# ÁGUA E TERRITÓRIO

## UM TRIBUTO A

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# LATE HOLOCENE NATURAL AND MAN INDUCED ENVIRONMENTAL CHANGES IN THE WESTERN IBERIAN COAST: ASSESSING FORCING FACTORS

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## Abstract

The Western coast of the Iberian Peninsula stands as an interface between both the Atlantic and Mediterranean climatic influences and marine / fluvial conditions. The paper aims to assess the environmental changes in the last ca 6000 years (both natural and anthropogenic induced) using multiproxy analysis (geomorphological and sedimentological data, elemental and stable isotope content, microfossil assemblages, radiocarbon dating, and historical records) applied to an embayed coast.

The results showed the prevalence of marine environment until 6272-6000 cal BP, but with fluvial infilling of the inner embayment, even before present sea level was reached (ca 4500-4000 cal BP). The influx of sediments was probably the result of the four recorded wet episodes (at modelled age cal BP (2σ): E1 – 6067-4770, E2 – 5806-4409, E3 – 5383-4088, and E4 – 4086-3905). These great sediment influxes along the previous 3000 years continues until 2110-1962 cal BP triggering the downstream migration of the river mouth, the development of a sand barrier coast and of a sheltered lagoon inside the palaeo-embayment.

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Afterwards the sedimentation rate (SR) reached high values (0.19-0.48 cmyr-1), as the result of Roman intervention in the drainage basin where pastures and local fires are recorded, together with an increasing dryness.

A major disturbance is recorded in the Pollen Assemblages Zones (between PAZ II and PAZ III) and in the sediments around 1863-1706 cal BP (2σ), in the transition from the Roman Age to the Muslim invasion period, probably reflecting a hiatus in the sedimentary record. Onwards, SR reached 0.21-0.57 cmyr$^{-1}$. Two major hydro marine episodes may have contributed to this fact: the latter is the Lisbon tsunami (1755 AD) while the former may reflect the 16th Century tsunamis or a great marine storm episode.

An aeolian environment prevailed since then and the embayment was transformed into a dune field interrupted only by the narrow channel of the river whose mouth is often closed.

**Keywords:** Fluvio-marine interactions; tsunami; Holocene climatic fluctuations; anthropogenic intervention; Bayesian analysis; *Vicia faba*; Portugal.

## 1. Introduction

Coastal lagoons are common features, representing nearly 13% of the world's shoreline (Barnes, 2001; Troussellier, 2007). They may have very different sizes and configurations and are often shallow water bodies that can be separated from the ocean by a sandy/clastic barrier. They frequently occur in coastal lowlands, contiguous to the coastal plains (Barnes, 2001; Bird, 1994). However, this type of coastal systems can also occur in high rocky shores, associated with coastal recesses. These embayments are often associated with more ductile or fractured rocks. The genesis of both coastal system types are linked to Holocene sea level rise and stabilization (Angulo *et al.*., 1999; Cabral *et al.*, 2006; Dinis *et al.*, 2006; Jia *et al.*, 2012; Plater and Kirby, 2011). Since then, river system response triggered the influx of sediments across river catchments and the infilling of estuaries, coastal lagoons and embayments with sediments and organic matter (Isla, 1995; Kjerfve and Magill, 1989; Troussellier, 2007). The abundance of sediments available to siltation depends on climate, vegetation cover and adjustments in the hydrographic basin, as well as on land use changes (Morton *et al.*, 2000; Nichols, 1989). They may also present different signatures, namely those related to marine hydrodynamic episodes (overwash and tsunamis; Donato *et al.*, 2009; Goff *et al.*, 2000) and small changes in sea level (El Banna and Frihy, 2009; Haenssler *et al.*, 2013; Ljung *et al.*, 2006; Pérez-Ruzafa *et al.*, 2007; Thorndycraft and Benito, 2006; Vilanova *et al.*, 2010). The forcing factors change from wave to tide or river dominant hydrodynamic environments (Fornari *et al.*, 2013; Morris and Turner, 2010; Vilas *et al.*, 1991).

Holocene climatic fluctuations, despite being of minor amplitude in the long-term global climate (Wanner *et al.*, 2008, 2011) have provoked changes on vegetation cover and type. Although the doubts about these episodes and their extension (global or regional/local impacts) during the Holocene, cooling episodes (Bond *et al.*, 1997, 2001) and warm and humid episodes, like the Iberian Roman Humid period (Martin-Puertas *et al*., 2009) or the Medieval Climate Anomaly in Iberia (Moreno *et al*., 2012), have been recognized.

Human intervention over the territory, with deforestation and agricultural and pastoral practices, contributed to slope protective layers denudation and, hence, to the increase of sediment transport and river mouth infilling. These changes are recorded in the sediment depositional sequences by its organic matter content including pollen and Non-Pollen Palynomorphs (NPP) (Delgado *et al*., 2012; Müller and Mathesius, 1999; Müller and Voss, 1999).

The study of the Holocene evolution of coastal lagoons and estuaries in Portugal has attracted many researchers (Arnaut-Fassetta *et al*., 2006; Boski *et al*., 2008; Chester, 2012; Schneider *et al*., 2010). After sea level stabilization (Dias *et al*., 2000) all estuaries and embayments recorded the beginning of siltation, in contrast with previous times, when these systems were open marine environments and the main forcing factor was the rapid sea level rise. Depending mainly on the availability of sediments of the river basins and on the inner continental shelf, sand barriers began to settle (ca 5000 BP or later). Local forcing factors have prevailed from then on. The coastal environment changed from marine dominance to lagoon systems and to fluvial environments (Alday *et al*., 2006; Cabral *et al*., 2006; Danielsen *et al*., 2012; Dinis *et al*., 2006; Duck and Silva, 2012; Freitas *et al*., 2002; Granja, 1999; Granja *et al*., 2010; Moura *et al*., 2007; Soares de Carvalho *et al*., 2006). During this phase two thresholds in environmental conditions seem to occur: the first one at 4000-2000 BP, when small estuaries and embayments became permanent lagoon environments; the more recent one at 700 BP, when the fluvial conditions prevailed with strong anthropogenic influence.

In several worldwide studied sites, climatic anomalies have been recorded between these thresholds and later: the Roman Warm Period (250 BC - AD 450), the Dark Ages Cold Period (450 - AD 950), and the Medieval Warm Period ($12^{th}$ Century) when most of the embayments were already infilled; a changing period during the $14^{th}$and the $15^{th}$ Centuries with a cold episode from 1305 to 1418 AD (Early Little Ice Age) and the Little Ice Age (LIA - 1350 to 1850 AD) with several cooling episodes, namely the Mauder Minimum (1640-1715 AD) and the Dalton Minimum (1795-1825AD) (Wanner *et al*., 2008). However, so far these small changes within the LIA have not been recognized in Portuguese estuaries and embayments.

The main goal of this paper is to evaluate the role of the forcing factors on coastal dynamics and the resilience of an embayed estuary coastline over the last ca 5000 years, after sea level stabilization, including the genesis and the existence of a coastal lagoon later infilled and replaced by a dune field. To achieve this goal, secondary objectives were established, namely: (i) to perform a detailed geomorphological characterization and to create a coring framework; (ii) to assess the different sedimentation environments based on the sampled sedimentary packages; (iii) to evaluate the different rhythms of sedimentation; (iv) to recognize the sedimentary sources (marine or fluvial); (v) to assess the small climate driven fluctuations; (vi) to evaluate the signatures of extreme episodes; and (vii) to define the stages of landscape evolution.

## 2. Study area

The study area - Santa Rita-Porto Novo is situated, in the wave dominated western Portuguese Atlantic Coast of the Portuguese mainland (SR in Figure 1), in the Estremadura region, 40 km NW of Lisbon on a cliff coast, with narrow and short beaches.

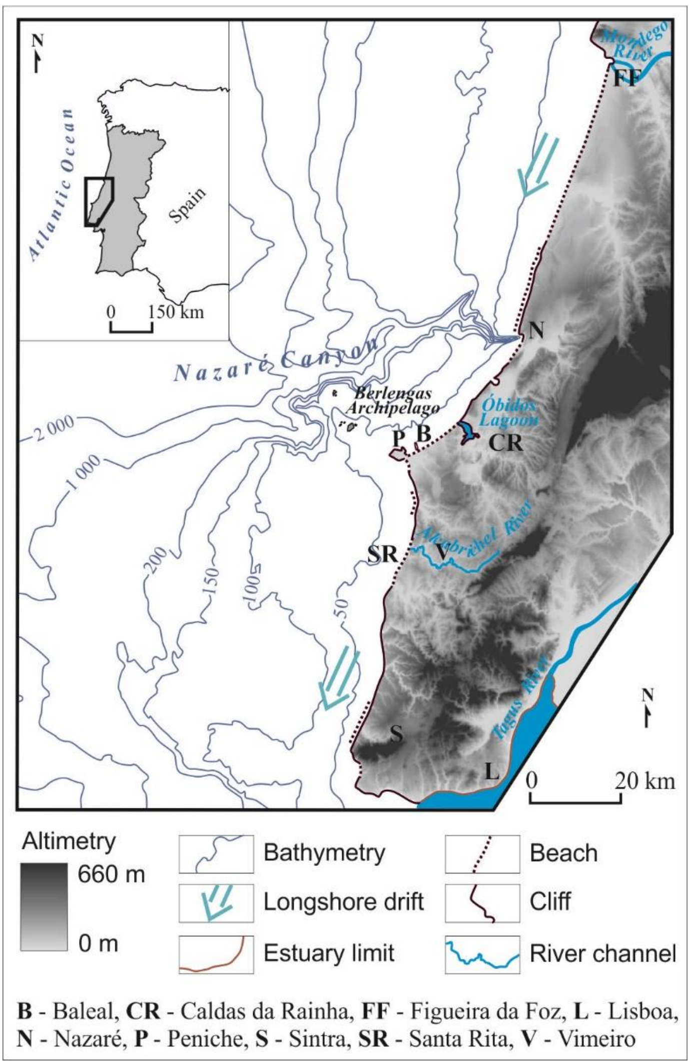


Figure 1. Regional setting of the studied area (Santa Rita – SR). B: Baleal; CR: Caldas da Rainha; L: Lisbon; N: Nazaré; P: Peniche; V: Vimeiro.

The present day environment is a mesotidal wave dominated coast (average tide amplitude of 3.08 m, average spring tide 3.67 m with a maximum recorded at 4.03 m at Cascais tide gauge; Carvalho, 1992; Ferreira, 1993; Pires and Pessanha, 1986; Trindade, 2010). According to the closest wave buoy data located in Peniche (P in Figure 1), mean significant wave height (Hs) is 1.2 m, frequently ranging between 1 and 3 m. Storms in the western coast are considered to have $H_s > 5$ m. Five years recurrence period for storm waves can be found at $H_{sstorm}$ 5.57 m and $H_{max}$ 6.98 m (Trindade, 2010).

Centennial relative sea level changes show an increasing trend with an average rate of 1.7 ± 0.2 mmyr$^{-1}$ between 1920 and 2000 at Cascais tide gouge (Dias and Taborda, 1992) near the study site. Recent geodetic studies highlight the successive increase in the rate of the sea level rise, estimated to have been 2.5 mmyr$^{-1}$ in 1990 and 2.9 mmyr$^{-1}$ in 2008 (Antunes and Taborda, 2009).

This stretch of the coast corresponds to a section where there is a lack of coastal sediments for three main reasons: (i) the lithology in these river basins is predominantly composed of limestones and marls, although locally there may be outcrops of sandstones and conglomerates, providing a low clastic sediment influx contribution to beach feeding (Figure 2), (ii) the cliffs are also predominantly cut into limestone and marl and (iii) the dominant longshore drift N to S yield a sparse coastal sediment supply due to grounds set in (i) and (ii), and the trapping of drifting sediments by the submarine canyon of Nazaré (Figure 1) (a gouf type, Vanney and Mougenot, 1981) and by the sandy features associated with the tombolos of Peniche and Baleal (Figure 1). Consequently, aeolian and beach sands are mainly of local provenance.

The distal sector of the Alcabrichel River is conditioned by a complex pattern of both lithology and rock structure arrangement. The main rock types present are the Jurassic sequence of the Hetangian gypsiferous marls and the superimposed Kimeridgian hard limestones. These rock materials are organized in two diapiric structures developed in the NNE-SSW direction, in line with the Caldas da Rainha diapir (CRd) and the Santa Rita-Santa Cruz diapir (SRd, Figure 2; Alves *et al.*, 2003; Chaminé *et al.*, 2004). Jurassic hard limestones constitute the highest areas of the coastal plateau, reaching 107 m amsl. The combined action of the kinetic behaviour and erosion of the marls created diapiric depressions, which bottom is at 2.93 m amsl. Further inland the carbonate rocks change to sandstones and conglomerates and to smoother landforms.

This lithological and structural complexity is reflected in the estuary morphology. According to Pritchard (1952) it can be considered tectonic (Figures 2 and 3). In the middle lower sector, the valley of the Alcabrichel River has various alternating morphologies that can be synthesized in: (i) a valley with a relatively wide floodplain reaching 500 m width where the river crosses the diapiric depressions (CRd, Figure 2; Maceira lowland, Figure 3) and (ii) a narrow gorge with a 60 m deep cut in the hard limestones (FV, Figure 3) and, (iii) a wide distal estuary crossing the other diapiric depression (SRd, Figures 2 and 3).

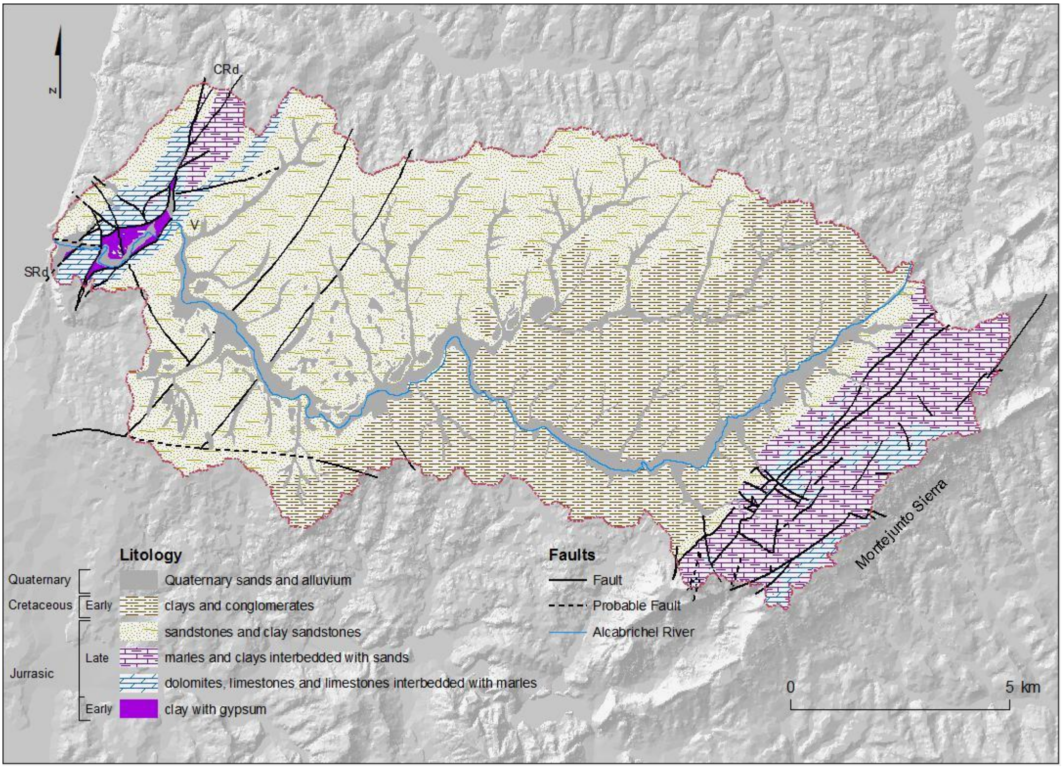


Figure 2. Lithology of the Alcabrichel river basin. SRd: Santa Rita diapir; V: Vimeiro; CRd: Caldas da Rainha diapir (further geological information in Alves *et al.*,2003).

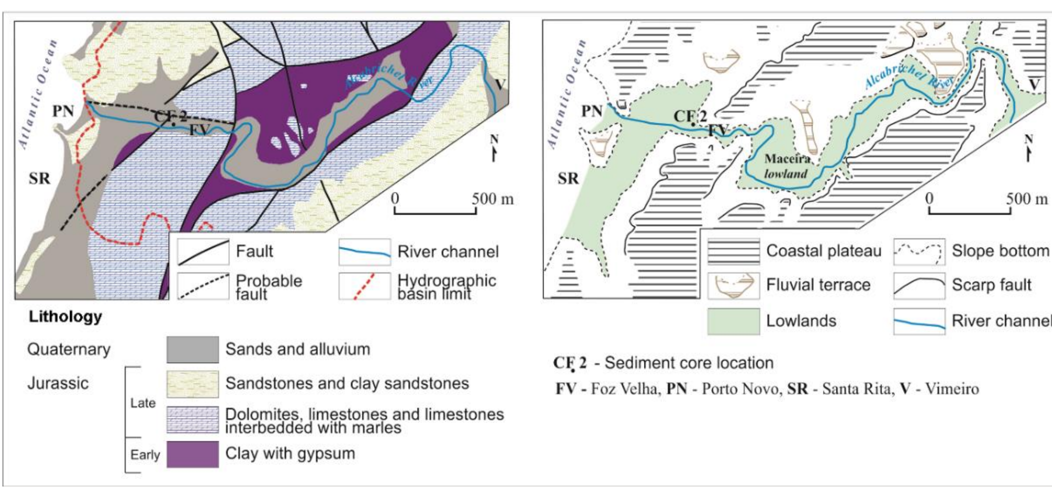


Figure 3. Geology and geomorphology of Alcabrichel tectonic estuary.

The coastline is jagged and consists of two pocket beaches separated by a rocky hill. Inland there is a dune field and a palaeo-cliff.

## 3. Methodological approach

### 3.1 Field survey, coring and sediment sampling

Coring site location was determined on the basis of a detailed geomorphological field survey and historical document analysis.

The site is located at the extreme northeast of the embayment Santa Rita-Porto Novo, where nowadays aeolian sand cover is less thick. The equipment used was a vibracore. The surface of the core (CF2) was at 3.58 m amsl (orthometric height) and reached 5.01 m depth (Figure 3).

Sediments were sub-sampled at 1 cm intervals, with the exception of the last 125 cm at the base of the core, where insufficient sediment forced a 2 cm sampling. The detailed sub-sampling aimed to detect small textural, elemental and isotopic changes. Unfortunately only a moderate number of samples were suitable for the investigation of pollen and NPP content.

325 samples were treated for sedimentological purposes (grain size analysis, using a combination of sieving for sediments > 63 µm and X ray sizing through a Sedigraph for sediments < 63 µm). Commonly used statistical parameters were obtained with SEDPC software (Henriques, 1998, 2003, 2004) and the Folk and Ward method (1957) enabled us to evaluate the grain size distribution.

### 3.2. Elemental and stable isotope content and radiocarbon dating

Terrestrial and marine environments are recorded in the sediments since they accumulate organic material from different sources, such as fluvial or marine organic matter. Elemental and stable isotopic composition was assessed (C, N, TOC, TN TOC/TN ratio, $\delta^{13}C$ and $\delta^{15}N$) allowing the determination of the source of the organic sedimentary matter and, consequently, the different conditions that affected the studied area in the past. Organic matter from marine environments, for instance, is enriched in $^{13}C$, in contrast with terrestrial organic matter, which is usually depleted in this isotope. Concerning the TOC/TN ratio, its value normally raises with the increase of terrestrial influence (Villas *et al.*, 1991).

However, these parameters may also be affected by other factors, such as diagenetic processes, anthropogenic activities and organic matter decomposition. Another limitation is that different sources may, in some cases, not be totally distinguishable, as the characteristic values can overlap to some extent (Lamb *et al.*, 2006). The presence of carbonates, on the other hand, may affect the $\delta^{13}C$ value. Therefore, a pre-treatment procedure is necessary and different procedures have been tested (Kennedy *et al*., 2005; Mahiques *et al*., 2007; Ryba and Burgess, 2002; Schubert and Nielsen, 2000).

Nevertheless, these parameters by themselves or, as is more usual, in conjunction with each other are useful tools for discriminating sedimentary sources and identify environmental changes and episodes that have occurred. These parameters were determined in 53 samples carefully selected from core CF2.

Accurate and precise dating is essential for the construction of reliable palaeo-environmental and palaeo-climatic models based on multi-proxy analysis of sedimentary records. Radiocarbon dating is one of the most common dating methods used to develop chronological frameworks.

In estuarine environments, where fluvial-marine interaction is more intense, the reworking of organic materials often affects the $^{14}C$ dates which induces difficulties in the establishment of a robust chronological framework. Bayesian analysis provides an important tool not only to evaluate the data set, namely to identify possible outliers and age-depth reversals, but also to establish accurately a robust chronological framework and to determine sedimentation rates (Bronk-Ramsey, 2008, 2009b). This approach was performed using the OxCal calibration software (Version 4.1) (Bronk-Ramsey, 2009a) that allows the incorporation of the stratigraphic sequence on the data set analysis. The radiocarbon dates using the AMS (Accelerated Mass Spectrometry) technique, were obtained from the organic matter extracted from 10 sediment samples, each one corresponding to a sediment thickness of 1 or 2 cm.

### 3.3. Palynology

Pollen samples were obtained from eight of the extracted sub-samples. The moderate number of pollen samples was related to the fact that the deposit contained large amounts of sand and silt and low levels of organic content. Sand content in sediments is a factor known to result in high degree of oxygenation and destruction of pollen exines (eg. Moore *et al*., 1991). The samples were subjected to standard laboratory treatment (Fægri and Iversen, 1975) including hydrogen fluoride (HF) exposure for 48 h. After chemical preparation two of the samples (244 cm and 289 cm) were rejected due to lack of pollen.

Pollen and microfossil data of the samples are presented in a percentage pollen diagram. All data were calculated as percentages of Total Regional Pollen sum (TRP) including pollen of dry-soil species. Pollen of taxa occupying  wetland areas (mainly hygrophilous) are likely to dominate the pollen content and result in large fluctuations of the pollen curves reflecting local changes (Janssen, 1973). These taxa together with Non-Pollen Palynomorphs (NPP) were therefore not included in the pollen sum but calculated as percentages of TRP. Charcoal fragments larger than 5 µm were counted. The pollen diagram was constructed using Tilia and Tilia graph (Grimm, 1991). Due to scattered sample representation as a result of poor pollen preservation in the intermediate layers, the palynological results are presented in the form of a histogram.

### 3.4. Historical documents and charts

To access information from the last millennium, several historical documents were studied, which includes texts from the 12th Century, produced by our monarchs and by the monks installed near the coast. The monasteries constituted the way that the Portuguese monarchs used to create settlements and populate the lands that were being conquered, especially from the Muslims. The monks constituted the most literate population and left written records of their daily activities, the environment in which they lived and the problems they felt.

More recent documents were also used such as topographic maps (from the 20th Century, corresponding to several topographic surveys), and orthophotomaps.

## 4. Results

### 4.1. Sedimentological data

*The sedimentological units*. Three major units may be pointed out from the analysis of sediment grain size throughout the core (Figure 4): (i) the lower unit (U1), from the bottom up to 166 cm is a clay dominant unit (clay content range from 19 to 72%), with four thin layers with a gravel component (≤ 11%), (ii) the middle unit (U2), from 166 cm to 18 cm, where silt and sand are dominant (from 5 to 90%) and gravel is present (< 7%); (iii) the upper unit (U3) solely constituted by sand (Figure 5 and Table 1).

Detailed observation of the U2 revealed three subunits distinguished by the sand and silt content (Table 1). In these subunits it is possible to identify thin layers representing short episodes of enrichment in sand or in clay, corresponding to more or less energetic conditions respectively.

*Sediment characterization by statistical methods.* Silts and clays are dominant in the core sediments. Subunits U2b and U3 are the exception (Figure 4 and Table 1). U3 is composed by medium sands, moderately sorted, positively skewed (with a tail on fines). U2b is composed by fine sands, very poorly sorted, positively skewed.

The sediments of the other units and subunits are mainly extremely poorly sorted and negatively (with a tail on coarse material) or less positively skewed. The sediments of U1 have the lowest selection and most are negatively skewed.

At the bottom of U1 there is distinctive sediment consisting of very coarse silt, very poorly sorted and positively skewed.

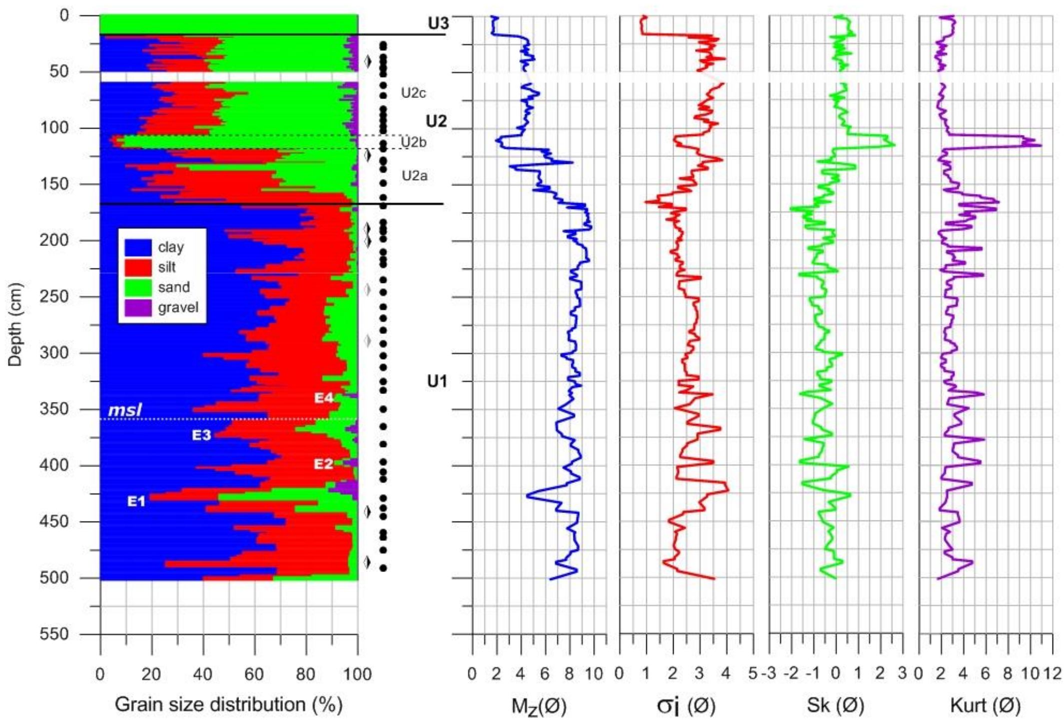


Figure 4. Sedimentology of the CF2 core units and subunits described in the text. The diamonds stand for pollen samples and black dots for geochemical analysis.

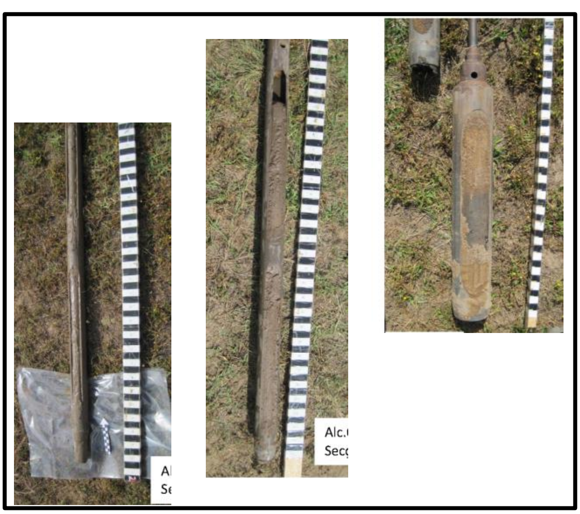

Figure 5. Elements of the core. The two on the left belong to U1 and the other to U2.

Table 1. Synthesis of sedimentary parameters.

Cl- clay, Si – silt, Sd – sand, Gr – gravel

| Units (cm) | Sediment content (%) | | | | Calibr. (Ø) | Sk (Ø) | Sub-units/ Events (cm) | Sediment content (%) | | | | Calibr. (Ø) | Sk (Ø) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Cl** | **Si** | **Sd** | **Gr** | | | | **Cl** | **Si** | **Sd** | **Gr** | | |
| **U3** (18-0) | 0 | 0 | 100 | 0 | 0.78-1.00 | 0.28-0.56 | | | | | | | |
| **U2** (166-18) | 4-49 | 3-73 | 2-90 | ≤7 | 0.91-1.89 | -0.27 to - 1.11 | **U2c** (110-18) | 14-41 | 7-31 | 46-54 | ≤7 | 1.89-0.91 | -0.67 to -1.11 |
| | | | | | | | **U2b** (119-110) | 4-8 | 3-8 | 84-90 | ≤3 | 0.98-0.88 | -0.67 to -0.98 |
| | | | | | | | **U2a** (166-119) | 10-49 | 24-73 | 2-69 | ≤2 | 1.84-0.98 | -0.27 to -0.98 |
| **U1** (500-166) | 19-72 | 25-71 | 3-52 | 5-11 | 2.45-0.94 | 0.63 to -1.52 | **E4** (336-337) | 62 | 30 | 3 | ≤5 | 3.47 | -1.62 |
| | | | | | | | **E3** (370-365) | 49 | 27 | 19 | ≤5 | 3.76 | - 0.66 |
| | | | | | | | **E2** (399-396) | 65 | 26 | 3 | ≤6 | 3.49 | - 1.63 |
| | | | | | | | **E1** (427-422) | 19-32 | 27-35 | 52-22 | ≤11 | 3.27-4.05 | 0.63 to -0.57 |

From statistical parameters analysis it can be inferred that sediments were deposited in a sheltered environment which suffered sporadic pulses of higher energy. These pulses are represented by the layers with sand and the highest gravel content, particularly evident in U1 (E1 to E4, Figure 4), though also recognizable in U2.

*Grain quartz texture and shape*. The morphoscopy of quartz of selected samples was performed according to the classification of Powers (1953). Angular grains mean less transport, closer sources and/or less energetic environment than rounded grains. Shiny grains are related with water dominant environments while frosted and pierced grains are mainly attributed to sub-aerial processes. Samples from U1 and U2c are mainly composed by angular to sub-angular grains. Some samples from subunit U2a and U2b, and U3 have a high percentage of rounded and sub-rounded pierced grains.

Concerning grain texture, shiny surfaces are dominant, followed by pierced grains.

The morphoscopy of U2b seems to present two sets of sediments, one from an aquatic and the other from a continental source.

The units and subunits seem to represent a dominant water driven and sheltered/confined environment and to have originated from a relatively nearby source.

*Changing environment deduced from sedimentological data*. Considering the sediment sequence and their composition, five clusters can be identified (Figure 6):

(i) a silty clay cluster represented by U1, concerning a low energy and probably confined environment, but with several pulses of energetic periods/episodes which correspond to outliers in the defined packages (namely E1, Figure 4); (ii) a sandy silt cluster illustrating U2a, corresponding to the first phase of major silt and sand infilling, with a high hydrodynamic episode near the top (circa 130cm); followed by (iii) a sand cluster represented by U2b, a 10 cm thick layer, which must represent a major extreme hydrodynamic episode; (iv) a clayey sand cluster corresponding to U2c, similar to U2a but finer; and finally (v) a sand cluster (U3) matching to the present day environment which is a dune field (medium and moderately sorted sand).

### 4.2. Microfossil assemblages and signals

Only six of the eight selected samples contained pollen and they represent the vegetation development of the site (Figure 7). Scattered sample representation was a result of poor pollen preservation in the intermediate layers due to the high sand content and resulting oxygenation and corrosion of pollen exines.

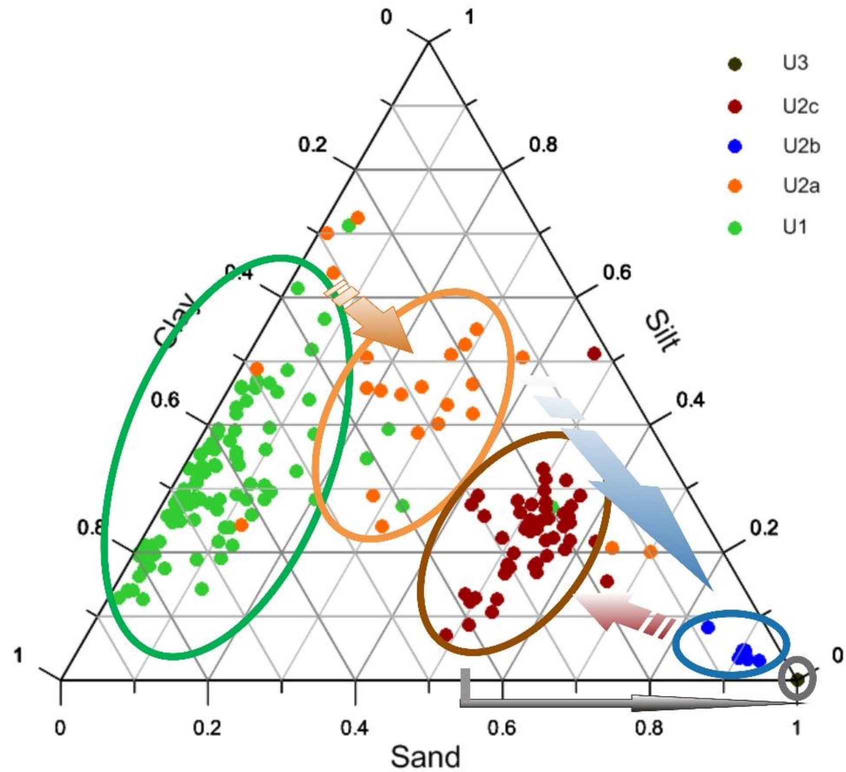


Figure 6. Time sequence of sedimentological units and subunits of CF2 corresponding to the five clusters described in the text.

The diagram may therefore be considered as giving glimpses or "snap shots" into the vegetation history of the site through ca 6000 years of deposition of sediments. Large variations in pollen and NPP assemblages were encountered during the time span represented by the core (Figure 7). The pollen diagram was, nevertheless, divided into three Pollen Assemblage Zones (PAZ) based on similarities in pollen assemblages of the samples in each zone.

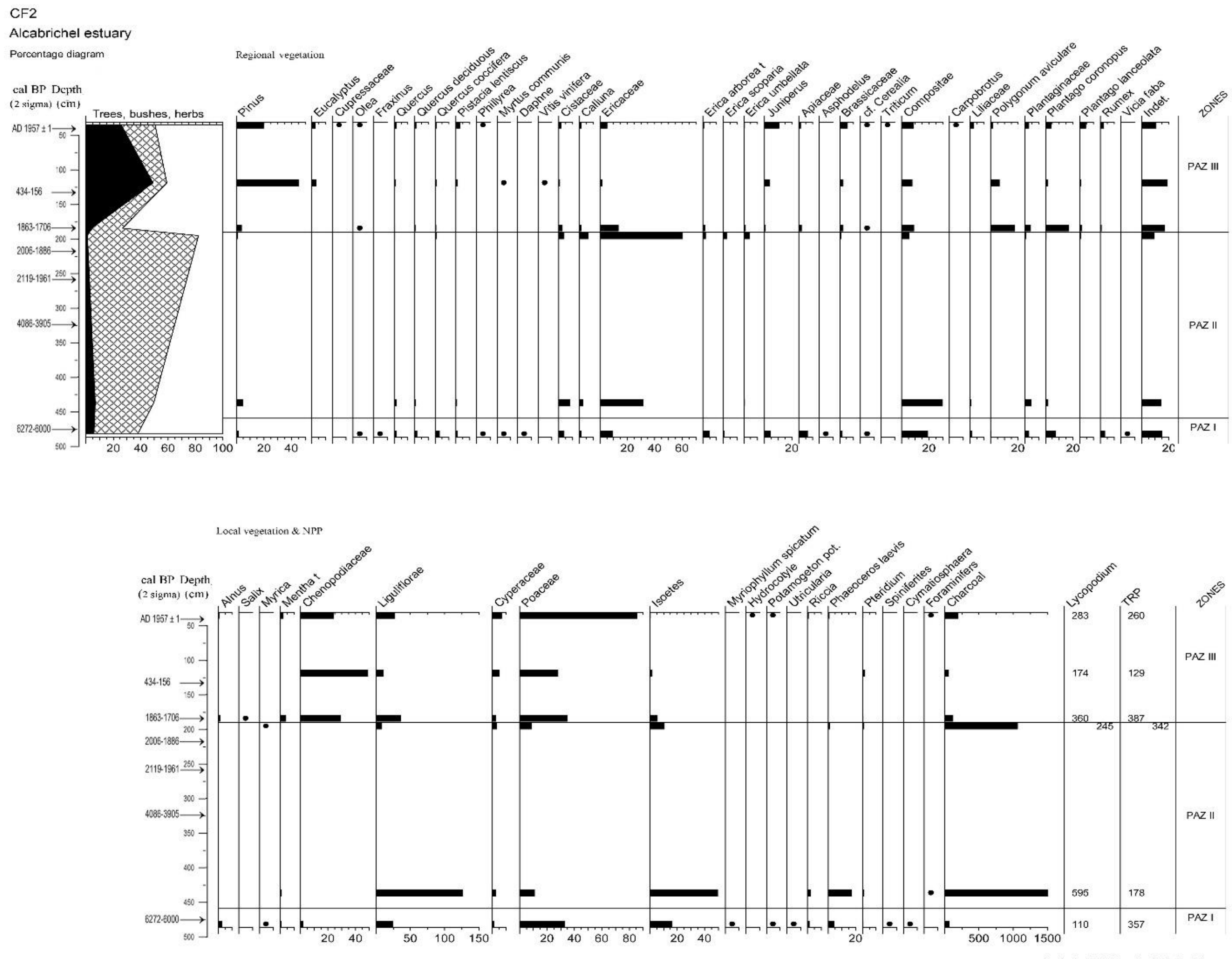


Figure 7. Pollen diagram for core CF2 (see Figure 4).

*PAZ I, Garrigue*. At the base of the core (482 cm) the pollen content indicates garrigue vegetation represented by *Quercus* (incl. *coccifera* t), *Olea, Pistacia, Phillyrea, Myrtus communis, Juniperus, Daphne* and taxa of the Cistaceae. *Pinus* is represented with low values and probably did not belong to the near environment. A cluster of pollen of *Vicia faba* was encountered at this level indicating cultivation of broad bean at the time. Presence of pollen of cf. cerealia may equally represent cultivated species but we cannot discard the inflection of cerealia type produced by salt-marsh/dune Poaceae (Mateus, 1992; Moore *et al*., 1991). Pollen and spores from local hygrophilous vegetation is dominated by grass species with some occurrences of aquatic/semi-aquatic quillworths (*Isoetes*) and hornworths (*Phaeoceros laevis*) as well as aquatic plants like *Myriophyllum, Potamogeton* and *Utricularia*. Pollen of *Alnus* (alder) indicates scattered occurrences of this tree nearby. Marine indicators (dinoflagellate cysts and *Cymatiosphaera*) are encountered at this level.

*PAZ II, Heathland*. In PAZ II (459 – 190 cm) there is a considerable increase in the representation of pollen from various species of the Cistaceae and Ericaceae family. A large proportion of the Ericaceae pollen grains are not distinguishable to species level. Small and badly developed pollen in clusters indicate that the plants of this family were present locally. *Erica erigena* is a shrub that grows in marshes and wet habitats and some of the pollen may have originated from this species. There are, however, variations in sizes and shapes of the pollen determined to Ericaceae indicating that more than one species is represented (Mateus, 1989). The local microfossil signal is dominated by *Isoetes* sp., *Phaeoceros laevis* and Compositae sect. liguliflorae. Few indications of marine influence are encountered in this zone implying a more fresh water influenced wetland. Charcoal particles are found in high quantities. PAZ II is represented by only two samples, one at the bottom and the other near the top of this phase, as the other two were discarded due to lack of pollen. It is important to remember that this phase represents a time span of nearly 3000 years and that the two analysed samples may be seen as two “windows” into the vegetation register of these millennia.

*PAZ III, Open pine forest*. At the border between PAZ II and III abrupt changes are found in the pollen curves within few centimetres (between 195 cm and 184 cm), demonstrating radical changes in the environment. Pollen from Ericaceae show a dramatic reduction and pollen from ruderal and possibly cultivated plants like *Plantago coronopus, Polygonum aviculare and Brassicaceae* rapidly increased. Pollen of *Triticum* and cf. cerealia was registered at this stage.

The local signals are also acute and show a similar trend with rapid increases in pollen of grasses (Poaceae) and Chenopodiaceae, the latter often indicating a salt-marsh environment, while spores of hygrophilous plants like *Isoetes* and *Phaeoceros laevis* almost disappear. Charcoal particles strongly decreased.

Later on pollen of *Pinus* became dominant and pollen of exotic species like *Eucalyptus*, Cupressaceae and *Carpobrotus* appeared for the first time.

Some indications of marine influence were found seen by remains of foraminifers (Figure 7).

### 4.3. Elemental and stable isotope contents and sedimentation rates

Several parameters, namely the carbonate content (inorganic carbon) and the elemental and stable isotope composition (TOC, TN, TOC/TN, δ13C, δ15N) of sediments allow the identification of the sources of the organic sedimentary matter and also to determine eventual changes of those sources along time.

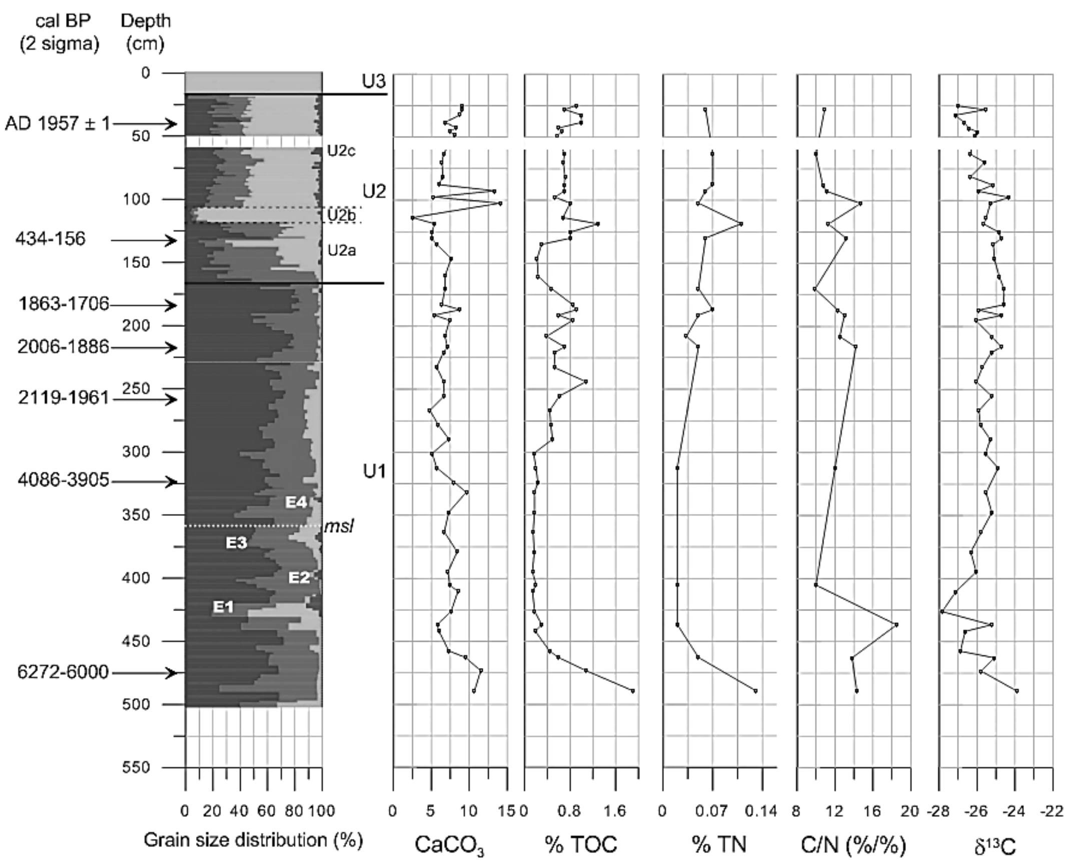


Figure 8. Elemental and isotope analysis of core CF2 and radiocarbon dates (see Figure 4).

In the analysed core (CF2) the carbonate content (Figure 8 and Table 2) ranges from 2.5% to 14.1%, with a mean value of 7.3%. After an initial decrease, between 491 cm and 430 cm, its content remains stable; with an exception between 115 cm and 90 cm, where the highest variations occur (maximum and minimum percentages are recorded in this interval).

Total organic carbon (TOC) content decreases between 491 cm and 460 cm (Figure 8), becoming relatively constant until 300 cm. Between this depth and 100 cm, a general increase is observed, and 3 major peaks are registered at 245 cm, 190 cm and 119 cm, with TOC content reaching 1%. Globally, TOC values range from 0.1% to 1.9%, with a mean value of 0.6%.

Concerning total nitrogen (TN) content, only in 15 samples it was possible to determine its value. However, despite the few values available, the TN vs. depth diagram (Figure 8) presents a profile similar to that one found for TOC vs. depth. The maximum TN content, recorded at 119 cm, is 0.13%, i.e. a peak that matches with that one found for TOC at the same depth.

The values obtained for the C/N ratio (%/%) (Figure 8) ranged from 9.9% and 18.5%, with a mean value of 12.5%, while the C/N ratio (molar) ranged between 11.6% and 21.6%, with a mean value of 14.6%. A peak was registered at 437 cm.

The $\delta^{13}C$ depth variation allows the identification of 3 distinct areas (Figure 8). A decrease from -23.91‰ to -27.12‰ can be observed between 491 cm and 412 cm. A gradual increase follows, from 412 cm to 171 cm, reaching -24.58‰; then decreases until the surface where takes the value of -25.66‰. The mean value obtained was of -25.66‰.

*Radiocarbon dating and Bayesian modelling*

Ten sediment samples were radiocarbon dated using AMS in order to establish a chronological framework for the core that can help the evaluation of the changes observed in several measured parameters and also the estimation of time intervals where the identified episodes have occurred. The OxCal program, developed by Bronk-Ramsey (2008, 2009a, 2009b), uses statistical models, based on Bayesian statistics, to build up deposition models. After building a valid model, it is possible to determine deposition rates of any segment of the core and to interpolate episodes recorded at specific depths, estimating its occurrence time interval. A Bayesian model was then set up to analyse the chronological data considering some constraints namely sample depth, core sampling year and information from other significant core analyses. In this way, sedimentation rates were calculated, and time intervals were accurately determined for the boundaries of the different units and subunits recognized in the sedimentary column. Results are listed in Table 2.

Some outliers were identified and excluded from the model, such as Beta-349150 (7340±40 BP) and Beta-346151 (6730±40 BP).

Table 2. Chronological framework. pMC: percent Modern Carbon.

| Depth (cm) | Internal Ref./ Sed.Unit | Beta Ref. | $\delta^{13}C$ (‰) | Radiocarbon Date (BP) | Calendar Date (cal BP)[a] | | Sedimentation Rate (cm/yr) |
|---|---|---|---|---|---|---|---|
| | | | | | 1σ | 2σ | |
| 40 | 1.27/U2c | 322976 | -26.6 | 111.2 ± 0.4 pMC | AD 1957±1 | AD 1957±1 | 0.21-0.57 |
| 89 | 2.18/U2c | 322977 | -25.7 | 660 ± 30[b] | 665-565[b] | 673-558[b] | |
| 105 | | | | | 306-140 | 401-89 | |
| 120 | | | | | 417-234 | 425-147 | |
| 132 | 2.44/U2a | 322978 | -24.2 | 250 ± 30 | 423-284 | 434-156 | |
| 170 | | | | | 1805-1254 | 1827-682 | 0.03-0.04 |
| 184 | 3.35 | 322979 | -24.8 | 1840 ± 30 | 1809-1726 | 1863-1706 | |
| 196 | | | | | 1893-1762 | 1953-1723 | 0.19-0.48 |
| 218 | 3.59 | 322980 | -24.3 | 2020 ± 30 | 1986-1904 | 2006-1886 | |
| 259 | 4.22 | 346148 | -24.6 | 2040 ± 30 | 2110-1988 | 2119-1961 | |
| 301 | | | | | 3970-3069 | 4044-2438 | 0.03-0.04 |
| 323 | 4.74/E4 | 346149 | -24.9 | 3670 ± 30 | 4078-3929 | 4086-3905 | |
| 359 | 5.17 | 349150 | -26.2 | 7340 ± 40[b] | 8190-8050[b] | 8300-8020[b] | 0.05-0.09 |
| 373 | E3 | | | | 4969-4269 | 5383-4088 | |
| 402 | E2 | | | | 5498-4725 | 5806-4400 | |
| 416 | 5.49 | 346151 | -26.2 | 6730 ± 40[b] | 7650-7570[b] | 7670 –7510[b] | |
| 427 | E1 | | | | 5884-5185 | 6067-4770 | |
| 475 | 5.83 | 346152 | -25.0 | 5350 ± 40 | 6260-6019 | 6272-6000 | |
| 501 | | | | | 6652-6114 | 7320-6023 | |

[a] Calibration using the IntCal09 curve (REIMER *et al.*, 2009) and the program OxCal 4.1 (Bronk Ramsey, 2008, 2009a,b). [b] Outliers

## 4.4. The historical information

The available archaeological data suggest that humans, 5000 years ago, were more dependent on agriculture and pastoralism rather than on marine resources. The majority of settlements were located inland (Arruda, 1999/2000; Arruda and Vilaça, 2006) before the Roman period. There are exceptions, such as the Castro of Zambujal, a fortified Copper Age settlement, situated ca 10 km SE of Alcabrichel (Dambeck *et al.*, 2010; Kunst, 2010), which is related to a permanent establishment.

In the Roman period the coastal territory in Estremadura was strategically occupied. The territorial organization in Roman Civitas was often conditioned by natural boundaries. This was the case in the studied area, where the Alcabrichel River functioned as the division between two Roman Civitas (Fontes, 2002).

The medieval network in the Atlantic area was imprinted from the Romans. The Muslim territorial organization after the Islamic invasion of 711 AD continued the occupational patterns substantially identical to the Roman-Visigoth.

The first existing reference for attempts of settlement in the study area date back to the 9th Century – the Penafirme Monastery (now in ruins and partly covered by climbing dunes). In the 13th Century this site was windy, but of difficult assault by Muslims, with nearby fertile lands of the Alcabrichel river valley and fish fauna and other sea food of a coastal lagoon at the mouth of the same river (in Silva, 1999, p.83), in addition to fresh water springs in the limestone massif (*arrebentão*- sudden spring outflow). This lagoon was probably situated at the mouth of the Alcabrichel River (Girão, 1949-51), however, slightly south of the present day mouth near the rocky small islet of Porto Novo (Figures 2 and 9).

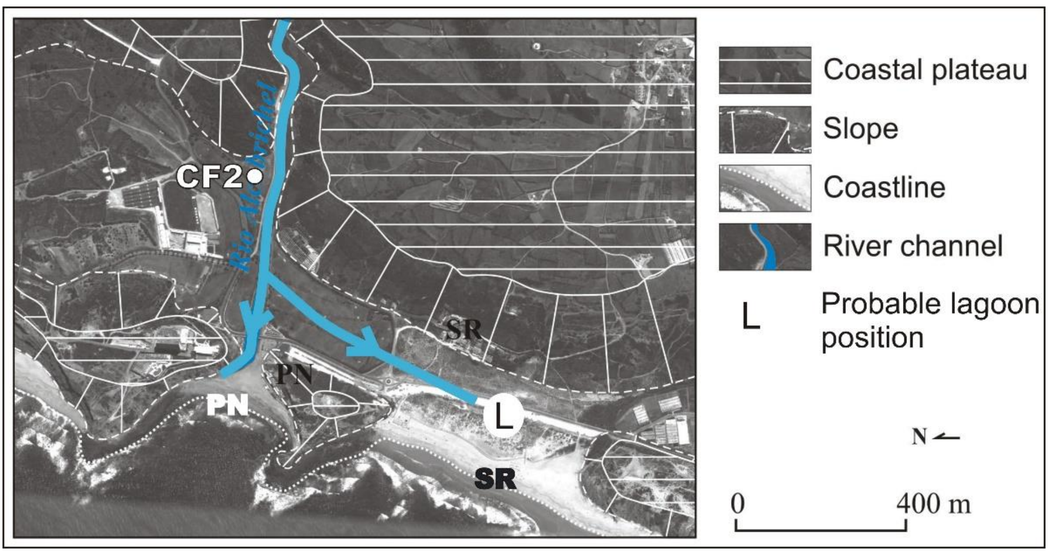


Figure 9. Hypothetical two mouths of the Alcabrichel River and the lagoon that remained in the 18th century. L: lagoon; CF2: core position; PN: Porto Novo beach; SR: Santa Rita beach.

In this sense, the stretch of coast currently encompassed by the beach of Sta Rita and Porto Novo would be characterized, around the 9th Century, by a barrier lagoon system, in which depositional dynamics of materials allowed the existence of a faunal diversity incompatible with advanced stages of silting. However, during the 13th Century the lagoon almost disappeared, filled by aeolian sand (Silva, 1999) and probably by overwashes as mentioned by the monks in the 17th Century ("because the bravery of that sea, with its mighty waves that easily moves the sands, over the years came to clog, and close all entry of the sea").

Girão (1949-51) suggests that the mouth of the Alcabrichel River was characterized by two channels surrounding the islet of Porto Novo (Figure 9).

This whole sequence of episodes can be viewed in the context of a regional trend towards estuarine siltation recognized in the generality of the Portuguese rivers.

Other relevant historical information concerns the impact of the Lisbon tsunami in the year 1755. The priest of a local church describes the tsunami as “an extraordinary run-in and run-out occurred three times, drying all the area with an extremely violent run-out followed by extensive flooding” (Duarte, 1756). The three highest waves were interpreted by local people as having reached between 16 and 20 m.

## 5. Discussion

The detailed analysis of the proxies shows major and minor changes in the embayment environment.

*The open estuary*

From the base of the core (501 cm) to 440 cm, dated 6272-6000 cal BP (2σ) at 475 cm, the pollen and NPP content together with the $^{13}C/^{12}C$ ratios point to a marine influenced wetland with sand and silt always > 25%. Pollen and microfossils confirm a weak marine signal and a eutrophic alder (*Alnus*) fringed wetland in the nearby estuary. The find of a cluster of *Vicia faba* pollen at the base of the sediment column, indicates local cultivation of this legume at this early stage. Pollen of cf. cerealia at this level may equally have originated from such early cultivation. Neolithisation started in the Iberian Peninsula around 7500 cal BP (Zilhão, 2011) and early Neolithic sites were mainly located along the coast and near waterways and estuaries, similar to the CF2 location, in this part of Portugal (Zilhão, 2003). *Vicia faba* was one of the first introduced cultivated plants and despite the void of pollen of this legume in Portuguese Neolithic sites until this study, charred grains are reported from various Iberian early Neolithic archaeological sites (Antolín and Buxó, 2011; Sampaio and Carvalho, 2002; Zapata *et al*., 2004). Pinto da Silva (1988) refers to *Vicia faba* seeds as among the most common legumes encountered in Portuguese archaeobotanical assemblages with a large geographical and chronological distribution. Hopf (1981) encountered carbonized seeds of *Vicia faba* var. *minor* from early Bronze Age layers in the nearby Castro of Zambujal. The encountered pollen cluster confirms human occupation adjacent to the open estuary.

The deposition rate for this phase ranges between 0.05 and 0.09 $cmyr^{-1}$ (Table 2).

*The adjustment of the estuary to the sea level*

After the previous phase and until ca modelled ages 4000-4500 cal BP (440 cm- 358 cm) the local environment changed from an open estuary to a mainly fresh water influenced wetland. This observation is based on the fact that sediments are mainly composed of fine material, essentially clays, revealing a low energetic palustrine environment (Figure 10). The deposition rate for this phase ranges between 0.03 and 0.04 $cmyr^{-1}$.

The pollen signal seems to indicate a seasonally inundated wetland. The dominant species are semi-aquatic quillworths (*Isoetes*) and species of the Ericaceae family (possibly the wetland species *Erica erigena*).

Shrubs of Ericaceae and Cistaceae characterized the regional landscape. This is typical vegetation in a semi-natural heathland dependent on pastures and/or burning for its existence. High percentages of charcoal particles seem to confirm the anthropogenic influence on this environment.

The sediments show several episodes of floods (E1 to E4 in Figure 4) marked by packages of gravel, sand and silt inside U1, corresponding to fluvial energetic episodes. E1 has the largest magnitude, represented by 12 cm of coarser sediments, poorly sorted, with angular and sub-angular grains and with high content of calcium carbonate. The $\delta^{13}C$ of E1 has the lowest value of all the analysed samples. These results point towards a terrestrial origin. E1 has a modelled date of 6067-4770 cal BP (2 σ).

Other energetic episodes with identical sediment signature, although with smaller magnitude, were recognized in U1. The time span between the first and the last of these energetic episodes is less than ca 2000 years and the analysed proxies suggest a plausible climatic fluctuation, with episodes of more intense precipitation (Figure 10). The position of Iberia in the European climatic context is quite complex, between Atlantic and Mediterranean influences. Magny and Haas (2004) point out to the different climatic signal in several places and accentuate the possible intensification of wet conditions in the western facade when drier conditions prevailed in south-eastern Iberia (Mayewski *et al*., 2004). The E1 can correspond to the 5550-5300 cal BP episode, mentioned by Magny and Haas (2004) as a cold period, which could have been a wet episode in the western Iberia. This signal is marked in our study at a lower latitude (39° 10’ N) than recognized before. At the moment, the hypothesis of the E2, E3 and E4 being the result of climatic fluctuations is not to set aside, despite the important anthropogenic influence in the drainage basin shown by the high content of charcoal particles and a reduced arboreal cover, during this period of adjustment spanning from the Neolithic to Early Bronze Age. Present day sea level (at 358 cm below ground in CF2) was reached during this period, ca 4000-4500 cal BP.

The recorded fluvial response seems to be the result of a combination of slow sea level rise and stabilization with climatic fluctuation and anthropogenic influence as forcing factors.

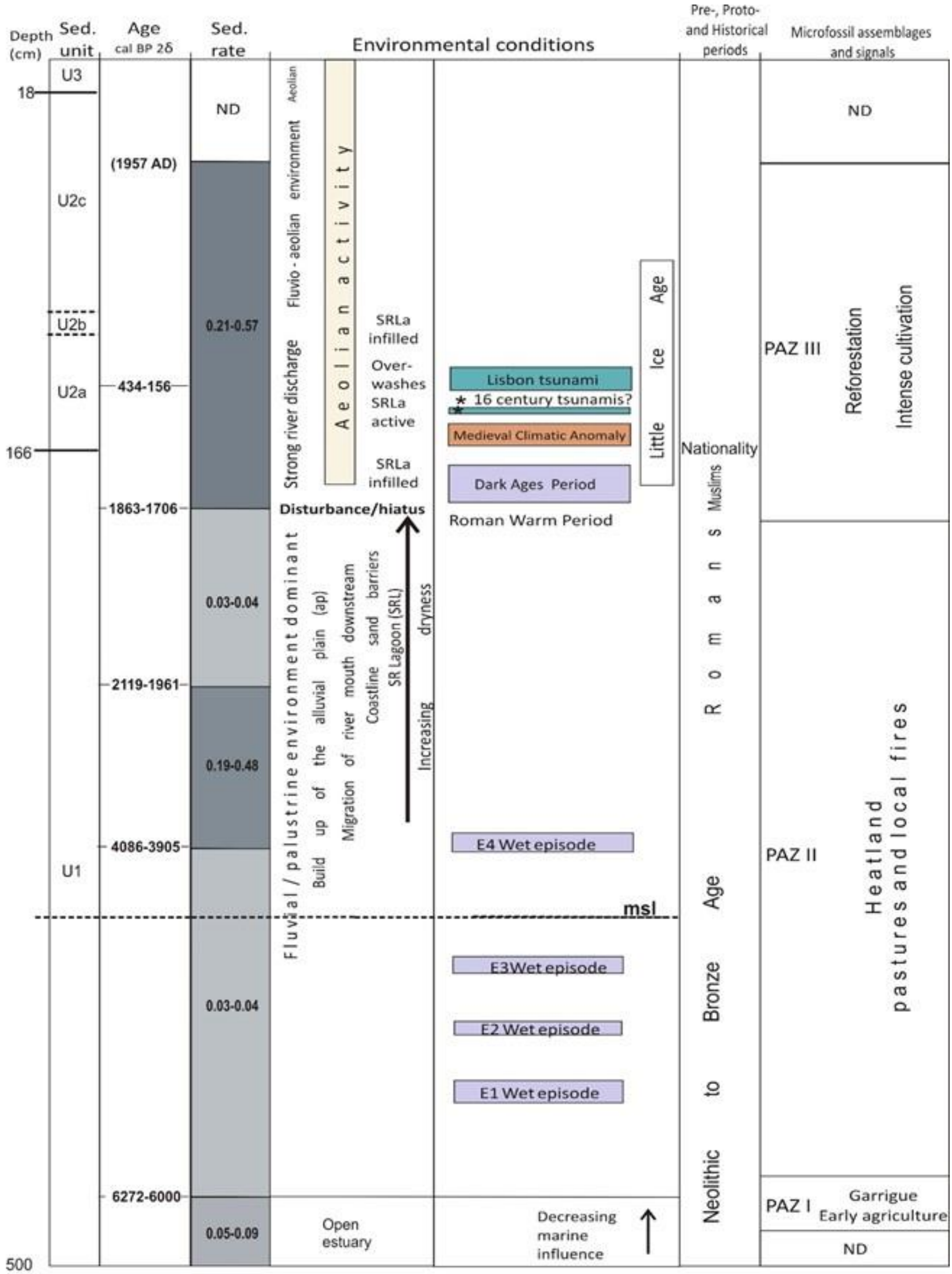


Figure 10. Synoptic chart of the palaeoenvironmental evolution since circa 6000 years cal BP. SRL/SRLa: Santa Rita lagoon; ND: no data.

*The alluvial plain infilling*

The alluvial plain infilling continued after the sea level reached its maximum, mainly by the accumulation of fine fluvial sediments. From around 4000 cal BP, two phases are distinguishable in the sediment sequence indicating a gradually dryer environment. The first phase (4000-2100 cal BP) is wetter than the second one (ca 2100-1700 cal BP), as indicated by the decreasing sand content in the latter. This trend corresponds to a large increase in the sedimentation rate from the first (0.03-0.04 $cmyr^{-1}$) to the second phase (0.19-0.48 $cmyr^{-1}$).

This trend towards a drier wetland is also recognized by pollen between PAZ II and III (1863-1706 cal BP) showing a strong reduction of hygrophilous plants in agreement with the sedimentological data. The shrub-cover was largely reduced, and ruderal and cultivated plants became frequent demonstrating human influence on the environment during Roman times.

*The disturbed alluvial plain*

There is a time lag between the rapid change identified in the pollen content (195-184 cm), and a very prominent change in grain size distribution at the limit between U1 and U2 (170 cm). This could have been caused by a natural delay in the response of slope erosion after disturbance by anthropogenic action influencing the vegetation cover. The abrupt change recorded in the core seems to be the result of several forcing factors in the transition between the Roman Warm Period and the Dark Ages Cold Period (1350-1000 cal BP). In the core, this transition is recorded by an influx of coarser sediments with aeolian contamination and with an increase in the sedimentation rate (from 0.03-0.04 $cmyr^{-1}$ to 0.21-0.57 $cmyr^{-1}$). The possibility of a hiatus being the cause of the abrupt change in the sediment column and the origin of the low calculated sedimentation rate (0.03-0.04 $cmyr^{-1}$) cannot be excluded.

The U2a marks the transition between a dry period and a wetter one. This conclusion is based on the large amount of fluvial coarse sediments (sand and gravel) showing the importance of river discharges. In addition to angular and sub-angular sand grains, this subunit contains rounded and sub-rounded grains, some with pierced surfaces. This fact implies two distinct sediment transport environments: fluvial and aeolian, as marine signals are detected neither in the sediment content nor in palynology. The $\delta^{13}C$ is inconclusive in this subunit. The climate implications are i) a windier regime and ii) rainy periods with larger flood frequency, between xeric episodes. Subunit U2a includes the initial part of the Little Ice Age (LIA) climatic fluctuation. Monks reported these windy conditions, which generated the climbing dunes over the palaeo-cliffs, contributed to the ruin of the monastery and to the infilling of the lagoon.

High aeolian activity was also detected in other coastal areas of Portugal during LIA (Almeida, 1995; André *et al*., 2009; Costas *et al*., 2012; Danielsen *et al*., 2012; Noivo, 1996).

The pollen sample at the top of U2a shows the large scale reforestation (pine) of Portugal´s littoral to counteract the sand dune progradation over agricultural land (Figure 10). A comparable development is encountered in other investigations (Danielsen, 2008; Danielsen *et al*., 2012; Granja, 1990; Mateus, 1992; Mateus and Queiroz, 1993; Queiroz, 1999).

There is a thin layer of coarser sediments near the top of U2a similar to (but smaller than) the episode that happens in U2b. The U2b corresponds to a strong energetic hydrodynamic episode with fine sands, very poorly sorted, with high percentage of rounded and sub-rounded grains, and a low content of inorganic carbon. Considering the radiocarbon date (after 434-156 cal BP) it is possible that this was the result of the tsunami that followed the Lisbon earthquake (1755).The values of $\delta^{13}C$ at this subunit fluctuate to a high point, suggesting marine influence as expected in the case of a tsunami.

Comparison of the sedimentological characteristics of the two major episodes inside U2 (in U2a – thin sand layer, and U2b), show an identical signature, although of different magnitude. Two earthquakes with tsunamis were reported in 1504/5 and in 1531 AD (Baptista and Miranda, 2009), with great flooding in the Lisbon region. The identified thin layer may hence be the result of these forcing factors. Tsunamis turbidites have also been recorded and studied in the SW continental margin (Abrantes *et al*., 2008; Gràcia *et al*., 2010).[6]

The U2c is the subunit with the coarsest sediment in all U2, containing gravel and a large percentage of sand and silt, where the grains are mainly angular. The dominance of angular grains indicates a mainly fluvial source, despite the similarity in grain size distribution between U2a and U2c. This last subunit recorded several floods represented by sand and gravel. The end of LIA in the region has no sedimentological signature.

The upper pollen sample contains pollen of *Triticum* (wheat), a cleistogamous cereal, showing cultivation of this cereal at the locality itself. Pollen of exotic trees and herbs are found and the introduced plant *Carpobrotus* was identified in this sample. This species was referenced for the first time in Portugal in 1910 (Almeida and Freitas, 2006).

The last documented environmental change corresponds to a dune field, represented by the top 20 cm sediment, which shows conditions similar to the current ones since the last Century.

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[6] In order to highlight the origin of this two sandy layers, a research were developed during 2016 and 2017, based on morphoscopic, chemical and microtextural features in the quartz grains. The results confirm the tsunamic origin of SubUnit 2b, but suggest a storm episode to the sandy thin layer of SubUnit 2a (Tudor, 2017).

## 6. Conclusions

The multidisciplinary research carried out in the embayed coast spanning over the last 6000 years, allowed us to draw several conclusions about the coastal zone evolution, and reveals new data about climatic interactions with fluvio-marine evolution, as well as different kinds of extreme episodes.

The early environmental conditions recorded inside the inner part of the embayed coast (CF2 position), before 6000 cal BP suggest the presence of an open estuary with marine influence. The find of a cluster of *Vicia faba* pollen at the base of the sediment column shows Neolithic cultivation in the vicinity of the open estuary at the time.

Between this time and ca 4500 cal BP, when the present sea level was reached, three wet episodes were recorded: (i) E1 at 6067-4770 years cal BP (2σ), (ii) E2 at 5806-4408 years cal BP (2 σ), (iii) E3 at 5383-4088 years cal BP (2 σ). These episodes happened in less than 1000 years interval showing a shorter rhythm than the Bond events.

Another wet episode was recorded, E4, at 4086-3905 years cal BP (2σ), after the sea reached the present level. All the E episodes contributed to the build-up of the alluvial plain inside the estuary.

No other clear wet pulses were recorded in the CF2 core besides those possibly hidden inside the package of high sedimentation rate, which may just as well have been the result of Roman interventions in the drainage basin. Human influence is shown by the abundance of charcoal particles.

The sediments filled up the alluvial plain and the influx of sediments probably caused the migration of the river mouth to a distal position and the formation of a sand barrier on the coastline, closing off and forming the Santa Rita lagoon.

During the Roman Warm Period, culminating in a period with increased dryness, the alluvial plain suffered a disturbance at 1863-1706 years cal BP.

During the Dark Ages there are signals of strong river discharge at the same time as aeolian activity is found. This may be explained by the increased anthropogenic activity recorded in the microfossil content during this phase. The Dark Ages were a cold period in higher latitudes but the possibility of this period being a wet one in western Iberia, cannot be excluded. In that case, the great amount of sand in U2a could be the result of climatic and anthropogenic forcing factors. This hypothesis is not in contradiction to the aeolian activity recorded in the core sands, because this activity could have been seasonal.

The Santa Rita lagoon was partly infilled in the 12$^{th}$ Century during the xeric episode of the Medieval Climatic Anomaly.

The sequence of tsunamis, during the 16$^{th}$ and 18$^{th}$ Centuries, may have overwashed the sand barriers and invaded the old embayed bay. The Santa Rita lagoon was re-activated according to the historical documents. It is possible that the mouth of the river migrated to its present position. In the 19th Century the lagoon disappeared and the fluvio-aeolian environment prevailed in the old embayed coast, with increasing anthropogenic pressure.


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