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D23: model of recurrence interval for the large magnitude earthquake and tsunami events occurred in the Gulf of Cadiz

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WP6 - Paleotsunami and Paleoseismic records

D23: Model of recurrence interval for the large magnitude earthquake and tsunami events occurred in the Gulf of Cadiz

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Summary

The final objective of this paleoseismic and paleotsunami study is to propose a model of recurrence interval for the large magnitude earthquake and tsunami events occurred in the Gulf of Cadiz during the Holocene (i.e. instrumental, historical, pre-historical and geological times), based on an integrated onshore (WP6 Task 6.1) and offshore (WP6 Task 6.2) approach. We first present the main events identified onshore (extreme wave events and tsunamites) and offshore (sismo-turbidites). Secondly, we discuss how they fit with the published catalogues of instrumental and historical earthquakes and tsunamis. Finally, we define a correlation onshore and offshore, to propose a recurrence rate for earthquakes and tsunamis in the Gulf of Cadiz, with implications for the assessment of geo-hazards in the SW Iberian Margin.

Extreme wave events (EWE) generated by storm or tsunamis left a number of recognisable signatures in the Holocene sedimentary archive of the coastal zone of the

broad Gulf of Cadiz. Despite the difficulties in interpreting the sedimentary and geomorphological diagnostic features, in ascribing storm or tsunami source-mechanisms and evaluating the accuracy of the chronology, the onshore geological record indicates that at least seven EWE impacted this coast with severe intensity since 7000 cal yrs BP, producing dramatic geological, geomorphological and sedimentological changes. It is uncertain whether all these EWEs were produced by tsunamis or (at least partly) by storms and the regional-local scale of the inundations is not fully understood at the present state of knowledge. A rough estimate of 1200-1500 yr average period separating widespread high intensity and destructive EWE seems to emerge from the data studied. Not all the recorded EWE (either regional or local) are related with tsunamis and this figure should be taken with caution. In the case of the Portuguese coast, the geological record suggests that the average return period of extreme and regional events could be somewhat larger, of the order of 2000 years.

Regarding the offshore deposits, age correlation together with textural, mineralogical, physical properties and geochemical signatures reveals a total of 7 widespread turbidite events for the Holocene. Precise dating of the most recent turbidite event (E1) based on ^{210}Pb and ^{137}Cs geochronology provides an age of AD 1971 ± 3. This age corresponds to a high-magnitude instrumental earthquake in the region: the 1969 Horseshoe Earthquake (Mw 8.0). Calibrated ^{14}C ages of subsequent widespread turbidite events (E3 and E5) correlate with the dates of important historical earthquakes and paleotsunami deposits in the Gulf of Cadiz area, such as AD 1755 and 218 BC, respectively. If older synchronous events (E6, E8, and E10) with ages ranging from 4960-5510 yr BP to 8715-9015 yr BP are also taken into account, a great earthquake recurrence interval of about 1800 years is obtained for the Holocene. Our correlations suggest that the turbidite record may be considered as a proxy for paleoseismic activity in low-convergence rate margins, and a valuable complementary tool in earthquake and tsunami hazard assessment along the coasts of the Iberian Peninsula and North Africa.

A. Onshore Extreme Wave Events

1. Introduction

A number of features formed in the Holocene onshore sedimentary archive and coastal geomorphology of the broad Gulf of Cadiz have been interpreted by several authors as fingerprints of **Extreme Wave Events (EWE**) generated by storm or tsunamis. It should be noted that to a large extent these interpretations heavily rely upon expert judgement and lack objective validation given the inexistency or limited quality of coeval independent data. Moreover, and especially since the Christmas 2004 Sumatra event, a number of features along this coastal fringe, either previously attributed to storm activity or newly found and studied, have been preferably (re-) interpreted as related to tsunami forcing, but the strength of the scientific reasoning providing support to such origin is in many cases clearly insufficient.

Further complications arise from the dating methods used in these studies (and underlying principles controlling the comparability of reported ages: e.g. luminescence, ^{210}Pb, ^{137}Cs, ^{14}C, archaeological contexts) in different locations and environmental settings (e.g. carbonate-dominated *versus* siliciclastic coastal systems, prograding *versus* eroding and rocky *versus* depositional coasts, different distribution of upwelling intensity in time and space), time of the research (e.g. the accuracy of ^{14}C methods substantially increased in the last three decades and the influence in apparent ageing determined by local and global reservoir effects of both the marine and terrestrial environments are not at all conveniently understood in this part of the world) and use of different carriers (e.g. shells, wood, charcoal, particulate organic matter, bulk sediment, quartz grains). Altogether, these variables introduce uncertainties and influence the accuracy and precision of age constrains. This may be especially problematic in the present case, where the value of tsunami deposits as accurate synchronous markers at the regional scale may be strongly compromised, just like their use to discriminate between impacts related with local sources and localized impacts, from regional events, necessarily of larger magnitude and extension of cost affected.

2. Results

Notwithstanding these difficulties, the combination of results from geological/geomorphological research developed under the NEAREST project with previously published material yielded the information compiled in Table 1 (from Lario et al., 2010). This can be summarized as follows for discussing the time of emplacement of sedimentological and geomorphological evidences along the coast under study that most probably represent activity of tsunami-borne EWE.

This summary represents the state of the art at the date of this deliverable and reflects essentially the expert judgement of the NEAREST WP 6 research team.

- **ca. 7000 calBP**. EWE recorded in Valdelagrana spit barrier system (Lario, 1996). Some data suggest a tsunami event, but neither conclusive nor contemporary evidences in other areas of the Gulf of Cadiz have been reported so far. Sheffers and Kelletat (2005), a paper that has been extensively cited in catalogues, ascribe to a tsunami of approximately the same age a number of scattered megaclasts in the rocky coast near Lisbon, Portugal, a location somewhat far from the geographical area studied in this workpackage. Regardless the location, we chose to discard this reference and event in result of: (1) inaccuracy of datings reported; (2) studies undertaken under the NEAREST project cast serious doubts on the displacement of those blocks, which are better interpreted as near in-situ karst collapse and downwearing remnants, slightly displaced by gravity rather than clasts transported inland by any other mechanisms.

- **ca. 5700-5300 calBP**. EWE in Valdelagrana and Punta Umbría spit barrier systems at ca. 5700-5600 calBP and interpreted in both cases as storm-generated (Lario, 1996; Ruiz et al., 2007). Similar deposits reported in Doñana have been assigned to a **tsunami at 5300 calBP** (Ruiz et al., 2005; Cáceres et al., 2006). The described sedimentary features are not conclusive for tsunamis, but there is evidence of major EWE that swept broad areas of the SW Iberian coast causing dramatic geomorphological changes and leaving deposits in some places. We suggest that all these deposits may correspond to the same event and that the disparity in age results from using different mollusc taxa for radiocarbon dating, added by the low number of samples analyzed and the use of the same reservoir effect in distinct environments.

- **ca. 4500-4100 calBP**. One large EWE reported in Doñana marshlands and recorded as a marine layer intercalated in the inner marsh deposits of the estuary. The event caused major geomorphological changes (breaching and erosion) in the Doñana spit barrier. The sedimentary record does not allow distinguishing between tsunami and severe storm as the cause of this EWE (Lario et al., 1995; Lario, 1996; Ruiz et al., 2005; Cáceres et al., 2006).

- **ca. 3900-3700 calBP**. One EWE has been described and interpreted as a tsunami event in Doñana spit barrier. Despite the problems of radiocarbon dating discussed above, it has been concluded that this is an independent event because it eroded sediment of the former EWE deposits (4500-4100 cal BP). The magnitude of the EWE could be smaller than the previous ones, but its effects might have been magnified because the spit was already badly damaged. In any case, the record of this EWE seems to be more local, as it has not been reported in other areas of the Gulf of Cadiz (Ruiz et al., 2005; Cáceres et al., 2006).

- ca. 2700-2200 calBP. A number of cites refer to an EWE of this range of ages in many places alongshore (Punta Umbría, Doñana, Valdelagrana...) (Lario et al., 1995; Lario, 1996; Dabrio et al., 1999; Lario et al., 2001, 2002; Luque et al., 2002; Cáceres et al., 2006; Ruiz et al., 2004, 2008a). The effects of this EWE were: breaching and erosion of spit barriers, introduction of sandy layers with marine bioclasts in the inner space of estuaries, and chenier development suggesting either tsunami or storm surges as the responsible agent. However, the occurrence of washover fans with two or three superimposed fining upward sedimentary units containing shells of marine molluscs, rip-up clasts and mud cups strongly suggest a tsunamigenic origin for these deposits. Widespread occurrence of EWE features along the coast and other effects of regional extent, such as the reorganization of the back barrier drainage patterns of estuaries (e.g. Tinto-Odiel), coupled to historical evidence of a tsunami in Galbis' (1932) catalogue, support this assumption. Age discrepancies for this presumably single event are probably due to flaws in the radiocarbon dating method, or even to the coincidence of a tsunami during a period of climatic instability and strong storm surges that increased the effects of the EWE.

The correlation with published catalogues of historical earthquakes (Galbis, 1932; Campos, 1991) is very often imprecise because a single tsunami can produce separate features, vertically-superposed fining upward sequences or coarse-grained units, likely to be considered of different ages, assuming that they were deposited by separate events. On the other hand, it is also possible that a given 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 perfectly well correspond to the same event but erroneously assigned to different ages in separate localities.

Andrade et al. (2004) dated a number of detached marsh beaches in the Ria Formosa lagoon (Faro, Algarve) from 1305-1205 cal BC, 805-780 cal BC, 515-400 cal BC, and 880-990 cal AD, and most of these dates (3255-3155 cal BP, 2465-2350 cal BP and 2755-2730 cal BP) roughly correspond to the time interval heading this paragraph. The ages reported at this location should be taken as maximum estimates because they refer to organic material dispersed in sediment of the marsh immediately underlying the sand of detached beaches (which in cases occur stacked and separated by marsh deposits), field evidences suggesting that limited substrate erosion may have occurred just prior the emplacement of the sand. In their study, Andrade et al. (2004) favour a multiple storm-triggered origin for the Faro marsh detached beaches. However, the knowledge update and synthesis on EWE affecting the region of the Golf of Cadiz in the NEAREST project, provides grounds to suggest that the temporal coincidence between features described in both the Faro coast and Spanish shores, within the broad time interval of ca. 2700-2200 calBP may be related to one or several tsunami events, or multiple-source (tsunami and storm) EWE.

- **ca. 2000 calBP**. The occurrence in Doñana of chenier deposits of this age suggests an EWE; the basal erosion surface, presence of marine fauna in lagoonal sediment and correlation with the Galbis (1932) catalogue of historical earthquakes support the interpretation of this EWE as a tsunami.

The same event has been invoked in Bolonia Bay (Alonso et al., 2004) to interpret layers of bioclastic sand and in Algeciras Bay (Arteaga & González, 2004), where sedimentary features point more definitely to the tsunamigenic nature of the event; however, given the preliminary nature of the latter case-study, it is more cautious to assign it provisionally to an EWE of undetermined nature. It must be also considered that, although Galbis (1932) - among others - report a tsunami at 60 BC, both this author and the original compiling author (Moreira de Mendoça, 1758) indicate that the tsunami was only felt in the Atlantic coast of Portugal and Spain (Galicia), with no reports referring the Gulf of Cadiz.

Finally, the 2300-2200 calBP tsunami deposits reported from Valdelagrana spit barrier may also fit in this time period because the age will correspond just with the pre-tsunami surface.

- ca. 1500 calBP. Bioclastic sandy silts drilled in Doñana marshlands have been interpreted as tsunamigenic following correlation with the seismic catalogue (Ruiz et al., 2006) and probably correlate to the same event that Rodriguez Vidal et al. (2008) dated from 1700 cal BP. However, considering that the sedimentological data are inconclusive, and the local occurrence of these deposits, this layer may represent a EWE with limited impact only.

- 1755 AD Lisbon earthquake and tsunami. There is an ample historical documentary record of the geological effects of this EWE in over 35 sites along the southern Portuguese, south-western Spanish and Atlantic Moroccan shores, and its geological effects on the Gulf of Cadiz have been extensively reported (e.g. Campos, 1991; Andrade, 1992; Martín Solares, 2001; Luque, 2002; Allen, 2003; Andrade et al., 2003; Dawson et al., 2005; Kortekaas & Dawson, 2007; Costa et al., 2008; 2009; Andrade et al., 2010; Cunha et al., 2010; Dinis et al., 2010). Despite of the wide spatial coverage of the flooding described by eye-witnesses, there is not a continuous sedimentary record of this event (Luque et al., 2001, 2004; Luque, 2002). Historical maps and written documents support the tsunamigenic interpretation of the sedimentary units deposited during this event in Valdelagrana

(Luque et al., 2001). These sequences can be used also as reference to identify tsunami deposits in other areas or study sites sharing similarities in morphology, source materials and long-term morphological evolution. There are reports of the geological impacts of the 1755 Lisbon tsunami in Tinto-Odiel estuary (Morales et al., 2008), Valdelagrana spit and Guadalete estuary (Dabrio et al., 1999, Luque et al., 2001), and Conil (Luque et al., 2004) along the Spanish coastal ribbon. In the Algarve coast of Portugal, reliable sedimentary evidence of this flooding has been described in the Sagres-Lagos region (Martinhal, Barranco, Furnas, Boca do Rio lowlands, cf. Dawson et al., 1995; Hindson et al.,1996, 1999; Kortekaas et al., 1998; Andrade & Hindson,1999; Andrade et al., 1997, 1998, 2003, 2004, 2010); Kortekaas, 2002; Allen, 2003; da Silva et al., 2006; Kortekaas & Dawson, 2007; Costa et al., 2008, 2009, 2010C,2010D; Hindson & Andrade, 2009; Cunha et al., 2010; Oliveira et al., 2008; 2009; Oliveira, 2010), central (Alcantarilha and Salgados filled estuary/lagoon and Faro marshes, e.g. Dinis et al., 2010A; Costa et al., 2009, 2010A, 2010B, 2010C, 2010D, 2010E; Andrade et al., 2004) and eastern Algarve (Tavira backbarrier, Andrade, 1992).

-1722 AD and 1761 AD earthquakes and tsunamis. Despite the large intensity of the AD 1722 and AD 1761 tsunamis reported in historical records, geological research failed to ascribe any correspondent sedimentary signatures along the Gulf of Cadiz. This may be an effect of a local character of the former and of the time proximity between both these events and the great AD 1755 tsunami, which may make their signatures undistinguishable at the present resolution capability of dating methods.

Other sites where date control of the EWE or tsunami or storm origin are less certain, have been cited along this coastal segment in Trafalgar (Whelan & Kelletat, 2003; Alonso et al., 2004), Tarifa (Alonso et al., 2004) and Rabat (Mahmmdi et al., 2008).

Table 1. *EWE (tsunamis and storm deposits) reported in the wide Gulf of Cadiz.*

Age	Sedimentological / geomorphological features	Reference	Original authors interpretation	Data support/problems
Barranco and Furnas lowlands, western Algarve				
(Endolithic shells) 250 ± 40 BP 360 ± 40 BP	Boulder/cobble deposits located landward, beyond reach of extreme storms; incrusting and endolithic faunas of shallow marine environment; association with marine-facies sand layer	Costa et al. (2008; 2009; 2010c;2010d); Oliveira (2010); Oliveira et al. (2008) and inedited work developed under NEAREST Project.	AD 1755 tsunami	Reservoir effects in endolithic shells debatable
Boca do Rio and Martinhal lowlands, western Algarve				
TL: AD1734±69 OSL: AD1525±34 AD1531±34 AD1575±33 AD1699±23 AD1677±26 AD1648±21 AD1633±23 AD 1597-1442 AD 600 AD 1921 1204 BC ^{137}Cs & ^{210}Pb: AD 1753	Extensive sand laminae with boulders, rip-up clasts, erosive base, wide lateral extensión, fining and thinnig up and inland, large run-in distance, marine macro and microfauna, marine geochemical proxies, microtextural features in quartz grains, texture, structures, embedded in estuarine-lagoonal sediment	Allen (2003); Andrade&Hindson (1999); Andrade et al.(1997; 1998; 2003; 2004; 2010); Costa et al. (2009; 2010c;2010d); Cunha et al. (2010).da Silva et al.(2006); Dawson et al. (1995); Hindson et al. (1996; 1999); Hindson & Andrade (2009); Kortekaas (2002); Kortekaas & Dawson (2007); Kortekaas et al. (1998); Oliveira et al.(2009) and inedited work developed under NEAREST Project	AD 1755 tsunami	
Alcantarilha estuary, central Algarve				
Not objectively determined yet, deduced by lateral correlation and similarity with Salgados	Marine sand fan with marine macro-fauna embedded& covering estuarine sediment, erosive base, limited lateral extension, large run-in.	Dinis et al. (2010a) and inedited work developed under NEAREST Project	AD 1755 tsunami	No OSL and ^{14}C data available yet, chronology supporting age, limited sedimentological & paleoecological results and coring
Salgados lagoon, central Algarve				
^{137}Cs & ^{210}Pb 18th century AD	Marine sand fan with micro- and macro-marine fauna embedded in lagoon sediment, erosive base, wide lateral extension, fining upward&inland.	Costa et al. (2009; 2010a; 2010b; 2010c; 2010d; 2010e) and inedited work developed under NEAREST Project	AD 1755 tsunami	Chronology resting upon limited ^{210}Pb and ^{137}Cs studies
Faro barrier and marshes, central Algarve				
1305-1205 cal BC 805-780 cal BC 515-400 cal BC 880-990 cal AD	Chenier-like chain of sand detached beaches with marine fauna partially outcropping and embedded in marsh sediment. Erosive base, limited lateral continuity.	Andrade et al.(2004)	Storms, <u>not tsunami</u>	^{14}C dating problematic, limited study of long term and permanent sedimentation regime, por samplin density of marsh surface.Though debatable, a sunami origin cannot be discarded for part of these events
Tavira barrier island (Ria Formosa, Eastern Algarve)				
TL: AD 1743±49 (inedited date obtained by R. Parish)	Marine sand lamina with micro- and macro-marine fauna embedded in lagoon sediment, erosive base; multiple washovers preserved in backbarrier geomorphology,	Andrade (1992)	AD 1755 tsunami	Work not replicated in the same island chain, limited dating results
Punta Umbría spit barrier/ Tinto-Odiel marshland				
5705 calBP	Sands with micro- and macro- marine shells	(Ruiz et al., 2007)	Storm, <u>not</u> tsunami	
2700-2400 calBP	Spit barrier breaching and reorganisation of the back-barrier drainage system	(Lario, 1996)	Storm surge	
2000 calBP-act. 1531 AD 1755 AD	Five HEL (High Energy Levels) characterized by erosional bottom, shell accumulation and sand, muddy-sand deposits	(Morales et al., 2008)	Tsunamis	Probably 1755 AD tsunami record (HEL-2) and a younger storm record (HEL-1).
Doñana spit barrier / Guadalquivir Marshland				
5310 calBP	Fine-grained deposits with shell fragments, breaching of the spit barrier, chenier	(Ruiz et al. 2005, Cáceres et al., 2006)	Tsunami	Correlation with other authors

	development			
4500-4200 calBP	Spit barrier breaching	(LARIO ET AL.,1995; LARIO, 1996)	Storm surge	
4200-4100 calBP	Deposits with marine fauna in the estuary	(RUIZ ET AL. 2005)	Tsunami & storms	Correlation with other authors
4200-4100 calBP	Cheniers development and fine-grained deposits	(CÁCERES ET AL., 2006)	Tsunami	Correlation with other authors
3900-3700 calBP	Cheniers development and spit barrier breaching + erosion the lagoon and in old cheniers deposits	(RUIZ ET AL. 2005, CACERES ET AL., 2006)	Tsunami	Correlation with other authors
2600-2500 calBP	Sand layer with marine fauna between estuarine deposits, erosional base, high magnetic susceptibility. Spit barrier erosion	(LARIO, 1996; LARIO ET AL., 2001, 2002)	Tsunami	Historical seismic catalogue Conjunction of sedimentological features
2700-2400 calBP	Spit barrier erosion and breaching	(LARIO ET AL., 1995, LARIO, 1996)	Storm surges	Climatic instability
2700-2210 calBP	Chenier sedimentation	(RUIZ ET AL., 2008A)	Tsunami	Correlation with seismic catalogue
2400-2200 calBP	Silt and sand with marine and estuarine fauna. Spit barrier breaching	(RUIZ ET AL., 2004)	High energy event	
2400-2250 calBP	Spit barrier erosion and breaching	(CÁCERES ET AL., 2006)	Tsunami	Correlation with other authors or seismic catalogue
ca.2000 calBP	Chenier development	(RUIZ ET AL., 2004)	High energy event	
2020-1990 calBP	Erosion of the lagoon deposits, input of marine fauna and chenier accumulation	(CÁCERES ET AL., 2006)	Tsunami	Correlation with other authors or seismic catalogue
1560-1510 calBP	Bioclastic sandy silts above erosive surface	(RUIZ ET AL., 2006) (cited as 1700 calBP by RODRIGUEZ VIDAL ET AL., 2008)	Tsunami	Historical seismic catalogue
Valdelagrana spit barrier/ Guadalete marshland				
ca.7000 calBP	Input of coarse sediment (sands), marine shell fragments and increase in magnetic susceptibility	(LARIO, 1996)	Storm	
ca.5600 calBP	Input of coarse sediment (sands), marine shell fragments and increase in magnetic susceptibility	(LARIO, 1996)	Storm	
2700-2400 calBP	Spit barrier breaching and reorganisation of the back-barrier drainage system	(LARIO ET AL., 1995; LARIO, 1996; DABRIO ET AL., 2000)	High energy event	
2300-2200 calBP	Washover fans, repeated fining upward sequence (2 to 3 times), marine shell fragments, armed mounted clasts, erosional lower limit	(LUQUE ET AL., 2002)	Tsunami	Concluding characteristics of the deposits
1755 AD	Washover fans, repeated fining upward sequence (3 to 4 times), marine shell fragments, armed mounted clasts, erosional lower limit.	(LUQUE ET AL., 2001)	Tsunami	Concluding characteristics of the deposits. Dated by historical documents and historical maps
1755 AD	Breaching of spit barrier and washover fans	(DABRIO ET AL., 1999)	Tsunami	Dated by historical documents and maps
Conil-Algeciras coast				
2150-1825 calBP	Bolonia. Coarse sand with bioclasts	(ALONSO ET AL., 2004)	Tsunami	Correlation with the Baelo Claudia earthquake
ca.50 AD	Carteia, Algeciras. Coarse sandy layer, fining upward sequence, mounted clast, bioclasts, calcareous rhodolites, erosional lower limit	(ARTEAGA & GONZÁLEZ , 2004)	High energy event, probably a tsunami	Dated by roman archaeological remains context. Sedimentary characteristics close to those of tsunami deposits
1755 AD?	Trafalgar cape. Large rock blocks oriented and imbricate	(WHELAN & KELLETAT, 2003; ALONSO ET AL., 2004; WHELAN & KELLETAT, 2005)	Tsunami associated to the 1755 Lisbon earthquake	No accurate chronology
1755 AD?	Los Lances beach, Tarifa. Washover fans	(ALONSO ET AL., 2004)	Tsunami associated to the 1755 Lisbon earthquake	No sedimentological data No accurate chronology
1755 AD	Conil. Washover fans	(LUQUE ET AL., 2004)	Tsunami associated to the 1755 Lisbon earthquake	Dated by historical documents and maps
Morocco Atlantic coast				
Not determined	Rabat coast: single and aligned and imbricate megaclasts sitting on top of cliffs	MHAMMDI ET AL.(2008)	1755 tsunami	No chronology at all
149.12±0.45 pMC <113.09±0.37pMC	Moulay Bousselham Lagoon: thin discontinuous marine sand layer embedded within lagoonal mud	Inedited work developed under NEAREST Project	Storm?	Limited field data and sediment characterization and poor chronological constrains

B. Offshore Turbidite Events

1. Introduction

In the SW Iberian Margin excluding special climatic events, earthquakes are the most likely triggering mechanism for synchronous, widely-spaced distributed turbidites during the Holocene, when the sea level was relatively stable. In this section, we present the different turbidite events identified on the main depositional basins of the SW Iberian Margin: Tagus Abyssal Plain, Infante Don Henrique Basin and Horseshoe Abyssal Plain, where the records from large turbidites triggered along the margin are preserved. We decided to avoid turbidites from the Lagos and Portimao Canyons drainage pathways as they have strong erosive potential and could be locally triggered. Turbidites from the Seine Abyssal Plain have not been included either, as their chronology is not available yet.

Based on the textural, physical properties, geochemical signatures and ages of the turbidites presented in Deliverable D22 complemented by pre-existing multicores and gravity cores we established a regional correlation of widespread turbidite events for the last 16 Kyr.

The main objectives are:

1) To establish a regional correlation of turbidite events based on the ages presented in deliverable D22. In addition we will also integrate results from ^{210}Pb dating of the recentmost events (Garcia-Orellana et al., 2006) and from a local study at the Marquês de Pombal Fault area (Vizcaino et al., 2006);

2) To propose a correlation between widespread turbidite events and instrumental and historical earthquakes, and tsunami deposits from the Gulf of Cadiz;

3) To determine a recurrence interval of large earthquakes that occurred during the Holocene, highlighting the potential of the turbidite record as a marine paleoseismic indicator in low-convergence rate margins and constituting a valuable tool for assessment of earthquake and tsunami hazard along the coasts of the Iberian Peninsula and North Africa.

The new findings on turbidite paleoseismology have been presented in a research article which is now in press in the *Quaternary Science Reviews* journal (Gràcia et al., 2010).

2. Criteria for Turbidite correlation: Event definition

In this marine paleoseismic study we use the fundamental concept of "event" (E). This may be constituted by one or more mass transport episodes (turbidite or debrite) correlated across different depositional areas. The correlation between turbidite deposits may be based on a number of factors of which the most important is chronology. Different turbidite deposits located far apart from one another will be regarded as the same turbidite event if their calibrated ages overlap at 1σ uncertainties. As part of the same event, these turbidites will be known hereinafter as "synchronous" or "coeval". In addition, when synchronous turbidites are found in at least two of these widely separated depositional areas, these events will be referred to as "widespread".

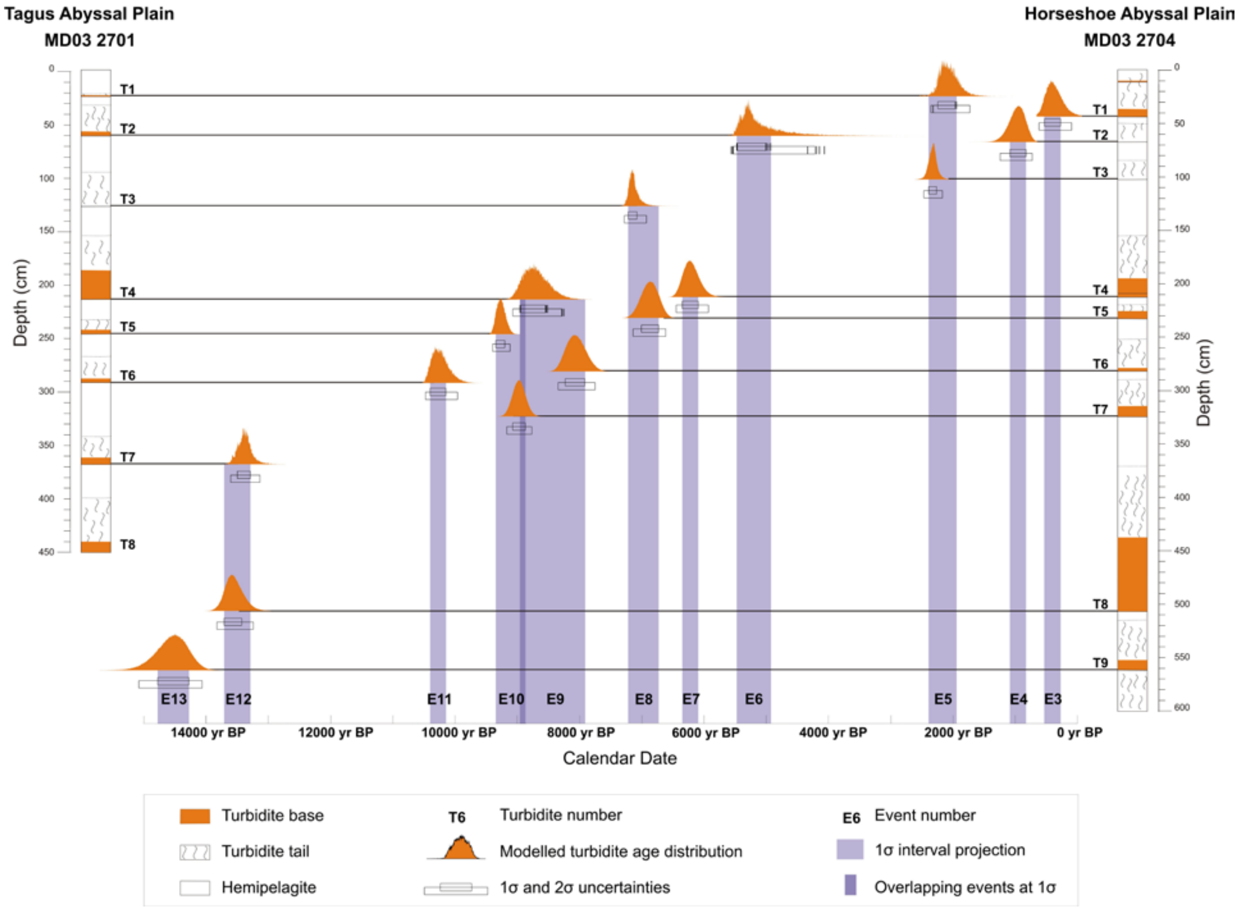

Fig. 1. *Age correlation of turbidites from the Tagus Abyssal Plain and the Horseshoe Abyssal Plain and definition of "events". Probability distribution curves of modelled turbidite ages (orange) were obtained using P_Sequence from OxCal 4.0 software (Bronk-Ramsey, 2008). Black horizontal lines link turbidite bases and their respective calibrated ages. Modelled turbidite ages (1σ) are projected on the time axis by a purple band, where event numbers are indicated.*

As previously mentioned, radiocarbon dating was performed in the hemipelagic material found below each turbidite layer. Since hemipelagic thickness might have been partially reduced by erosion from the overlying turbidite, we decided to use the youngest age from each event to characterize its occurrence. This geological criterion allows us to disregard the older turbidite ages of a given event which are probably affected by the ageing effect of erosion.

Other criteria can also be used to correlate turbidite events. Sedimentological aspects, such as hemipelagic thickness between different turbidite sequences (e.g. Gutiérrez-Pastor et al., 2009), are also important factors that strengthen the correlation. In addition, physical parametres (magnetic susceptibility and density) and geochemical composition (K/Ti and Ca/Ti) may also reinforce the correlation between different turbidites (e.g. Goldfinger et al., 2007), especially if they are from the same source area. In summary, if turbidite deposits from different cores (T) meet the aforementioned correlation criteria, these turbidites will be considered to be synchronous and will form part of the same turbidite event (E).

3. Turbidite events from the SW Iberian Margin

Detailed turbidite characterization and accurate chronology (see Deliverable D22) allowed us to conduct a synchronicity test between turbidite deposits from the four piston cores described in this report (Figs. 1, 2, 3, 4). In addition, we also included the age results from four gravity cores of the MPF area (Vizcaino et al., 2006) and six multicores, two from the MPF area and four from the same locations as the CALYPSO piston cores (Garcia-Orellana et al., 2006). The most recent turbidite events (E1 and E2) in the SW Iberian Margin are characterized by very thin (< 2 cm thick) silty-clay deposits identified and dated in multicore MC1 (Garcia-Orellana et al., 2006). E1 and E2 were not detected in the CALYPSO piston cores. Their turbidite deposits reflect different sediment characteristics and distribution. E1 is characterized by thicker turbidites that were identified in all the basins studied (TAP, IDHB and HAP) whereas E2 was locally observed only in the IDHB and MPF area. Precise dating based on ^{210}Pb and ^{137}Cs geochronology provides ages of AD 1971 ± 3 and AD 1908 ± 8 for the turbidite events E1 and E2, respectively (Garcia-Orellana et al., 2006) (Fig. 3). The uppermost turbidite event recognized in the CALYPSO piston cores (T1 in both MD03 2702 and MD03 2704) is E3, which occurred at around 300

– 560 yr BP (Figs. 1, 3, Table 2). This event can also be correlated with the most recent turbidite identified by Thomson and Weaver (1994) in the TAP at 300 ± 120 yr BP, and in the HAP at 140 ± 120 yr BP. E4 was only identified in core MD03 2704 and is characterized by a muddy turbidite with MS and Ca/Ti values lower than those detected in E3 (Fig. 6). This event occurred around 855 – 1110 yr BP.

Table 2*. Calibrated ages of the turbidite events. Calibration is based on Marine04 curve (Hughen et al., 2004) included in OxCal 4.0 calibration software. Turbidite ages are modelled using the P_Sequence model of deposition from OxCal 4.0 (Bronk Ramsey, 2008).*

Core #	Core depth (cm)	Hemipelagic depth (cm)	Turbidite number #	Distance from the turbidite base or tail to the sample (cm)	Max. Probability Cal age (Cal yr BP)	1σ Cal age ranges (Cal yr BP)	2σ Cal age ranges (Cal yr BP)	Turbidite event #
MD03 2701	25	23	**T1**	**1**	**2170**	**1980 – 2280**	**1770 – 2395**	**E5**
TAP	65	34	**T2**	**1**	**5325**	**4960 – 5510**	**4135 – 5590**	**E6**
	130	66	**T3**	**1**	**7185**	**7105 – 7250**	**6955 – 7310**	**E8**
	213	90	**T4**	**6**	**8765**	**8540 – 8985**	**8275 – 9095**	**E9**
	228	102	**T5**	**3**	**9310**	**9230 – 9370**	**9140 – 9425**	**E10**
	286	122	T6	4	10345	10175 – 10425	9985 – 10500	E11
	370	172	T7	1	13385	13310 – 13515	13155- 13625	E12
		204	*T8*	*31*	*15630*	*15020 – 16630*	*14690 – 17360*	*E13*
MD03 2702	68	21	**T1**	**12.5**	**460**	**385 – 545**	**305 – 625**	**E3**
IDHB	232	158	**T2**	**4**	**8020**	**7880 – 8145**	**7690 – 8235**	**E9**
MD03 2703	43	34	***T1***	***62***	***2310***	***2080 – 2620***	***1830 - 2900***	***E5***
HAP-West	169	95	T2	1	6420	6340 - 6505	6250 - 6585	E7
	184	98	**T3**	**2**	**6835**	**6690 – 6985**	**6565 - 7105**	**E8**
	224	116	**T4**	**2**	**8320**	**8185 – 8425**	**8040 – 8530**	**E9**
	258	119	**T5**	**2**	**8870**	**8715 – 9015**	**8600 – 9165**	**E10**
	347	143	T6	2	13170	12950 – 13325	12675 – 13455	E12
	400	164	*T7*	*19*	*15885*	*15695 – 16090*	*15490 – 16300*	*E13*
	438	169	T8	1	16340	16160 – 16635	15945 – 16915	E14
MD03 2704	48	3	**T1**	**3**	**455**	**300 – 560**	**120 – 645**	**E3**
HAP-East	62	7	*T2*	*1*	*975*	*855 – 1110*	*755 – 1270*	*E4*
	103	23	**T3**	**0.5**	**2345**	**2285 – 2415**	**2195 – 2490**	**E5**
	213	75	T4	4	6255	6110 – 6365	5950 – 6465	E7
	233	82	**T5**	**4**	**6895**	**6745 – 7020**	**6630 – 7155**	**E8**
	282	91	**T6**	**3**	**8075**	**7930 – 8240**	**7765 – 8355**	**E9**
	324	100	**T7**	**2**	**8985**	**8880 – 9090**	**8780 – 9180**	**E10**
	506	147	T8	2	13585	13430 – 13715	13245 – 13830	E12
		158	*T9*	*9*	*14545*	*14275 – 14780*	*14065 – 15080*	*E13*

In Italics are represented the ages modelled by extrapolation from the top of a neighbouring turbiditic interval. In Bold are depicted the widespread Holocene turbidite events. Overlaid in grey is the youngest turbidite age characterizing the occurrence of each Holocene event.

The next event (E5), detected in the cores from the TAP and HAP, is widespread. This event includes the uppermost turbidite T1 from cores MD03 2701 and MD03 2703, and turbidite T3 from MD03 2704 (Fig. 2). This suggests that the top of cores MD03 2701 and MD03 2703 suffered a sediment loss with respect to core MD03 2704, where the base of the turbidite characterizing E5 in this core is located around 1 m downcore. E5 is characterized by muddy to silty turbidites with similar values of MS and Ca/Ti in all three cores (Fig. 2), and occurred at around 1980 – 2280 yr BP (Figs. 1, 3, Table 2). Vizcaino et al. (2006) identified a turbidite deposit in the MPF area with a similar calibrated age (1940 ± 55 yr BP) (Fig. 4). Event E6 includes turbidite T2 of core MD03 2701 from the TAP (Fig. 1). E6 is the most biogenic turbidite deposit of core MD03 2701 and this could account for the similar values in physical properties and geochemical composition with respect to the hemipelagites (Fig. 2). E6 occurred around 4960 – 5510 yr BP (Figs. 1, 3; Table 2). A coeval turbidite was identified by Vizcaino et al. (2006) in the MPF area (Fig. 4).

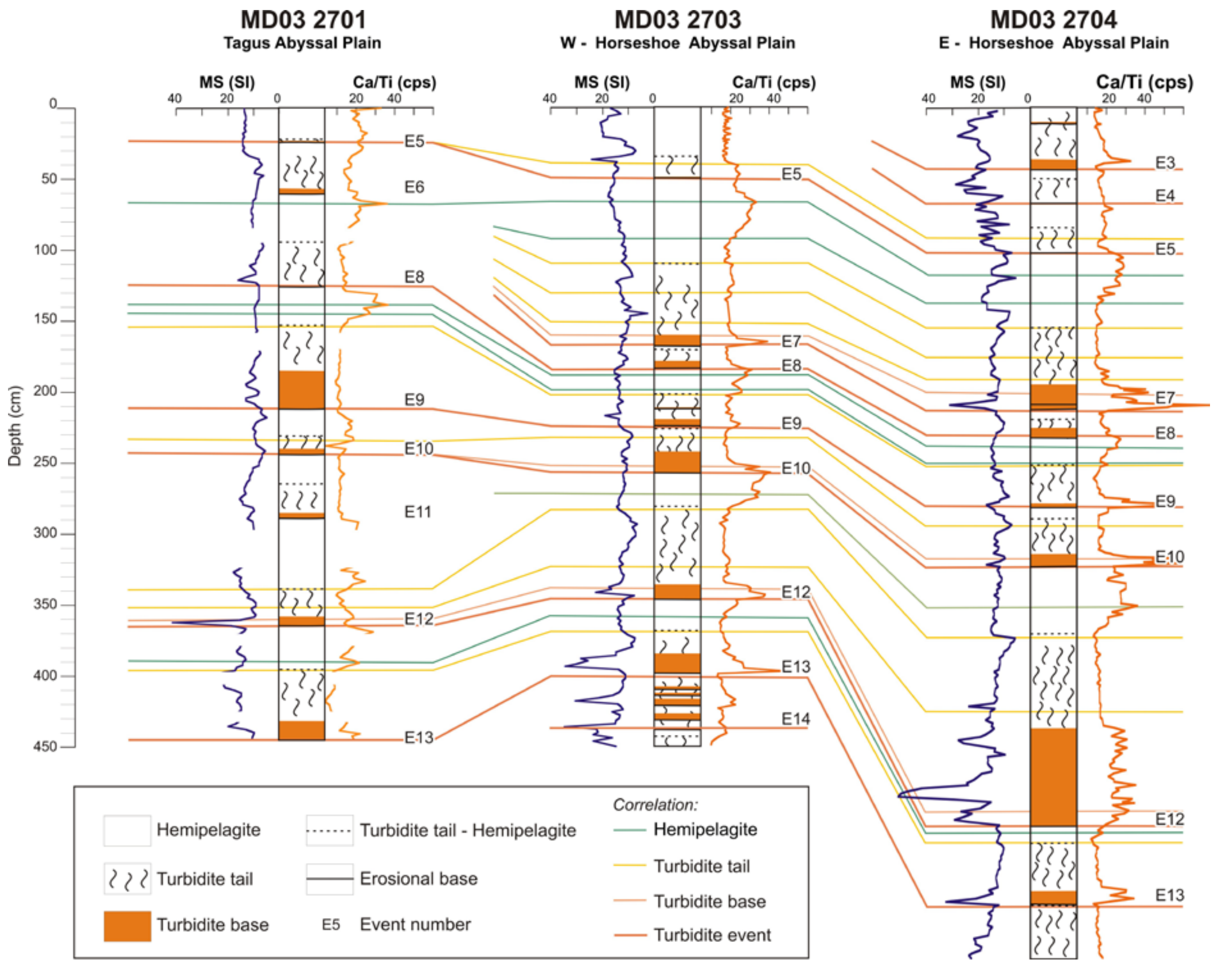

Fig.2. *Peak-to-peak correlation of magnetic susceptibility (MS) and Ca/Ti data between cores from the Tagus (MD03 2701) and Horseshoe abyssal plains (MD03 2703 and MD2704). Dark orange lines correlate turbidite bases. Light orange lines link MS and Ca/Ti signals between turbidite bases, yellow lines correlate turbidite tails, and green lines hemipelagites.*

Event E7 was locally detected in the deep-sea cores from the HAP and includes turbidites T2 from core MD03 2703 and T4 from MD03 2704. This event is characterized by the thickest Holocene turbidites (58 cm thick in core MD03 2704), coarse turbidite bases, the highest values of MS, density, K/Ti and Ca/Ti, and the lowest values of lightness of all Holocene sections (Fig. 2). E7 occurred around 6110 – 6365 yr BP (Figs. 1, 3, 4; Table 2). Event E8 is widespread and was detected in cores MD03 2701 (T3) from the TAP and MD03 2703 (T3) and MD03 2704 (T5) from the HAP. Their turbidite deposits are characterized by low amplitudes in physical properties and geochemical composition (Fig. 6). E8 occurred at around 6690 – 6985 yr BP (Fig. 3; Table 2).

E9 is a widespread event and was detected in cores MD03 2701 (T4) from the TAP, MD03 2702 (T2) from the IDHB, and MD03 2703 (T4) and MD03 2704 (T6) from the HAP. Turbidite T4 of core MD03 2701 from the TAP is thicker, coarser grained, and has an older age than the rest of the E9 turbidites (Figs. 1, 3; Table 2). This suggests a relatively high erosional potential, which would explain the older age of this turbidite. Given the stratigraphic position of T4 and T5 from this core, we assigned T4 to E9 and T5 to the immediately older event (E10) (Fig. 1). E9 occurred at around 7880 – 8145 yr BP. E10 is the oldest widespread event in the Holocene and was detected in cores MD03 2701 (T5), MD03 2703 (T5) and MD03 2704 (T7). E10 occurred around 8715 – 9015 yr BP (Fig. 4; Table 2). E9 and E10 are characterized by high amplitude geochemical signatures detected in the two cores from the HAP (Fig. 2). The first event recorded during the Holocene is E11, only detected in core MD03 2701 (T6), which occurred at 10175 – 10425 yr BP (Table 2).

As regards the Last Glacial-Interglacial Transition period, the last event is E12, a widespread turbidite event identified in cores MD03 2701 (T7) from the TAP, and MD03 2703 (T6) and MD03 2704 (T8) from the HAP (Figs. 1, 2, 3). The three turbidite deposits characterizing E12 show differences in texture and in physical and geochemical properties. T8 of core MD03 2704 from the HAP is the thickest turbidite identified (> 1 m thick) characterized by a coarse grain-size base showing large pulses in the MS (Fig. 2). In addition, the slightly older age of T8 of core MD03 2704 suggest that it may have eroded the underlying sediment (Figs. 2, 4). E12 occurred around 12950 – 13325 yr BP (Fig. 3; Table 2). E13 is the oldest widespread turbidite event and was detected in core MD03 2701 (T8) from the TAP and cores MD03 2703 (T7) and MD03 2704 (T9) from the HAP. Its turbidite ages were extrapolated from the overlying deposits characterizing E12 (Fig. 3). E13 occurred at around 14275 – 14780 yr BP (Table 2). The oldest event is E14 only detected in core MD03 2703 (T8) from the HAP (Figs. 2, 3), which occurred at around 16160 – 16635 yr BP (Table 2).

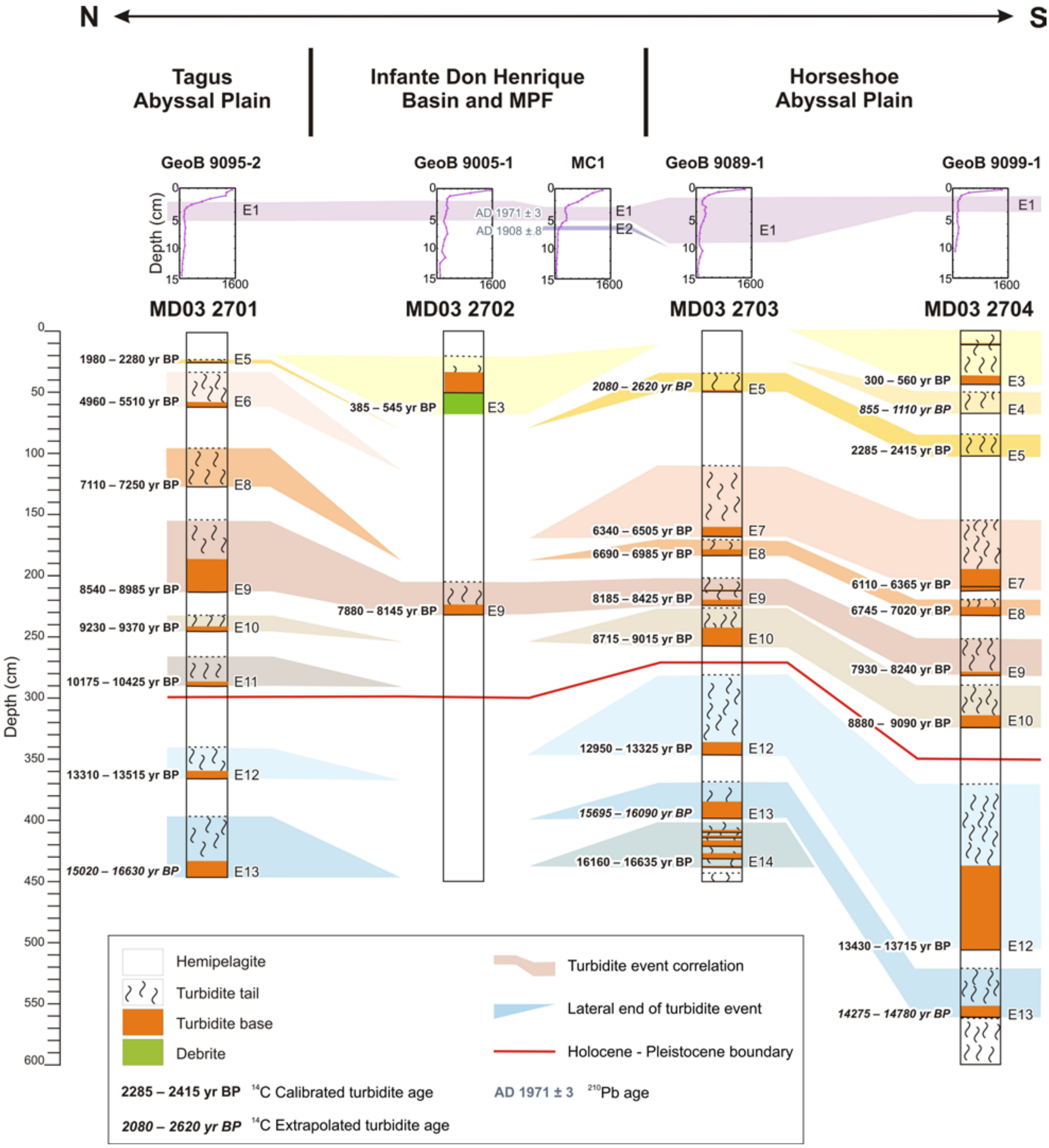

Fig. 3. *Chronostratigraphic event correlation from the Tagus to the Horseshoe abyssal plains integrating the turbidite ages obtained from ^{210}Pb profiles (Bq/kg) of multicores (GeoB 9095-2, GeoB 9005-1, MC1, GeoB 9089-1 and GeoB 9099-1) presented by Garcia-Orellana et al. (2006), and the 14C calibrated and extrapolated turbidite ages from the sections of the CALYPSO piston cores studied (MD03 2701, MD03 2702, MD03 2703 and MD03 2704).*

Summarizing, 11 Holocene turbidite events (E1 to E11) and a total of 14 events for the last 16.5 kyr (E1 to E14) were identified in the SW Iberian Margin including the TAP, the

IDHB, MPF area and the HAP. In the Holocene, only 7 of the total 11 turbidite events (E1, E3, E5, E6, E8, E9 and E10) are widespread, i.e. detected in cores from at least two of the different depositional areas (Figs. 1, 2). The remaining four Holocene turbidite events (E2, E4, E7 and E11) were only identified in sediment cores from one of the basins (Fig. 3).

4. Triggering mechanisms of turbidite events in the SW Iberian Margin

Turbidites have been used as a proxy for paleo-earthquakes since 1952, when the study of the 1929 Grand Banks Earthquake and associated turbidity current was published (Heezen and Ewing, 1952). However, they found difficulties in linking the gravity flow deposits with the 1929 Earthquake mainly because turbidity currents may be triggered by different processes. Adams (1990) proposed four triggering mechanisms for turbidite generation: a) sediment loading, b) wave-induced slumping, c) tsunamis and d) large earthquakes. This list was expanded by Goldfinger et al. (2003) adding e) crustal earthquakes, f) slab earthquakes, g) aseismic accretionary slip wedge, i) hyperpycnal flows, and j) gas hydrate dissociation. Tides (Sarı & Çağatay, 2006) and postglacial isostatic rebound (Blumberg et al., 2008) have also been regarded as possible turbidite triggers. A number of these mechanisms are related to local processes but only earthquakes, storm waves and hyperpycnal flows can trigger widespread turbidites in a region (Goldfinger et al., 2003). Hyperpycnal flows and storm waves seem to be the most important turbidite triggering mechanisms during the low-stand glacial periods, when there is a direct sediment supply from rivers to submarine canyons (Goldfinger et al., 2007). However, in an active, mid latitude margin such as the SW Iberian Margin, and during the high-stand Holocene period, earthquakes are the most likely mechanism for turbidite generation.

In turbidite paleoseismology, synchronicity is probably the most accepted criterion for suggesting that turbidity currents are triggered simultaneously by an earthquake. As defined by Adams (1990), Nelson et al. (1996) and Goldfinger et al. (2003, 2007) synchronicity is based on the “confluence channel test”, i.e. the same number of turbidite events should be found upstream and downstream from the confluences between tributaries, slope channels and deep-sea channels. In the SW Iberian Margin, sediments are transported from the shelf edge and upper slope directly to the abyssal plains through large, deeply incised canyons. The particular physiography of this margin is unsuitable for

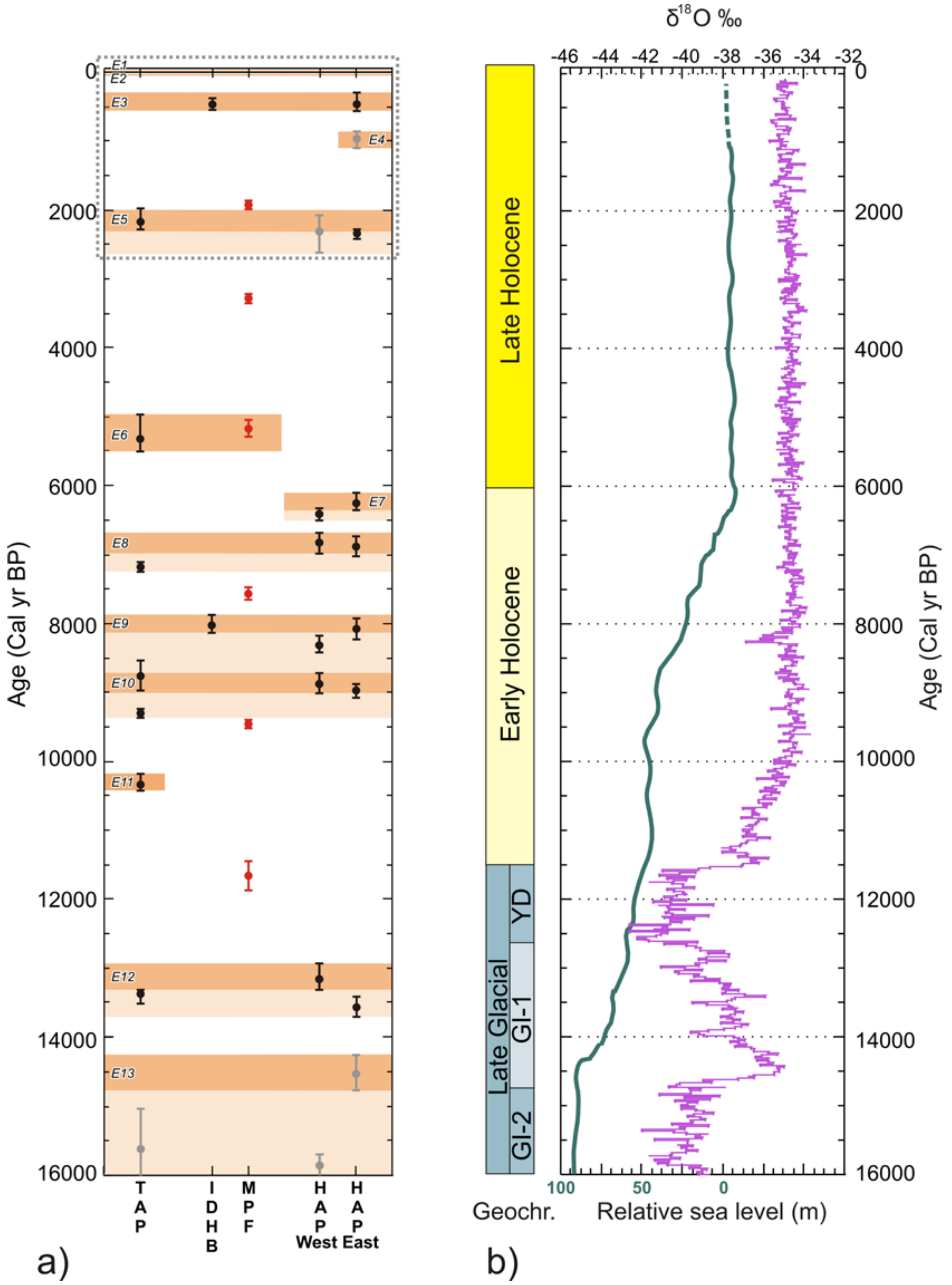

Fig. 4. *a) Turbidite ages separated by study areas for the last 16000 years. TAP: Tagus Abyssal Plain; IDHB: Infante Don Henrique Basin; MPF: Marquês de Pombal Fault area; HAP: Horseshoe Abyssal Plain. The time interval including all turbidite ages for event is depicted by light orange bands. The 1σ age given to each event (E1 to E13) corresponds to the youngest turbidite age and is depicted by a dark orange band. The ages of turbidites presented in this work are depicted in black and grey (extrapolated), and the ages of turbidites from the MPF area are shown in red (Vizcaino et al., 2006). Dashed-line rectangle corresponds to Figure 5. b) Eustatic sea level curve (green) and GISP2 $\delta^{18}O$ curve (purple) modified from Hernández-Molina et al. (1994) and Jouzel (1994), respectively.*

applying the channel confluence test. Instead, the synchronicity test in this study is based on the existence of coeval deposits located in widely separated depositional areas (slope basins and abyssal plains) (Figs. 1, 2, 3).

Although it may be assumed that earthquakes are the most likely triggering mechanism of turbidites in the SW Iberian Margin during the Holocene, we should not exclude other non-seismic causes for the emplacement of widespread turbidite events (Fig. 3). Of the 7 widespread events (E1, E3, E5, E6, E8, E9 and E10), event E9 occurred immediately after the well known 8.2 kyr climatic event (e.g. Bond et al., 1997, 2001). Although an earthquake cannot be ruled out as the triggering mechanism for the E9 turbidite event, the 8.2 kyr event may have created a climate-related instability in the SW Iberian Margin slope. Despite being widespread, we do not regard event E9 as seismically triggered (Fig. 4).

The non-widespread Holocene turbidite events (E2, E4, E7 and E11) may have been generated by low to moderate earthquakes, although we cannot exclude other non-seismic causes (Fig. 4). We are unable to assign an earthquake origin to the turbidite events during the Late Pleistocene because their triggering could have also been related to the rise of sea level and associated instability processes.

5. Linking Holocene turbidite events with historical earthquakes and tsunami deposits in the Gulf of Cadiz

To lend support to the hypothesis that earthquakes are the main triggering mechanism of the widespread turbidite deposits in the SW Iberian Margin, we correlate these turbidite events with the instrumental and historical seismic records. Numerous seismic events have been instrumentally recorded in the area since the 1960s, the largest being the Horseshoe Earthquake in 1969 (Mw 8.0) (Fukao, 1973) (Table 3). In addition to the instrumental data, historical record allows us to investigate the seismicity for the last two millennia (Table 2) including great earthquakes, such as the 1755 Lisbon Earthquake and Tsunami (e.g. Martins and Mendes Victor, 2001; Martínez Solares and López Arroyo, 2004; Baptista and Miranda, 2009) (Figs. 4, 5).

Instrumental and historical records of earthquakes and tsunamis enabled us to identify three widespread turbidite events in the SW Iberian Margin for the last 2500 years: E1, E3 and E5 (Fig. 5a). E1, which occurred at around AD 1971 ± 3 dated by ^{210}Pb chronology (Garcia-Orellana et al., 2006), was correlated with the AD 1969 Horseshoe Earthquake (Mw 8.0) (Fukao, 1973). E3 occurred at 300 – 560 yr BP, was also identified by Thomson and Weaver (1994), Lebreiro et al. (1997), Abrantes et al. (2005) and Vizcaino et al. (2006). This turbidite event is contemporaneous with the AD 1755 Lisbon Earthquake and Tsunami (e.g. Baptista et al., 1998; Martínez Solares and López Arroyo, 2004) (Fig. 5a).

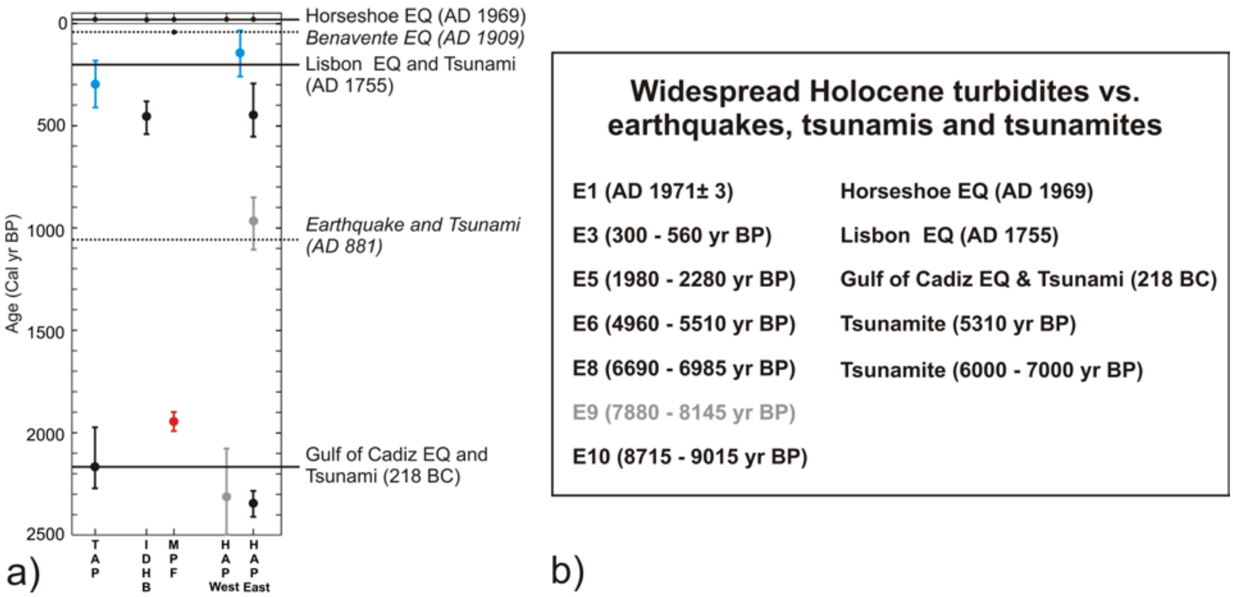

Fig. 5. *a) Turbidite ages separated by study areas for the last 2500 years. Black lines correspond to the ages of instrumental and historical earthquakes and tsunamis of estimated Mw ≥ 8.0 that occurred during this time period whereas dashed lines correspond to historical earthquakes and tsunamis of estimated Mw≥ 6.0 and < 8.0. The ages of turbidites presented in this work are depicted in black and grey (extrapolated) and the ages of turbidites from the MPF area are shown in red (Vizcaino et al., 2006). The ages of the youngest turbidites from the TAP and HAP by Thomson and Weaver (1994) are depicted in blue. b) Age of the widespread turbidite events linked to the instrumental and historical earthquakes, tsunamis and paleotsunamis of the SW Iberian Margin. E9 (in grey) is a widespread turbidite event that might be related to the 8.2 kyr cold event.*

Although there is an ample historical record of the effects of the AD 1755 Tsunami along the Atlantic coast, its preserved tsunamites seem to be limited to few locations on the Algarve coast (e.g. Andrade et al., 1994; Dawson et al., 1995) and Spanish shore of the Gulf of Cadiz (e.g. Lario et al., 2001; Luque et al., 2001; Lario et al., 2010) (Tables 1 and 3). It should be noted that E3 is a thin widespread turbidite event in the SW Iberian Margin. A relationship between the turbidite thickness and earthquake magnitude in this margin cannot be demonstrated because of other factors such as sediment availability in the source area and stability conditions. Coeval with E5 (1980-2280 yr BP) was the large historical earthquake and tsunami that occurred around 218 BC in the Bay of Cadiz in Roman times (e.g. Galbis, 1932; Luque et al., 2002; Ruiz et al., 2008; Lario et al., 2010) (Fig. 5; Tables 1 and 3). Morphological coastal changes triggered by this earthquake together with the magnitude of its sedimentary deposits suggested that this event was probably as destructive as the AD 1755 Earthquake and Tsunami (Luque et al., 2001, 2002; Ruiz et al., 2005, 2008; Lario et al., 2010; Baptista and Miranda, 2009). Two local turbidites (E2 and E4) may also be related to moderate historical earthquakes. Garcia-Orellana et al. (2006) suggested that E2 was coeval with the Benavente Earthquake in 1909 (Mw 6.0) (Moreira, 1984; Mezcua et al., 2004; Stich et al., 2005b) (Table 3). E4 (855-1110 yr BP) seems to be coeval with the AD 881 historical earthquake and tsunami (Galbis, 1932; Mezcua and Martínez Solares, 1983) (Fig. 5a; Table 3).

Table 3. *Largest instrumental earthquakes, historical seismic record, historical tsunamis and tsunami deposits (tsunamites) from the SW Iberian Margin.*

Age	Name	Source location Location of tsunamites	Magnitude M*	Intensity (MSK)	Type of Record	References
AD 2007	São Vicente EQ	Horseshoe Fault	6.0	-	Instrumental EQ	19
AD 1969	Horseshoe EQ	Horseshoe Abyssal Plain	8.0	VII	Instrumental EQ and T	2, 21
AD 1964	Guadalquivir Bank EQ	Gulf of Cadiz	6.1 - 6.6	-	Instrumental EQ	12, 16
AD 1960	-	Atlantic Morocco	6.2	-	Instrumental EQ	12
AD 1909	Benavente EQ	Lower Tagus Valley	(6.0)	IX-X	Historical EQ	4, 14, 17
AD 1858	Setúbal EQ	Lower Tagus Valley	(7.1)	IX	Historical EQ	3, 4
AD 1761	North Atlantic	Gloria Fault zone	(6.7)	VI-VII	Historical EQ and T	3, 21
AD 1755	Lisbon EQ and Tsunami	SW Iberian margin	(8.5 - 8.7)	X-XI	Historical EQ, T and TD	5, 6, 7, 9, 13, 22
AD 1722	Tavira EQ	Offshore Algarve	(6.5)	VIII	Historical EQ and T	1, 4, 10, 21
AD 1531	Vila Franca de Xira EQ	Tagus Estuary	-	IX-X	Historical EQ and T	1, 8, 21
AD 881	-	Cádiz	-	X-XI	Historical EQ and T	1, 3
AD 382	Cape São Vicente EQ	SW Iberian margin	-	VII -X?	Historical EQ and T	1, 10, 21
60 BC	Portugal and Galicia EQ	W Iberian margin	-	IX ?	Historical EQ and T	1, 10, 21
2200-2300 yr BP	218 BC EQ and Tsunami	Gulf of Cadiz	-	-	Historical EQ, T and TD	1, 11, 20, 22
3700-3900 yr BP	-	Doñaña marshlands	-	-	EWE (local TD?)	15, 20, 22
4100-4500 yr BP	-	Doñaña marshlands	-	-	EWE (TD?)	15, 22
5300-5500 yr BP	5310 yr BP Tsunami	Gulf of Cadiz	-	-	TD	15, 20, 21, 22
6000-7000 yr BP	-	Guincho Beach, Lisbon	-	-	TD (giant boulders and cobbles)	15, 18, 21, 22

M* = In brackets, estimated magnitude; EQ = Earthquake; T = Tsunami; TD = Tsunami deposit; EWE = Extreme Wave Event.
(1) Galbis, 1932; (2) Fukao, 1973; (3) Mezcua and Martínez Solares, 1983; (4) Moreira, 1984; (5) Andrade et al., 1994; (6) Dawson et al., 1995; (7) Baptista et al., 1998; (8) Justo and Salwa, 1998; (9) Luque et al., 2001; (10) Martins and Mendes Victor, 2001; (11) Luque et al., 2002; (12) Buforn et al., 2004; (13) Martínez Solares and López Arroyo, 2004; (14) Mezcua et al., 2004; (15) Ruiz et al., 2005; (16) Stich et al., 2005a; (17) Stich et al., 2005b; (18) Scheffers and Kelletat, 2005; (19) Stich et al., 2007; (20) Ruiz et al., 2008; (21) Baptista and Miranda, 2009; (22) Lario et al., 2010.

Before 2500 yr BP, we should look for the geological record of past earthquakes and tsunamis. Unfortunately, there is no paleoseismic catalogue available for SW Iberia but instead, there is a relatively good record of paleotsunamis. Paleotsunami studies are based on sedimentological fieldwork in lagoons and marshes from the Iberian Peninsula around the Gulf of Cadiz and west Portuguese coast (e.g. Andrade et al, 1994; Dawson et al., 1995; Lario et al., 2001; Luque et al., 2001, 2002; Ruiz et al., 2005, 2008; Scheffers and Kelletat, 2005; Baptista and Miranda, 2009; Lario et al., 2010). The tsunami record provides information of tsunamis as far back as 6000 - 7000 yr BP, when the shoreline stabilized after sea level rise (Fig. 4b). The size of an earthquake-generated tsunami depends on the magnitude of the earthquake, focal depth, fault type and aftershock area, and distance between the epicenter and shore (e.g. Luque et al., 2001). Correlation between widespread offshore turbidites and tsunami deposits onshore strengthens the hypothesis of a seismic origin for both (Fig. 5).

Turbidite event E6, dated as 4960 – 5510 yr BP, may be correlated with a coeval tsunami deposit that occurred around 5310 yr BP and found in reworked washover fans near Doñana (Cadiz) (Ruiz et al., 2005, 2008; Baptista and Miranda, 2009; Lario et al., 2010) (Figs. 4, 5). Widespread turbidite event E8 (6690 - 6985 yr BP) may be correlated with the 6000 - 7000 yr BP tsunamite (Ruiz et al., 2005; Scheffers and Kelletat, 2005; Baptista and Miranda, 2009; Lario et al., 2010) (Tables 1 and 3). Excluding the climate-related event E9 (8.2 kyr cold event), synchronicity of widespread turbidites is the only criterion for suggesting that the oldest Holocene event E10 (8715 – 9015 yr BP) could also have been seismically triggered (Fig. 5b).

C. Onshore - Offshore Correlation

1. Recurrence interval of large magnitude earthquakes based on onshore EWEs

Among the events listed and summarized in Table 1, at least **7 EWE** come out as having induced widespread and intense geological, geomorphological and sedimentological changes in the SW coasts of the Iberian Peninsula **throughout the last 7000 years**, leaving recognizable, but difficult to interpret, features (Lario et al., 2010). This allows us to suggest a first estimate of the recurrence interval for large EWEs at the scale of the broad Gulf of Cadiz. However, the meaning of this estimate for the purposes of management of coastal risk, should clearly separate regional, high magnitude events with potential to affect extensive segments of this coast (tsunamis, typically triggered by large magnitude dip-slip earthquakes), from local inundations, certainly recurrent at shorter time-scales, but more limited in impacts, and generated by a varied suite of mechanisms (e.g. storms, tsunamis triggered by terrestrial and submarine slope mass movements).

At the present state of knowledge, we are still far from being able to determine the source mechanism (storm, tsunami) and spatial scale of impacts departing only from the geological records of the inundations; the same limitation applies to our ability in ascribing undisputable high-resolution chronological constrains to the geological record of EWE, regardless their association with storms or tsunamis. The latter result from assumed/inferred ages (if radiocarbon or OSL are not available) or from the validity and accuracy of the measured radiocarbon ages if the sampled shell remains belong to different species of molluscs, or the reservoir effect is inadequately managed, or different dating techniques are used, as mentioned above.

In any case, it is tempting to calculate recurrence periods for EWEs, and **a periodicity of 1200-1500 yr for widespread high intensity and destructive events** along this coast seems to emerge (Lario et al., 2010; Lario et al., in press). However, when calculating recurrence periods, it is inadequate to assign all the regionally recorded EWEs (even the local ones) to tsunamis. This figure should be taken as a cautious estimate and it certainly incorporates both local and regional-scaled events. In the case of the Portuguese coast, the geological record pinpoints only one large and regional-scale event throughout the last 2000 years and though this interval somewhat overestimates the dimension of the recurrence interval above, it may represent a closer estimate, given the larger distance separating this coast from a number of source areas concentrated close to Gibraltar, with a larger probability of affecting the Spanish sections of the coast.

Analyses of the relationships between the recorded EWEs and high-energy marine/coastal processes at various scales, e.g. those forced by prolonged climatic instability, yield more realistic outputs. In fact, the Klaus extratropical cyclone that affected south-western Europe in January 2009 revealed that extreme marine climate conditions can be actually reached in the Gulf of Cadiz, and also proved that destructive EWEs in the area can be triggered by extreme climatic systems.

2. Recurrence interval of large magnitude earthquakes based on offshore turbidites

Finally, we sought to determine how often great magnitude (Mw ≥ 8.0) seismic events, such as the AD 1755 Lisbon Earthquake and Tsunami, occurred in the SW Iberian Margin. In this regard, Ribeiro et al. (1996) suggested a broad recurrence interval of about 300 - 1500 yr, and Gutscher et al. (2004) of about 1000 - 2000 yr, but none of them was based on marine paleoseismic studies. Based on the correlation between turbidite events and historical earthquakes and tsunamis, we established that the three widespread turbidite events (E1, E3 and E5) that occurred during the last 2500 years correspond to great instrumental and historical earthquakes of estimated Mw ≥ 8.0 (Fig. 5a). In contrast, local, non-widespread turbidite events (E2 and E4) that occurred during the same period of time, seem to correlate with historical earthquakes and tsunamis of lower magnitude (around Mw 6.0 - 7.0) (Fig. 5a). Hence, the historical record suggests that widespread turbidite events require great magnitude (Mw ≥ 8.0) earthquakes to be generated. Extrapolating to the pre-historical period, a Mw ≥ 8.0 is suggested for the oldest Holocene widespread events (E6, E8 and E10). Hence, considering the **6 Holocene widespread turbidite events as seismically triggered** (Fig. 5b), a recurrence period of approximately **1800 years** is determined for great earthquakes (Mw ≥ 8.0). The relatively good correlation between deep-sea turbidites and instrumental and historical seismic events and tsunami deposits suggests that turbidite records may be used as a paleoseismic indicator in the slow-convergence SW Iberian Margin.

3. Onshore - offshore correlation: Recurrence interval

At least 7 EWEs capable of inducing widespread, dramatic geological, geomorphological and sedimentological changes have hit the SW coasts of the Iberian Peninsula in the last 7000 yr, leaving recognizable, but difficult to interpret, features. A periodicity of 1200-1500 yr for widespread high intensity and destructive events along this coast (part of which may not correspond to tsunamis) seems to emerge, and should be taken as a cautious estimate. At the present state of knowledge, we cannot determine the source mechanism and spatial scale of impacts of all EWE departing only from the geological records of the inundations. Uncertainties affecting the resolution of chronological constrains derived from the geological record are still large, thus influencing the dimension of the inferred return intervals. In the case of the Portuguese coast, the dimension of that time interval may be closer to about 2000 years.

Widespread turbidites deposited during the Holocene suggest that they are related to great earthquakes (Mw≥ 8.0) that occurred in the SW Iberian Margin. If we regard the 6 Holocene widespread turbidite events as seismically triggered, the recurrence interval for great earthquakes is determined as approximately 1800 years.

A first comparison between the recurrence rates of large magnitude events based on tsunamis and tsunami deposits and turbidite paleoseismology was made. The results show a relatively good coherence between the **1200-1500 years obtained from EWEs** (Lario et al., 2010) **to 2000 yr for the Portuguese coast** and the **1800 yr obtained from the deep sea turbidites** (Gràcia et al., 2010).

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