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Recent high-energy marine events in the sediments of Lagoa de Óbidos and Martinhal (Portugal): recognition, age and likely causes

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Abstract. A key issue in coastal hazards research is the need to distinguish sediments deposited by past extreme storms from those of past tsunamis. This study contributes to this aim by investigating patterns of sedimentation associated with extreme coastal flood events, in particular, within the Lagoa de Óbidos (Portugal). The recent stratigraphy of this coastal lagoon was studied using a wide range of techniques including visual description, grain-size analysis, digital and x-ray photography, magnetic susceptibility and geochemical analysis. The sequence was dated by ^{14}C, ^{210}Pb and Optically Stimulated Luminescence. Results disclose a distinctive coarser sedimentary unit, within the top of the sequence studied, and shown in quartz sand by the enrichment of elements with marine affinity (e.g., Ca and Na) and carbonates. The unit fines upwards and inland, thins inland and presents a sharp erosive basal contact. A noticeable post-event change in the sedimentary pattern was observed. The likely agent of sedimentation is discussed here and the conceivable association with the Great Lisbon tsunami of AD 1755 is debated, while a comparison is attempted with a possibly synchronous deposit from a tsunami in Martinhal (Algarve, Portugal). The possibility of a storm origin is also discussed in the context of the storminess of the western Portuguese coast and the North Atlantic Oscillation. This study highlights certain characteristics of the sedimentology of the deposits that may have a value in the recognition of extreme marine inundation signatures elsewhere in the world.

1 Introduction

With the aim of identifying geological traces of extreme coastal flooding events during the last millennium, The Lagoa de Óbidos, a Portuguese coastal location, was studied and the data obtained compared with the stratigraphic record of Martinhal on the Portuguese south coast, an area selected for comparison because abrupt marine inundations deposits have been previously recognized in its stratigraphy (Dawson, 1994; Dawson et al., 1995; Andrade et al., 1997; Kortekaas, 2002; Kortekaas and Dawson, 2007).

Extreme events such as abrupt marine invasions due, for example, to tsunamis, extreme storms and co-seismic subsidence, have an undoubtedly important significance for coastal evolution. Over the past 25 yr, an increasing number of investigations have dealt with the interpretation of the lithological signature of extreme marine invasions, mainly focusing on palaeotsunamis, but also on the comparison with large storms and their sedimentological signatures (e.g., Kortekaas and Dawson, 2007; Kunz et al., 2010; Bertrand et al., 2011). Due to specific depositional conditions, the sediment sequences in coastal lagoons are among the best geological settings to detect units deposited by abrupt marine invasions because the low energy of lagoons is suitable for the preservation and detection of sudden energy increases in their sedimentary record. The definition of sedimentological criteria indicative of tsunami deposits has been extensively debated in the literature (e.g., Hindson et al., 1996; Goff et al., 1998, 2001; Hindson and Andrade, 1999; Gelfenbaum and Jaffe,

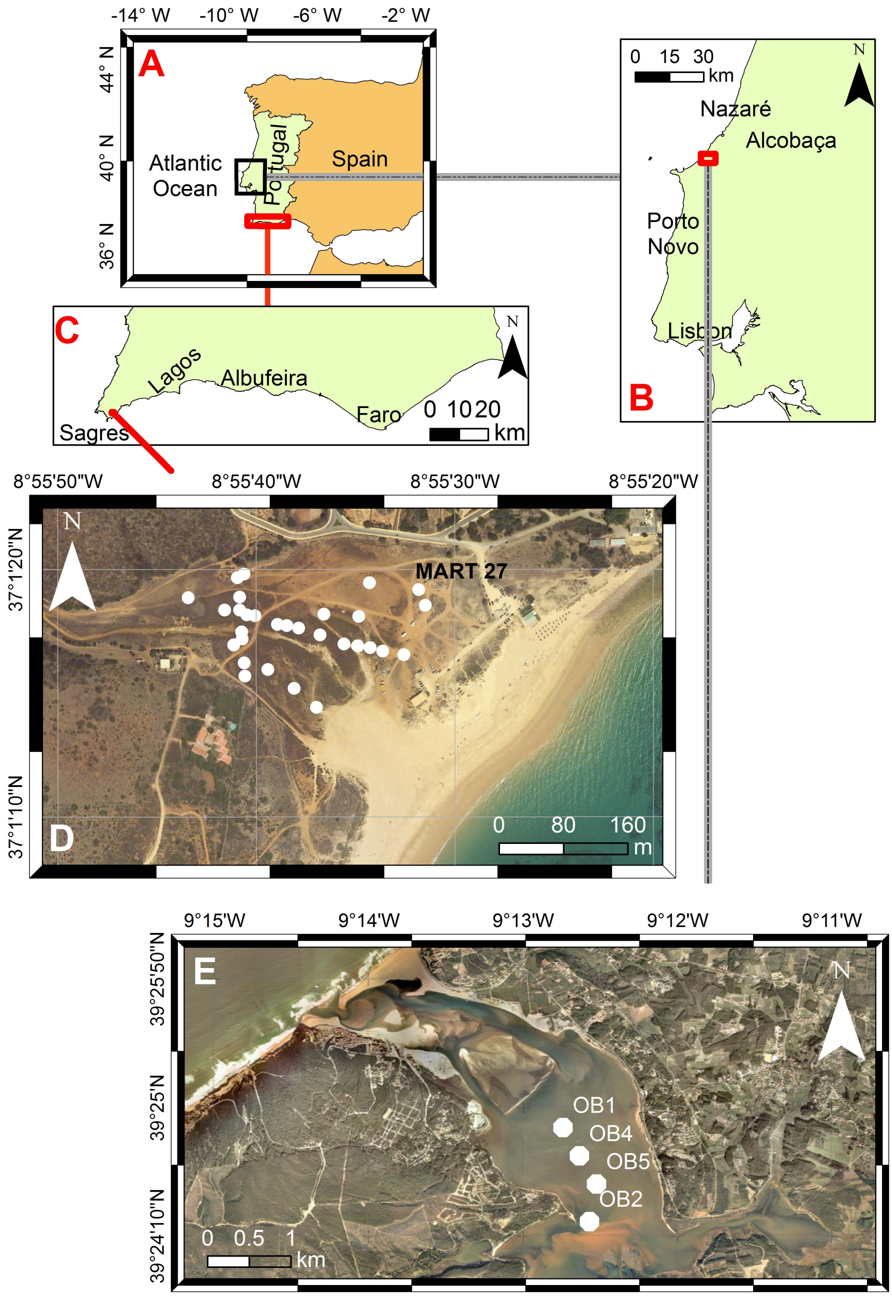

Fig. 1. Location map of Lagoa de Óbidos and Martinhal. **(a)** general location map of the two study areas (Martinhal and Lagoa de Óbidos). **(b)** regional location map of Lagoa de Óbidos. **(c)** regional location map of Martinhal. **(d)** core location (27 March) in Martinhal. Other cores, previously studied (Kortekaas and Dawson, 2007) are also marked. **(e)** core locations within Lagoa de Óbidos lagoonal space.

2002; Andrade et al., 2003; Dawson and Stewart, 2007; Paris et al., 2007, 2009; Chagué-Goff, 2010; Szczucinski, 2011). To some extent the criteria presented are simply indicators of a high-energy marine invasion, whatever the cause. Intensive research (e.g., Atwater, 1986; Atwater and Moore, 1992; Liu and Fearn, 1993; Atwater et al., 1995; Bruzzi and Prone, 2000; Dawson et al., 1991, 2000; Kortekaas, 2002; Liu and Fearn, 2000; Nanayama et al., 2000; Andrade et al., 2003, 2004; Kortekaas and Dawson, 2007) has been carried out in this fundamental aspect of how to distinguish tsunamigenic sedimentary formations from other marine invasive deposits. Tsunamis, however, are major sedimentary events and, usually, their peculiarity and their uniqueness is one criteria used. However, the problem remains; it is exceptionally difficult to differentiate tsunami deposits from units deposited by major storms and this work attempts to address

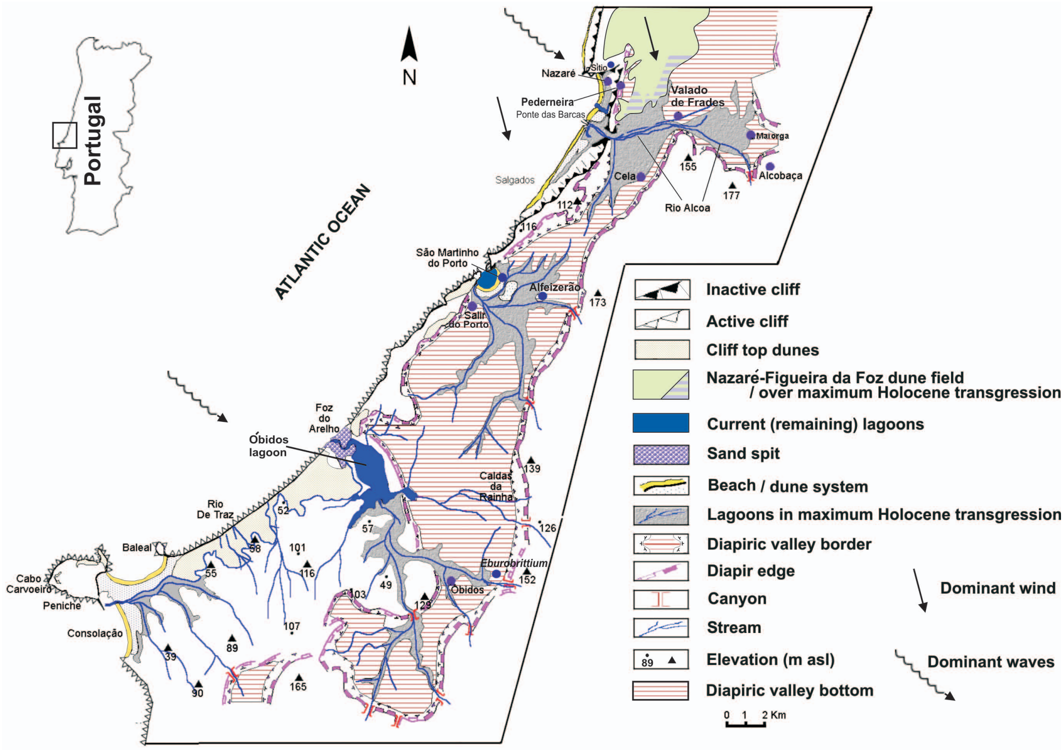

Fig. 2. Regional geomorphological map of the stretch of the western coast of Portugal where Lagoa de Óbidos is located (Dinis et al., 2006).

this relevant issue in an area known for being subjected to tsunamis, such as the AD 1755 tsunami that flooded Lisbon, and storm events, such as the 1739 "Barbara" (Pfister et al., 2010) or the more recent 1978 storm (Daveau et al., 1978).

Both Lagoa de Óbidos and Martinhal (Fig. 1) are low-energy depositional environments with significant susceptibility to marine invasions which enhance the possibilities of detecting anomalous units that could be correlated with coastal extreme flooding. Furthermore, recently, new cores were extracted from Martinhal and the age of its stratigraphic units was reviewed using a large set of new Optically Stimulated Luminescence dating (Cunha et al., 2010). The objectives of the work presented here are to contribute to the definition of sedimentological criteria to identify major abrupt marine inundations in coastal stratigraphy.

2 Regional setting

Lagoa de Óbidos (Fig. 1a and b), located on the western coast of Portugal, is a shallow depression of irregular shape with an axis oriented NW-SE (Fig. 1e). The present-day lagoon is what remains from a vast lagoonal system that once washed the walls of the historical village of Óbidos and reached the Roman town of *Eburobrittium*, a few kilometres further inland, with a setting and evolution similar to the now fully silted up Pederneira Lagoon between Nazaré and Alcobaça (Fig. 2) (Freitas, 1989a, b; Henriques, 1992; Dinis et al., 2006). Those systems are located in depressions created by co-seismic processes around the Caldas da Rainha Fault, drowned by marine transgression during the Holocene (Ferreira et al., 2009). The Lagoa de Óbidos inlet (the so-called "Aberta"), is located between steep cliffs that reach more than 10 m above sea level (Fig. 1e and Fig. 2). The northward littoral drift is here contrary to the southward-dominated drift elsewhere along the Portuguese western coast. This high-energy, swell-dominated coastal sector is exposed to WNW to NNW swell generated at high latitudes in the North Atlantic and prevailing more than three quarters of the year, with a yearly mean significant height and peak period offshore of 2–2.5 m and 9–11 s and the modal height and period range between 1.5–3 m and 9–14 s (Carvalho and Barceló, 1966; Costa, 1994). Due to the shallow gradient of the beach, the nearshore wave regime in the study area is somewhat reduced in height to 2 m (Carvalho and Barceló, 1966). The marine-dominated area of the lagoon receives sand from the near-by beaches and the ca. 1500 m long sand barrier, with some wash-over fans also distinguishable. The flood-tidal fans stretch along one third of the lagoon axis, also marking the landward limit of seasonal storm deposits. The central and deepest area of the lagoon, reaching approximately 2 m, is within the river-dominated part where the Real, Arnóia and Cal Rivers are the main sedimentary contributors. Within the lagoon transport is made by uniform suspension, except in the inlet area where transport is by both suspension and dragging (Rodrigues and Quintino, 1985). A set of natural conditions creates a high depositional rate, both the littoral drift and tidal hydrodynamics, and the slope of a small hydrographical network (approximately 450 km^2) eroding various geological formations, including Quaternary, Cretaceous and Jurassic sandstone. Over recent years the Lagoa de Óbidos has been subjected to intense dredging to prevent the closure of the inlet and to increase the depth in some areas of the lagoon, with an inevitable impact on its stratigraphy and water exchange with the sea (Henriques, 1992; Freitas, 1989a, b, 1992; Oliveira et al., 2006; Costa, 2006; Malhadas et al., 2010). The position of the lagoonal barrier drifts frequently, mainly due the artificial breaching and intense dredging, that also contributes to the lowering of the barrier height.

Martinhal (Fig. 1c) is a small valley separated from the sea by a sand barrier consisting of dunes and a beach (Fig. 1c and d. The Martinhal lowland is formed by two small streams cutting through Upper Jurassic limestone. The largest stream, Barranco das Mós, enters the valley from the NW and creates a small alluvial fan, and a smaller stream enters from the north. The barrier is normally a continuous feature throughout the year but when breached during storm short episodes, marine flooding occurs in the lowland (Andrade et al., 1997; Kortekaas and Dawson, 2007). In the centre of the lowland, the surface consists of silt with saltmarsh vegetation. At the outer edge and in the higher NE part, the surface is sandy with very little vegetation except for some grass. The tidal range in the area is approximately 2.1 m, reaching about 3 m during spring tides.

3 Methodology

A range of sedimentological analytical techniques, i.e., stratigraphic description, grain-size analysis, digital and x-ray photography, magnetic susceptibility, and geochemical analysis, and multiple dating methods, i.e., ^{14}C, ^{210}Pb and Optically Stimulated Luminescence, were applied to detect and compare units deposited by high-energy marine events.

The sediment corer used in Lagoa de Óbidos was a 5 cm diameter Livingstone piston corer that allowed recovery of sediment cores collected below the lagoonal water column. The acquisition of cores (in October 2002) was made from the side of a Zodiac boat after stabilizing the boat in each station with the use of two anchors. Water depth was measured before collecting the samples. The coring procedure described by Wright (1991) was followed. No significant sediment compaction or deformation was detected in any core. Occasionally alternate holes were used to ascertain that the stratigraphic sequence was uninterrupted (overlapping sections). The core from Martinhal was obtained with an Eijkelkamp hand gauge auger with a 3 cm diameter chamber and used to study the stratigraphy and a 10 cm gouge auger was used to take samples. In order to recover sand under the water table, a Van der Staay suction corer was used.

Standard core description was conducted according to the Ocean Drilling Program (ODP) visual core description form (Mazzullo et al., 1988). The detailed macroscopic visual description included grain-size, sedimentary structures, the nature of contact between stratigraphical units and the Munsell chart colour. Digital and x-ray photographs were taken on every core studied to better visualise and identify its stratigraphic units and its peculiarities. Magnetic susceptibility measurements, used to correlate cores with a 2 cm resolution on unopened cores, were conducted using a Bartington MS2C magnetometer.

Loss-on-Ignition (Bengtsson and Enell, 1986) was measured in every core from Óbidos and on core 27 from Martinhal. Loss-on-Ignition was made at 105 °C during 12 h for the loss of water, at 550 °C during 2 h for the loss in organic matter and at 925 °C during 24 h for the loss of carbonates.

All cores of Lagoa de Óbidos were sub-sampled every 2 cm for Ca, Fe, K, Mg, Na elemental content of sediments, analysed by a Flame Atomic Absorption Spectroscopy with a Thermo Jarrell Ash S11 and a Perkin-Elmer Model 2380 Spectrophotometer. In the core retrieved in Martinhal, elemental analysis was also conducted by a Phillips Oxford Instruments XR300 XRF (X-Ray Fluorescence). The samples were ground and approximately 4 g were analysed.

Grain-size analysis was conducted using a Malvern 2000 Series Laser Granulometer on samples from all cores. Statistical grain-size parameters, e.g., mean, standard deviation, skewness and kurtosis, were calculated (MacManus, 1988).

Radiocarbon dates collected within organic sediment of Lagoa de Óbidos were obtained at the Poznan Radiocarbon Laboratory, Poland. Conventional ^{14}C ages were calculated with a δ^{13}C correction for isotopic fractionation (Stuiver and Polach, 1977) based on the ^{13}C/^{12}C ratio measured by an AMS-system simultaneously with the ^{14}C/^{12}C ratio. The ages have been calibrated using the OxCal v3.10 software (Bronk Ramsey, 2001). It must be stressed that since no reservoir effect was considered, following the practice of publications concerning similar context (e.g., Freitas et al., 2002), the calibrated age presented can be overestimated.

The OSL date was obtained at the Geochronology Laboratory, University of Gloucestershire, UK. The sediment was extracted from a 10 cm long segment of the extruded section (OB1.2) under controlled laboratory lighting conditions. The peripheral two millimetres of sediment was removed to exclude material potentially exposed to light during core extrusion. The quartz within fine sand (125–180 µm) fraction was isolated. Dose rate calculations, following those described by Aitken (1985), incorporated beta-attenuation factors (Mejdahl, 1979), dose rate conversion factors (Adamiec and Aitken, 1998) and the absorption coefficient of present water content (Zimmerman, 1971), with a 25 % relative uncertainty attached to reflect potential temporal variations in past moisture content. It should be noted that the water content of the sample was obtained sometime after coring,

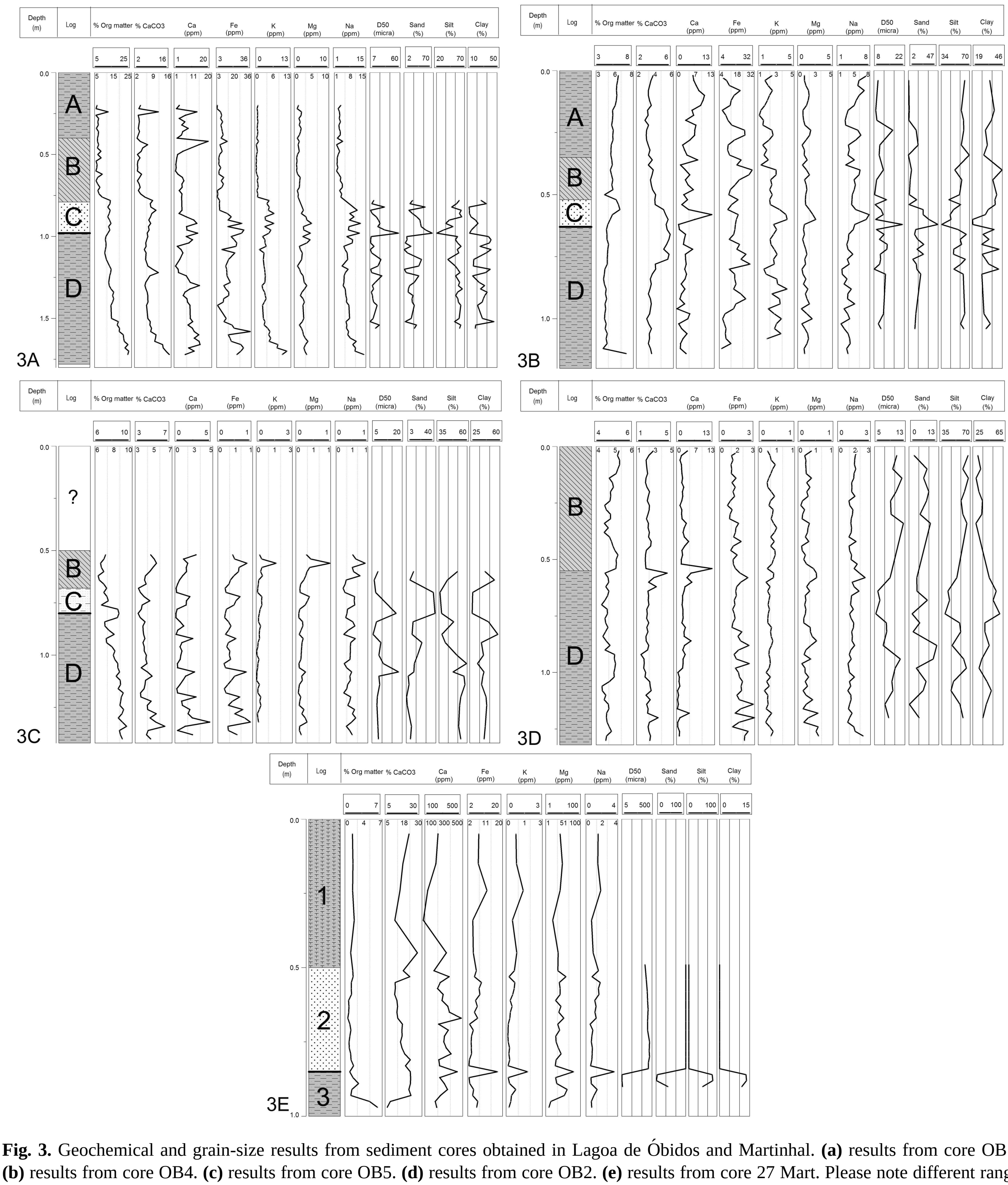

Fig. 3. Geochemical and grain-size results from sediment cores obtained in Lagoa de Óbidos and Martinhal. **(a)** results from core OB1. **(b)** results from core OB4. **(c)** results from core OB5. **(d)** results from core OB2. **(e)** results from core 27 Mart. Please note different range of values for each core and proxy. For core locations please check Fig. 1d and e.

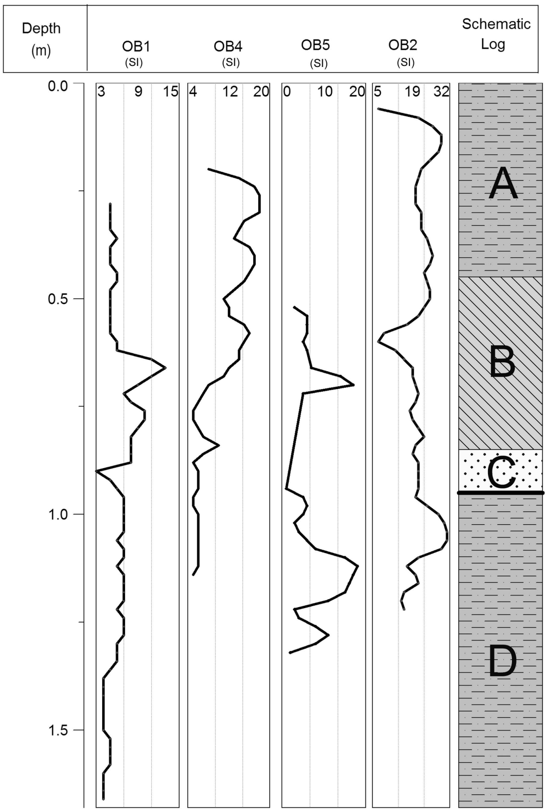

Fig. 4. Magnetic susceptibility results obtained for cores from Lagoa de Óbidos (please note different range of values for each core) – for core locations please check Fig. 1e.

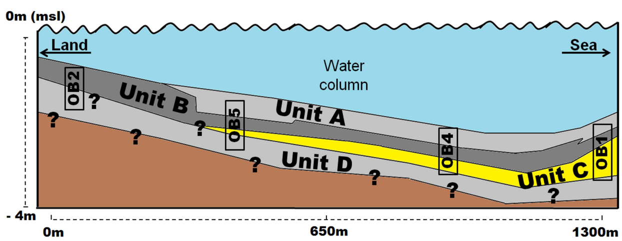

Fig. 5. Schematic stratigraphic profile (including cores OB1; OB4; OB5 and OB2) based in the lithostratigraphy of Lagoa de Óbidos (for core locations please check Fig. 1e).

increasing the uncertainty. Estimations of cosmic dose followed the calculations of Prescott and Hutton (1994).

^{210}Pb measurements established the sedimentation rate for the top of the stratigraphic column, using samples every cm on the top 30 cm and every 5 cm on the following 40 cm. The samples were analysed in an Ortec Alpha Spectrometer and the results obtained were then calculated based in the Constant Rate Supply method (Appleby and Oldfield, 1983).

Table 1. OSL results obtained for unit C from Lagoa de Óbidos (please note that the data of core collection was 2002).

Sample	OB1 (base of Unit C)
Total wet γ dose rate (Gy ka^{-1})	0.83 ± 0.14
Neutron Activation Analysis K (%)	2.09 ± 0.10
Neutron Activation Analysis Th (ppm)	10.05 ± 0.52
Neutron Activation Analysis U (ppm)	3.25 ± 0.16
Total wet β dose rate (Gy ka^{-1})	1.28 ± 0.21
Cosmic dose rate (Gy ka^{-1})	0.18 ± 0.02
Total dose rate (Gy ka^{-1})	2.30 ± 0.25
Dosimetry (Gy)	0.31 ± 0.02
Age (years)	136 ± 17

4 Results

4.1 Lithostratigraphy, geochemistry and textural features of Lagoa de Óbidos cores

Four cores were used to form a transect with an orientation NNW-SSE (Fig. 1e). Geochemical and grain-size data of the cores from Lagoa de Óbidos (Fig. 3a, b, c and d) allow the identification of four stratigraphic units. Magnetic susceptibility measurements show also a correlation between cores, namely a drop at the base of Unit C (Fig. 4). Stratigraphical correlation and depositional geometry based on all available data are presented in Fig. 5. The stratigraphic consistence between the different cores suggests that any sedimentary (natural or anthropogenic) remobilisation is unlikely.

Unit A, the top one, present in the three westernmost stations, consists of clay and silt. In places it was also possible to identify some laminae, alternating coarser, light millimetric silt and clay material with finer, darker clays.

Unit B, consisting of fine mud, without any visible subunits, is present in all stations. The contact between unit B and the overlying unit is transitional.

Unit C consists of olive green, almost clean, sand to sandy mud, which fines inland. It is not present in core OB2, the easternmost and most inland station. The shell richness of this unit contrasts with the rest of the sedimentary column. A load cast was also recognised at the base of this unit in core OB1. Furthermore, plant fragments were also observed mainly in the base of the deposit. The textural signature of unit C (Figs. 3a, b, c and d) is marked by a sharp increase in grain-size mean and sand content at the base of the unit in cores OB1, OB4 and OB5.

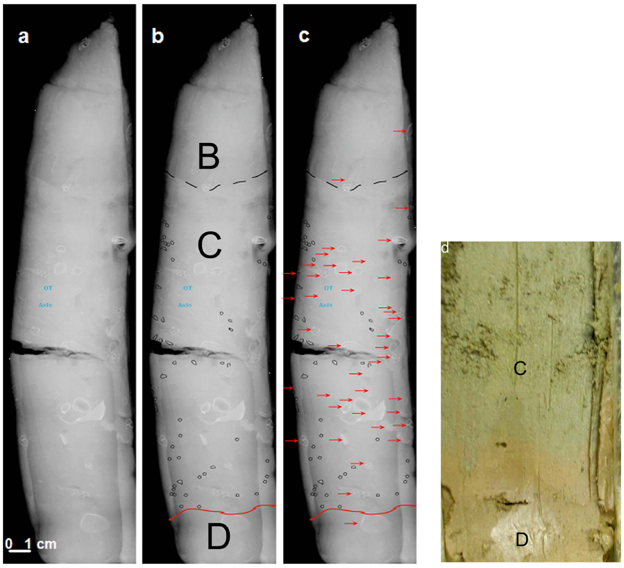

Fig. 6. **(a)** X-ray photography of unit C from core OB4. **(b)**-X-ray photography of unit C from core OB4 – the black circles indicates coarser clasts. **(c)**-X-ray photography of unit C from core OB4 – the arrows indicates fossil fragments. **(d)** Photography of contact between unit C and D in core OB4 (for core location please check Fig. 1e).

Unit C in core OB1 seems to trigger a significant change in geochemical conditions: the values for organic matter, carbonates, Ca, Fe, K, Mg and Na significantly decrease above it.

In core OB4 unit C can be characterised by an increase in organic matter and carbonate content, as well as a rise in values of all elements analysed. In core OB5 a similar pattern was detected, with the exception of K where no significant change was observed. Unit C is absent in core OB2, but it can be correlated with an interval near the top of unit D (around 0.6 m depth) with increases in carbonates, Ca, Fe, Mg and Na contents, followed by an increase of average organic matter. However, the range of variance is low, thus, inhibiting robust interpretations of these results.

Unit D, the deepest unit, consists of silty mud, with minor sand content, darker in the eastern stations and present in all. In places, this unit contains discontinuous millimetric-scale interlaid clay laminae of dark brown and light brown.

The contact between unit D and the overlying unit C is erosional and some thickness of Unit D is apparently missing (Fig. 6). The abruptness of the contact between units D and C suggests a sudden, high-energy and short-lived depositional event.

4.2 OSL, Radiocarbon and ^{210}Pb dating of Lagoa de Óbidos

All the dates obtained are in stratigraphic order, despite the uncertainty.

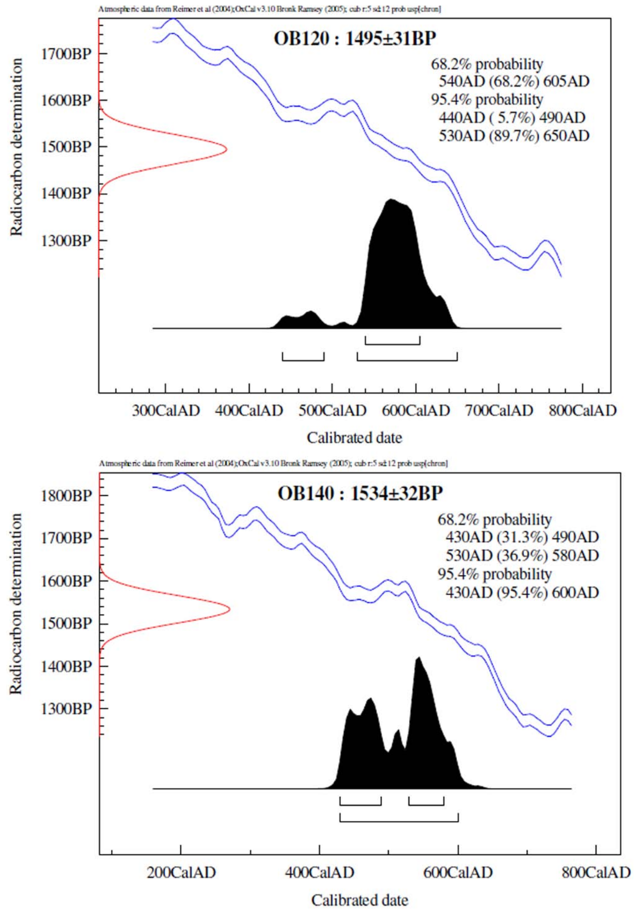

Fig. 7. Radiocarbon calibrated results from samples OB1.2_120 cm and OB1.2_140 cm. Please note that range of ages obtained overlap.

The date of the base of unit C on core OB1 obtained with OSL was 136 ± 17 yr (Table 1). This date is, however, problematic. As discussed below, there are no historical records of a major abrupt marine invasion in the region at that time, around AD 1850. As discussed below, several reasons can contribute to explain what we believe to be, an underestimation for the age of the event-layer, related to the complexity of both the method and the sedimentary event. OSL results are reliable when the sedimentary environment favours full bleaching of sand prior to burial (Cunha et al., 2010), a condition generally achieved in shallow sub-aqueous contexts. Possible explanations for age underestimation are (i) a significant period of exposition or thin burial in shallow water after the depositional event, (ii) an assumed too low water content, and (iii) the reduced number of aliquots measured (12), considering the natural variability of quartz response. Note also that water content used in age calculations lower than the actual would result in a younger age, and that the sample content was measured with a significant delay after coring.

Table 2. Radiocarbon results from samples collected in core OB1 (120) and OB1 (140).

Sample	Material	pmC	Error	Yrs Cal ^{14}C Age	Error	$\delta^{13}C$	Error	Current micro ams
OB120	Organic sediment	83.01	0.33	1495	31	−16.2	0.8	24.1
OB140	Organic sediment	82.61	0.33	1534	32	−25.3	1.5	16.3

Radiocarbon dates were obtained from organic sediment collected at depths ca. 30 and 50 cm below unit C (Fig. 7a and b). The radiocarbon dates were obtained in samples from core OB1.2 (1.20 and 1.40 m below surface), respectively 1495 ± 35 yr BP and 1535 ± 53 yr BP (Fig. 7 and Table 2). Because the range of ages obtained (Fig. 7) largely overlap, a date of ca. 1385 yr Cal BP (AD 565) can be roughly considered for a depth of 1.30 m below the surface. The radiocarbon dates imply a strong erosive event or a very low sedimentation rate underlying unit C.

^{210}Pb analyses allowed the establishment of a sedimentation rate for the top of the stratigraphic sequence (i.e., units A and B) of close to 8.7 mm yr^{-1}.

4.3 Results for the Martinhal core

Three lithostratigraphic units (Fig. 3e) were identified and correlated with the units presented by Kortekaas (2002) and Kortekaas and Dawson (2007) for other cores and trenches collected in Martinhal (located in Fig. 1d).

The top unit (unit 1) has a total thickness of 50 cm and consists of several sandy and silty sub-units with different thicknesses, and includes shell fragments. In contrast, unit 2 is coarser with underlying and overlying units and is composed of very coarse to coarse sand with no clay or silt, slightly fining upward. This unit has some shell fragments and its erosional lower boundary is marked by a sharp increase in sand and rip-up clasts. All these characteristics are clear in the X-ray images. The thickness of unit 2 in core 27 Mart was 35 cm. Unit 3 consists of light brown silty clay. The thickness of this unit is approximately 190 cm. Grain-size results of the uppermost part of unit 3 and unit 2 of core 27 Mart are presented in Fig. 3E and attest the strong contrast between the clay-dominated unit 3 and the sandy unit 2.

Geochemical results show a good correlation with sedimentological and stratigraphic evidence, and highlight the uniqueness of unit 2 (Fig. 3e). Loss-on-Ignition results demonstrated that the deposition of unit 2 was characterised by an increase of carbonates. The top metre of core 27 Mart shows abrupt increases in the concentration of Ca, Fe, K, Mg and Na at the base of unit 2. Within this unit, high Fe content indicates, probably, abrupt inputs of oxic waters, but the peak in the lower boundary can also be related to the permeability barrier created by the muddy unit 3. The concentrations of Ca, Mg and Na in unit 2 are compatible with a marine input. The contact between units 3 and 2 indicates a sharp increase of the concentrations of Fe, Ca and K (Fig. 3e). The middle part of unit 2 shows a considerable decrease of Fe, but especially low amounts of K, probably related to the rarity of clay minerals and K-feldspars.

5 Discussion

5.1 High-energy marine deposit recognition and comparison between Lagoa de Óbidos and Martinhal

The contribution of abrupt marine invasions to the geological record is significant. Lagoa de Óbidos and Martinhal are both coastal areas subject to marine invasions, but only by energetic events capable of crossing the sand barriers that separate the Atlantic Ocean from both lowlands. However, there is some contrast between these two sites. The sand barrier at Lagoa de Óbidos is a wide and perennial barrier that prevents the impact of common marine events: although marine water invades the lagoonal space, the marine-sourced and coastal sediments are not detected beyond the sand barrier. In contrast, the barrier at Martinhal is easily bypassed by strong storms, explaining the more frequent high-energy deposits (unit 1). Furthermore, the distance from the coastline to the core locations in Óbidos varied from 1500 to 3000 m, while core 27 Mart is located just over 100 m of Martinhal beach. Thus, the specific geomorphological features favoured a higher frequency in the sedimentary record of abrupt marine invasions in Martinhal when compared with Lagoa de Óbidos.

A wide range of techniques was used to recognize the record of abrupt marine invasions, including stratigraphic, grain-size and geochemical proxies. Due to the uniqueness coastal stratigraphy and the sedimentological characteristics of unit C at Lagoa de Óbidos and of unit 2 at Martinhal, it is suggested that a major tsunami was possibly a mechanism responsible for their deposition. The spatial distribution of the high-energy deposits can enlighten its genesis; for instance Dawson et al. (2004) and Goff et al. (2009) suggested that a greater penetration inland is expected for tsunami waves compared with storm waves. The AD 1755 tsunami was the biggest tsunami to affect the Portuguese coast during historical times and is the best candidate as the source of those units. In both areas of study, the event responsible for the deposition of Units C (Lagoa de Óbidos) and 2 (Martinhal) was unique in the stratigraphy of the last millennia. Furthermore, the sedimentological and geochemical changes caused after the event are made obvious by the detected features that are commonly associated with tsunami deposits (Fig. 3 and Table 3).

5.2 Historical record of Lagoa de Óbidos evolution and the effects of the AD 1755 event

The history of the region is clearly marked by the lagoon, with the main aspects of its maximum expansion and infill summarized by Dinis et al. (2006). The Roman *civitas* of *Eburobrittium* had a harbour with a probable sea access until the 2nd half of the 5th century AD. Phases of accelerated infill seem to be related to demographic increase and land-use after the Christian Re-conquest (late 12th to early 14th centuries) and during the Portuguese Age of Discovery (mid 15th to late 16th centuries). From the 16th century onwards several references (e.g., maps and historical documents) acknowledge that it was vital to keep the "Aberta" (inlet) opened and also demonstrate that the lagoon surface was decreasing dramatically. There has been some dredging in the lagoon (mainly in the Aberta), especially over the last two decades.

The first reference to Lagoa de Óbidos as a lagoon instead of an estuary is from AD 1736 and AD 1751 (Freitas, 1989a, b), proving the existence of a robust sand barrier in the inlet. Detailed historical records of the AD 1755 tsunami in Lagoa de Óbidos are not available, but it must be stressed that the area around the lagoon was sparsely populated at the time.

However, information on the tsunami impact in the area can be obtained from the official inquiries made after the AD 1755 disaster and local parish records, both quoted by Pereira de Sousa (1919, 1928, and 1932) and Oliveira (2005), in addition to other coeval sources. The run-up estimation for Oeiras (west of Lisbon) and ca. 80 km south of the Lagoa de Óbidos, was 5 to 6 m (Oliveira, 2005). In Porto Novo, around 30 km south of Lagoa de Óbidos, the AD 1755 tsunami climbed the cliffs of the narrow Alcabrichel river valley up to ca. 20 m above mean sea level (Pereira de Sousa, 1928). The impact of the same tsunami, probably combined with the effect of the earthquake, destroyed a segment of the walls of the Peniche fortress (15 km south of the Lagoa de Óbidos inlet). In the Vieira de Leiria beach (ca. 55 km north) the tsunami penetration caused the overflow of the Liz River (Pereira de Sousa, 1932). About 80 km north of the Óbidos inlet, the wave, estimated by eyewitnesses at 10 m, climbed the beach in Buarcos and penetrated deeply into the Mondego Estuary (Oliveira, 2005). Approximately, sixty km further north, the tsunami probably caused a jump in the inlet position and overwashed the barrier of the Aveiro lagoon (Corrochano et al., 2000). Even if the historical sources can overestimate the run-up, numerical modelling for the 1755 tsunami wave(s) in the coastal reach depicted in Figures 1 and 2 points to an open sea maximum water elevation of 1 to 3 m and a deflection towards the east (Renou et al., 2011). For the same event, modelling calculates a main wave height, depending on the tidal level, of between 7.0 and 4.3 m reaching Figueira da Foz, a coastal village about 80 km north of the Lagoa de Óbidos (Ribeiro et al., 2011), and 9 to 4 m in Oeiras, 80 km to the south (Baptista et al., 2011). The run-up was certainly significantly higher than the wave amplitude in the open ocean, probably by two to four times (Levin and Nosov, 2009).

The tidal level at the moment of the tsunami impact on the coast is uncertain. Historical records point to high tide in Lisbon, and low tide in Oeiras (Pereira de Sousa, 1928; Nozes, 1990). Astronomical calculations for the Lisbon area by Oliveira (2005) indicate 2 h = before low-tide, during estuarine ebb flow, but Baptista et al. (2011) point to a neap tidal level, near the maximum. In agreement with this last calculation, high tide conditions are referred to in Vieira de Leiria, 55 km north of Lagoa de Óbidos (Pereira de Sousa, 1932) and Buarcos (Figueira da Foz; Oliveira, 2005). The tsunami was composed of three waves, at least as stated to Lisbon (Pereira de Sousa, 1928; Nozes, 1990) and Porto Novo, 30 km south of Lagoa de Óbidos (Pereira de Sousa, 1932). Although the detailed historical record is absent for Lagoa de Óbidos and Martinhal themselves, we believe the characteristics of the AD 1755 tsunami waves were similar to the adjacent areas described above, with a run-up clearly capable of overwashing and even breaching the sandy barrier.

5.3 The storminess of the western Portuguese coast

The depositional record of the main Atlantic fluvial basins of Iberia shows that increased frequencies of large floods form clusters around AD 1430–1685 and AD 1730–1810 (Thorndycraft and Benito, 2006). During the Little Ice Age, increased coastal sand invasion and dune accretion in the western coast of Portugal were inferred by Dias et al. (2000), as well as for the AD 1770–1830 period by Clarke and Rendell (2006) and related to phases of increased oceanic storminess.

Negative North Atlantic Oscillation (NAO) index winters are associated with a southward shift in Atlantic storm activity and a noticeable increase in Iberia. This is reflected, notably in Portugal, by increased precipitation and fluvial floods (Trigo et al., 2004), as well as a higher sea level caused by barometric lows and reinforced westerly winds (Guerra et al., 2000). Well-known atmospheric circulation patterns show that those conditions correspond quite closely to the winter storms affecting the western Portuguese coast with

Table 3. Comparison of unit C (Óbidos) and unit 2 (Martinhal) sedimentological criteria associated with tsunamigenic deposition (based in literature; see references in the text).

Type of Criteria	Criteria	Unit C(Óbidos)	Unit 2(Martinhal)
Stratigraphic	Fines inland and upwards	Detected	Detected
Stratigraphic	Each wave can form a distinctive unit	Not detected	Not detected
Stratigraphic	Sub-units representing run-up and backwash might be present	Not detected	Not detected
Stratigraphic	Lower contact is unconformable or erosional	Detected	Detected
Stratigraphic	Can contain intraclasts	Not detected	Detected
Stratigraphic	Loading structures at the base of the deposit	Detected	Not detected
Grain-size	Usually an anomalous sand unit in a finer sequence	Detected	Detected
Geochemical	Increases in Na, Cl, Ca and Mg can occur when compared with under and overlying sediments	Detected	Detected
Palaeontological	Shell rich units	Detected	Not detected
Palaeontological	Changes in marine microfauna (e.g. foraminifera, ostracods)	Not analysed	Detected
Palaeontological	Plant fragments or buried soils	Detected	Not detected

waves from the western quadrant (Instituto Hidrográfico, 2005), which are responsible for most of the annual precipitation (Trigo et al., 2004). Consequently, it can be assumed for this coast that NAO-negative values tend to correspond to higher storminess and more intense northward littoral drift during winter.

An inverse correlation between NAO values and solar activity was recently established (e.g., Kirov and Georgieva, 2002) and consequently low solar irradiance corresponds to lower storminess in Mediterranean Europe. Similarly, during the late Maunder Minimum (AD 1675–1715), a period with reduced precipitation in southern Portugal can be deduced from the historical record, but with a rise entering the 18th century (Alcoforado et al., 2000). The Dalton Minimum was roughly between AD 1795 and AD 1825 (Kirov and Georgieva, 2002; Vaquero et al., 2006) and corresponds to a reduced number of floods in the Atlantic Tagus basin (Central Iberia; Benito et al., 2003).

Data and model comparison by Brewer et al. (2007) come to an understanding that negative NAO occurred most frequently during the AD 1650 to 1850 period. The multiproxy reconstruction by Luterbacher et al. (2002) of winter NAO shows a clear dominance of NAO-negative for AD 1500–1830, including slightly positive trends for 1520–1540 and 1710–1750; the period 1830–1870 has obvious NAO-positive moving average and single winter data, changing to a sequence oscillating around zero, but with great peaks (either positive and negative) till AD 1910. Pfister et al. (2010) mention the January 1739 "Barbara" storm, considered as the most intense storm to affect Central and Northern Portugal in historical times.

The synoptic situation of this storm is quite similar to that of the 25th February 1978 storm, which breached the sand-barriers of coastal lagoons and deeply eroded foredunes on the western coast of Portugal (Daveau et al., 1978).

Since mid-16th century, an increase in storminess, related to a dominance of NAO-negative winters over the period AD 1715–1795 (including the 1739 "Barbara" storm), might have reduced the width and altitude of the Lagoa de Óbidos sand barrier, thus favouring the penetration of a high-energy event.

5.4 The tsunami hypothesis and the age of the high-energy events studied

The sedimentary record of the AD 1755 tsunami has been identified on the west coast of Portugal, namely in the Tejo estuary (Andrade et al., 2003) and in the continental shelf (90 m water depth) in the Tejo outlet near Lisbon (Abrantes et al., 2005). In this latter case the tsunamigenic layer, lying over an erosive surface, was calculated as corresponding to the loss of around 40 cm of sediment.

So far, the ages obtained in the units interpreted as resulting from high-energy events studied in this research do not prove the hypothesis of an AD 1755-tsunami origin. However, the reasons presented above show uncertainty in those dates and consider that more accurate age data are needed. If unit C in the Lagoa de Óbidos was laid down by a storm or a storm cluster with high magnitude, it should probably correspond to a unique phase in regional climatic evolution prone to high storminess. However, as seen above, considering NAO, solar activity and regional storm records (both sedimentary and documentary), stormy phases were recurrent from the 16th to the 19th century, thus, contrasting with the stratigraphic uniqueness of unit C. On the other hand, the historical record of tsunamis for the same period is quite clear, with the AD 1755 event as the single possibility. Accordingly, an age around AD 1850 for unit C is highly unlikely and the value of OSL dating should be considered as untrustworthy, as suggested in the dating results section. Therefore, based mainly in its peculiar sedimentary characteristics, it can be concluded that the best candidate as responsible for the deposition of unit C in the Lagoa de Óbidos is the AD 1755 tsunami.

According the available historical and modelling data, the high tide situation when the AD 1755 tsunami reached the Lagoa de Óbidos, probably favoured the penetration inland of this exceptional high-energy marine inundation, overcoming the barrier and inlet weakened by previous decades of high storminess.

The sedimentation rate for the top 45 cm of core OB4 (most of unit A) of approximately 9 mm/year is relatively high. However, it agrees well with the lithology of unit A and is to be expected, as the lagoon has increased its sedimentation rate during the last century, as shown by Freitas (1989a, b), Freitas et al. (1992, 1999, 2002) and Ferreira et al. (2009). The ages obtained are in stratigraphical order, despite methodological and sedimentary constraints that create obstacles to unambiguous sedimentary interpretations. It is observed that the sedimentation rates obtained are in agreement with the known recent historical data for the region (a sharp increase in recent years, demonstrated by the 9 mm yr^{-1} obtained with ^{210}Pb). Furthermore, the sedimentation rate between the top sequence (measured with ^{210}Pb) and unit C (if this unit is assumed as being deposited by the AD 1755 tsunami) is in the order of 2.1 mm yr^{-1}, while the underlying layer presents a sedimentation rate (inferred after analysis of radiocarbon dates) in the order of 0.3 mm yr^{-1}. Despite several age uncertainties, the general picture emerging from this study is of a clear increase in the depositional rate above unit C, and a significant change in water and sediment circulation and deposition in the lagoon after the high-energy event. Such change is also evident in the geochemistry of cores OB1 and OB4, both presenting a higher marine influence. Thus, it can be suggested that the event that affected the Lagoa de Óbidos, responsible for the deposition of unit C, changed the configuration of the inlet complex, affecting the physical and ecological conditions of the lagoonal system. The inland penetration of the event responsible for the deposition of Unit C is absent in core OB2 where the typical mud sedimentary pattern is consistent throughout the stratigraphic column, once more confirming that the common marine invasions sedimentary influence is limited to the ebb-shield of the flood delta.

The age of the presumably tsunami-laid Martinhal's Unit 2 was quite problematic considering earlier dating (Kortekaas and Dawson, 2007), probably due to reworking, but the recent OSL set, published by Cunha et al. (2010), indicates a reliable AD 1755 age. Furthermore, many sedimentological features observed in unit C (Lagoa de Óbidos) are also detected in the tsunamigenic unit 2 (Martinhal).

6 Conclusions

The effects of abrupt marine inundations on the local lithology of two coastal areas of Portugal, Lagoa de Óbidos and Martinhal, were analysed. Lagoa de Óbidos is a shallow lagoon protected by a barrier located in the Western central coast of Portugal and Martinhal is a flat estuarine valley located in the south-west coast of Portugal. Both areas, as with many coastal areas in Portugal, are known via historical documents to have been affected by the AD 1755 tsunami. To detect a sedimentary signature of the AD 1755 tsunami in Lagoa de Óbidos and to compare it with a tsunamigenic unit in Martinhal were the overall aims of this research. To achieve those objectives the samples were submitted to the same group of analyses. The results of the two sites studied were compared following a set of tsunamigenic diagnostic criteria as defined in the literature.

In Lagoa de Óbidos, this study detected one unit plausibly deposited by the AD 1755 tsunami, however, the conclusions are hindered by the age-depth model despite the use of three dating techniques. The dates are discussed in the within the framework of a tsunami deposit causing erosion (loss of sediment below the event) whilst also considering methodological questions, like post-depositional bleaching leading to underestimated OSL ages.

It can be concluded that the common signature for both deposits, Lagoa de Óbidos and Martinhal, includes:

i. peculiarity within the stratigraphic column;

ii. enrichment in elements with marine affinity (such as Ca and Na), in carbonates and in quartz sand;

iii. a sharp erosive lower boundary associated with reworked material and loss of sediment at the base of the event;

iv. coarse texture with a clear contrast with adjacent units;

v. fining of the units inland;

v.i a noticeable post-event change in the sedimentary pattern.

These features are widely recognized as common tsunami deposit characteristics. However, due to the age uncertainties, caution is necessary when stating that the Lagoa de Óbidos unit C was laid down by the AD 1755 tsunami; nevertheless, the hypothesis of an age around AD 1850 and a storm origin were discussed in the context of the regional climate evolution, and considered unlikely.

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