Guadalete (Cádiz) and Guadalquivir (Doñana marshlands) rivers, as summarized in Lario *et al*. (2010), Rodríguez Vidal *et al*. (2011), and Ruiz *et al*. (2013).

3.1.1. Geological data on the 218 BC tsunami event

Data compiled by Lario *et al*. (2010, 2011) allow them bracketing the timing of tsunami occurrence and related extreme wave events (EWE) between 2,700 and 2,200 cal. BP. Recent specific research on this event in the Doñana marshlands has been published by Rodríguez-Vidal *et al*. (2011). These authors identified and dated the tsunami (218 – 209 BC) in the context of the palaeogeography of the ancient *Lacus Ligustinus* (present Doñana marshlands), described by the Greek geographer Strabo in the 1st century AC. More recently, Ruiz *et al*. (2013) developed a synthesis on tsunami deposits recorded in estuarine zones around the Gulf of Cádiz. However, the first publications identifying and dating this historical tsunami in littoral deposits of the Gulf of Cádiz were those developed in the Valdelagrana spit-bar and Doñana marshlands by Lario *et al*. (2001), Dabrio *et al*. (2000) and Luque *et al*. (2001, 2002). This ancient earthquake has been also identified in oceanic turbiditic beds near the Gorringe Bank, interpreted as seismically-induced submarine landslides dated at 2,200 – 2,000 cal. BP (Gràcia *et al*., 2010; Lario *et al*., 2011). Figure 2 illustrates the location of the different sites with geological evidence documenting the ancient tsunami in the context of the old littoral palaeogeography of the Gulf of Cadiz.

In the Tinto-Odiel estuary, the tsunami event caused the breach of the Punta Umbría spit-bar, the generation of a large washover fan and deposition of marine bioclastic sand layers within the old marshes, the emergence of the primitive Punta Umbria inlet and the overall reorganization of the back-barrier drainage pattern in the old estuarine zone (Morales *et al*., 2008; Lario *et al*., 2010; Ruiz *et al*., 2013). Additionally, core data from the inner part of the estuary include suspect tsunamite beds with a mixture of estuarine and reworked marine microfauna (Morales *et al*, 2008), pointing to the penetration of 4-5 m high tsunami waves, for about 11 km landwards within the old estuarine zone.

The most complete record of the tsunami has been described In the Doñana marshlands and associated spit-bar systems (Doñana and Algaida spit-bars). First data come from the Lucio del Pescador and Lucio del Lobo ponds, presently located about 18 – 20 km landwards from the present Guadalquivir river mouth in Sanlucar de Barrameda (Cádiz). Core data show the deposition of a high energy sandy level, with marine shells and high magnetic susceptibility, interbedded in the silty estuarine deposits, interpreted as the result of the breaching and re-sedimentation of the ancient Doñana spit-bar by a tsunami event in 2,500-2,300 cal. BP (Lario *et al*., 2001; Dabrio *et al*., 2000). Similar sandy layers with mixed estuarine and marine fauna were found in the cheniers of Vetalengua and Las Nuevas (16 -13 km inland), bracketed between 2,400 – 2,350 cal. BP, are interpreted in a similar way (Ruiz *et al*., 2004, 2008). Finally, Rodríguez-Vidal *et al*. (2011) provide a large number of geological data, documenting a great deal of geological effects of this ancient tsunami within the present Doñana marshlands. The most relevant geological and environmental tsunami effects documented in this area are: (a) beach erosion in the Doñana spit bar; (b) deposit of bioclastic ridges and clayey beds (cheniers and marsh strands) along or very close to the ancient lagoon margins caused by tsunami waves or post-tsunami tidal fluxes; (c) breaching of ancient spit-bars (La Algaida) as a consequence of the tsunami and subsequent backwash; and essentially (d) the record of sub-tidal sandy layers (even 3 m thick) with shells and rounded clasts in infra-littoral environments located near the ancient lagoon outlet coming from the erosion of the spit-bars of Doñana and La Algaida, dated at 420 – 50 BC (Rodríguez-Vidal *et al*., 2011). Data from these authors indicate the record of a 5 m high tsunami, which penetrated more than 16 km in the ancient estuarine zone and caused the nearly depopulation of the zone, not recovered until the 1st century AD when Roman saltworks are documented in La Algaida spit-bar (Rodríguez-Vidal *et al*., 2011).

In the Guadalete estuary there is a good record of a tsunami event dated at 2,300 – 2,000 cal. BP that caused the breaching of the Valdelagrana spit-bar about 7 km east of Cádiz, and generated different washover fans, 300-400 m long and 1.5 m thick (Luque *et al*., 2002). These washover fans are featured by three stacked fining-upwards sequences, with erosional bases, mixed estuarine and marine macro and microfauna, as well as rip-up mud clasts eroded from the estuarine marsh areas (Luque *et al*., 2001, 2002). These authors document similar washover fans developed in this same area as a consequence of the AD 1755 Lisbon event, and conclude that a similar-size tsunami event occurred during the early Roman period in the Gulf of Cádiz.

The analyses of offshore turbiditic beds (Gràcia *et al*., 2010) identify seven Holocene earthquake events from four cores obtained in the Gorringe Bank zone (suspect seismic source), 100 to 200 km away from the SW coast off Portugal. Three of the four cores record the "Event 5" dated at 1,980-2,280 cal. BP, as a 20 cm thick turbidite bed, which is related to the 218 BC event, suggesting a minimum magnitude of Mw 8.0.

Therefore, there is a relatively good geological record of this historic tsunami along the littoral zone of SW Spain between the Tinto-Odiel estuary (Huelva) to the Guadalete estuary (Cádiz), along a coastal strip 140 km in length. The environmental effects generated by the 218 BC tsunami in the Doñana marshlands (Rodríguez-Vidal *et al*., 2011) entail a strong geomorphological disturbance in previous spit-bar systems (> 2,300 cal. BP; Zazo *et al*., 1994; Ruiz *et al*., 2004) and in the inland brackish lagoon, resulting in a palaeogeographical scenario similar to the earlier historical descriptions of the ancient *Lacus Ligustinus* (Guadalquivir estuary) by the Roman chroniclers *Strabo*, *Pomponio Mela* and *Pliny the Elder* during the 1st century AC (i.e. García y Bellido, 1983). Ferrer Albelda (2012) discusses the differentiation (disambiguation) between *Lacus Ligustinus* and *Sinus Tartesicus*, commonly confused in the historic literature. According to this author, the "*Lacus Ligustinus"* corresponds to the ancient Guadalquivir estuary, whilst the "*Sinus Tartesicus"* corresponds to the Guadalete estuary in the environs of the ancient island of Gades (Cádiz) as illustrated in figure 2.

3.1.2. Historical descriptions and palaeogeography

Historical descriptions for pre-earthquake times (*Ora maritima* of *Avienus*; Gavala, 1959), clearly indicate that a large island occurred in the ancient mouth of the Guadalquivir River at the old brackish lagoon (*Lacus Ligustinus*), as well as the branching of the river course in three large channels for at least two times. This description refers to the old mouth of the Guadalquivir River into the *Lacus Ligustinus* downstream Sevilla and not to the present outlet of the estuary into the Atlantic Ocean, suggesting the occurrence of a proto-delta prograding into the brackish lagoon downstream Coria del Rio and giving place to distributary channels and several outlets (Fig. 2). Downstream this location, the descriptions of *Avienus* only indicate that there was a huge salt-marsh area, referring to the ancient brackish lagoon and marshlands. In fact, these descriptions match with palaeogeographical reconstructions by Rodríguez-Ramírez *et al.* (1996) for the period 2,500 – 2,300 BP, which support the occurrence of emergent marshlands in the western zone of the lake as illustrated in figure 2. Following the text of *Avienus*, *"only the old tribes inhabited the margins of the marshlands till the maritime zone"* (the present Guadalquivir outlet area) is cited, but this description didn't include details of this maritime zone. The next reference in the text of *Avienus* directly shifts to the Guadalete estuary (*Sinus Tartesicus*) and the Old Island and city of Cádiz (*Gades*). Therefore, many palaeogeographical interpretations from the "*Ora maritima"* of *Avienus* misleadingly interpret the present outlet of the Guadalquivir with those described in the ancient text, in reference to the old mouth of the river in the ancient *Lacus Ligustinus*. The palaeogeography of the ancient outlet zone is testified by the historical occurrence of the two large island-like areas called "Isla Mayor" and "Isla Menor". These island-like areas are presently bounded by several branches of the Guadalquivir River and tributaries, but remain emerged even during the yearly highest tides, supporting the preliminary palaeogeographical approach illustrated in figure 2. In the present outlet area, palaeogeographical reconstructions (Rodríguez-Ramírez *et al*., 1996) indicate the occurrence of an incipient Doñana spit-barin the western border of the

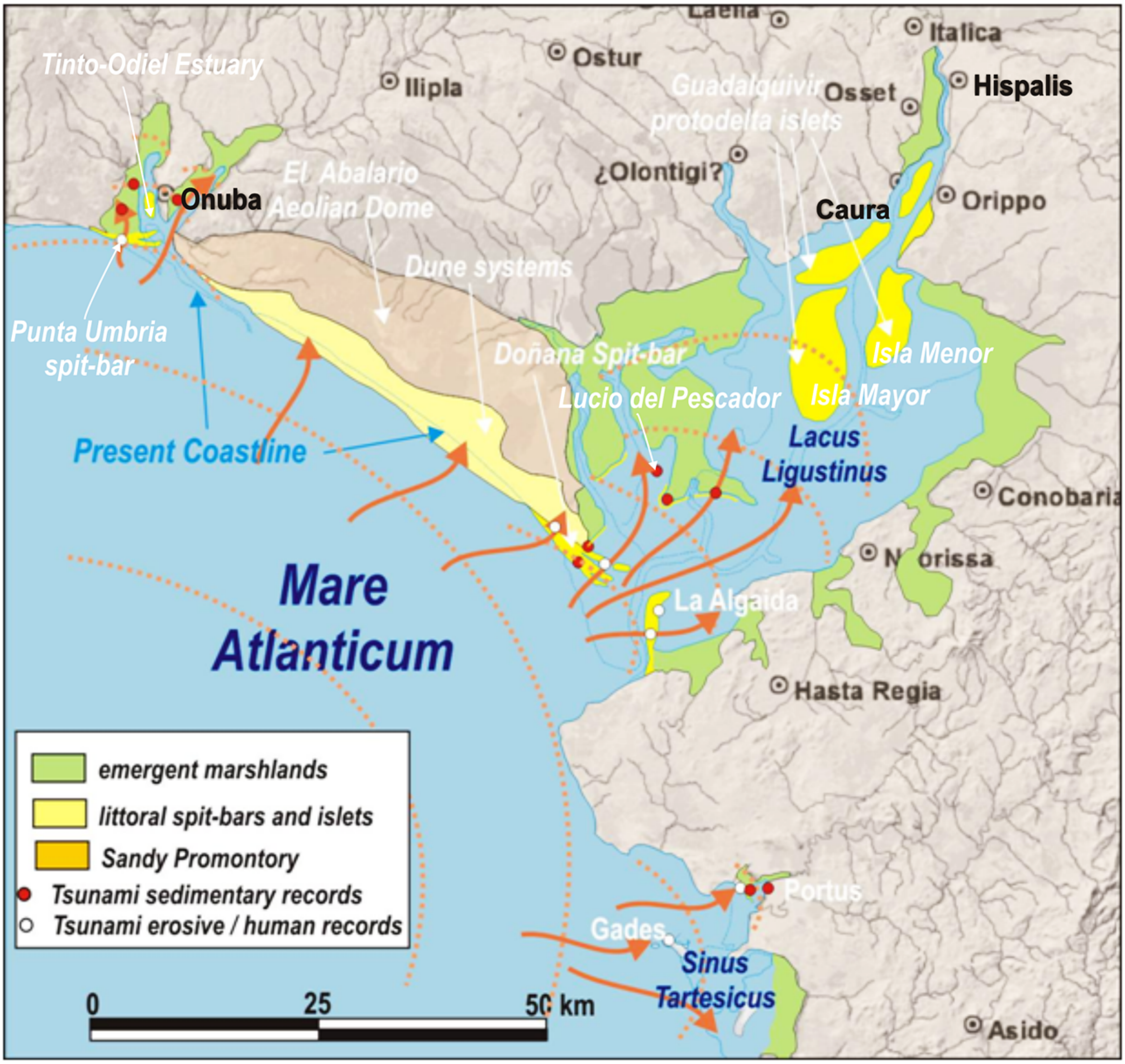

Figure 2.Palaeogeography of the “Lacus Ligustinus” (present Doñana Marshlandds) during the 1^{st} century AC based on descriptions of roman geographers and palaeogeographic models of the zone reflecting the 218 BC post-tsunami geography of the affected area. Orange arrows illustrate theoretical tsunami penetration in the ancient estuarine zones of Onuba (Tinto-Odiel), “Lacus Ligustinus” (Guadalquivir) and “Sinus tartesicus” (Guadalete). References for historical documents and palaeogeographical models in text. Base-map modified from Ferrer Albelda et al. (2008).

Figura 2. Paleogeografía del Lacus Ligustinus (Marismas de Doñana) durante el siglo I DC basado en las descripciones de geógrafos romanos y modelos paleogeográficos de la zona ilustrando la geografía romana de la zona surgida tras el tsunami del 218 AC. Las flechas naranjas representan las teóricas zonas de penetración del tsunami en los antiguos estuarios de Onuba (Tinto-Odiel), “Lacus Ligustinus” (Guadalquivir) y “Sinus tartesicus” (Guadalete). Las referencias de los datos históricos y paleogeográficos usados para la reconstrucción en texto. Mapa-base modificado de Ferrer Albelda et al. (2008).

Lacus Ligustinus, whilst the eastern one was flanked by the large N-S oriented La Algaida spit-bar (Fig. 2). For the rest of the zones, different palaeogeographical proposals, based in the study and dating of spit-bars (i.e. Rodríguez-Vidal, 1987; Zazo *et al*., 1994; Rodríguez-Ramírez *et al*., 1996; Dabrio *et al*., 2000) and tsunami research (Luque *et al*., 2002; Ruiz *et al*. 2004; Morales *et al*., 2008; Lario *et al*., 2010) allow to perform the reconstruction displayed in figure 2.

Descriptions of the zone after the earthquake mainly come from those of the 1st century AD by *Strabo*, *Mela* and *Pliny the Elder* (Ferrer Albelda *et al*., 2008). The descriptions of these Roman geographers clearly refer to the present Guadalquivir mouth in the vicinity of Sanlúcar de Barrameda, indicating the occurrence of large lacustrine and marshland areas downstream Sevilla (*Lacus Ligustinus*) and the development of two river mouths towards the Atlantic Sea (Fig. 2). These two outlets were separated by the La Algaida Island, which developed as a consequence of the breakage of a previous spit-bar by the 218 BC tsunami event (Rodríguez-Vidal *et al*., 2011), and its occurrence is congruent with palaeogeographical models proposed for the Doñana spit-bar (Zazo *et al*., 1994) and Doñana marshlands (Rodríguez Ramírez *et al*., 1996).

3.1.3. Seismic implications

The compiled data document the occurrence of a tsunami event in the ≈ 218 BC, causing strong environmental effects in all the estuarine areas of the Gulf of Cádiz, from Huelva to Cádiz, and inducing important palaeogeographical changes. Data gathered for the Spanish Catalogue for Earthquake Environmental effects (Silva and Rodríguez-Pascua, 2014) indicate the occurrence of a 4-5 m high tsunami wave penetrating c. 12 – 18 km within the ancient marshlands. These parametric data indicate a minimum intensity of IX in the ESI-07 scale (Michetti *et al*., 2007), supporting the occurrence of a tsunami event similar to the AD 1755 Lisbon earthquake-tsunami. The different palaeogeography settings (open estuaries, with incipient spit-bars) favoured widespread environmental damage and a larger run-up of the tsunami waves along the ancient estuarine zones. Additionally, historical descriptions clearly indicate that the zone suffered strong seismic shaking inducing the collapse of buildings and numerous injuries and fatalities along the littoral zone of Andalucía (Gulf of Cadiz),specifically in the old insular city of Gades, the oldest and most important *metropolis* in the zone during the early 3rdcentury BC (Galbis, 1932).Consequently, in spite of the destruction induced by the subsequent tsunami a minimum intensity of VIII EMS-98 can be considered for this ancient city.

Assuming the Gorringe Bank as the seismic source area for this ancient earthquake-tsunami (i.e. Rodríguez Vidal *et al*., 2011) the epicentral distance for *Gades* will be of about 400-450 km (Fig. 1). This suggests a seismic intensity in the Guadalquivir and Tinto-Odiel estuaries ≥ IX and a macroseismic intensity (I_o) ≥ X in the offshore epicentral area, where multiple submarine landslides of this age have been documented (Gràcia *et al*., 2010). In order to differentiate this earthquake-tsunami from later events occurred during the Roman period in the area, we propose to designate the 218 BC as the *"Lacus Ligustinus Earthquake"* according to the ancient geographical location in which most geological data identify this ancient event in reference to the first paper widely reporting these data by Rodríguez-Vidal *et al*. (2011).

3.2. AD 40-60 Earthquake in Baelo-Claudia (Tarifa, Cádiz)

This event lacks of any historical description and it is only supported by archaeological data (Sillières *et al*., 1995, 1997) and subsequent archaeoseismological (Silva *et al*., 2005, 2009) and palaeoseismological research (Grützner *et al*., 2012; Silva *et al*., 2013). Furthermore, data compiled by Lario *et al*. (2010) show geological evidence of a suspect contemporary tsunami event in the Doñana marshlands, the Bolonia and Algeciras bays, at around cal. 2,000 BP. This event is not included in the Spanish Catalogue of historical earthquakes (Martínez Solares and Mezcua, 2002), but it has been recently incorporated to the Spanish Catalogue of Earthquake Environmental Effects (Silva and Rodríguez-Pascua, 2014).

3.2.1. Geoarchaeological and Archaeoseismological data

Original data supporting earthquake damage in the ancient Roman city of *Baelo Claudia* was provided by Menanteau *et al*. (1983) who, on the basis of numerous both archaeological anomalies and dates, indicated that the destruction and eventual abandonment of the city was caused by an earthquake in the AD 280 – 365. However, the first author that suggested the occurrence of a previous earthquake in the city was Sillières (1995). This author identified numerous architectural and stylistic anomalies, as well as the widespread re-utilization of old architectural elements (column drums, old capitols, etc.), both in public and private buildings, during the reconstruction and enlargement of the city in the second half of the 1st century AD. First archaeoseismological studies in the city (Silva *et al*., 2005) identified damage and collapse levels in the old city wall, as well as the occurrence of a "demolition horizon" throughout the entire lower sector of the city, upon which the new monumental city was rebuilt. Further research (Silva *et al*., 2009; Giner-Robles *et al*., 2013) mapped the damaged sectors of the wall and identified repair works in the old wall, proposing an age range of AD 40-60 for the first earthquake occurred in *Baelo Claudia*. These authors also pointed out that the second seismic event affecting the new monumental city occurred in AD 280-290, as supported by new dating results presented in Grützner *et al*. (2010). However, the site was not completely abandoned by the Romans until the second half of the fourth century (AD 365-395; Silva *et al*., 2009).

Recent compilation of data for the Spanish Catalogue of Earthquake Environmental Effects (Silva and Rodríguez-Pascua, 2014) indicates the occurrence of extensive damage in the lower part of the ancient Roman settlement built before the 1st century AD. The damage affected the entire perimeter of the ancient city wall, destroying about the "one third" of its extent (Sillières, 1997). This destruction affected the original towers, bastions and gates, which were repaired and rebuilt during AD 50 – 60 (Sillières, 1997; Silva *et al*., 2005). The lower part of the city (c. 8 ha) was entirely demolished in order to build the new Monumental city after the acquisition of the rank of Roman City (*Oppidum Latinum*) in AD 41 – 48 (Sillières, 1997). The seismic event is post-dated by the occurrence of an anomalous and thick *"demolition horizon"* related to ground leveling works on the whole lower sector of the city for the construction of monumental buildings, such as the *Macellum*, *Basilica*, *Forum Temples*, *Theatre*, etc. (Silva *et al*., 2005). Recent archaeological revisions (Bendala *et al*., 2010) indicate that the construction works for most of these monumental buildings started around AD 50 and were completely finished in AD 70-80. However, recent geoarchaeological data from the Theater (Finker and Sillères, 2006; Fincker and Moretti, 2009) and the Isis Temple (Grützner *et al*., 2010, 2012) suggest that the seismic event occurred during the earlier works for city rebuilding and enlargement soon after AD 40.

The Theatre displays two clear phases of construction from AD 10-20 to AD 70-80. The Theatre works stopped for half a century (20 to 70 AD), after which the initial building project was modified, using different constructive materials and adding new external buttress for the reinforcement of the building (Finker and Sillères, 2006; Fincker and Moretti, 2009). These authors consider this large non-operative time-span in the theater works an anomaly, but they do not offer an explanation for it. On the other hand, radiocarbon dating of materials embedding the collapsed columns of the *Isis Temple* (Grützner *et al*., 2012) indicate an age bracketed between 2,050 and 1,900 BP, which overlaps the archaeological dating of its construction around AD 60 (Bendala *et al*., 2010). This anomalous fact suggests the destruction of the Isis Temple during its construction, related to a large coseismic landslide event (> 5000 m^3) affecting the eastern sector of the city and documented by geophysical prospecting (Silva *et al*., 2013). On the basis of these anomalies, recent interpretations suggest that after the acquisition of the *"Oppidum Latinum"* the old

Roman city started to be improved. However, during the early building works an earthquake occurred so, taking advantage on the triggered destruction, the whole lower sector of the ancient city was demolished (demolition horizon) and a new city design outlined (Silva y Giner Robles, 2014).Therefore, the age of the proposed earthquake (AD 40-60) overlaps the earlier construction works for most of the monumental buildings (c. AD 50), the reparation works in the city wall (AD 30 - 50) and the anomalous interruption of the Theatre works (AD 20 to 70).

In contrast to the well documented AD 260-280 earthquake, the AD 40-60 event is only evidenced by few archaeological data in the city walls, Isis Temple and Theater, since rebuilding works removed any probable evidence within the city. However, onshore and offshore geological and geophysical research around the Bolonia Bay area have identify several late Quaternary active faults as probable near-field seismic sources (Silva *et al*., 2005, 2009; Grützner *et al*., 2012). Onshore geological analyses include three fault trench analyses in the N-S normal fault system of the Sierra de la Plata and the Cabo de Gracia left-lateral fault about 3 km west of the city. Offshore seismic reflection profiles (Grützner *et al*., 2012) also identify N-S trending structures in the Bolonia Bay (≤ 20 km S and SW of the city) with recent tectonic activity. Available data indicate that the offshore N-S oriented faults are the most probable seismic sources, since onshore fault trenching analyses didn`t throw conclusive palaeoseismic evidence (Grützner *et al*., 2012). Dimensions of identified offshore fault segments indicate that all these N-S oriented structures are able to generate Mw 5.5 – 6.0 seismic events, capable to trigger VIII ESI-07 minimum local intensities in the littoral zone of the old Bolonia Bay (Silva *et al*., 2009; Grützner *et al*., 2012).

3.2.2. Palaeogeography and probable evidence of an intervening tsunami event

Geological evidence points to the probable occurrence of a moderate tsunami event (bioclastic washover sands), dated at 2,150-1,825 cal. BP, about 500 m east of the ancient Roman city (Alonso-Villalobos *et al*., 2003) which overlap with the AD 40-60 earthquake (Fig. 3). Other authors identify similar sandy energetic layers of marine origin linked to the destruction and abandonment of a pottery workshop area in the Roman city of *Carteia* (Algeciras Bay) interpreted as a tsunami event occurred during the second half of the 1st century AD (Arteaga and González Martín, 2004). In both cases, it represents a moderate tsunami event up to 3-4 m high with a low inland penetration (< 300 - 500 m). In the case of *Baelo Claudia*, this moderate event would have been only capable to flood the lower sector of the city down of the present location of the *Decumanus maximus* (c. 6 m a.s.l.) causing damage in the old harbour and fish factory areas located along the ancient coastline (Fig. 3).

Following palaeogeographic reconstructions for the ancient Roman city based on geomorphological mapping, geophysical surveys, boreholes, geoarchaeological data and submarine archaeological remains (Alonso-Villalobos *et al*., 2003; Silva *et al*., 2005, 2009), the ancient Bolonia Bay was protected by an old spit-bar system as displayed in figure 3. This figure shows the occurrence of "hypothetical" marsh areas and tidal channels in the inner zones of the old spit-bar system according to the meso-tidal nature of this littoral area and geomorphological data. Archaeological submarine findings and geophysical data by Alonso-Villalobos *et al*. (2003) support this coastline and harbour reconstruction during Roman times. Following these authors, the probable tsunami event would be the main responsible of the erosion and disappearance of the ancient beach barrier sheltering the old harbour zone (Alonso-Villalobos *et al*., 2003). In any case, both the moderate size of the probable tsunami and the occurrence of a sheltering beach-barrier, were the reason why only the areas below the *Decumanus maximus* (c. 6 m a.s.l.) were affected by the suspect tsunami event (Fig. 3). Consequently, the destruction of nearly the entire city wall

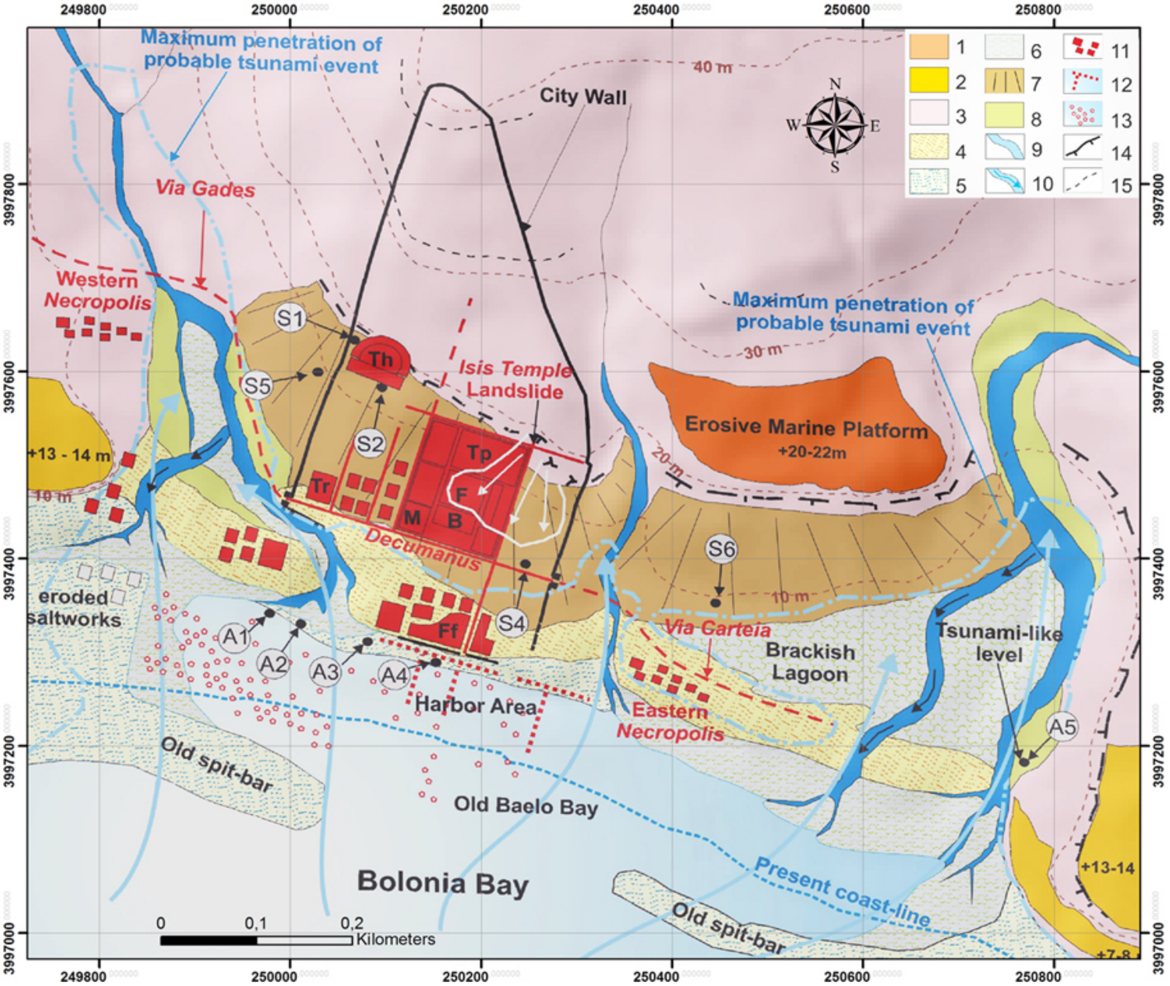

Figure 3. Palaeo-geomorphological map of the Bolonia bay area during the 1st century AC based on geomorphological mapping (Silva et al., 2005) and submarine archaeological data from Alonso Villalobos et al. (2003) around the ancient urban area of Baelo Claudia. Are also included the locations of the boreholes (S) developed by Vorsevi (Borja et al., 1993), and (A) Alonso Villalobos et al. (2003).Legend: (1) Marine abrasion platform; (2) Late Pleistocene Marine terraces; (3) Betic substratum; (4) Holocene spit-bar system including D1 and D2 dune system of south Spain; (5) Roman spit-bar system; (6) marshlands; (7) Post-Roman colluvium; (8) Flood plains; (9) Active channel beds and distributaries; (10) Presently abandoned distributary channels; (11) Buildings and archaeological remains; (12) Roman harbour structures; (13) Accumulations of blocks and ashlars stones; (14) Palaeocliff; (15) Bedrock scarps. Roman buildings: (Th) Theatre; (Tp) Temples; (F) Forum; (B) Basilica; (M)Macellum; (Ff) Fish factories; (Tr) Roman Baths. Base-map LIDAR terrain model (resolution: 5m).

Figura 3. Mapa Paleo-geomorfológico de la Bahía de Bolonia durante el siglo I AD basada en cartografías geomorfológicas (Silva et al., 2005) y datos arqueológicos submarinos de Alonso Villalobos et al. (2003) en el entorno del conjunto urbano de Baelo Claudia. Se indican las localizaciones de los sondeos (S) realizados por Vorsevi S.A. (Borja et al., 1993) y (A) Alonso Villalobos et al. (2003). Leyenda: (1) Plataforma de abrasión marina; (2) Terrazas marinas del Pleistoceno Superior; (3) Sustrato bético; (4) Barra litoral Holocena, incluyendo los sistemas dunares D1 y D2 del sur de la Península; (5) Barra litoral romana; (6) marismas; (7) Coluvión post-romano; (8) llanuras aluviales; (9) Canales fluviales y distributarios activos; (10) canales distributarios abandonados actualmente; (11) Edificaciones y restos arqueológicos; (12) Estructuras portuarias romanas; (13) Acumulación de bloques y sillares, actualmente sumergidos; (14) Paleoacantilado; (15) resaltes rocosos. Edificios romanos: (Th) Teatro; (Tp) Templos; (F) Foro; (B) Basílica; (M) macellum; (Ff) Factorias de salazón; (Tr) Termas. Mapa base Modelo del terreno LIDAR de 5m de resolución.

and the lower sector of the city rebuilt on the "demolition horizon" was a consequence of seismic shaking (Silva *et al*., 2005). However, the occurrence of a moderate tsunami event is congruent with the offshore location of the probable seismic sources less than 20 km SW of the city (Grützner *et al*., 2012). The suspect tsunami record (bioclastic washover sands) can be also interpreted as storm-surge deposits and its cataloguing as a true tsunami event needs additional evidence (Lario *et al*., 2010).

The apparent involvement of a moderate tsunami in the destruction of the lower sector of the city should be substantiated by a relevant archaeological anomaly related to the eastern necropolis of the city as highlighted by Prados Martínez (2011). According to this author the second burial level of the eastern necropolis, dated at < AD 68, displays an anomaly difficult to interpret within the Roman funerary practices. In this burial level several tents of tombs located immediately to the south of the *Via Carteia* (eastern prolongation of the *Decumanus maximus;* Fig. 4) present a disorganized pattern with larger rich and smaller poor burials mixed and consistently oriented to the sea (south). Additionally, a nearly specific anomaly for this burial level, is the anomalous concentration of old funerary "sacred poles" (Bonsor Dolls) found in all the graves, also oriented towards the sea (Prados Martínez, 2011). According to this author, the seaward orientation of the tombs is an outstanding anomaly in the Roman funerary practices, where graves were consistently oriented towards the main route adjacent to the necropolis in all cases. In our case, only this second burial level is seawards (southwards) oriented whilst the other previous and later burial levels are oriented to the *Via Carteia* (northwards) consistently with the Roman funerary practices (Prados Martínez, 2011). Only in the necropolis of *"Isola Sacra"*, located in the ancient Roman harbour of Ostia (Italy), a similar anomalous case of seawards facing tombs has been documented. On the other hand, the mixed and disorganized pattern of poor and rich tombs is also anomalous, since in the Roman world the zones for rich and poor people burials were commonly separated (not mixed).

Finally, many of the *"sacred poles"* found in this burial level are also facing to the sea and most of these sculptured dolls symbolize "scare or crying human faces" as literally described by Prados Martínez (2011). This author links the occurrence of the "sacred poles" to the North-African Ibero-Phoenician tradition persisting around the Gibraltar Strait during Roman times, but the rest of the funerary anomalies documented in the eastern necropolis remain presently unsolved (Prados Martínez, 2011). On the contrary, the concurrence of all the aforementioned anomalies in the second burial level of the necropolis would indicate the occurrence of a catastrophic event killing a large amount of people and inducing the massive burial of tens of citizens (rich and poor ones) during the second half of the 1st century AD. The 40-60 AD earthquake event, affecting to the lower sector of the city, would account by itself for these massive and disorganized burials, but the anomalous seaward orientation of the tombs and the sea-facing occurrence of scare-like face poles in the graves strongly suggest the intervention of an energetic wave-event (EWE). Consequently, this preliminary interpretation of the funerary anomalies during the second half of the 1st century AD reported by Prados Martínez (2011) is not in disagreement with the occurrence of a moderate earthquake-tsunami event triggered by a near-field seismic source, otherwise congruent with the offshore nature of the probable seismic sources identified in the Bolonia Bay area (Grützner *et al*., 2012).

4. Palaeoseismic analyses for littoral areas in the Mediterranean zone of SE Spain

4.1. AD 1048 Orihuela Earthquake (Alicante)

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,* first reported by Espinar Moreno (1994) in reference to the ancient "*Muslim kingdom of Tudmir"* (present Alicante and Murcia Regions) The original Arab text (12th Century AD) by *al-Udri* is entitled *"News on earthquakes occurred in the farming areas (nahiya), cities of Murcia and Orihuela"*.

The original description 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 (Alfaro *et al*., 2001, 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.

Following these descriptions, Espinar Moreno (1994) located the earthquake between Murcia (*Mursiya*) and Orihuela (*Ûryula*) because those were the only populated urban sites in that epoch. Presently, the macroseismic epicentre is located in Orihuela with an assigned minimum intensity of VIII EMS (Martínez Solares and Mezcua, 2002), and no macroseismic data are available for localities located east of Orihuela. This is an anomaly, since some authors indicate that the earthquake was similar to the well-documented 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. In this zone, the most severely affected localities were Almoradí, Benejúzar, Rojales, Benijófar, Algorfa, etc., all them of Arab origin, founded from the 9-10th centuries AD (i.e. Gutiérrez Lloret, 1995; Azuar Ruiz, 1999; Parra Villaescusa, 2013). Recent data indicate that the *"Rábitas Califales*" (little mosques) of Guardamar del Segura (10th century), about 18 km east of Orihuela (Fig. 4), were partially destroyed by this earthquake (Franco Sánchez, 2014). This author documents the southwards collapse of the mirháb and the southern wall of a mosque (M-II) of this archaeological site, relating its eventual abandonment to the earthquake destruction. 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. 4). 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 (i.e. Giner, 2003; Alfaro *et al*., 2012).

4.2. 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. 4). This large bay corresponds to the Ibero-Roman *"Sinus Ilicitanus"* described by Roman geographers, most of them largely based on the already mentioned *"Ora maritime"* of *Avienus* (i.e. Badie *et al*., 2000; Gagnaison *et al*., 2007). All these descriptions indicate the occurrence of a large shallow-marine bay with three main islands (Fig. 4), corresponding to the Tabarca Island, El Molar range-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 Range Island giving place to the generation of a variety of marshlands, salt marshes and lagoon areas (Blázquez and Usera, 2004; Giménez Font, 2009). Palaeogeographic reconstructions by Tent-Manclús (2013) consider time windows of 500 years from pre-Roman (4,000 BC) to present times (AD 2,000) based on seismic stratigraphy of the zone, sea-level models for the western Mediterranean, subsidence/uplift rates models, digital elevation models and Landsat thematic-mapper images. In fact, the old embayment of the Lower Segura Depression (*Sinus ilicitanus*) was featured by the occurrence of shallow marshlands, which were progressively filled and/or drained from Roman times (Fig. 4). 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 in charge of the Cardenal Beluga, old bishop of Cartagena (Bernabé Gil, 1999; Giménez Font, 2009). The last artificial drainage works of the ancient marshlands were carried out during the second half of the 20th century, during the years 1950 – 1956 (Delgado *et al*., 1988). At present, only El Hondo Lake (c. 4 km^2) is preserved as a protected remnant of the old swampy bay zone (c. 750 km^2; *Sinus Ilicitanus*) featuring the Lower Segura Depression in ancient times (Fig. 4).

First works featuring the ancient *Sinus Ilicitanus* as a micro-tidal shallow-marine estuarine area under the sedimentary influence of "prograding delta bodies" are those by Blázquez and Usera (2004) and Giménez Font (2009). Previous works on the zone only provide sketch-maps on the probable distribution of swampy areas and salt-marshes from historical Middle-Age documents (i.e. Gutiérrez Lloret, 1995; Azuar Ruiz, 1999) or historical development of Muslim to modern irrigation systems in the zone (Parra Villaescusa, 2013). Following the work of Tent-Manclús (2013) from pre-Roman to Roman times (1st century AD) the Segura river-delta front was located in the vicinity of the Callosa Range south of the San Isidro rocky islet, (Figs. 4 and 5). The 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. 5). Tent-Manclús (2013) identifies an anomalous subsidence event between the AD 1 and AD 200, which triggered the abandonment of the old NNE Roman delta-channel that shifted to an E-W orientation, flowing along the present localities of Almoradí, La Daya and San Fulgencio (Fig. 4). This new delta prograde 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 the Lower Segura zone (i.e. Gutiérrez Lloret, 1995; Azuar Ruiz, 1999). In historical documents of the early 14th century *("Libros del Repartimiento de la Huerta de Orihuela"*) similar palaeogeographical conditions are reported (Azuar Ruiz, 1999).

Descriptions of the zone made by the Arabic geographer al-Udri in the 11th century (Sánchez-Pérez and Alonso, 2004) indicate that: *"The river of Tudmir* (Segura river) *has water mills that irrigate the orchards of this territory. The main channel of the river starts in Qattara Askaba* (Alcantarilla)*, and reaches the properties of the inhabitant of Mursiya* (Murcia)*, to the limit of the farmstead of Taws* (Cox?)*, which belongs to the city of Ûryula*

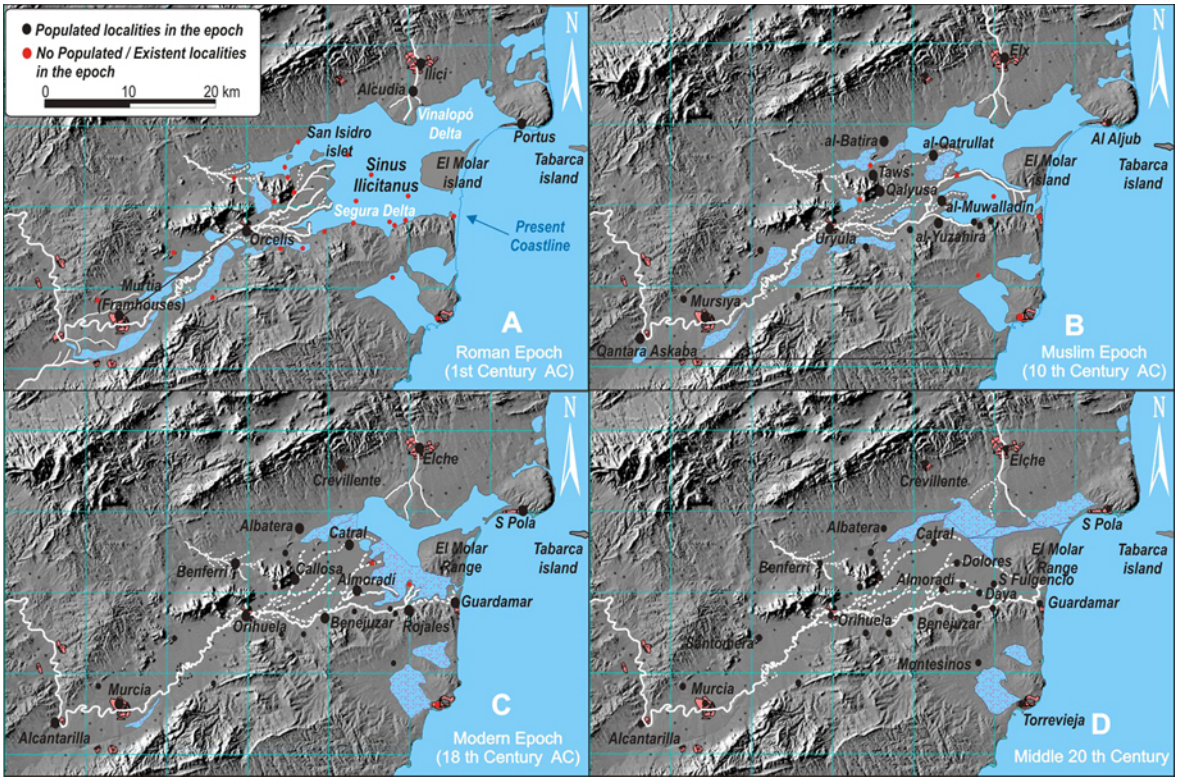

Figure 4. Palaeogeographical reconstruction of the Lower Segura Depression and Segura valley based on the proposals of Tent-Manclús (2013), reconstructions of ancient acequia systems (irrigation channels), historical data on reclaimed lands of the ancient Sinus Ilicitanus and palaeogeographical descriptions from Roman to Muslim times by Pocklington (1989), Azuar Ruiz (1999), Gutierrez Lloret et al. (1999); Sánchez-Pérez and Alonso (2004) and Parra Villaescusa (2013). Base map 25 m resolution DEM Instituto Geográfico del Ejército.

Figura 4. Reconstrucción paleogeográfica de la Depresión del Bajo Segura basada en las propuestas paleogeográficas de Tent-Manclús (2013), reconstrucciones de los sistemas de acequias y periodos de desecación artificial del antiguo Sinus Ilicitanus Ibero-Romano y descripciones paleogeográficas de época romana y musulmana realizadas por Pocklington (1989), Azuar Ruiz (1999), Gutiérrez Lloret et al. (1999); Sánchez-Pérez y Alonso (2004) y Parra Villaescusa (2013). Mapa base DEM Instituto Geográfico del Ejército de 25 m de resolución.

(Orihuela). *The inhabitants of Ûryula opened a large canal in the river, which starts from their lands* (Acequia Mayor of Orihuela – Main irrigation Canal) *reaching the place called al-Qatrullat* (Catral) *over a length of 28 miles (*43 km; Alcantarilla – Catral)*. The main channel of the river ends at the South of this site, in the agricultural region called al-Muwalladín* (Almoradí) *flowing towards the farmstead known as al-Yuzahira* (near Algorfa). *From this site the river flows into the sea at the place known as al-Mudawwir* (Almodovar)*".*

These original descriptions suggest the occurrence of two main channels of the Segura river branching in Orihuela, the first one flowing to the NE towards Catral (converted into an irrigation canal) and the main one flowing to the towards the Almoradí –Algorfa area (East) as illustrated in figure 5. However, there is still an open debate regarding the location of the old site of Almodovar (village disappeared in AD 1266), also mentioned by other Arab geographers such as *Al-Idrisi* and *Al-Dimasqhi*, in reference to the old outlet of the Segura river (Sánchez-Pérez and Alonso, 2004). The descriptions and palaeogeographic reconstructions of the zone during Muslim times (Gutiérrez Lloret, 1995; Azuar Ruiz, 1999; Giménez Font, 2009) clearly indicate that the inner coastline of the *Sinus ilicitanus* marshlands was bordering the localities of Almoradi-La Daya-Algorfa in the South and Catral in the North, presently at about 14 km from the shoreline (Fig. 5).

4.3. The ancient delta of the Segura River and population of the zone during the 10th to 11th centuries

Reconstructions of the irrigation systems during the Muslim period in the zone (i.e. Azuar Ruiz, 1999; Bernabé Gil, 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 of the western area of the present Lower Segura Depression. These reconstructions allow inferring the occurrence of two main delta lobes drained by two main channels and several meandering distributaries. For this work, we have projected all the irrigation systems and old tracks-ways with meandering or anomalous bent geometry on digital elevation models of the zone. The projection results in fingered patterns (foot-bird patterns), resembling the distributary patterns of river-dominated deltas (Fig. 4), which is consistent with the micro-tidal nature of this Mediterranean coast. Additionally, it has been noted that the major irrigation canals (acequias) and some of the largest tracks in the studied zone, constituted the main ancient delta-channels, presently about 3-4 m above the adjacent plains, suggesting the occurrence of channel-levee systems (probably enlarged and fixed during the Muslim epoch). 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 clear man-made nature.

The analysis of irrigation systems of the Lower Segura Depression indicate the occurrence of two main river-dominated delta lobes prograding in the ancient wetlands (remnants of the *Sinus Ilicitanus*) as illustrated in figures 4 and 5. These deltaic bodies occupied the eastern zone of the Lower Segura Depression west of Almoradí (Fig. 5), from which some delta-channels fragmented the ancient marshlands separated from the sea by growing spit-bar systems (Fig. 5). This historic scenario fits well with the palaeogeographical reconstructions of the zone for the Muslim period developed by Gutiérrez Lloret (1995), Azuar Ruiz (1999), Giménez Font (2009) and Tent-Manclús (2013). In any case, the strategy of transformation of old distributary channels of deltas (or alluvial fans) in well-developed irrigation systems was imported by the Egyptian people (Yund Army) occupying the zone since the 9th century AD, as illustrated by the irrigation systems developed in the alluvial fans of the Segura River at Murcia, and the Guadalentín River at Lorca (i.e. Pocklington, 1989; Silva *et al*., 2008).

Figure 5 illustrates the most probable geometry and features of the Segura river-delta protruding into the old estuarine zone. The oldest delta-lobe (A1; Fig.5), located between the localities of Callosa and Catral (NE Orihuela), corresponds to the old Roman delta lobe drained by the *"Acequia Mayor de Orihuela-Callosa"* described by *al-Udrí* (main Roman river channel) and five main distributaries (acequias of Albatera, Moncada, Algimet, Benimancox and Bemira) occupying an area of c. 9-10 km^2. The second lobe (A2; Fig.5), located between the localities of Molins and Almoradí (East Orihuela), corresponds to the delta lobe active from post-Roman to early Muslim times (< 9th century AC) drained by the "Acequia Vieja de Almoradí" (main Muslim river channel) with four main distributaries (acequias of Aceyt, Teyl, Almisgram and Mayayo) occupying an area of c. 5 km^2. From the 10th century AD the eastern delta lobe largely prograded into the eastern marshlands generating a "bird-foot delta" and different minor delta lobes at AlmoradÍ, San Fulgencio, El Molar and Catral (B1 to B4; Fig.5). In our palaeogeographical reconstruction we have also included the main channel of the Segura River identified by Tent Manclús (2013), with arched geome-

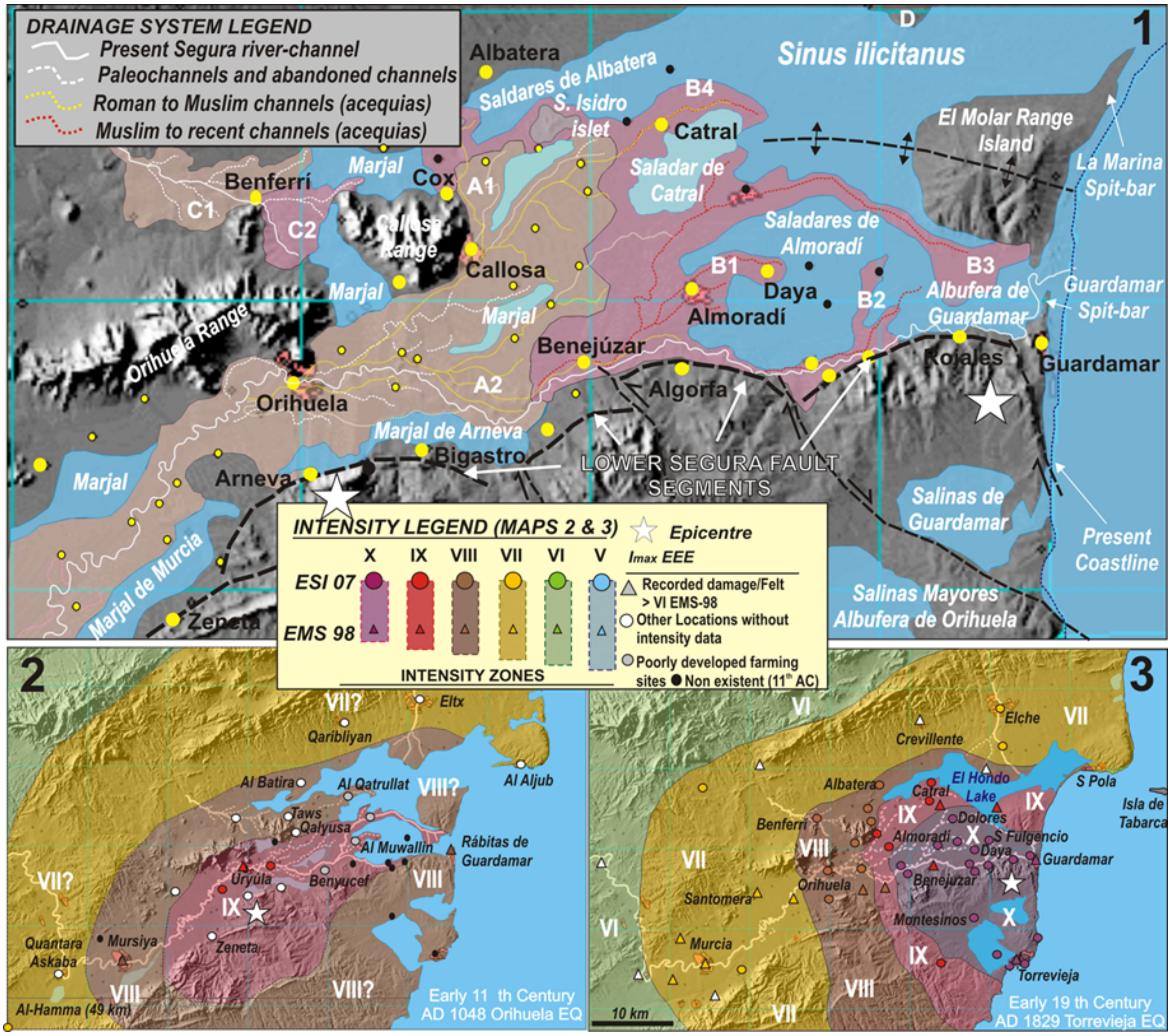

Figure 5. (1) Theoretical reconstruction of active delta lobes and channel systems of the Segura River during Roman (A) and Muslim (B) times protruding in the ancient marshlands of the Sinus Ilicitanus. Also is illustrated the evolution of the rambla-delta of Benferrí (C) during both epochs and the location of the main segments of the Lower Segura blind-fault and El Molar Range Anticline (in red). (2) hypothetical reconstruction of ESI-07 intensity zones during the AD 1048 Orihuela earthquake based on the theoretical ground-susceptibility induced by the location of inactive pre-Muslim and active Muslim delta lobes and marshlands. (3) ESI-07 Intensity zones triggered by the AD 1829 Torrevieja earthquake after the nearly complete artificial dissecation of the ancient Sinus ilicitanus. Maps 2 and 3 produced for the Catalogue of Geological Effects of Earthquakes in Spain (Silva and Rodríguez-Pascua, 2014).

Figura 5. (1) Reconstrucción teórica de los lóbulos activos del antiguo delta del río Segura durante época romana (A) y musulmana (B), progradando en el interior del antiguo Sinus ilicitanus. También se muestra la evolución dela rambla-delta de Benferrí durante ambas épocas y la localización de los diferentes segmentos de la Falla inversa ciega del Bajo Segura y el anticlinal de la Sierra de El Molar. (2) Reconstrucción hipotética de las teóricas zonas de intensidad ESI-07 (IX y VIII) en función de las susceptibilidad del terreno, condicionada por la actividad deltaica (lóbulos activos e inactivos) durante el terremoto de 1048 AD. (3) Zonas de intensidad ESI-07 generadas durante el terremoto de Torrevieja de 1829 AD, ya con la práctica totalidad de la depresión desecada artificialmente. Los mapas 2 y 3 han sido producidos durante la elaboración del Catálogo de efectos geológicos de los terremotos en España (Silva y Rodríguez-Pascua, 2014).

try and flowing close to the southern sector of the Molar Range (ancient island) where developed an small delta lobe (B3; Fig. 5). This main channel, converted into an irrigation canal (Acequia Vieja de Almoradí), is still documented in the early 14th century (Azuar-Ruiz, 1999). Its path is clearly delineated, delimiting the large works for the artificial drainage of the eastern zone of the Lower Segura Depression carried out by the Cardenal Beluga in the 18th century (Fig. 4). Historical reconstructions of the Lower Segura Depression during Muslim times (Gutiérrez Lloret, 1995; Azuar Ruiz, 1999) are largely based on the historic documents *"Libros del Repartimiento de la Huerta de Orihuela"* (Torres Fontés, 1988), written between AD 1266 and AD 1312, after the *"Reconquista"* (Christian Reconquest) of the Tudmir Kingdom. These landscape reconstructions identify and locate the main marshlands (marjales) and salt-marshes (saladares) not improved for agriculture during Muslim times, and consequently non-productive swamped wetlands in the epoch as illustrated in Fig. 5. The palaeogeographical model developed in this paper provides a geological basis for the aforementioned landscape reconstructions based on historical descriptions.

According to the palaeogeographical reconstructions of the zone by Tent Manclús (2013), the present E-W course of the Segura river, adjacent to the Lower Segura blind fault, was firstly outlined after the 11th century, and nearly stabilized in the 14th century with its present outlet into the Mediterranean in the vicinity of Guardamar del Segura (Fig. 4), when the old distributary system of the Segura delta was converted into irrigation canals. The AD 1048 Orihuela earthquake probably triggered important landscape changes in the small delta-lobes and eastern channels of the Segura River into the marshlands. Landscape changes would probably include the almost definitive southwards shifting of the main Segura River that facilitated the Muslim occupation of the zone and the enlargement of the irrigation systems on the former (maybe abandoned) delta distributary channels, after the AD 1048 earthquake. This can be interpreted as another abrupt subsidence event in the zone as those identified by Tent Manclús (2013) during Roman times between AD 1 and AD 200, otherwise coherent with the kinematics of the Lower Segura blind fault zone. Reverse activity of the fault promoted the occurrence of E-W active surface folding within the Lower Segura Depression (Alfaro *et al*., 2012). The most relevant E-W anticline is placed in the El Molar Range, generating a subsiding syncline zone to the South, between the anticline and the present Segura River channel, parallel to the fault trace (Fig.5). Repeated seismic activity would cause rapid subsidence events South of El Molar anticline promoting repeated southwards shiftings of the main river channel. Inter-seismic periods, with limited progressive surface folding, will allow the progradation of delta channels northwards till the southern flank of El Molar anticline (Figs. 4 and 5).

4.4. Palaeogeographical implications for seismic hazard analyses in the Lower Segura Depression

The progressive growth of the Segura river-delta and palaeogeographical reconstructions from Roman times provided in this work has a relevant impact in the interpretation of seismic damage records in the zone. A first implication is that during the AD 1048 Orihuela event the main localities in the zone were Murcia, Orihuela and Callosa as described by al-Udri (11th century AD). In contrast, 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. On the contrary, the zone between Murcia and Orihuela, including both cities, was located in the ancient Roman delta lobe. Therefore, the description of the AD 1048 earthquake only mentioned these two main localities in which urban development were already important. In contrast, in the surrounding agricultural areas only generalized ground cracking, hydrogeological and liquefaction processes are mentioned. This is in agreement with the dominantly swampy nature of the zones in the epoch. Consequently, besides earthquake environmental effects, it is nearly impossible to obtain other macroseismic data previous to the human development of the eastern zone of the Lower Segura Depression from 11th century AD. The exception is the destruction of the "Rábitas Califales" in Guardamar del Segura built on the emergent spit-bar of Guardamar in the eastern end of the Lower Segura Depression (Fig. 5). This newly reported EAE data indicate that the entire Lower Segura Depression from Orihuela (West) to Guardamar (East) underwent significant ground shaking of intensities VIII to IX ESI-07 as proposed by Franco-Sánchez (2014). Figure 5 (2) depicts the hypothetical intensities zones and the earthquake macroseismic epicentre probably linked to the western segment of the Lower Segura Fault.

The second implication is that a presumed southward shifting of the Segura main river-channel occurred after the AD 1048 Orihuela earthquake as inferred from the palaeogeographical models proposed by Tent Manclús (2013). This fact can be preliminary interpreted as a significant earthquake environmental effect (EEE), which normally occur from intensities ≥ IX (Michetti et al., 2007) and allows to propose the location of the macroseismic epicentre on the western segment of the Lower Segura Blind Fault (Fig. 5). As aforementioned, the southwards shifting of the Segura River main-channel towards the fault trace can be interpreted as a coseismic subsidence event along the fault and m-scale uplift (bulging) to the North along the axis of El Molar anticline. Moreover any cm-scale uplift in a micro-tidal estuarine environment (< 15 cm) would facilitate the emergence of large areas and facilitate the human occupation of the zone for agricultural expansion. Following this idea, the abrupt subsidence event identified by Tent Manclús (2013) during Roman times (AD 1 – AD 200), triggering a similar shifting of the Segura River main-channel, could be also interpreted as an ancient earthquake affecting the Lower Segura Depression. In any case, these are only preliminary hypotheses that must be tested through future palaeoseismological investigations, but if eventually proved will imply recurrence periods for Torrevieja-type events of c. 800 - 1000 years in the area.

The third implication is related to environmental and building damage distribution during the well-known AD 1829 Torrevieja earthquake (Mw 6.6; IX-X EMS; Martínez Solares and Mezcua, 2002). Following the palaeogeographical reconstruction proposed in this work, it is clear that the strongest seismic damage induced by this earthquake event is focused in the eastern zone of the Lower Segura Depression affecting the localities built on the old Muslim delta channels and lobes (Fig. 5). 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. Data from Larramendi (1829) indicate that sand ejections affected an area of about 5 km^2 in the Muslim delta lobe (Eastern zone), but also about 3.2 km^2 around Orihuela in the old Roman delta lobe (Western zone). The localities of Almoradí and Benejúzar, placed in the eastern Muslin delta-lobe, 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), 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 (Emergeo, 2013, Rodríguez-Pascua *et al*., 2015). Figure 5 (3) illustrates the ESI-07 intensity zones corresponding to the AD 1829 Earthquake according to the documented building and environmental damage, compiled for the production of the Catalogue of Earthquake Geological effects in Spain (Silva and Rodríguez-Pascua, 2014). In the macroseismic maps of figure 5 the isoseismals have been delineated according to the ancient palaeogeography of the zone for both historical periods (Fig. 4).

4. Conclusions

This paper offers a geological basis on the palaeogeography of past estuarine environments described by Roman and Arab geographers in different Atlantic and Mediterranean zones in southern Spain. Palaeogeographic reconstructions developed in this paper evidence that past littoral landscapes affected by ancient and historical earthquakes were largely different to the present ones and underwent severe changes as a consequence of tsunami events (Atlantic zones) or rapid subsidence-surface uplift processes (Mediterranean zones). Most of the palaeogeographic interpretations are based on the combination of geological, historical and/or archaeological data provided by a large number of previous studies to illustrate the evident need of multidisciplinary approaches for the macroseismic analysis of ancient and historic earthquakes.

Currently, macroseismic analysis of past earthquakes in Europe are conducted through the application of the EMS-98 intensity scale (European Macroseismic Scale) largely based on historical descriptions of building damage (Grüntal, 1998). The application of this scale exclude intensity assessments based on environmental damage (i.e. coseismic landslides, liquefaction or tsunamis) and provide poor guide lines on the evaluation of induced damage by environmental earthquake effects. On the other hand, these conventional macroseismic evaluations of past earthquakes don't consider the ancient palaeogeography of the affected zones. As illustrated in this paper, a "seismic palaeogeography" is necessary to perform "realistic" approaches for past earthquakes. This will benefit the evaluation of probable site effects and intensity distributions in "populated" and "non populated areas", since the latter are out of the "capability" for conventional macroseismic investigations of past (and recent) earthquakes based on the EMS-98 scale (i.e. building damage).

The ESI-07 intensity scale (Environmental Seismic Intensity; Michetti *et al.*, 2007) provide an useful tool for the geological macroseismic assessment of ancient and poorly documented historical earthquakes. This can be applied to surface-faulting and no surface-faulting past seismic events, allowing an independent analysis of intensity distribution. In fact, the examples used in this paper are not related with surface-faulting earthquakes, but with relevant secondary earthquake effects (tsunamis, landslides or liquefaction) documented from the geological record or inferred from ancient landscape reconstructions and changes. The recently published Spanish Catalogue of Earthquake Geological Effects (Silva and Rodríguez-Pascua, 2014) gathers geological and environmental information for past and recent seismic events. This has been summarized in this paper for three outstanding examples in which the collected geological and archaeological macroseismic information clearly exceeds the scarce available historical data.

Figure 1 illustrates the present state of knowledge on the geological record of earthquake and tsunami events in the Iberian Peninsula, including ancient earthquakes. As indicated in the Figure 1 the available information for these events is of *"Quality G"*, which means (Silva and Rodríguez-Pascua, 2014): Information for events, generally not included in conventional seismic catalogues, from which the most outstanding information comes from geological analyses recently published in scientific journals (palaeoseismic and archaeoseismic research papers). These contrast with *"Quality A"* events (fully documented by epoch reports, newspapers, historians and recent geological analyses) and *"Quality B"* ones (vaguely documented by historical information, but with some geological analyses published from the late 19th century). *"Quality C"* events (vaguely documented by historical information and without geological analyses) have been not included in figure 1.

As illustrated in this paper, the geological information of *"Quality G"* events can be in the range of many of the *"Quality A"* ones, such as the AD 1829 Torrevieja earthquake (Fig. 5), documented by the epoch-field reports of Larramendi (i.e. 1829) and De Prado (1863). This is because strong seismic events, above intensity VII, are usually printed in the stratigraphy, in the landscape (Michetti *et al*., 2005) and in archaeological sites (if any).Quaternary geology (Palaeoseismology) and more recently Geoarchaeology (Archaeoseismology) are the more suitable disciplines to: (a) recover past unknown earthquakes; (b) complete the macroseismic information of poorly known historically documented events.

The three ancient events studied in this paper illustrate that (1): The realistic analysis of ancient earthquakes requires the reconstruction of old palaeogeographic scenarios based in a wide range of multidisciplinary data; (2) The palaeoseismological and archaeoseismological background data can be clearly extended beyond the classical fault-trenching analyses in the case of no-surface faulting earthquakes; (3) Off-fault data from the analyses of secondary earthquake environmental effects improve the macroseismic information in ancient non-populated areas (i.e. Michetti *et al*., 2005, 2007). The last is of application in near-field cases (*Baelo Claudia* and Orihuela), but also in the far-field (Atlantic Punic Event), providing an unique tool to study the distribution of intensity zones for ancient earthquakes and/or non-populated areas in historical ones.

Additionally, earthquake archaeology can put constrains on the directivity of earthquake archaeological effects, pointing to the geographical quadrant more prone to be located the seismic source, as in the case of *Baelo Claudia* (Giner *et al*., 2013). However in this particular case, the seismic source remains obscure, but very probably in an offshore location SSW to the ancient Roman city (Grüztner *et al*., 2012). Seismic profiles from these authors show steep submarine slopes and related slump deposits linked to N-S mapped offshore faults. Recently, Hoffmann *et al*. (2014) described something similar to the *Baelo Claudia* case: an "enigmatic tsunami" in the Arabian Sea caused by an onshore Mw 7.7 earthquake in Pakistan (> 200 km away). The first interesting issue enhanced by these authors is that minor ground shaking was sufficient to trigger an offshore slump c. 100 km away, and a subsequent tsunami, as steep slopes and loose material were present in the source area. Second, the resultant tsunami showed a very strong directivity effect (Hoffman *et al*., 2014). Similar cascade-effect processes could explain why tsunamites are observed in the Bolonia Bay only, and also why the estimated run-up is comparably large (c. 6 m height). Therefore an onshore seismic source, triggering a sort of catastrophic cascade effects cannot be rejected for the *Baelo Claudia* study case. On the contrary In the Orihuela case, for sure the Lower Segura fault zone was the responsible for the earthquake, but the particular activated segment remains unclear, likely the western segment.

Regarding to this last earthquake, the palaeogeographical analyses developed in this paper, can help to understand the Norman invasion (Vikings) suffered by Orihuela in the AD 859, after different attacks in Huelva, Sevilla and Algeciras directly from the sea (Franco Sánchez, 2014). Today the Viking assault to Orihuela is an *"historical enigma"* since the rest of the attacks of the Vikings in Spain, Portugal and the Western Mediterranean, were to littoral localities directly from the sea, but Orihuela is located about 18 km inland. Now the palaeogeography of the zone during the Muslim epoch (Fig.4) allow to explain the Viking`s ships navigated across the *"Sinus ilicitanus"* reaching the southern river-delta mouths and following upstream the Segura river and old estuarine areas towards the Muslim *Uryula* (Orihuela).

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