Holocene palaeotsunami catalogue of SW Iberia

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ABSTRACT

Many on-shore studies focused on high energy marine events occurred in the Gulf of Cadiz have been published since the 1990s. Most of the findings came from sedimentary, palaeontological and geomorphological records on estuaries, marshes, beach-barriers (spit-bars), and some coastal lowlands. Recent off-shore investigations in SW Iberia considered turbidite deposits as a proxy to recognise palaeoearthquakes in this zone. The comparison of datasets from both on-shore and off-shore records indicate that at least five tsunami events generated by strong earthquakes affected this area during the last 7000 years, previous to the more recent and well-documented 1755 AD Lisbon earthquake tsunami event. The catalogue of Holocene palaeotsunami presented here is supported by geological and geomorphological evidences, but also for archaeoseismic and palaeoseismic evidence and written reports for the more recent events occurred during historical times. The recurrence interval for these catastrophic events can be bracketed between 1200 and 1500 years.

1. Introduction

Seismic activity in the Gulf of Cadiz appears to be related to Azores–Gibraltar transform fault zone (Gloria Fault). The tectonic pattern of this area operates as a strike-slip movement in the western part (Azores) and as a north–south compression to the east (Gibraltar) (Udías et al., 1976; Buforn et al., 1988). Commonly, the 1755 Lisbon earthquake epicentre has been located 200 km southwest of San Vicente Cape (Fukao, 1973; Martínez Solares et al., 1979). Recently, however, drill core and seismic profile data suggest an incipient subduction area west of Portugal where the tsunami origin may possibly have been located (Baptista et al., 1998; Zitellini et al., 1999, 2001). Data from off-shore southern Portugal revealed a number of active faults that may represent an earthquake and tsunami hazard to the coast of SW Iberia and NW Africa (Gràcia et al., 2003a, b, 2010; Terrinha et al., 2003; Zitellini et al., 2004).

Off-shore studies are related to multidisciplinary marine geological and geophysical campaigns focused on the study of the active tectonics of SW Iberia. Recent papers have tried to highlight the potential of the turbidite record as a marine palaeoseismic indicator, as well as the correlation with the on-shore tsunamites record (Garcia Orellana et al., 2006; Vizcaino et al., 2006; Gràcia et al., 2010).

The studies focused on on-shore record of these events have also attempted to distinguish features produced by tsunami and other extreme wave events (EWE), such as severe storm surges (Lario et al., 2010). Most surveys of EWEs in the area have concentrated on: Guadalquivir (Lario et al., 1995, 2001a, b; Lario, 1996; Ruiz et al., 2004, 2005; Cáceres et al., 2006), Tinto-Odiel (Lario, 1996; Ruiz et al., 2007; Morales et al., 2008), and Guadalete (Lario et al., 1995; Lario, 1996; Dabrio et al., 1999; Luque et al., 2001, 2002) estuaries, the littoral lowland on the south-eastern coast of the Gulf of Cadiz (Luque, 2002; Whelan and Kelletat, 2003, 2005; Alonso et al., 2004; Luque et al., 2004), and the Algarve (Andrade, 1992; Dawson et al., 1996) (Fig. 1). These studies described the sedimentary record of high energy events in the Gulf of Cadiz and concluded that most of them were tsunamigenic in origin. Following this conclusion, recurrence intervals were deduced (Morales et al., 2008; Ruiz et al., 2008a). The reported sediments are usually interbedded in estuarine or spit barrier sedimentary units that act as effective sedimentary sinks, likely to preserve geomorphological features that witness the palaeoenvironmental changes. Lario et al. (2010) summarised these studies and concluded that destructive events in this area created by EWE have a periodicity of 1200–1500 y, but not all were generated by tsunamigenic events.

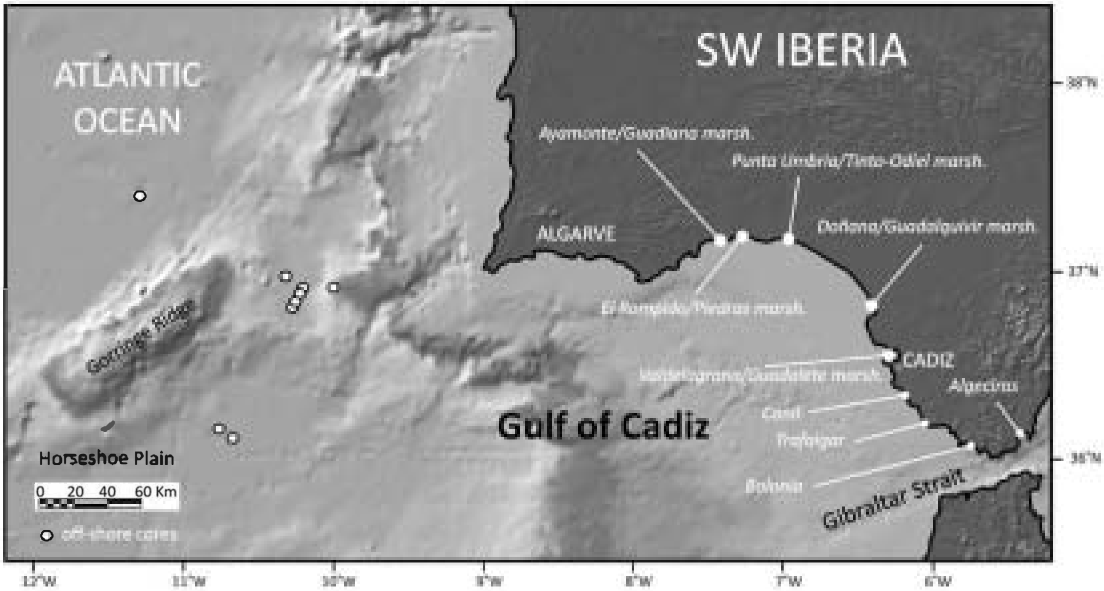

Fig. 1. Location of sites discussed in the text.

2. Off-shore record of earthquake-triggered turbidites

Although some work suggested the presence of earthquake-triggered turbidites in this area (Thomson and Weaver, 1994; Lebreiro et al., 1997) it was only recently that the first paper about turbidite seismology in the SW Iberian margin appeared, studying the sediments related to 20th century earthquakes (Garcia-Orellana et al., 2006). Vizcaino et al. (2006) studied four gravity cores and found some events recorded as debris flows and turbidites that allowed estimation of a recurrence interval of mass movement deposits of less than 2000 y Gracia et al. (2010) studied this data from sediment cores and identified eleven turbidite events during the Holocene, but they used only the seven most widespread turbidite events (i.e. present in two or more sites) as a proxy to recognize palaeoearthquakes. In addition to the 20th century events, the ones related to large earthquakes (Mw $\geq$ 8.0) are E3 (300–560 cal BP), E5 (1980–2280 cal BP), E6 (4960–5510 cal BP), E8 (6690–6985 cal BP) and E10 (8715–9015 cal BP).

3. Record of EWE on-shore

Geomorphological and sedimentological features generated by extreme wave events (EWE) are common along the coasts of the Gulf of Cadiz, and have been assigned to either tsunami or storm surges (Lario et al., 2010). During recent years, numerous studies have tried to characterise the sedimentological features of tsunami and storm events, and concluded that the deposits generated by both types of events exhibit similar textural, structural and sedimentary properties (Morton et al., 2007, 2008a, 2008b; Jaffe et al., 2008). A common conclusion is that, as such deposits indicate only the occurrence of a high energy event, the marine origin of the event, and the inundation of coastal areas by sea water, they can only be referred to as extreme wave events or EWE (Kortekaas, 2002; Kortekaas and Dawson, 2007; Bridge, 2008; Jaffe et al., 2008; Switzer, 2008; Switzer and Jones, 2008; Lario et al., 2010). With this premise, Lario et al. (2010) reviewed all literature about high energy events in Gulf of Cadiz and concluded that at least seven EWEs capable of inducing widespread, dramatic geological, geomorphological and sedimentological changes have hit the SW coasts of the Iberian Peninsula in the last 7000 y, leaving recognisable, but difficult to interpret, features. These events are dated at ca.7000 cal BP, ca.5700–5300 cal BP, ca.4500–4100 cal BP, ca.3900–3700 cal BP, ca.2700–2200 cal BP, ca.2000 cal BP, ca.1500 cal BP and 1755 AD (Lisbon earthquake).

Baptista and Miranda (2009) presented a revision of the Portuguese catalogue of tsunami and included a list of high energy events that affected the Spanish coast. However, they listed only some of the high energy events cited in the literature, although some of them are not clearly identified as tsunamigenic.

4. Discussion: on-shore evidence of palaeotsunami and their correlation with the off-shore record

The record of earthquake-triggered turbidites off-shore in this area (Gràcia et al., 2010) and the extreme wave events (EWE) that reached the SW coast of Iberia (Lario et al., 2010) allow correlation of these events, assignment of a tsunamigenic origin to some of the off-shore deposits, and identification of those regional events affecting the entire study area, generated by seismic sources in the Gulf of Cadiz area (Fig. 2).

The oldest EWE is recorded in Valdelagrana spit barrier system (Lario, 1996). Data such as increased magnetic susceptibility suggest the occurrence of an intervening tsunami event, but this is not validated by other complementary data on-shore. This event has an age of ca.7000–6800 cal BP, and can be reasonably correlated in age to the E8-turbidite event (Gràcia et al., 2010), Therefore, a tsunamigenic origin for the on-shore deposits is possible.

An EWE in Valdelagrana and Punta Umbría spit barrier systems is described ca. 5700–5600 cal BP, and interpreted in two studies as storm-generated (Lario, 1996; Ruiz et al., 2007). Similar deposits occurring at the Doñana marshlands have been assigned to a tsunami at 5300 cal BP (Ruiz et al., 2005; Cáceres et al., 2006). These data indicate the occurrence of major palaeo-EWEs that swept broad areas of the SW Iberian coast, causing relevant geomorphological changes and leaving deposits in the stratigraphic record of particularly vulnerable coastal environments. Lario et al. (2010) suggest that all these suspect tsunamigenic deposits may correspond to a unique singular event. The discrepancy in the reported numerical ages comes from the use of different biological taxa for radiocarbon dating, from the limited amount of radiocarbon samples analysed, and from the use of the same reservoir effect for differently affected coastal environments. Gràcia et al. (2010) noted a large earthquake

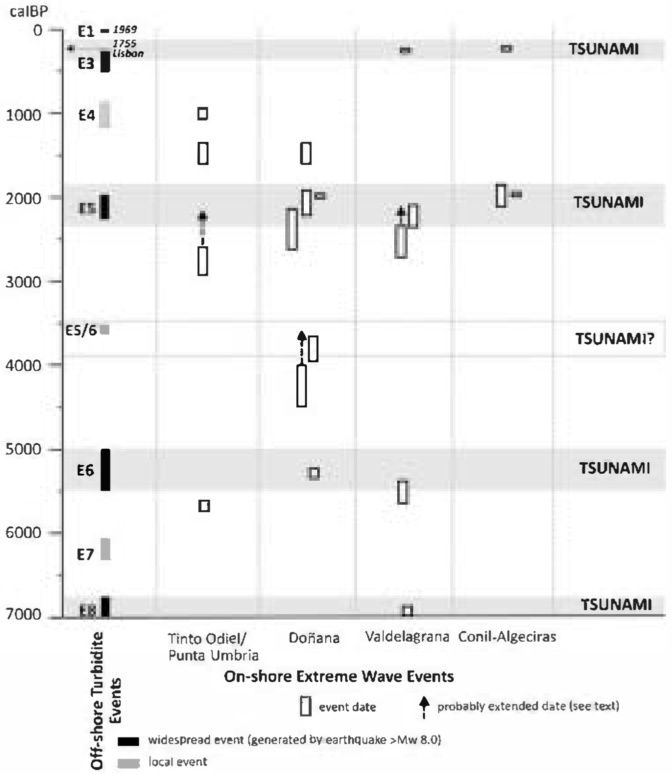

Fig. 2. Correlation of on-shore EWE (summarised in Lario et al., 2010) and off-shore turbidites with tsunamigenic origin (Vizcaino et al., 2006; Gràcia et al., 2010).

linked with the E6-turbidite event, suggesting the generation of a tsunami that affected the coast ca.5500–5000 cal BP, a similar time-span as discussed above.

Between ca. 4500–4100 cal BP, a large EWE in the Doñana marshlands was recorded as an interbedded marine layer within the inner marsh deposits of the Guadalquivir river estuary. This event caused major geomorphological changes, triggering the breaching and sudden erosion of the Doñana spit barrier. However, the sedimentary record does not allow distinguishing between tsunami and severe storm for the causative EWE (Lario et al., 1995, 2010; Lario, 1996; Ruiz et al., 2005; Cáceres et al., 2006).

A younger, ca. 3900–3700 cal BP, EWE has been also described and interpreted as a tsunami event by Ruiz et al. (2005) and Cáceres et al. (2006). These authors concluded that this is an independent event because their deposits are in an erosive unconformable relation to those generated by the former EWE (4500–4100 cal BP). In any case, the record of this EWE seems to be more local, as it has not been reported from other areas of the Gulf of Cadiz (Lario et al., 2010). In addition, there is no record of widespread turbidite deposits generated by a strong earthquake of this age (Gràcia et al., 2010). Local earthquake-related turbidite deposits have been reported by Vizcaino et al. (2006) at ca.3600 cal BP. These have been labelled as E5/6-turbidite in Fig. 2. In this case, it is possible to assign the event to a moderate seismic event (Mw < 8.0) that generated a local tsunami at ca.3600 cal BP. As this same coastal area was affected by a previous large EWE, the magnitude of the tsunami could be smaller than the previous ones related with stronger seismic events (Mw ≥ 8.0), but its apparent effects might be over-magnified because the coast was already largely damaged.

The largest record of EWE deposits recorded along the Gulf of Cadiz coast have been noted in many places along shore, such as the key-points of Punta Umbría, Doñana, and Valdelagrana (Lario et al., 1995, 2001a, 2001b, 2002; Lario, 1996; Dabrio et al., 1999; Luque et al., 2002; Ruiz et al., 2004, 2008b; Cáceres et al., 2006). Widespread occurrence of EWE features along the coast (breaching of spit barriers, intruding sandy layers with marine bioclasts in the inner estuaries, chenier development, occurrence of washover fans) and other effects of regional extent, such as the reorganisation of the back barrier drainage patterns of estuaries (e.g. Tinto-Odiel), coupled to an historically documented tsunami (Galbis, 1932) support this assumption. Although radiocarbon data range from 2700 to 2200 cal BP, age discrepancies for this apparently single event are probably due to flaws in the radiocarbon dating method. If this chronology refers to the pre-tsunami sediments, probably the youngest age for this event would be the most accurate. In Doñana, similar deposits are dated ca.2000 cal BP (Ruiz et al., 2004: Cáceres et al., 2006) by correlation with the existing catalogues (i.e. Galbis, 1932). Between Conil and Algeciras, tsunamigenic deposits ca.2000 cal BP have been suggested (Alonso et al., 2004; Arteaga and Gónzalez, 2004), but Lario et al. (2010) pointed that it is also possible that a given particular event was assigned to different ages in separate localities (Galbis, 1932). For instance, the events reported between 245 and 209 BC were compiled from diverse sources (Moreira de Mendoça, 1758) and may well correspond to the same event, assigned erroneously to different ages in separate localities. It must be also considered that, although Galbis (1932) reported a tsunami at 60 BC, both he and the original compiling author (Moreira de Mendoça, 1758) clearly reported that the tsunami only affected the Atlantic coasts of Portugal and Spain (Galicia), with no reports from the Gulf of Cadiz. In relation to the plausible off-shore record of this event, an E5-turbidite event has been dated ca.1980–2280 cal BP, bracketing the age (ca.2000–2200 cal BP) for the aforementioned tsunami event.

Becker-Heidmann et al. (2007) noted a tsunami after AD 1450 in *Baelo Claudia*, based on some charcoal remains. However, Reicherter at al. (2010) concluded that, "the deposits cannot clearly be assigned to tsunami action, moreover the dating of the charcoal does not lead to a certain interpretative result".

The well-documented 1755 Lisbon tsunami-earthquake is clearly associated with the E3-turbidite in the off-shore record (Gràcia et al., 2010). This recent EWE has an abundant historical written record for more than 30 sites along the south-western Spanish shores, complemented by extensive analyses of its geological effects on the Gulf of Cadiz area (Campos, 1991; Dabrio et al., 1999; Martinez Solares, 2001; Luque et al., 2001, 2004; Luque, 2002; Morales et al., 2008; Lario et al., 2010).

Finally, the last relevant event in the area (1969 AD Horseshoe Earthquake: Mw 8.0) triggered the E1-turbidite event. However, there is no associated on-shore geological record.

5. Conclusions: on-shore catalogue of palaeotsunami and recurrence intervals

Comparison of the on-shore geological record with the recently published off-shore records of palaeotsunami in the SW coastal area of the Iberian Peninsula (Gulf of Cadiz) makes it possible to identify five main EWE's generated by tsunami affecting the area for the last 7000 y, prior to the well-known 1755 Lisbon tsunami-earthquake. These five events have calibrated ages of ca.7000–6800 cal BP, ca.5500–5000 cal BP, ca. 3900–3600 cal BP and ca.2200–2000 cal BP (Fig. 2), consistent with the off-shore record of earthquake-related turbidite deposits (Gràcia et al., 2010). One of these events is historically documented and noted in the existing seismic and tsunami catalogues for Spain (i.e. Galbis, 1932; Martínez Solares and Mezcua, 2002). A single event occurred during Roman times (ca.2000–2200 cal BP event) affecting the entire Gulf of Cadiz area (Fig. 2). At some of the documented points (i.e. Algeciras and Bolonia, Fig. 1) apparent archaeoseismic evidence is reported (Alonso et al., 2004; Arteaga and González, 2004) for this event, and its calibrated age is close to the archaeological evidence of earthquake occurrence at the ancient Roman city of *Baelo Claudia* in Bolonia Bay (Silva et al., 2005, 2009; Becker-Heidmann et al., 2007). However these authors did not find clear evidence of intervening marine flooding within the damaged Roman ruins. In any case, rejection is not possible since the evidence for the first archaeoseismic event at this site (60–90 AD) is largely based on the occurrence of a widespread demolition horizon, rebuilding and reinforcement evidence in city walls, and local deformations. Therefore, the development of a widespread demolition horizon for city rebuilding could mask any evidence of flooding. Silva et al. (2005) noted, in one of the sedimentary cores at the Theatre area, a thin marine layer at +12 m above sea-level, beyond the thick horizon of demolition. In addition, new radiocarbon ages for the damaged basal zone of the Isis Temple at +10 m above sea-level have consistent ^{14}C dates between ca 1900–2000 BP, from the large amount of marine gastropods incorporated in the massive ruin deposits (Grützner et al., 2010). Therefore, the occurrence of an intervening tsunami-related flooding in the destruction of *Baelo Claudia* during the late 1st Century AD is still an open debate.

The remainder of the more ancient on-shore tsunami evidence catalogued in this work are mainly supported by sedimentological and locally geomorphological data. Their classification and cataloguing within the ESI-2007 Intensity Scale (Michetti et al., 2007) will provide relevant data for further realistic seismic hazard analyses in the southern Atlantic coastal shores of the Iberian Peninsula, aside from the natural vulnerability of these coastal areas for tsunami flooding. Taking into account the bracketed calibrated ages for the palaeotsunami catalogued in this paper, the recurrence interval for damaging tsunamis in the Gulf of Cadiz area can be broadly bracketed at 1200–1500 y. However, the causative seismic source, or sources, for damaging tsunami in the area remains obscure, even for the case of the more recent historical event, the well-documented 1755 AD Lisbon earthquake tsunami.

The catalogue of palaeotsunami presented in this work is supported by on-shore and off-shore geological and geomorphological evidence, covering the last 7000 y. The more recent events also incorporate archaeoseismic evidence for Roman times, and historical written reports (Lisbon Event), which has been recently checked and validated with different palaeoseismological and archaeoseismological analyses.

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