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SEDIMENTARY EVIDENCE OF PALAEO-TSUNAMI DEPOSITS ALONG THE LOUKKOS ESTUARY (MOROCCAN ATLANTIC COAST)

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ABSTRACT

Analysis of the CARLA-11 core drilled along the lower Loukkos valley near Larache in northern Morocco shows a thin level of shelly sand at 465 to 482 cm depth, whose sedimentological features are those of a high-energy, certainly a tsunami deposit. The level can be subdivided into 3 subunits: Subunit 1 (6 cm) shows a sharp erosive base and comprises basal medium to coarse sands containing numerous marine shell fragments of bivalves, plant fragments and rip-up clasts of organic matter. Subunit 2 (7 cm) is a flame structure consisting of coarse sand containing a layer of organic matter and another one of greyish clay. Subunit 3 (4 cm) is similar to subunit 1 and consists of coarse sands containing numerous complete or broken shells of bivalves, plant fragments and dark organic matter. The deposit is mostly composed of subangular to subrounded quartz grains derived from nearby Miocene sandstones. Benthic and planctonic foraminifera are common within the samples. Magnetic susceptibility measurements show two major lows at ~350 cm, and especially at 477 cm within the high-energy deposit. Subunit 1 can be interpreted as the result of the first wave uprush of a tsunami,

the fine mud level of subunit 2 capping subunit 1 can be interpreted as emplaced during a decantation phase, and subunit 2 probably corresponds to a second wave uprush, Subunit 3 might be interpreted as the result of the backwash (outflow phase). The age of this event can be roughly dated between 5 and 3 ky BP according to recent dating of nearby levels.

Keywords: *Loukkos, Gulf of Cadiz, sedimentology, high-energy events, tsunami*

1 INTRODUCTION

The Gulf of Cadiz is a well-known seismogenic and tsunamigenic zone, to which are related catastrophic events such as the Lisbon earthquake and tsunami on 1st November 1755, one of the strongest earthquakes in human history. Several studies along the coastal areas of Portugal, Spain and Morocco, which are the regions that are most exposed to the tsunami threat, have shown that the 1755 and older events (listed in Baptista and Miranda 2009; Maramai et al. 2014) were recorded along the coasts by either the displacement of large boulders (Scheffers and Kelletat 2005; Whelan and Kelletat 2005; Mhammdi et al. 2008; Medina et al. 2011) or the deposition of generally thin shelly sand levels within the generally finer marsh or lagoonal sediments (Dawson et al. 1995, Luque et al. 2001; Scheffers and Kelletat 2005; Kortekaas and Dawson 2007; Morales et al. 2008, 2011; Font et al. 2010, 2013; Rodriguez-Vidal et al. 2011; Costa et al. 2012; Cuven et al. 2013).

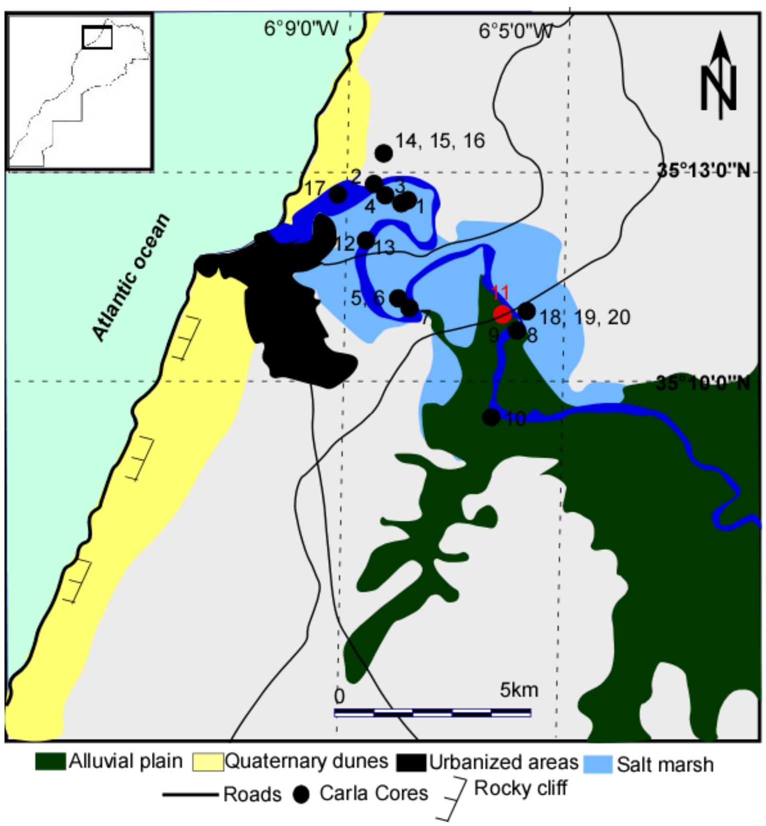

Figure 1. Simplified map of the Oued Loukkos lower valley and estuary, and location of the cores of the CARLA campaign.

As indicated in the previous paragraph, although large boulders related to high-energy events were observed in Morocco, thin sandy levels typical of tsunami deposits (washovers) were only recently described along the Moroccan coast at Oualidia (Mellas 2012). In 2004, a coring campaign (named CARLA) was carried out along the Loukkos estuary in Northwest Morocco (Fig. 1). One of the cores (CARLA-11) showed the presence of a level rich in coarse sands and shell fragments, similar to high-energy deposits (tsunamis, storms), intercalated within low to medium-energy fluvial and lacustrine strata (Fig. 2). This paper exposes the results of the sedimentological, grain size and magnetic susceptibility analyses of the high-energy levels of core CARLA-11 in order to discuss their eventual tsunamic origin.

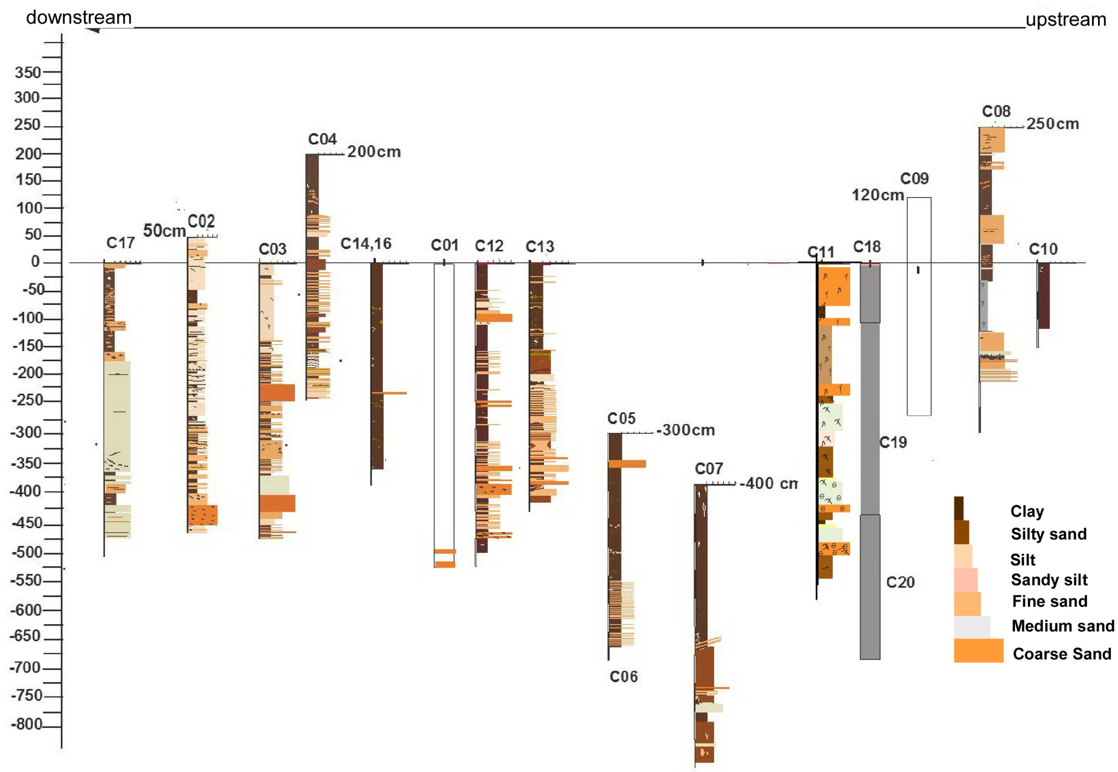

Figure 2. Compilation and correlation of the cores obtained during the CARLA campaign along the Loukkos lower valley. Location in Figure 1.

2 GENERAL SETTING

The CARLA-11 core is situated on the left bank of the lower valley of the Loukkos river (oued) in northwest Morocco (**Fig. 1**; x=35°10.933'N; y=6°07.245'W), the largest river of the region with a watershed of 3,740 km2. Topographically, the lower valley of Oued Loukkos is very flat (10–15 m.a.s.l) with a negligible slope. The valley is even below sea level at 44 km from the river mouth. The main channel depth varies from –2 to –4 m a.s.l. but may reach –15 m a.s.l. (Snoussi 1980).

The climate of the Loukkos basin is of Mediterranean type with an oceanic influence (El Gharbaoui 1981, 1987). The average annual rainfall is 700 mm. The hydrological network of the Loukkos watershed is formed by surface waters of the Loukkos river and its tributaries. The Loukkos drainage is characterized by an irregular inter-annual regime; the low flows are generally zero, except for streams that drain the water from the left bank with an average flow of 500 l/s (El Gharbaoui 1981, 1987).

The mesotidal Loukkos estuary is a tide-dominated system (tide of 3.5 m, semi diurnal with $T \sim 12$ h 20 min), according to the classification of Dalrymple (1992). For the Larache coast, Tejera de León and Duplantier (1981) indicate that the main wind direction is W-WNW with a mean velocity of 5-10 m.s-1, and that the main swell (amplitude >0.5 m) direction is N290° to N305° according to a quoted brief study by LHCF from October 1969 to January 1970. However, swell with maximum energy has a SW direction.

The history of the Loukkos valley started after the Villafranchian (Early Quaternary), represented by mostly continental red deposits overlying Pliocene sandstones and Miocene marine marls (Bouhmadi et al. 1994). Fluvial deposition characterizes the valley during the Quaternary except during the Flandrian (called Mellahian in Morocco) transgression and more recently by the progression of the sandy spit (Trentesaux et al. 2005; Aloussi 2008; Carmona and Ruiz 2009).

3 CORING AND ANALYTICAL METHODS

During the CARLA sampling campaign carried out in 2004, twenty cores were collected along the Loukkos estuary using a Vibrocoring apparatus of Lille University (Fig. 2). The cores were 7.6 cm in diameter and 2–5 m in length (depth). One half of each core was preserved and archived and the other was used for sedimentological analyses. For the present study, we describe one of the most distal cores with respect to the river mouth, which was chosen in order to avoid the interference with deposits related to proximal coastal dynamics. The other cores will be described later in a more detailed paper focused on sedimentology.

Sedimentary facies are described following the classification of Reineck and Wunderlich (1968) based on color, texture, structure, bedding and type and concentration of accessory materials such as plant fragments, organic matter content, mud and peat clasts. Carbonate content was measured using a Bernard calcimeter. Grain size analyses of the <2 mm sediment fraction were performed using a

Coulter Laser LS230 particle sizer at the University of Lille; the distinguished classes were clays (<4 µm), fine silt (4–15 µm), medium silt (15–30 µm), coarse silt (30–63 µm), very fine sand (63–125 µm), fine sand (125– 250 µm), medium sand (250–500 µm) and coarse sand (500–1000 µm) (Table 1). Magnetic susceptibility (MS) was measured each 2–10 cm by using a MFK1 kappabridge (AGICO ent.) at the Laboratory of Rock Magnetism of the Institute Dom Luís, University of Lisbon, Portugal. Before, hand samples were filled into 2•2•2 plastic cubic boxes and MSs were subsequently normalized by the mass of the sample (expressed in m3/kg).

4 STRATIGRAPHY, SEDIMENTARY FACIES AND COMPOSITION

Core CARLA-11 (Fig. 3) is 523 cm long and shows four coarsening-upward sequences, each starting with silts and sandy clays and topped by coarse sands. The three upper sequences are ~1 m thick whereas the lower one is more than 2 m thick. In this article, we only describe the results of the analysis of the upper part of the lowest sequence, which we consider as a probable palaeo-tsunami deposit because of its particular sedimentary characteristics.

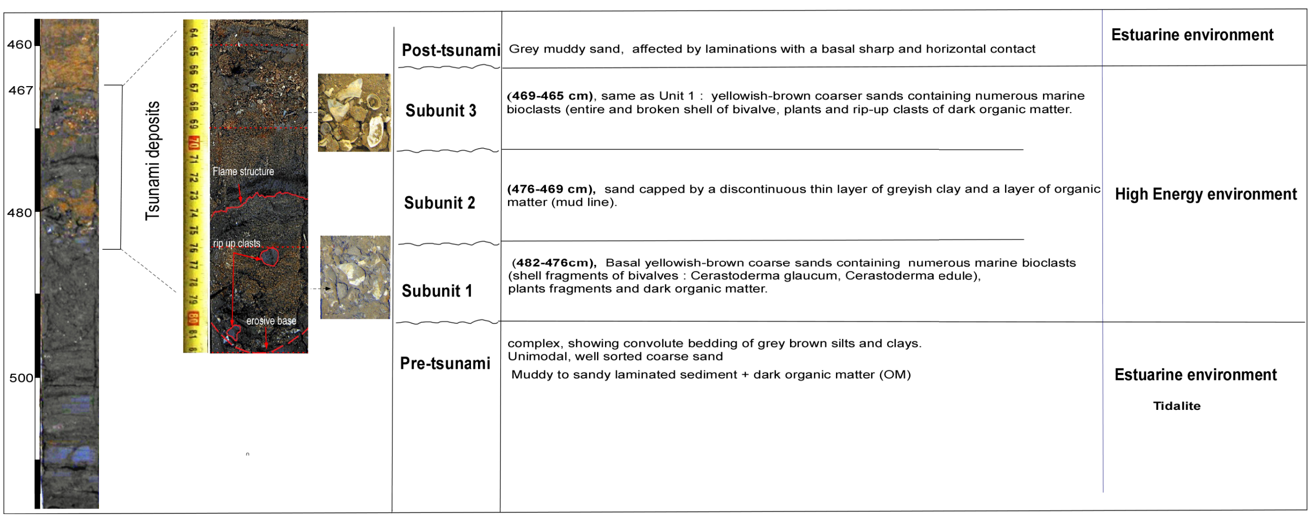

Figure 3. Photograph of the lower section of core CARLA-11 and description of the lithology of the observed subunits of the inferred tsunami deposit.

From the bottom of the core to 482 cm, the deposits correspond to a sandy mud with organic matter, which is sharply overlain by the lower contact of the high-energy marine deposit, which appears from 465 to 482 cm depth as a shelly coarse sand, that can be subvided into 3 subunits (Fig. 3):

1- The basal bed, subunit 1 (482-476 cm) shows an erosional base (Fig. 3) and comprises at its base yellowish-brown medium to coarse sands (median=536.7 µm; Fig. 4) with numerous marine shell fragments of bivalves *Cerastoderma glaucum* and *C. edule*, plant fragments and organic matter-rich rip-up clasts . The sediment is polymodal, poorly sorted (1.987 F) and very fine skewed (0.566 F).

2- Subunit 2 (476–469 cm) is a flame structure consisting of coarse sand (median=690 µm; Fig. 4) containing a layer of organic matter and another one of greyish clay. The deposit is polymodal, poorly sorted (1.496 F) and symmetrical (0.003 F).

3- Subunit 3 (469–465 cm) is similar to subunit 1 and consists of yellowish-brown coarse sands (median=618.7 µm; Fig. 4) containing numerous entire or broken shells of bivalves *Cerastoderma glaucum* and *C. edule*, plant fragments and dark organic matter. The sediment is bimodal, poorly sorted (1.866 F) and almost symmetrical (0.036 F).

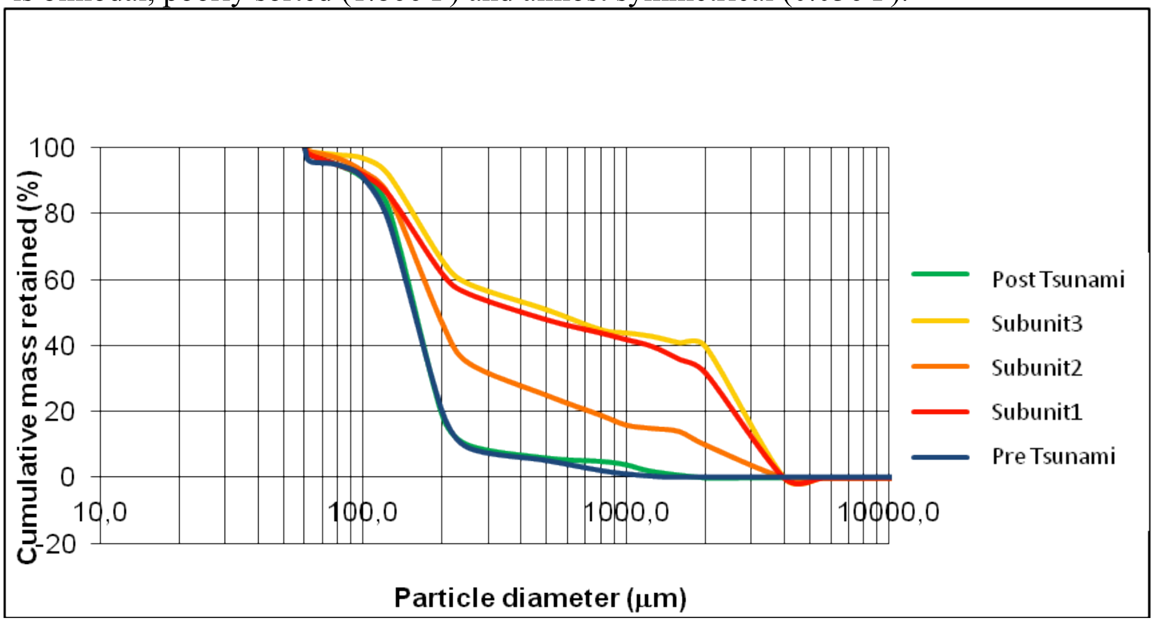

Figure 4. Cumulative frequency curves of the deposits of the subunits in core CARLA-11. Note that the pre- and post-tsunami samples have the same characteristics and that the two layers are "sandwiching" the tsunami sediments.

The upper boundary of the high-energy deposit contains coarse to fine sand to silt, and then forms a fining-upwards sequence which ends at 423 cm. The high-energy deposit is mostly (at 60–90%) composed of subangular to subrounded quartz grains (Fig. 5A) probably derived from beach sands supplied by the Loukkos river from nearby Cenozoic sandstones, together with sub-rounded orthopyroxenes (5–30%), other heavy minerals (10%), and minor amounts of goethite. In addition to the fragments of shells (mainly bivalves), numerous marine bioclasts were identified such as sponge spicules and calcareous rhodophyta (Fig. 5B), which are scattered throughout the bed, but can sometimes form shell levels. Under SEM, we observed fossil foraminifera (mainly planktonic) and more recent – mainly benthic – foraminifera. Observed smoothed and re-mineralized specimens are clearly reworked from the Tertiary strata of the Rif nappes, while those that are more fresh with angular breaks were living and have been transported by the waves from the sea (Fig. 6).

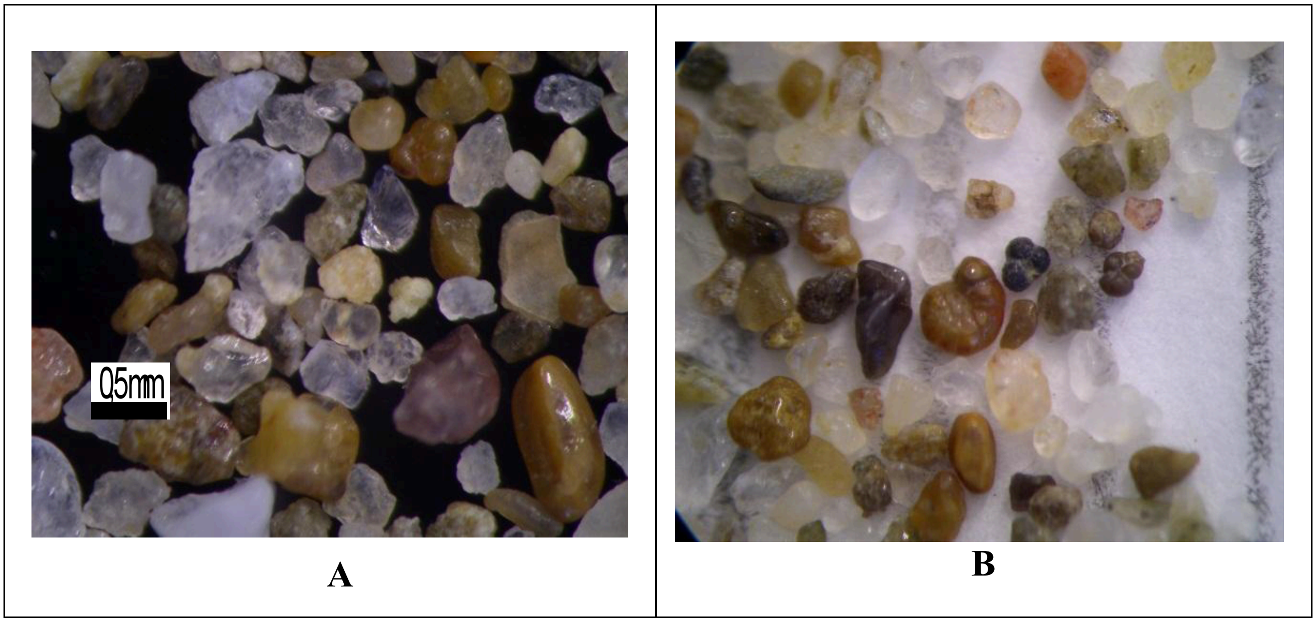

Figure 5. Optical microscope photographs of the shelly deposits of core CARLA-11.
A, quartz grains; B, foraminifera.

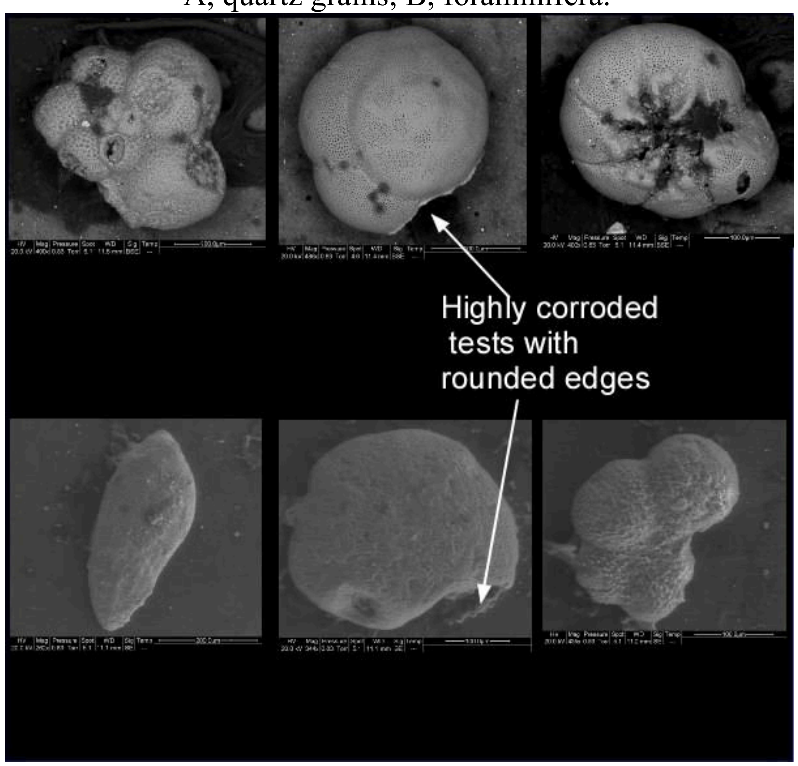

Figure 6. SEM of some Foraminifera found in the tsunami deposit of core CARLA-11.

In order to determine the flow type that transported the high-energy sediment, the samples were plotted in a C–M diagram (Passega 1957). Samples of the high-energy deposit of the Loukkos estuary plot mainly within the N–O and O–P segments (Fig. 7), which suggests that the majority of the grains were transported by rolling, and a small fraction by rolling and suspension under strong hydrodynamic conditions.

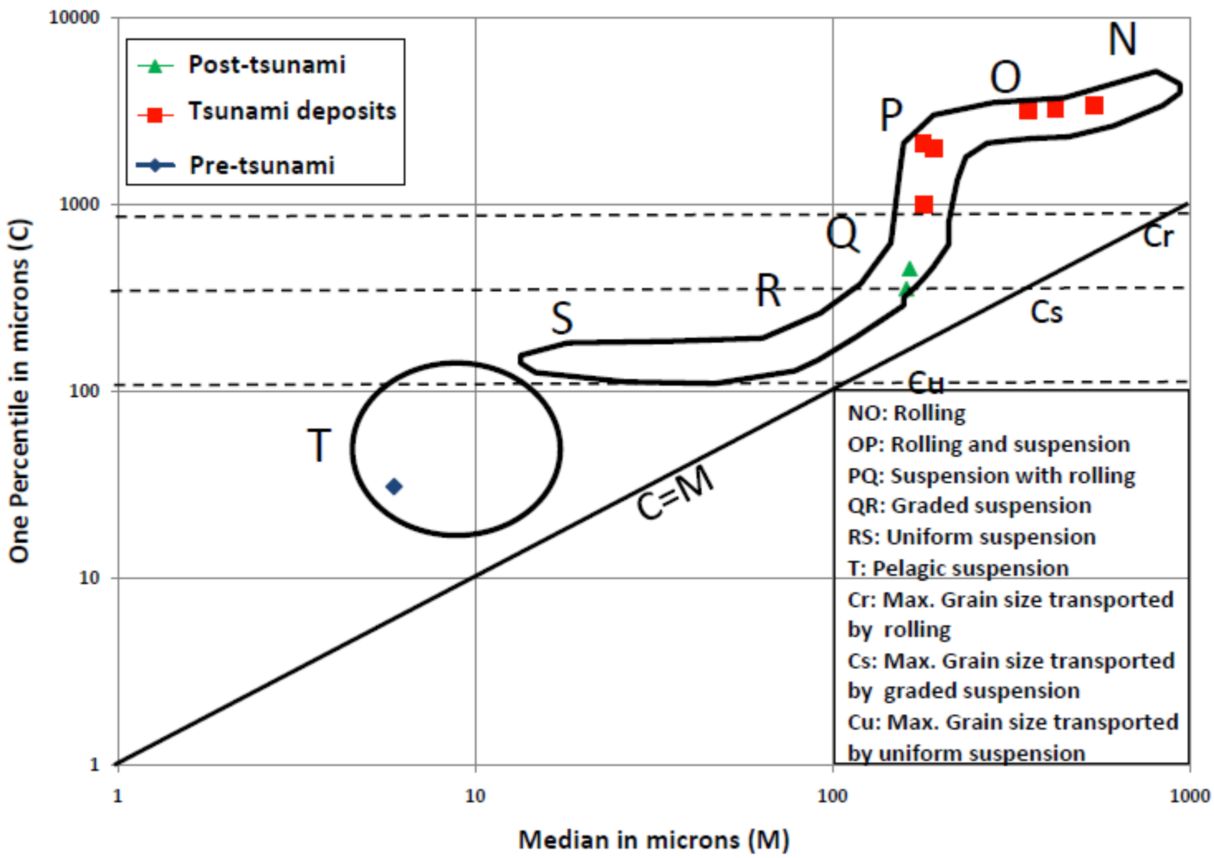

Figure 7. C-M Passega diagram of the samples of the tsunami bed of core CARLA-11.

Magnetic susceptibility measurements show no large differences between the high-energy beds and the upper part of the core, although the latter was not tightly sampled. However, two major lows appear at ~350 cm, and especially at 477 cm within the high-energy deposit (Fig. 8). The latter was sampled tightly and shows a clear vertical variability from one sample to another.

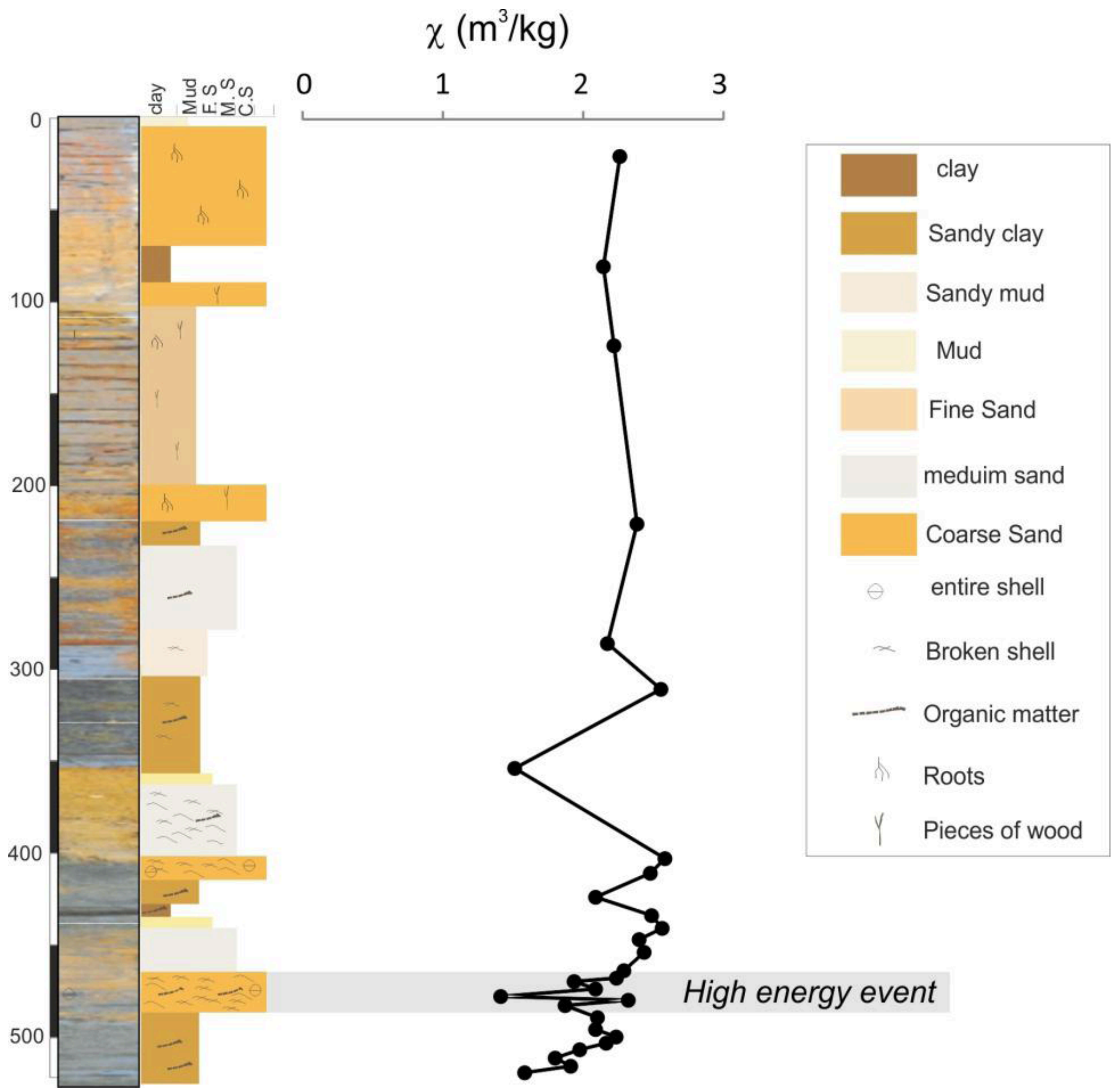

Figure 8. Magnetic susceptibility curve of core CARLA-11.

5 INTERPRETATION

The fact that such a marine shelly level was found within marsh fluvial deposits at a large distance from the river mouth is indicative of a high-energy event, which may correspond to extreme waves generated either by a storm or by a tsunami. In the following, we assess the tsunami scenario because of the very large distance to the river mouth (6 km on map) and because any explanation for the origin of this unit should include a plausible mechanism for depositing large (≤0.5 m diameter), angular, poorly sorted clasts, various sized shell fragments, and sand into the low-energy environment of the marsh estuary.

In the tsunami scenario, the observed sub-units can be interpreted as the following:

• Subunit 1 can be interpreted as the result of the first wave uprush, characterized by a pulse of sand-size sediments mostly composed of sand with bioclasts. The abrupt transition from dark grey clays to coarser deposits is indicative of a change in flow energy. Erosion of the underlying clay is attested by numerous rip-up clasts. Subunit 1 is very poorly sorted and dominated by traction. The fine mud level capping subunit 1 can be interpreted as emplaced during a decantation phase.

• Subunit 2 probably corresponds to a second wave uprush, but its characteristics differ slightly from subunit 1 in terms of composition (few marine bioclasts), texture (inverse grading) and sediment source (organic matter-rich rip-up clasts in the upper part of the subunit).

• Subunit 3 might be interpreted as the result of the backwash (outflow phase). Compared to uprush subunits, it is characterized by abundant small-size marine bioclasts, numerous rip-up clasts and renewed traction.

The tsunami deposit is poorly sorted, with negative skewness indicating that the transport was under high hydrodynamics during a short time (Tuttle et al. 2004). This may be the result of the first tsunami wave and the second less energetic tsunami inundation or the backwash from the first wave that comes from the offshore, erodes the material from the littoral and mixes it with reworked materials before being deposited.

Rip-up clasts (fragments of a cohesive substrate contained within a sedimentary deposit) indicate high-energy flows and also suggest that the material was not reworked for periods of time that are long enough to break apart the material into individual grains.

An assessment of the backflow transport conditions of this mixed material suggests that bedload transport was achieved by supercritical flows, whereas deposition occurred when currents had decelerated enough on the low-gradient lower valley. The marine-brackish to ‘chaotic’ assemblages comprising marine, brackish and freshwater taxa, and Foraminifera assemblages from mostly large to small benthic taxa, reflect the changes in flow condition during the waves.

6 POSSIBLE AGE

Because radiometric dating from the shells collected in the cores are still being performed, we use the ages determined by Carmona and Ruiz (2009) from nearby sites, which correspond to the Bou Hanani terrace, located to the west of CARLA-11, and Core 5, located at a distance of 4 km south of CARLA-11. The Bou Hanani terrace outcropping shells yielded ages of 4,740 ± 40 Ma to 5,080 ± 40 Ma B.P. which clearly correspond to the Holocene maximum inundation. Core 5 yielded ages of 3,080 ± 50 Ma B.P. at 3.1 m depth and 2,470 ± 40 Ma B.P. at 3.5 m. As the studied level is located at more than 4.5 m depth, the age of the tsunami deposit can be between 5,000 and 3,000 Ma B.P., assuming a steady deposition rate, which is a rough approximation in fluvial settings. This age interval is much older than any recorded event, since the oldest historical tsunami in the Gulf of Cadiz occurred some 2,000 years ago (60 BC according to Baptista and Miranda 2009).

7 DISCUSSION

In recent years, numerous studies have dealt with the geological record of past high-energy events such as storms, hurricanes and tsunamis, using (litho-)stratigraphical, sedimentological, geochemical, magnetic, faunal and radiocarbon datings for this purpose (e.g., Clague et al. 2000; Goff and McFadgen 2002; Radtke et al. 2003; Smith et al. 2004). These studies show that tsunamis and storms may significantly disturb the actual sedimentation regimes of coastal areas, by depositing sands far inland, a feature which constitutes the most common signature of flooding in intermediate to slightly reflective coastal environments. However, despite the increase in the palaeo-tsunami studies during the recent years, especially after the 2004 Indian Ocean event, it still appears problematic to distinguish from geological evidence the tsunami deposits from other coastal flooding events like storms (e.g. Kortekaas and Dawson 2007).

7.1 Distance to the shoreline

The fact that these marine deposits were found far inland (6 km on map, 14 km upstream) is a common case of tsunami deposition. For instance, in the Gulf of Cadiz, tsunami deposits of the 1755 event are located as far as 4 km and 16 km respectively from the Atlantic Ocean at Lagoa de Obidos in Portugal and from Huelva estuary in Spain (Morales et al. 2011; Costa et al. 2012). Tsunami deposits at Seven Mile Creek along the Coquille River estuary are located at 8 km from the shoreline (Witter 1999). At Young's Bay, along the Columbia River, they have been found 10 km upstream (Peterson et al. 1993). Tsunami deposits along the Bone, Niawiakum, and Palix rivers near Willapa Bay, Washington, reach up to 3 km inland (Reinhart and Bourgeois 1987; Reinhart 1991; Atwater and Hemphill-Haley 1997). Along the Niawiakum River, marine diatoms have been found overlying buried soils up to 4 km inland, 1 km beyond the limit of tsunami sediments (Hemphill-Haley 1995).

7.2 General depositional features

Tsunami deposits are typically produced through suspended load transport. There are common characteristic features, which have been described by numerous researchers (e.g. Dawson and Smith 2000; Goff et al. 2001; Tuttle et al. 2004; Morton et al. 2007): (i) Laterally extensive and thickly-bedded sand sheets (often structureless) showing landward thinning; (ii) normal or inverse grading; (iii) presence of marine microfossils and macrofauna. In contrast, storm deposits typically are produced through bedload transport and display extensive planar laminae, foresets, troughs, and climbing ripples with a maximum bed thickness close to shore thinning abruptly landward (Morton et al. 2007).

The typical depositional features comprise (Morton et al. 2007): (i) an erosional base; (ii) coarser sediments than in the overlying and underlying beds; (iii) a fabrics characterized by a remarkably poor internal arrangement; (iv) the presence of exotic sedimentary particles from environments external to those where they are deposited; and (v) abundance of alien marine organisms such as foraminifera, diatoms, and even mollusk shells. In the CARLA-11 section, all these features were encountered, so they attest for their origin from tsunami waves.

7.3 Sediment composition

The composition of tsunami sediments reflects the local coastal environments from which the sediment is derived (Jaffe et al. 2003; Goff et al. 2006; Morton et al. 2007). Several worldwide examples have recently been described for recent tsunamis; for instance, at Playa Jahuay in Peru, following the 21 June 2001 tsunami, the mineralogy of the tsunami deposit was similar to the sand found on the nearby beach and contrasted with the mineralogy of the underlying fluvial sand (Jaffe et al. 2003). Nanayama and Shigeno (2006) found that a bimodal distribution in deposits from the 1993 Hokkaido tsunami indicate both a marine sediment source and a terrestrial source. The deposits of the December 2004 tsunami in Indonesia have been described by Paris et al. (2007) as a poorly sorted sediment.

Heavy minerals, including magnetite, amphibole, ilmenite, garnet, zircon, rutile, monazite, and sillimanite, were present in the tsunami deposits of Java (Razzhigaeva et al. 2006; Bahlburg and Weiss 2007; Fritz et al. 2007; Narayana et al. 2007; Jackson 2008; Jagodziski et al. 2009).

Jagodziski et al. (2009) found a depletion of tourmalines in the tsunami deposit compared to the underlying deposits. Kortekaas and Dawson (2007) have shown that the tsunami deposits near Lisbon contain significant percentages of shells, shell debris and benthic foraminifera in shallow water environments. The altered Foraminifera have been used as a tsunami indicator; it provides information about energy and transport condition. (e.g. Mamo et al. 2009, and references therein; Uchida et al. 2010; Pilarczyk et al. 2011; Pilarczyk and Reinhardt 2012b) through their different taphonomic characters (Pilarczyk et al. 2011).

Measurements show that most of the sediments have a relatively high MS reflecting the magnetized clay content; however, low MS can be clearly observed at the tsunami deposit, which match the shelly sand levels described in the previous section (Font et al., 2010).

In our case, the composition of the CARLA-11 tsunami bed includes all these features. However, it is useless to compare the sands in the core to those of the present-day beach because of the older age of the deposit and the change in marine and fluvial dynamics since that time (~3-4 ky).

7.4 Summary

In Table 1 we list the observed characters among those proposed by Kortekaas and Dawson (2007) to distinguish between tsunami and storm deposits. Most observed features are those of tsunami deposits, but others could not be observed because of the age, the position and the technical conditions of the core, including severe oxidation.

Table 1. Characteristics of the CARLA-11 deposits which may be present in tsunami and storm deposits. P = present; A = absent; ? = unknown or not studied.

Evidence (tsunami/*storm*)	P/A	Comments
Morphological		
Wash-over fans behind breached barriers / *idem*	**?**	Ancient morphology
Stratigraphical		
Thins inland and becomes discontinuous / *thins inland*	**?**	Correlations are difficult
Fines inland / *idem*	**?**	Difficult to observe
Erosional basal contact / *idem*	**P**	
Large inland extent / *Relative smaller inland extent*	**P**	6-14 km
Sedimentological		
Boulders / *Boulder deposition has been reported*	**A**	Found at the beach
One or more fining upward sequences, sometimes homogeneous / *fining upward or homogeneous*	**P**	
Intraclasts from underlying material / *not found*	**P**	
Loading structures at the base / *not found*	**P**	
Bi-directional imbrications / *Unidirectional imbrication*	**?**	It is possible that coring altered structures
Poorly sorted (particle size ranging from mud to boulders) / *relatively better sorted*	**P?**	
Sedimentary structures very seldom found / *sedimentary structures more common*	**P**	It is however possible that coring altered structures
Geochemical		
Increase in geochemical elements indicating marine origin / *No information found, but similar signature is expected because of marine origin*	**?**	No geochemical analyses were performed because of high alteration of core
Palaeontological		
Marine fossils / *idem*	**P**	
Increased diversity (mixture marine and brackish fossils) / *mixture of marine and fresh water fossils*	**?**	
Relative well/poorly preserved fossils / *poorly preserved fossils*	**P**	
Plant fragments / *idem*	**?**	
Shell rich units / *shell fragments*	**P**	
Rafting light material / *not found*	**P**	
Buried plants at base / *idem*	**?**	

8 CONCLUSION

Numerous high-energy thin levels have been identified around the tsunamigenic Gulf of Cadiz in the last decade, and have been associated to tsunami waves, especially those following the Lisbon earthquake of 1st November 1755. These beds are preserved in the estuaries of the Algarve, Portugal and southern Spain. In Morocco, no such high-energy sandy deposits were described although most of the northwest coast of Morocco was strongly affected historical tsunamis, as attested by the existence of supra-littoral boulders in Rabat and Larache coasts (Mhammdi et al. 2008; Medina et al. 2011) whose displacement has been attributed to the tsunami of 1755. The present study is the first report of such fine deposits along the Moroccan coast, although they seem to belong to an early to middle

Holocene event. We expect that similar deposits of more recent age may be better preserved within calm lagoons such as the Moulay Bousselham or El Walidiya lagoons, as they are less exposed to fluvial actions than in estuaries.

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REFERENCES

Aloussi, L. 2008. Evolution spatio-temporelle de l'estuaire du Loukkos; étude préliminaire. DESA Memoir, Fac. Sci. Rabat, 58 p. + append.

Atwater, B. F., and Hemphill-Haley, E. 1997. Recurrence intervals for great earthquakes of the past 3,500 years at northeastern Willapa Bay, Washington. US Geological Survey Professional Paper, n°1576, pp.1-108.

Bahlburg, H., and Weiss, R. 2007. Sedimentology of the December 26, 2004, Sumatra tsunami deposits in eastern India (Tamil Nadu) and Kenya. International Journal of Earth Sciences, vol. 96, n°6, pp.1195-1209.

Baptista, M. A., and Miranda, J. M., 2009. Revision of the Portuguese catalog of tsunamis. Natural Hazards and Earth Systems Sciences, vol. 9, pp.25–42.

Bouhmadi, B., Benavente, J., and Cruz-Sanjulian, J. J., 1994. Geometria, piezometria y parametros hidraulicos de los acuiferos de la Cuenca baja del rio Loukkos (Marruecos). Geogaceta, vol. 16, pp. 11-14.

Carmona, P., and Ruiz, J. M. 2009. Geomorphological evolution of the river Loukkos estuary around the Phoenician city of Lixus on the Atlantic littoral of Morocco. Geoarcheology, vol. 24, n° 6, pp. 821–845.

Clague, J.J., Bobrowsky, P.T., Hutchinson, I., 2000. A review of geological records of large tsunamis at Vancouver Island, British Columbia. Quaternary Science Reviews, vol. 19, pp. 849–863.

Costa, P. J. M., Leroy, S. A. G., Dinis, J. L., Dawson, A. G. and Kortekaas, S. 2012. Recent high-energy marine events in the sediments of Lagoa de Obidos and Martinhal (Portugal): recognition, age and likely causes. Natural Hazards and Earth Systems Science, vol. 12, pp. 1367–1380.

Cuven, S., Paris, R., Falvard, S., Miot-Noirault, E., Benbakkar, M., Schneider, J.-L., and Billy, I. 2013. High-resolution analysis of a tsunami deposit: case study from the 1755 Lisbon tsunami in southwestern Spain. Marine Geology, vol. 337, pp. 98–111.

Dalrymple, R. W. 1992. Tidal depositional systems. Facies models: Response to sea level change, pp. 195-218.

Dawson, S., and Smith, D. E. 2000. The sedimentology of Middle Holocene tsunami facies in northern Sutherland, Scotland, UK. Marine Geology, vol. 170, n°1, pp. 69-79.

Dawson, A. G., Hindson, R., Andrade, C., Freitas, C., Parish, R., and Bateman, M. 1995. Tsunami sedimentation associated with the Lisbon earthquake of 1 November AD 1755: Boca do Rio, Algarve, Portugal. The Holocene, vol. 5, n° 2, pp. 209-215.

El Gharbaoui, A., 1981. La Terre et l'Homme dans la péninsule tangitaine. Etude sur l'Homme et le milieu Naturel dans le Rif occidental. Travaux de l'Institut Scientifique, Rabat, Série Géologie and Géographie physique, n°15, 439 p.

El Gharbaoui, A., 1987. Les climats, In: El Gharbaoui A (ed) La Grande Encyclopédie du Maroc; vol. Géographie physique et Géologie, Edition GEI, Rabat, pp. 14-31.

Font, E., Nascimento, C., Omira, R., Baptista, M. A. and Silva, P. F., 2010. Identification of tsunami-induced deposits using numerical modeling and rock magnetism techniques: a study case of the 1755 Lisbon tsunami in Algarve, Portugal. Physics of the Earth and Planetary Interiors, vol. 182, pp. 187–198.

Font, E., Veiga-Pires, C., Pozo, M., Nave, S., Costas, S., Ruiz Muñoz, F., Abad, M., Simoes, N., Duarte, S., and Rodriguez-Vidal, J., 2013. Benchmarks and sediment source(s) of the 1755 Lisbon tsunami deposit at Boca do Rio Estuary. Marine Geology, vol. 343, pp. 1–14.

Fritz, H. M., Kongko, W., Moore, A., McAdoo, B., Goff, J., Harbitz, C., and Synolakis, C. 2007. Extreme runup from the 17 July 2006 Java tsunami. Geophysical Research Letters, vol. 34, p. 12.

Goff, J. R., and McFadgen, B. G. 2002. Seismic driving of nationwide changes in geomorphology and prehistoric settlement—a 15th century New Zealand example. Quaternary Science Reviews, vol. 21, n°20, pp. 2229-2236.

Goff, J., Chagué-Goff, C., and Nichol, S. 2001. Palaeotsunami deposits: a New Zealand perspective. Sedimentary Geology, vol. 143, n°1, pp. 1-6.

Hemphill-Haley, E. 1995. Diatom evidence for earthquake-induced subsidence and tsunami 300 yr ago in southern coastal Washington. Geological Society of America Bulletin, vol. 107, n°3, pp. 367-378.

Jackson, K. L. 2008. Paleotsunami History Recorded in Holocene Coastal Lagoon Sediments, Southeastern Sri Lanka. Open Access Theses. Paper 171. http://scholarlyrepository.miami.edu/oa_theses/171

Jaffe, B., Gelfenbaum, G., Rubin, D., Peters, R., Anima, R., Swensson, M., and Riega, P. C. 2003. Identification and interpretation of tsunami deposits from the June 23, 2001 Peru tsunami. In Proceedings of the International Conference on Coastal Sediments, Vol. 2003, p. 13.

Jagodziński, R., Sternal, B., Szczuciński, W., and Lorenc, S., 2009. Heavy minerals in 2004 tsunami deposits on Kho Khao Island, Thailand. Polish Journal of Environmental Studies, vol. 18, n°1, pp. 103-110.

Kortekaas, S., and Dawson, A. G., 2007. Distinguishing tsunami and storm deposits: an example from Martinhal, SW Portugal. Sedimentary Geology, vol. 200, n°3-4, 208–221.

Luque, L., Lario, J., Zazo, C., Goy, J. L., Dabrio, C. J., and Silva, P. G., 2001. Tsunami deposits as paleoseismic indicators: examples of the Spanish coast. Acta Geologica Hispanica, vol. 3, n° 3-4, pp. 197–211.

Mamo, B., Strotz, L., and Dominey-Howes, D. 2009. Tsunami sediments and their foraminiferal assemblages. Earth Science Reviews, vol. 96, pp. 263–278.

Maramai, A., Brizuela, B., and Graziani, L., 2014. The Euro-Mediterranean tsunami catalogue. Annals of Geophysics, vol. 57, n°4, S035, doi: 10.441/ag-6437, pp. 1-26.

Medina, F., Mhammdi, N., Chiguer, A.; Akil, M. and Jaaidi, E.B., 2011. The Rabat and Larache boulder fields; new examples of high-energy deposits related to extreme waves in north-western Morocco. Natural Hazards, vol. 59, pp. 725-747, DOI: 10.1007/s11069-011-9792-x

Mellas, S. (2012). Evaluation du risque tsunamique sur le littoral atlantique marocain (Doctoral dissertation, Université Chouaib Doukkali).

Mhammdi, N., Medina, F., Kelletat, D., Ahmamou, M., and Aloussi, L. 2008. Large boulders along the Rabat coast (Morocco); possible emplacement by the November, 1st, 1755 a.d. tsunami. Sci. Tsunami Haz., vol. 27, n°1, pp. 17-30

Morales, J. A., Borrego, J., San Miguel, E. G., Lopez-Gonzalez, N. and Carro, B. 2008. Sedimentary record of recent tsunamis in the Huelva Estuary (southwestern Spain). Quaternary Science Reviews, vol. 27, pp. 734-746.

Morales, J. A., Gutérrez Mas, J. M., Borrego, J., and Rodriguez-Ramirez, A. 2011. Sedimentary characteristics of the Holocene tsunamigenic deposits in the coastal systems of the Cadiz Gulf (Spain). In: Mörner, N-A. (Ed.) The tsunami threat – research and technology, Intech, pp. 237-258.

Morton, R. A., Gelfenbaum, G., and Jaffe, B. E., 2007. Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples. Sedimentary Geology, vol. 200, n°3, pp. 184-207.

Nanayama, F., and Shigeno, K., 2006. Inflow and outflow facies from the 1993 tsunami in southwest Hokkaido. Sedimentary Geology, vol. 187, n°3, pp. 139–158.

Narayana, A. C., Tatavarti, R., Shinu, N., and Subeer, A. 2007. Tsunami of December 26, 2004 on the southwest coast of India: Post-tsunami geomorphic and sediment characteristics. Marine Geology, vol. 242, n°1, pp. 155-168.

Paris, R., Lavigne, F., Wassmer, P., and Sartohadi, J. 2007. Coastal sedimentation associated with the December 26, 2004 tsunami in Lhok Nga, west Banda Aceh (Sumatra, Indonesia). Marine Geology, vol. 238, n°1, pp. 93-106.

Passega, R. (1957). Texture as characteristic of clastic deposition. AAPG Bulletin, vol. 41, n°9, 1952–1984.

Peterson, C. D., Darienzo, M. E., Burns, S. F., and Burris, W. K., 1993, Field trip guide to Cascadia paleoseismic evidence along the northern Oregon coast: Evidence of subduction zone seismicity in the central Cascadia margin: Oregon Department of Geology and Mineral Industries, Oregon Geology, vol 5, pp. 99-114.

Pilarczyk, J.E., Reinhardt, E.G., Boyce, J.I., Schwarcz, H.P., Donato, S.V., 2011. Assessing surficial foraminiferal distributions as an overwash indicator in Sur Lagoon, Sultanate of Oman. Marine Micropaleontology, vol. 80, pp. 62-73.

Pilarczyk, J. E., and Reinhardt, E. G., 2012. Testing foraminiferal taphonomy as a tsunami indicator in a shallow arid system lagoon: Sur, Sultanate of Oman. Marine Geology, vol. 295, pp. 128–136.

Radtke, U., Schellmann, G., Scheffers, A., Kelletat, D., Kromer, B., and Uwe Kasper, H. 2003. Electron spin resonance and radiocarbon dating of coral deposited by Holocene tsunami events on Curaçao, Bonaire and Aruba (Netherlands Antilles). Quaternary Science Reviews, vol. 22, n°10, pp. 1309-1315.

Razzhigaeva, N. G., Ganzei, L. A., Grebennikova, T. A., Ivanova, E. D., and Kaistrenko, V. M. (2006). Sedimentation particularities during the tsunami of December 26, 2004, in northern Indonesia: Simelue Island and the Medan coast of Sumatra Island. Oceanology, vol. 46, n°6, pp. 875-890.

Reineck, H. E., and Wunderlich, F. 1968. Classification and origin of flaser and lenticular bedding. Sedimentology, vol. 11, n°1-2, 99-104.

Reinhart, M. A., and Bourgeois, J. 1987. Distribution of anomalous sand at Willapa Bay. In Washington-Evidence for large-scale landward-directed processes [abstract]: EOS, American Geophysical Union Transactions, vol. 68, p. 44.

Rodriguez-Vidal, J., Cáceres, L. M., Abad, M., Ruiz, F., González-Regalado, M. L., Finlayson, C., Finlayson, G., Fa, D., Rodriguez-Llanes, J. M. and Bailey, G. 2011. The recorded evidence of AD 1755 Atlantic tsunami on the Gibraltar coast. Journal of Iberian Geology, vol. 37, n°2, pp. 177–193.

Scheffers A, Kelletat D (2005) Tsunami relics on the coastal landscape west of Lisbon, Portugal. Sci Tsunami Haz, vol. 23, n°1, pp. 3-15.

Smith, D. E., Shi, S., Cullingford, R. A., Dawson, A. G., Dawson, S., Firth, C. R., and Long, D. (2004). The holocene storegga slide tsunami in the United Kingdom. Quaternary Science Reviews, vol. 23, n°23, pp. 2291-2321.

Snoussi M. 1980. Géochimie et minéralogie des sédiments fins de l'estuaire de Loukous (Côte atlantique marocaine); Contribution à l'étude d'un écosystème estuarien. D.E.S. de 3ème Cycle, Univ. Mohammed V, Fac. Sci. Rabat.

Tejera de León, J. and Duplantier, F. (1981) Origine et signification sédimentologique des dépôts meubles de l'estuaire du Loukkos et du prisme littoral adjacent (littoral nord atlantique marocain). Bull. Inst. Géol. Bassin d'Aquitaine, n°29, 133-159.

Trentesaux, A., Cirac, P., Mhammdi, N., Maazi, H., Malengros, D. and De Resseguier, A. 2005. Comblement récent de l'oued Loukkos (nord du Maroc) à la limite estuaire-fleuve, 10ème Congrès des Sédimentologues Français, Marseille, France, 7-16 octobre 2005.

Tuttle, M.P., Ruffman, A., Anderson, T. and Jeter, H., 2004. Distinguishing tsunami from storm deposits in eastern North America: the 1929 Grand Banks tsunami versus the 1991 Halloween storm. Seismological Research Letters, vol. 75, 117-131.

Uchida, J. I., Fujiwara, O., Hasegawa, S., and Kamataki, T. 2010. Sources and depositional processes of tsunami deposits: analysis using foraminiferal tests and hydrodynamic verification. Island Arc, vol. 19, n°3, 427-442.

Witter, R.C. 1999, Late Holocene paleoseismicity, tsunamis and relative sea-level changes along the south-central Cascadia subduction zone, southern Oregon, U.S.A. [Ph.D. Thesis]: Eugene, Oregon, University of Oregon, 178 p.

Whelan, F., and Kelletat, D. 2005. Boulder deposits on the southern Spanish Atlantic coast: possible evidence for the 1755 AD Lisbon tsunami. Science of Tsunami Hazards, vol. 23, n°3, 25–38.