GUADIANA RIVER ESTUARY

Investigating the past, present and future

Edited by
Delminda Moura, Ana Gomes, Isabel Mendes & Jaime Aníbal

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Forward

The Centre for Marine and Environmental Research (CIMA) is a multidisciplinary research centre of the University of Algarve. In addition to the scientific research and technological innovation, CIMA is involved in service delivery, graduate training and knowledge transference to the society.

The scientific dissemination to the society is the main goal of this book. The CIMA researchers develop their scientific activity using a multidisciplinary approach, which contributes to produce an integrate knowledge of the ecosystems' behaviour and to understand the evolution resulting from global changes and anthropogenic impacts. These activities are developed in several territorial foci, of which the Guadiana River and in particular its estuary is one of the most intensely studied by the CIMA researchers.

This book synthesizes part of the scientific knowledge undertaken by various researchers allowing an integrated view of the Guadiana River estuary. The authors had a high degree of freedom to write their chapters. It could not have been otherwise given the diversity of matters. However, there was a common point: transform the scientific writing, frequently hermetic, into easy comprehensive manuscripts for the general public without neglecting scientific rigor. Other scientists named in this book, to whom the editors and authors are grateful, have reviewed all the chapters and illustrated some annexes.

It is our hope that this book may contribute to the dissemination of the scientific knowledge, which is a common objective of the University of Algarve and the Centre for Marine and Environmental Research (CIMA: http://www.cima.ualg.pt/)

Editors

Preface

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Estuaries are some of the most dynamic and complex environments in the world. The places where rivers meet the sea are subject to cycles of constant change – from the waves and currents that move particles of sand and mud every second, to the daily ebb and flow of the tides and the more dramatic effects of periodic floods, droughts and storms. Over thousands of years, estuaries are created, destroyed and re-created by sea-level changes. Few of the earth's landforms enjoy such a brief and varied existence.

The complex interplay between terrestrial, fluvial, coastal and marine realms makes estuaries unique in terms of their landscapes and biodiversity. The mixing of salt and fresh water in estuaries is physiologically challenging to plants and animals, both aquatic and marine. Species inhabiting the transitional zones between land and sea have evolved to deal with these challenges in often surprising ways, adapting their lifecycles and metabolisms to take advantage of the rich resources that estuaries provide. Per square metre, estuaries rank among the most productive habitats worldwide (McLusky & Elliott 2004).

Estuarine resources have sustained human communities for millennia. Estuaries remain critical to human existence today, providing areas for transport and trade, aquaculture and fisheries, breeding grounds for birds, salt production, flushing of wastes, power generation, recreation, spiritual and aesthetic values. As rivers meet the coast, they drop their sediment load in intertidal zones, creating nutrient-rich mudflats, saltmarsh and mangrove habitats. Human societies have long relied on these newly created areas of land for agriculture and industrial purposes.

With their abundant supplies of food and timber, availability of freshwater and access to the open sea, estuaries launched the ships of the European 'Age of Discovery' and became epicentres for globalisation. This did not, however, translate into a universal societal appreciation and protection of the unique qualities of estuarine environments. Intense industrial exploitation around the world has left estuaries with a persistent legacy of pollution, both in terms of chemical compounds and the transfer of invasive species through international trade. In many ways, estuarine systems are the vanguards of the kinds of environmental changes that are expected to affect many other systems into the future.

Estuarine sediments, as well as being substrates for living biota, sequester vast quantities 'blue carbon'. Each year, release of this carbon from mangrove, saltmarsh and seagrass sediments through coastal degradation has been estimated to cause between 6-42 billion US dollars in economic damage (Pendleton et et al., 2012). Coastal zones have immeasurable value as buffers to rising sea levels, but find themselves at increasing risk of 'coastal squeeze' as their naturally dynamic landforms and ecosystems are constrained by immovable engineering structures. Coastal sedimentation processes have changed dramatically through river regulation and dam construction, reducing sediment supply and altering biogeochemical cycles. Scientists have been very active in trying to understand these processes of change so that the mistakes of the past need not be repeated. However, it is rare for a single estuarine system to be intensely studied by multiple scientific disciplines and for the resulting information to be gathered together in a single, easily-accessible place.

This book represents the culmination of decades of multidisciplinary scientific research on the Guadiana River and its iconic estuary. The Guadiana has the fourth largest drainage basin in the Iberian Peninsula, covering some 66,900 km^2. The river rises in the mountains of Cuenca Province of Spain and flows in a generally westward direction before veering south to meet the Atlantic Ocean. Compared to other major rivers of the Iberian Peninsula, the Guadiana has a relatively low fluvial discharge and high seasonal variability, thanks to its largely Mediterranean climate. Seasonal variation in river flow has increased in recent decades due to river regulation and water extraction for agriculture (Rocha et al., 2012).

The Guadiana estuary extends upstream some 70 km to the town of Mértola, with saltwater influence extending to Alcoutim, approximately 35 km upstream of the river mouth. Most of this meso-tidal estuary is constrained within a steep-sided valley composed of Palaeozoic greywackes and schists. Only the last few kilometres of the estuary escape geological control and fan out into a complex of saltmarshes, tidal creeks, mudflats, sand barriers and beaches. Historical maps show that this section of the Guadiana estuary has silted up rapidly over the last 200 years (Morales 1997). In Chapter 1, Erwan Garel describes his extensive research into the hydrodynamic processes that have created and continue to reshape the Guadiana's estuarine environment.

Sea-level rise poses a major risk to the present-day environment of the Guadiana estuary (Ferreira et al., 2008), including to its socio-economic potential and to important industries such as tourism. In Chapter 2, Tomasz Boski places these present threats within the context of longer-term changes in the coastal environment. The Guadiana estuary has been the site of detailed studies of how complex estuaries evolve with sea level rise (e.g. Boski et al., 2002), providing vital information for anticipating and managing changes in the future.

Some of the most intact coastal ecosystems in southern Iberia are to be found in the Guadiana estuary. Direct human impacts here have been limited historically by the estuary's location on a fiercely-defended political border between Spain and Portugal. At least 460 plant species are recorded in the estuary, including several rare and endemic species. The wetlands of Castro Marim are a declared site of international significance for waterbirds under the Ramsar Convention. The river's name itself is thought to be a mixture of the Arabic *wadi* and the Latin *anas*, meaning 'river of ducks'. Ana Gomes and Sarita Camacho introduce the rich biodiversity harboured by the estuary in Chapter 3, focussing on some of the lesser known plant and animal species that support the area's productive ecosystems.

Estuaries do not end immediately upon reaching the coast, but create a large transitional zone where river water enriched with terrigenous material mixes with seawater. These zones are often crucial for marine life and the maintenance of healthy fisheries. Isabel Mendes and Francisca Rosa describe the environments of the Guadiana continental shelf in Chapter 4, tracing the origins of the sediments and describing environmental changes caused by recent human activities in the river basin.

Saltpans are a major feature of the present-day landscape of the estuary. Salt production has a long tradition in the low-lying salinas around Castro Marim, Vila Real de Santo Antonio and Ayamonte. Their important historical, economic and environmental roles are discussed by Noa Sainz and Tomasz Boski in Chapter 5, including an exploration of their future under changing economic and climatic circumstances.

Since prehistoric times, the Iberian Pyrite Belt has provided mineral wealth to the rulers of southern Iberia. The Guadiana estuary bisects the area of ancient mining activity, forming a natural barrier between the historical regions of Andalucía and the Algarve. At times in their history, these areas have enjoyed harmonious relations and a thriving interchange of ideas, goods, people and culture. At other times, political tensions between the kingdoms of Portugal and Spain transformed the Guadiana into a military frontier, watched over by forbidding fortresses. In Chapter 6, Pedro Morais and Rita Domingues take us on a historical journey through this evolving landscape.

Mining activity since ancient times has left its mark in the form of heavy metal contamination in the sediments of the Guadiana estuary. While mineral extraction has diminished more recently, new sources of contamination are emerging through technological and societal change, often with unanticipated biological effects on estuarine species and food chains. Maria-João Bebbiano, Maria Gonzalez-Rey and Cristina Veiga-Pires delve into past, present and future contaminants in the Guadiana estuary in Chapter 7.

The authors are united in their deep appreciation for the Guadiana estuary and hope that you, the reader, will also be inspired to consider the uniqueness, richness and vulnerability of this marvellously muddy place.

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1. Present dynamics of the Guadiana estuary

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1.1. What is this Chapter about?

Estuaries offer natural protection from energetic ocean waves, and have been used as natural harbour and inland waterways since the beginning of civilisation. Nowadays, most of the largest cities in the world are located on estuaries that must cope with increasing economic and industrial developments. These sheltered coastal areas are also one of the most productive types of ecosystems on Earth and are of considerable value for humans and wildlife. Understanding the dynamics of estuaries is fundamental to maintain a balance between exploitation and conservation. In particular, the assessment of various features of uttermost socio-ecological importance (such as water quality, flood risk, ecosystem health and morphodynamics) must rely on a thorough knowledge of the operating hydrodynamic and sediment transport processes.

The main patterns of water and sediment transport at the Guadiana estuary result primarily from the tide and its interaction with the river discharge and channel morphology (Box 1.1).

The geomorphological characteristics of the estuary, including surficial sediment and bedform patterns, are presented in section 1.2. Information about the tidal signal near the estuary mouth and its distortion as it propagates upstream is provided in section 1.3. After an outline of the river discharge forcing, its influence upon the water circulation is described in section 1.4, considering separately weak and large freshwater inflows. The subtidal water exchanges between the estuary and the sea are of great importance for the health of the estuary and are presented in the following section 1.5. The main patterns of sediment transport, as both bedload and suspended load are reported in section 1.6. Compared with the tide and river discharge, other external forcing agents such as wind or waves have minor effects on the estuarine dynamics and are not addressed. Yet, ocean waves are the principal force that controls the morphodynamic evolution of the ebb-tidal delta which is summarised in section 1.7. The final section 1.8 emphasises those dynamic features that distinguish the Guadiana from other commonly described estuaries.

Box 1.1. How is known the dynamics of the Guadiana estuary?

Most of the current knowledge of the Guadiana estuary dynamics results from observational studies initiated in 1978 with hydrographic measurements. A more complete dataset was constituted two decades later, and is regularly updated with ongoing programmes or projects involving CIMA researchers. The most recent and relevant patterns related to the hydro- and sediment dynamics of the estuary are synthesized in the present contribution.

1.2. Geomorphology of the Guadiana estuary

1.2.1. Morphology

The Guadiana estuary is located at the southern border between Spain and Portugal (Figure 1.1). The estuary extends for 78 km, from its mouth to the weir of Moinho dos Canais, near the town of Mértola. This site marks the estuary head, the upstream limit with significant water level oscillations due to the tide. At the seaward entrance, the mouth is stabilized with a pair of parallel jetties built in 1972-74 (see section 1.7). The estuary is prolonged offshore by a submerged sandy ebb delta (Figure 1.1).

The Guadiana estuary can be divided into three sectors with distinct ecological and hydrological characteristics (Figure 1.1). The upper estuary runs from the head to Foz de Odeleite (km 23) and is generally filled up with freshwater; the middle estuary, from Foz de Odeleite to the International Bridge (km 7), is characterized by brackish water; the lower estuary includes the terminal seaward section, which

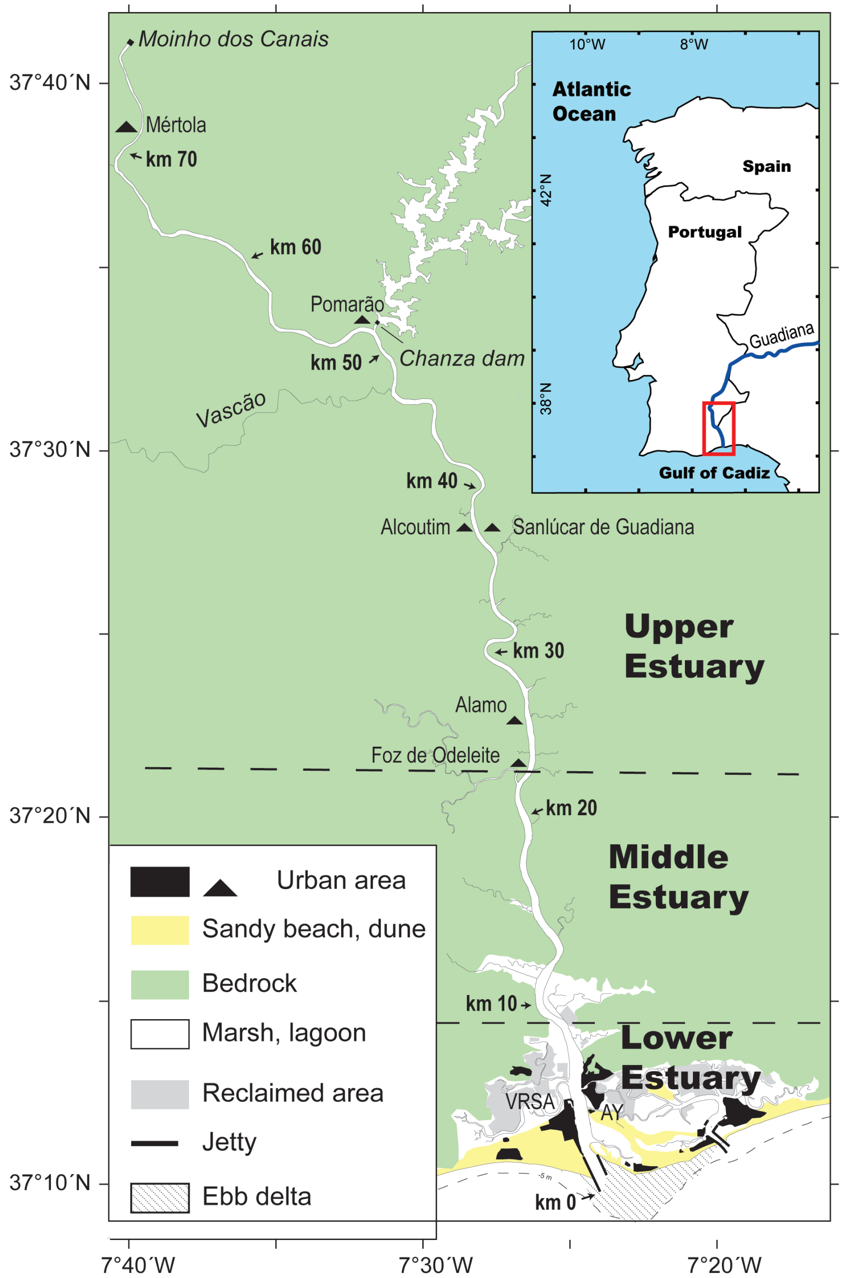

Figure 1.1.
Map of the Guadiana estuary (for general location, see inset), with indication of the distance from the mouth in km (arrows) and main municipalities along the estuary (VRSA: Vila Real de Santo Antonio; AY: Ayamonte).

is strongly influenced by seawater (salinity values are commonly > 30 g/kg during at least a part of the tidal cycle; see also Gomes & Camacho, chapter 3 in this book).

Along most of its course (upper and middle portions), the estuary is confined in a deep and narrow valley incised in the bedrock (Figure 1.2a). Only the lower estuary is embedded in soft sediment, allowing the development of salt marshes on both the Portuguese and Spanish margins (Figures 1.1, 1.2b). The salt marshes have endured intense transformations due to sediment infilling and strong anthropogenic pressure (e.g., urbanization, farming, aquaculture), and present nowadays a reduced extension (about 23 km^2 area).

Estuaries with long and narrow morphology such as the Guadiana are classified by some authors as "Rock-Bound Estuaries (Box 1.2).

The width of the estuarine channel is the largest near the mouth (about 800 m) and gets smaller upstream, being 70 m wide at Mértola. In detail, the channel is narrowing rapidly at the lower estuary and more slowly upstream. This width evolution can be described by an exponential function (Figure 1.3a), similar to many estuaries, including coastal plain estuaries having a width of several kilometres at the mouth.

Box 1.2. What are "rock-bound" estuaries?

Rock-Bound Estuaries (RBE) are defined as narrow and moderately deep estuaries with considerably larger tidal prism (the volume of sea water that enters during the flood) than average freshwater discharge. They are found in regions with strong structural control, where they coincide with major rivers characterised by seasonal periods of significant freshwater discharge. RBEs have been described in high-latitude regions affected by spring freshets that enhance significantly the discharge of rivers, such as the east coast of the USA. They have also been recognised in semi-arid environments, where high river discharge events are controlled by the seasonal rainfall regime, for example in the Iberian Peninsula. Unlike other systems with large watersheds that widen significantly before entering the sea (such as the extensively described coastal plain estuaries), RBEs are affected along their entire length (from the head to the mouth) by high river inflows. These events drive net seaward sediment transport within the estuarine channel and sand is exported to the nearshore at a yearly to centennial scale. This sediment transport regime distinguishes RBEs from other estuaries which are typically considered as sediment traps.

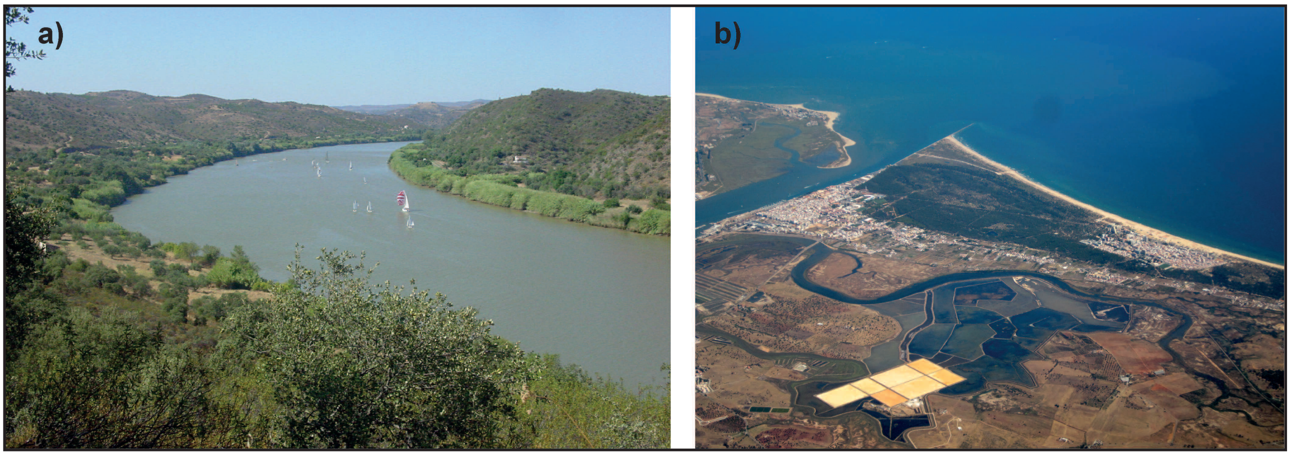

Figure 1.2.
Photographs of (a) the estuarine channel, near Alcoutim (km 40), where it is incised in a relatively steep and narrow bedrock valley, typical of the middle and upper reaches of the estuary (photograph by E. Garel, July 2015); and, (b) the lower estuary constituted by broad and flat intertidal and reclaimed areas (see also Figure 1.1).

The depth along the Guadiana estuary is highly irregular (Figure 1.3b). Very generally, the mean channel depth is about 4.5 m (referred to mean sea level, hereafter; see Box 1.3) at the lower estuary and increases up to more than 8 m at km 30. Further upstream, the mean depth decreases to about 4 m at km 50. From km 50 to the head, bathymetric data are not available. It is however generally assumed that the water depth decreases regularly down to 2 m towards the estuary head. In addition, a few sills (deposited across the channel during large floods) partly plug the flow within the last 15 km of the estuary. The mean depth of the entire estuary is about 5.5 m. No dredging has been performed within the estuarine channel, except at the entrance of the marinas of Vila Real de Santo Antonio and Ayamonte to secure boat access. The transverse morphology of the middle and lower estuary consists of a single meandering deep channel bordered by wide shoaling areas (cf. Figure 1.4a). The deep channel bottom is more than 3 m under the extreme equinox low water level (and generally deeper than 6 m). At the upper estuary, the channel cross-section tends to be more rectangular, with narrow transitions towards the shallow margins. The maximum water depth along the estuary is very variable, being generally between 7 and 11 m. Important variations are observed locally, with maximal depths (up to ~18 m) in front of creeks.

Box 1.3. What is the difference between "mean sea level" and "hydrographic zero"?

The mean sea level (MSL) is the average height of the sea surface for all stages of the tide. Computed over extended periods, it can be used as a reference (Datum level) for bathymetric or elevation maps. The "Hydrographic Zero" (HZ or also "Chart Datum") is another reference level located below the MSL which is typically used in nautical charts to ensure safe navigation. The HZ is a convention which varies in between countries (and sometimes within the country). It is commonly defined as the level of the lowest possible astronomical tide (under average meteorological conditions). In Continental Portugal, the HZ is located 2 m below MSL.

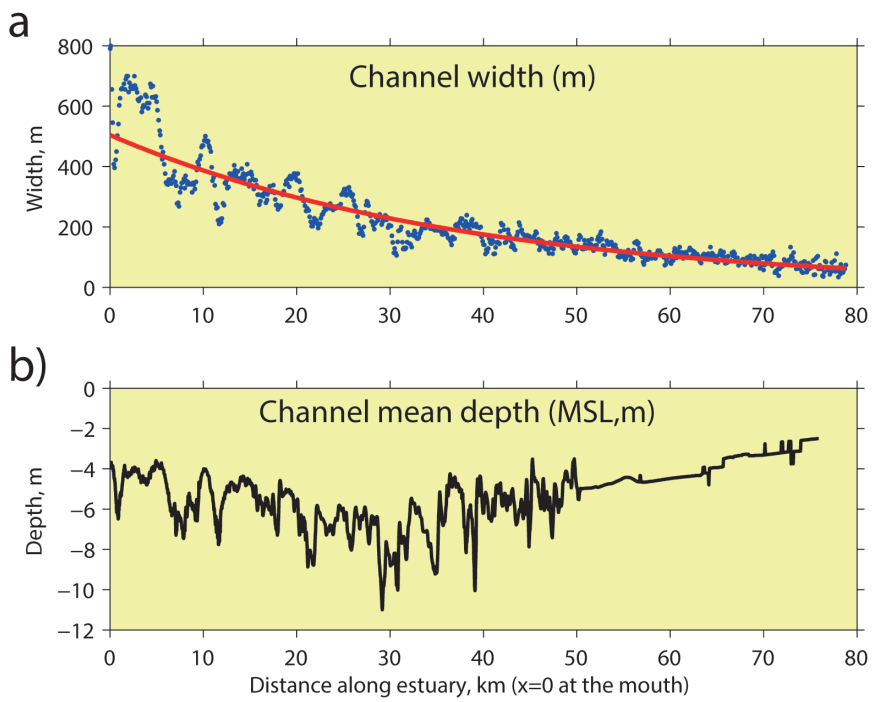

Figure 1.3. Morphological variations from the mouth (km 0) to the head (km 78) of the Guadiana estuary: (a) measured channel width (m, blue points) and its representation with an exponential function (red line); (b) mean depth (m) referred to the mean sea level (MSL).

1.2.2. Types of surface sediment along the estuary

At the lower estuary, surficial sediment in the deep channel consists mainly of well sorted medium sand (Figure 1.4b). This sand is composed of quartz, feldspar, bioclasts, plus lithic components of diverse origins. Gravels are also observed at the deepest locations, either mixed with sand or in small isolated pockets. Muddy very fine sand is found at the transition between the deep channel and shallow domains. The shallow bordering areas are constituted by muddy sediment (Figure 1.4b). The middle estuary is

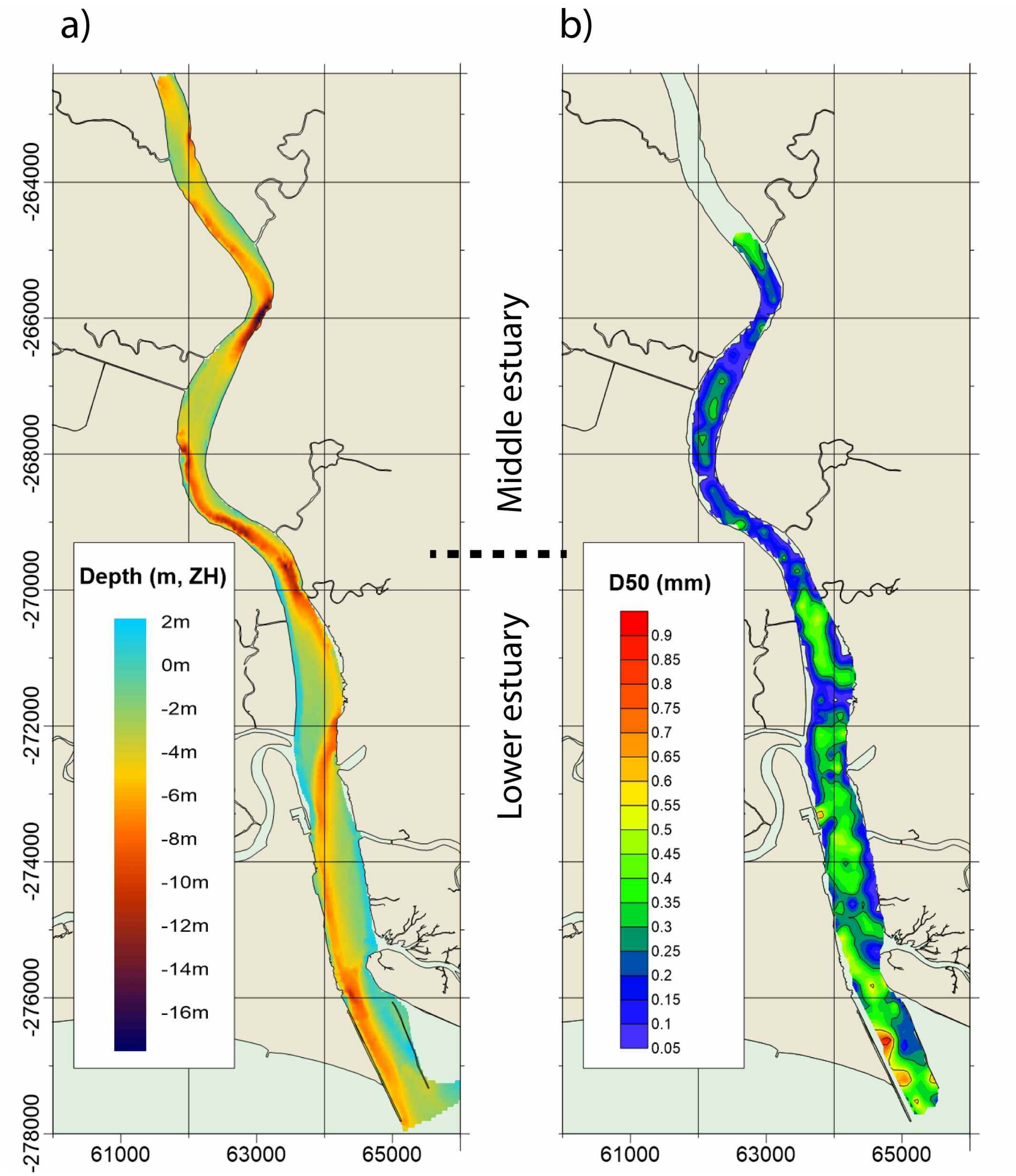

Figure 1.4.

(a) Bathymetry (m, referred to the HZ; see Box 1.3) and (b) surface sediment mean grain size (mm) at the lower and (southern part) of the middle estuary (project EMERGE - year 2000).

dominated by poorly sorted sediment, generally consisting of muddy sand or sandy mud with cohesive character, in particular near the margins (Figure 1.5). The middle estuary also presents the highest content (in abundance) of organic matter, in particular within the deep channel. The upper estuary consists mainly of gravel and sand from the river drainage basin, with mud deposits over the shallow margins.

1.2.3. Bedforms

Bedforms are morphological features such as dunes or ripples, produced by the transport of sediment by water (or air) flows. Very generally, bedforms in estuarine environments develop in very fine and coarser sand (i.e., ≥ 0.15 mm grain size diameter) and where current velocities can exceed 0.4 m/s. The current-induced ripples and dunes are asymmetric, with a steeper lee side indicating the net direction of bedload transport.

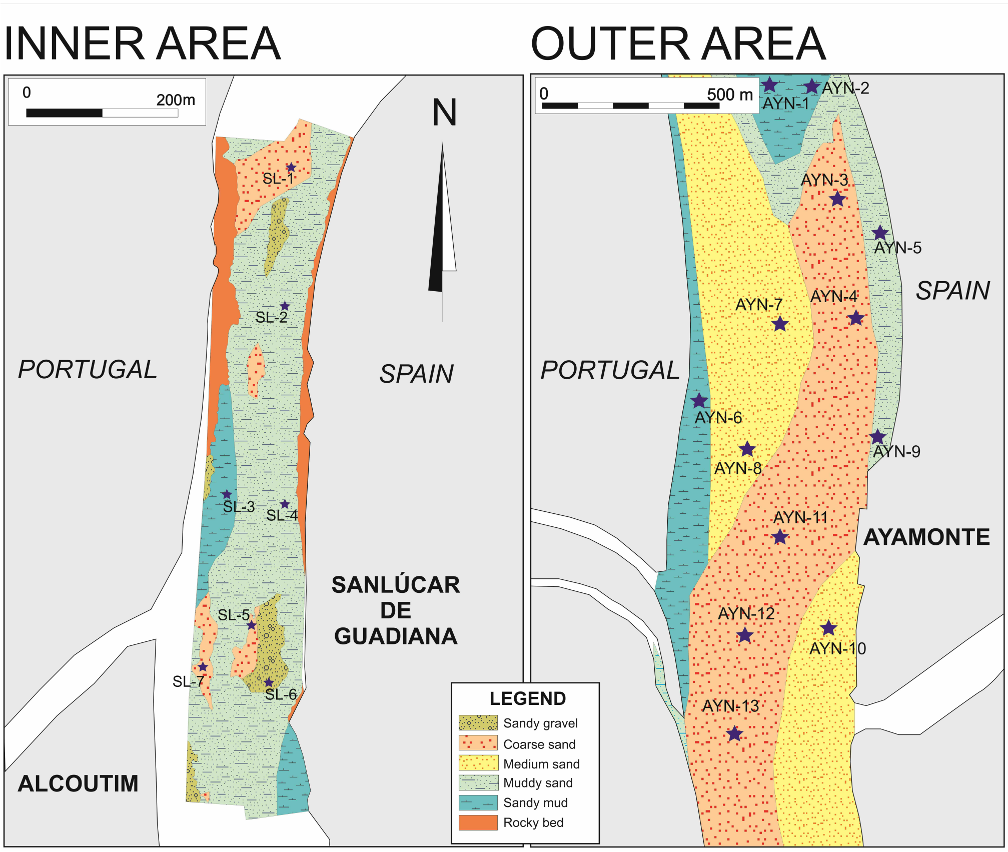

Figure 1.5.
Example of sediment facies at the middle estuary (left) and lower estuary (right). Courtesy of J.M.A. Morales (Huelva University).

Bedforms are rarely observed at the middle estuary due to the fine grain size and cohesive nature of sediments. At the lower estuary, sand dunes are common, as well as plane beds which are produce by high flow regimes. These dunes have a wave length of 4-12 m and a height between 0.5 m and more than 1 m. In general, the dune crests are perpendicular to the channel margins. These bedforms are also preferentially ebb-asymmetric in the deep channel, indicating a net bedload transport in the downstream direction (Figure 1.6a and also annex II). The shallower bordering areas consist generally of smaller dunes (e.g., 0.5 m in height and 5 m in wavelength) displaying both flood- and ebb-oriented asymmetries (Figure 1.6b).

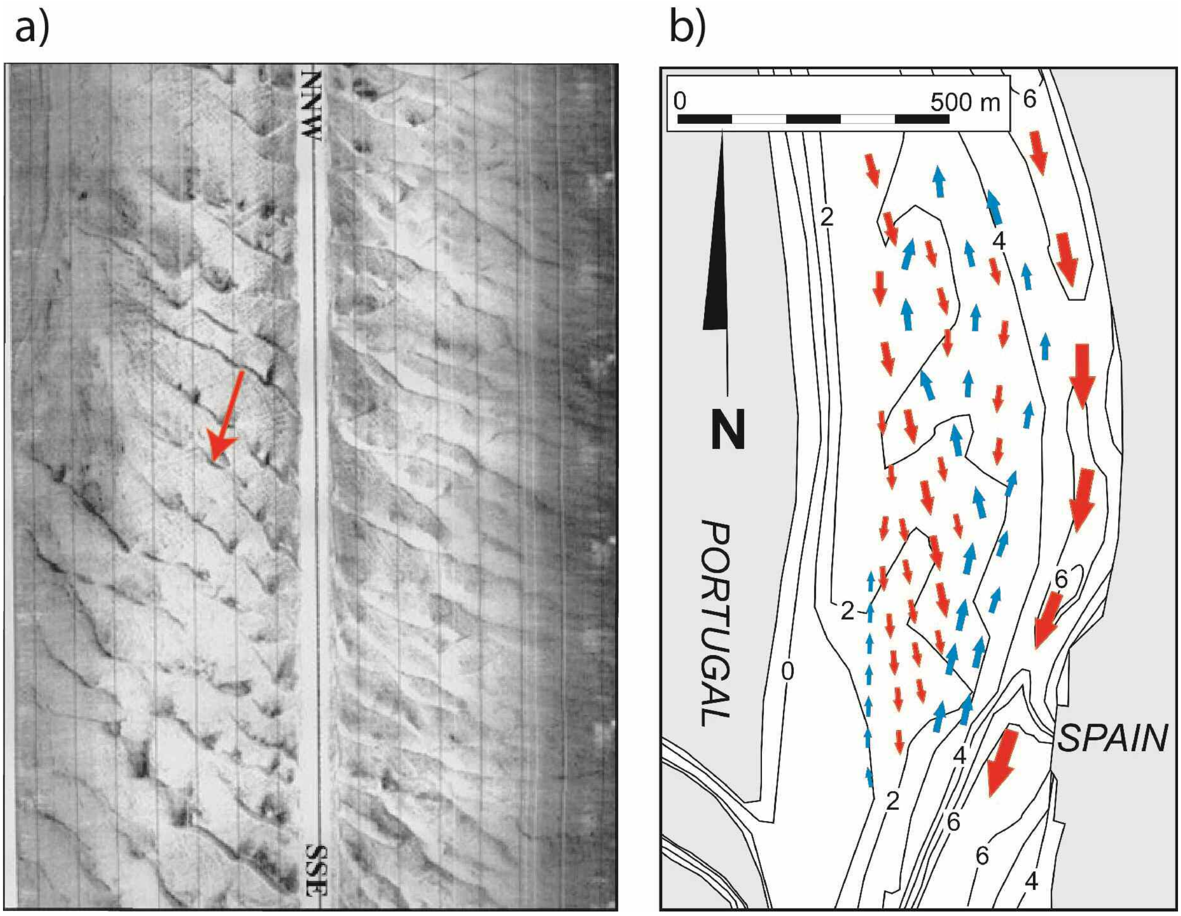

Figure 1.6.
(a) Side scan sonar image (white/black: high/low reflectivity) showing medium dunes with asymmetry indicating ebb-directed (southward) net bedload transport (e.g., red arrow); b) Net bedload transport at the lower estuary inferred from bedform asymmetry (red: downstream; blue: upstream; courtesy of J.M.A. Morales (Huelva University). Note that a and b represent distinct locations.

1.3. The dynamics of the tide

1.3.1. Tidal patterns at the lower estuary

With a mean tidal range (the difference between high and low water) of 2 m, the Guadiana is classified as a mesotidal estuary. The tidal signal is regular, dominated by water level oscillations with a period of 12h 25min in average (corresponding to about two high and low water levels every day). The tidal range is variable with cycles of about 15 days. The largest tidal ranges correspond to spring tides, and the lowest to neap tides. Two periods of spring and neap tides are generally observed each month. The mean tidal

ranges are 1.28 m at neap tides and 2.56 m at spring tides (with a maximum of 3.44 m). A typical example of tidal water level and velocity oscillations during one month is presented in Figure 1.7, based on records at the lower estuary from the SIMPATICO monitoring Station (see Box 1.4).
Maximum current velocities precede maximum tidal stage (high or low water levels) by about 2 hr. In other words, slack water (i.e., he period with zero velocity when the tide is turning from ebb to flood and

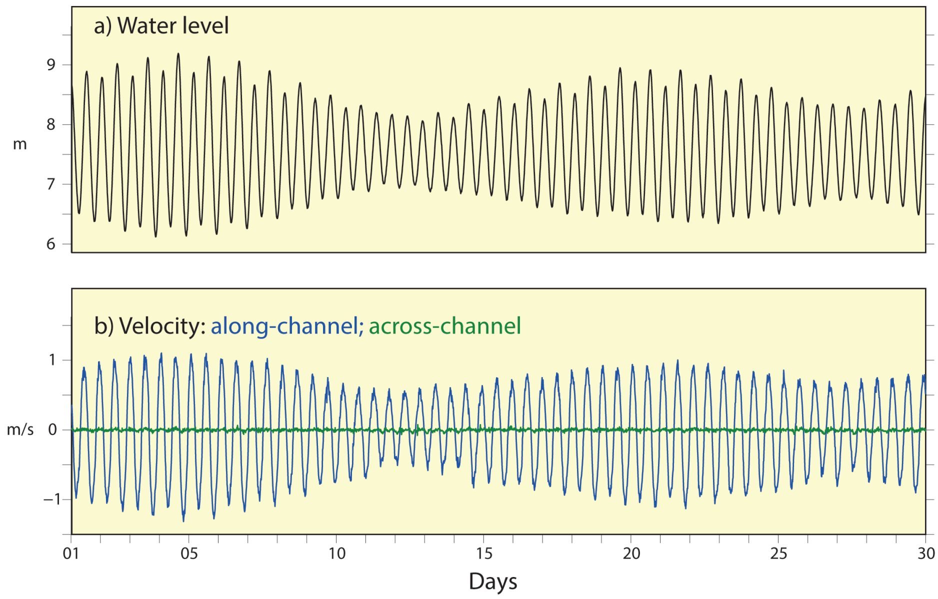

Figure 1.7.
(a) water level (m, referred to MSL), and (b) velocity (m/s) variations (blue: along-channel component; green: across-channel component) during one month at the deep channel of the lower Guadiana estuary.

Box 1.4. What is the SIMPATICO monitoring system?

The SIMPATICO (integrated system for in situ multi-parametric monitoring in coastal area) is an environmental monitoring station owned by CIMA that measures continuously in-situ water quality and currents at the lower Guadiana estuary. The instrumentation consists mainly of a surface buoy (see picture) equipped with a multi-parametric probe and a current-meter. The station provides unique months-long time-series at high frequency (hourly and 15 min) of current velocity (every 80 cm along the water column), water level, temperature, turbidity, dissolved oxygen, salinity, chlorophyll and pH. The data are available publicly at:
http://doi.pangaea.de/10.1594/PANGAEA.845750

Figure Box 1.4.
The surface buoy of the SIMPATICO system at the lower Guadiana estuary (photograph by E. Garel, 2009).

vice-versa) occurs about 1 hr after high or low water (Figure 1.8). This 1 hr time lag indicates that the tidal wave is a mixture of standing wave and progressive wave (see Box 1.5).

Because the estuarine channel is relatively narrow, the flow is principally parallel to the margins. The cross-channel flow component is weak (generally less than 3 cm/s) compared to the along-channel (or axial) velocity component (Figure 1.7b). Maximum axial velocities are generally observed in the deep channel and near the surface, where they can reach up to 1.4 m/s during the largest spring tides. These velocities may be much higher during periods of large river discharge (see Section 1.4). Considering the average of the flow along the water column, the maximum axial velocity during a tidal cycle is between ~1.3 m/s and 0.4 m/s, depending on the tidal range. It is commonly about 1 m/s at spring tide, and about 0.5 m/s at neap tide (e.g., Figure 1.7).

Laterally, the magnitude of the axial flow is driven by bathymetric variations. The velocity magnitude is weaker at shallower areas where the flow experiences greater bed friction. Around slack water, current reversal (from ebb-directed to flood-directed, and vice-versa) generally occurs first over over shallow areas and subsequently at the deep channel as the flow has a larger momentum over greater water depths.

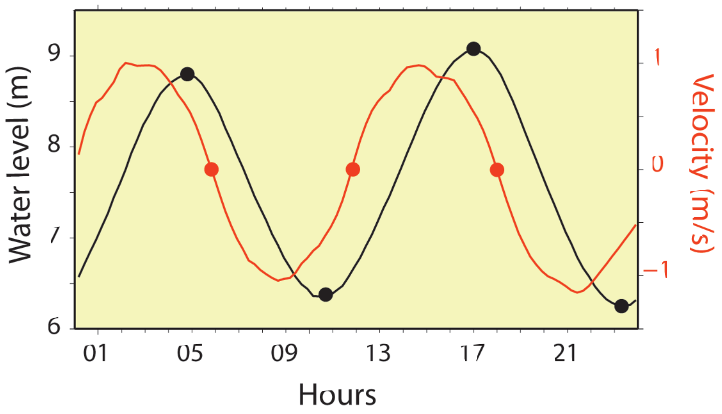

Figure 1.8.
Example of water level (black, m) and axial velocity (red, m/s) variations during 2 tidal cycles at the lower estuary. The time of maximum tidal stage and slack water are indicated with black and red spots, respectively, to illustrate the time lag (~1 hr) of peak water levels relative to current inversions.

Box 1.5. What are progressive and standing waves?

Progressive and standing (or stationary) waves are two types of waves with distinct characteristics. Progressive waves are those that advance on the sea: a crest, followed by a through, is seen moving along the surface. The amplitude of vertical variations is equal over all points. Maximum water level at a given location occurs at the same time as peak current velocity. On the opposite, standing waves remain at a fixed position, and the amplitude varies from zero (at "node" points) to maximum (at "antinode" points). Standing waves can be seen as the superimposition of two identical progressive waves travelling in opposite directions. This usually happens when one wave is the reflection of the other (see wave reflection in Box 1.6). Maximum water levels for a standing wave occur when the current is null (i.e., when it reverses in direction). In estuaries with semidiurnal tidal variations, the time lag between current and velocity is 0 hr for a purely progressive wave, and about 3 hr for a purely standing wave. However tidal waves at these systems generally consist of mixed waves with intermediate time lag (between 0 and 3 hr).

1.3.2. Tidal propagation upstream

The mean tidal range is approximately constant along most of the estuary (Figure 1.9, black line). Significant reduction of the tidal wave height is only observed near the head (upstream of km 60-70) due to truncation of the low water level by sills. At this upstream portion of the estuary, the lowest water level is observed at neap tide rather than at spring tide. This feature distinguishes the tidal river (from km 60-70 until the head) from the tidal estuary located downstream. In detail, some differences in tidal height propagation are observed between spring and neap tides (Figure 1.9, blue and red lines). In particular, along the lower and middle estuary (i.e., between the mouth and ~km 20), the tidal wave is significantly

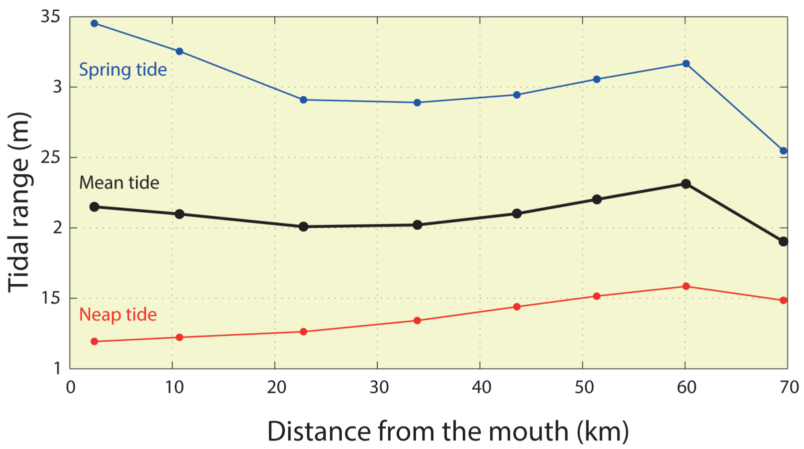

Figure 1.9.
Tidal range (m) along the Guadiana estuary at spring tide (blue), neap tide (red) and for a mean tide (black). Km 0 corresponds to the southern extremity of the western jetty. The dots indicate the location of the measuring stations.

damped at spring tide but slightly amplified at neap tide. By contrast, the tidal height is similarly amplified at the upper estuary for all tidal ranges. The spring-neap differences in water propagation observed at the lower and middle estuary are due to the non-linear relation between velocity and friction. At spring tide, the bed friction experienced by the flow is much stronger than at neap tide because of larger velocity magnitudes (as friction depends on the square of the velocity). These frictional effects result in tidal damping (see Box 1.6). Bottom resistance is therefore an important factor influencing the tidal range along the lower and middle estuary, at least at spring tide. By contrast, frictional effects are less at neap tide, and the tide is slightly amplified probably due to morphological convergence at the lower and middle estuary (see Box 1.6). At the upper estuary, the width of the channel changes slowly (see Figure 1.3a). Therefore, the amplification of the tidal wave height due to morphological convergence should be weaker than at the lower estuary. On the opposite, the largest tidal height amplification is observed at the upper estuary (Figure 1.9). This pattern is due to tidal wave reflection (see Box 1.6), which significantly affects the tidal range upstream of km 30-40.

1.3.3. Tidal asymmetry

When averaged over several months, the difference between ebb and flood duration is small (< 5 min) at the mouth, indicating small distortion. Differences are however observed in the tidal asymmetry between neap and spring tides (Figure 1.10a). At neaps, the flood phase tends to last longer (up to 1hr) than the ebb phase. The opposite is generally observed at springs (longer ebb phase). Furthermore, multiyear observations at the deep channel (from the SIMPATICO System, see Box 1.4) indicate that longer tidal phases are also associated to faster flows (Figure 1.10b). Thus the ebb is longer and faster at spring tide, but it is the flood which is faster and longer at neap tide. The transition between these two asymmetry regimes corresponds very approximately to the tidal range of 2 m. Hence, the lower Guadiana estuary

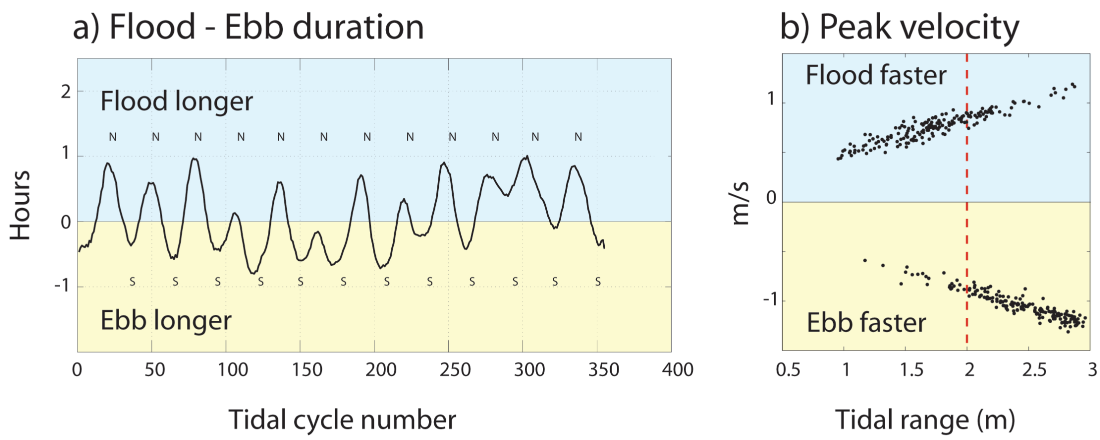

Figure 1.10.
Tidal asymmetry at the deep channel of the lower estuary: a) difference in flood – ebb duration in hr (y-axis with > 0: flood longer) for ~350 tidal cycles (x-axis), with indication of spring (S) and neap (N) tides; b) peak current velocity (m/s) against tidal range (m) for the ~350 tidal cycles of (a). The tidal range of 2 m is outlined with the dashed red line. The flood phase is longer with faster currents at neap; the ebb phase is longer with faster currents at spring.

Box 1.6. What effects modify the height of a tidal wave when propagating upstream?

At shallow estuaries, the tidal wave height is affected by the effects of shoaling, damping and reflection as it propagates upstream. Shoaling (or amplification) is due to the gradual change of the geometry of the system (mainly width, but also depth). This is an important phenomenon in estuaries where the channel width is decreasing significantly towards the head (morphological convergence), such as funnel-shaped coastal plain estuaries. Damping is the reduction of the tidal wave amplitude due to energy loss by friction between the flowing water and the bed. Hence, damping at shallow estuaries is more significant than at deeper systems. The tidal wave height in many estuaries results from the combination of shoaling and damping. If the effect of morphological convergence (i.e., shoaling) is stronger than the effect of friction (i.e., damping), then the wave is amplified; in the opposite case, the wave height is reduced as it propagates upstream. These two opposite effects may compensate each other, resulting in a constant tidal range along the estuary, as observed in many alluvial estuaries. In this case, the estuary is defined as "ideal" (or "synchronous"). Furthermore, the height of the tidal wave may be, in some cases, affected by reflection. Reflection refers to the propagation of wave opposite to the incoming wave motion due to the presence of a sudden obstacle. The reflecting obstacle might be a step change in water depth, in the case for example of a weir, a sharp bend of the estuarine channel or a vertical wall such as a dam. Partial reflection occurs in the first two cases as part of the wave is transmitted upstream, while the reflection is total in the case of a dam. The tidal range which is observed along the estuary results from the sum (resonance) of the incident wave and transmitted wave. This effect is generally stronger near the reflecting obstacle because the reflected wave is damped by friction as it propagates downstream. For resonance to exist, the period of the tidal wave should be close to the natural period of oscillation of the estuary. For instance, the Bay of Fundy has a natural oscillation period of ~13 hr and displays strong resonance as the semidiurnal tidal wave amplifies upstream as much as 16 m, constituting as such the world's largest tide.

departs from the typical cases of flood- or ebb-dominated estuaries where longer tidal phases are compensated by lower current velocities (see Box 1.7). The atypical (longer and faster) flows observed at the lower Guadiana estuary are attributed to modifications of the mean character of the flow due to the proximity of the inlet.

Typically, the shape of the tidal wave is increasingly distorted when propagating upstream in relation with reduced bed friction and faster tidal wave velocity around high water (see Box 1.7). Hence, the flood phase tends to be progressively shorter than the ebb one towards the head (Figure 1.11).

Box 1.7. What produce tidal asymmetry in estuaries?

Tidal asymmetry is due to the interaction of the propagating tidal wave with the bathymetry. As the speed of the tidal wave is controlled by the water depth, high water levels travel faster along the estuary than low water levels. In addition, bed friction is stronger at low tide than at high tide contributing to accelerate the flow at high water in comparison with low water. Because the tide is partially progressive (see Box 1.5), these effects typically result in a flood phase which is shorter than the ebb phase at a fixed location (in the case of a standing wave, these effects are equal during floods and ebbs, and the tide remains symmetrical). To compensate for the shorter flood phase, the tidal velocities are larger during the flood than during the ebb. Estuaries with such a shorter rising tide and larger flood currents are called "flood-dominated". "Ebb-dominance" is the opposite deformation (ebb shorter with faster flows) and is generally observed at estuaries with extended tidal marsh areas.

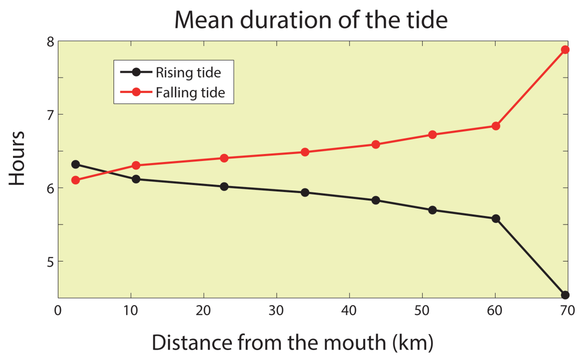

Figure 1.11.
Mean duration of the flood (black) and ebb (red) phases of the tide along the estuary. The dots indicate the location of the measuring stations

In detail, the deformation of the tidal wave is pronounced at spring tide but weak at neap tide (Figure 1.12). This is due to frictional effects related to the difference in tidal range between spring and neap tides (see Box 1.7). Shorter flood phases, in particular at spring tide, suggest flood-dominance. However, scarce velocity measurements indicate that ebb flows are not always weaker than flood ones even when the flood is shorter. Such ebb flow enhancement could be due to contributions of the freshwater flow component or to the bed slope.

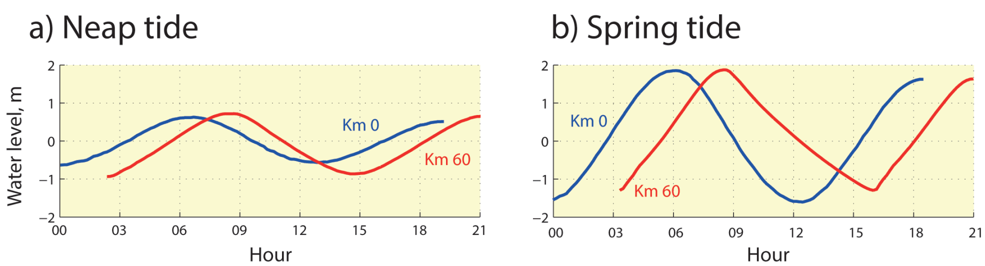

Figure 1.12.
Comparison of the tidal water level variations at km 0 (blue) and km 60 (red) during (a) a neap tidal cycle and (b) a spring tidal cycle.

1.4. Freshwater influence

1.4.1. River discharge into the estuary

The drainage basin of the Guadiana River is the fourth largest on the Iberian Peninsula with an area of 66,960 km^2 and a length of 810 km (see also T. Boski, chapter 2 in this book). The Guadiana runoff is closely related to the regional rainfall patterns due to pronounced shortage of soil and vegetation in the watershed. Strong seasonal and inter-annual variability is featured by prolonged periods of drought alternating episodic floods in winter and spring (Figure 1.13). For example, observations collected between 1947 and 2001 show that from January to March the average freshwater inputs to the estuary ranged from nearly 0 to 4,660 m^3/s with a mean of 440 m^3/s; from June to August, it ranged from 0 to 50 m^3/s with a mean value of 15 m^3/s. The maximum historical peak is 11,000 m^3/s in 1876, when water level reached 25 m above its usual height at Mértola. Since February 2002 the flow has been strongly regulated by the large Alqueva dam, located 60 km upstream from the estuary head across the Guadiana River. Some 23 km downstream, the Pedrogão dam forms a 2nd reservoir to pump back the water from the Alqueva reservoir at times of low demand. Since completion of this dam complex (for simplicity, hereafter referred to as the Alqueva dam), both the magnitude and frequency of floods have been drastically reduced (Figure 1.13).

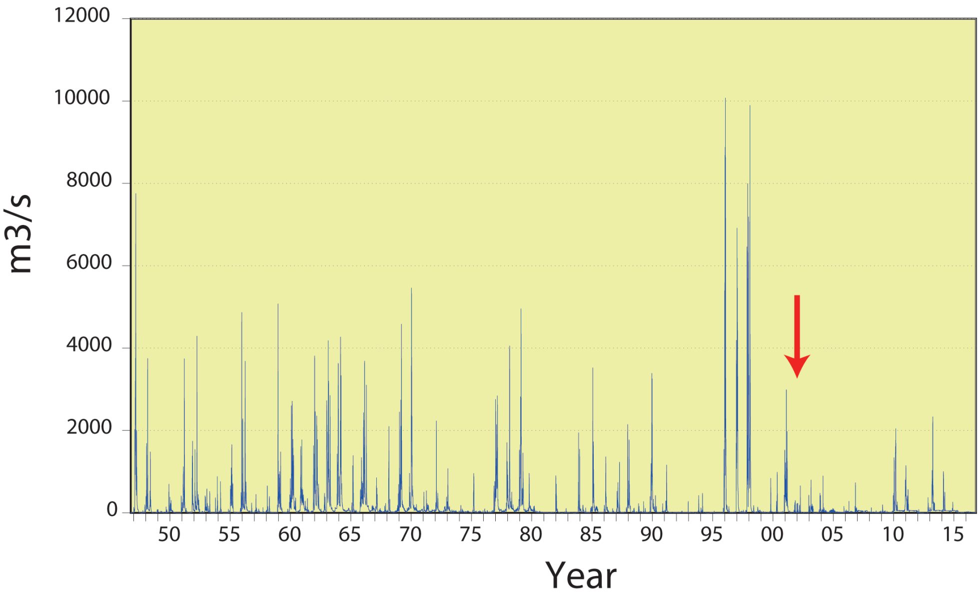

Figure 1.13. Daily averaged river discharge (m3/s) into the Guadiana estuary between 1947 and 2017. The red arrow indicates the closure of the Alqueva dam in February 2002.

The present freshwater discharge into the estuary is characterised by long (weeks to months) periods with low values, interrupted by moderate to high inflow events (up to 2,500 m^3/s) occurring in the winter or spring seasons. The low values correspond to the ecological flow for maintaining minimal ecosystem services, which is computed based on rain records at a meteorological station located nearby (Portel). It is typically up to 50 m^3/s and should never be less than 3 m^3/s. Moderate to high discharge events correspond to periods of water release from the Alqueva dam and to periods of intense rainfall in the region. During the last 14 years (2002 – 2016), there were only 4 episodes of significant water release from the Alqueva dam, during the first months of 2010, 2011, 2013 and 2014, with discharge roughly between 1,000 and 2,500 m^3/s (Figure 1.13). The discharge of rain-induced events is generally weaker, up to ~1,000 m^3/s.

1.4.2. Effects of low freshwater inflows into the estuary

When the freshwater inputs to the estuary are low, the salinity front is located at about 25 km from the mouth (near Foz de Odeleite) at low water level, marking the limit between the middle and upper estuary (Figure 1.14). The front moves upstream during flood tide, up to km 40, approximately (near Alcoutim). It should be noted that these features were observed in 2001 and might have been altered due to the present regime of strong flow regulation by the Alqueva dam.

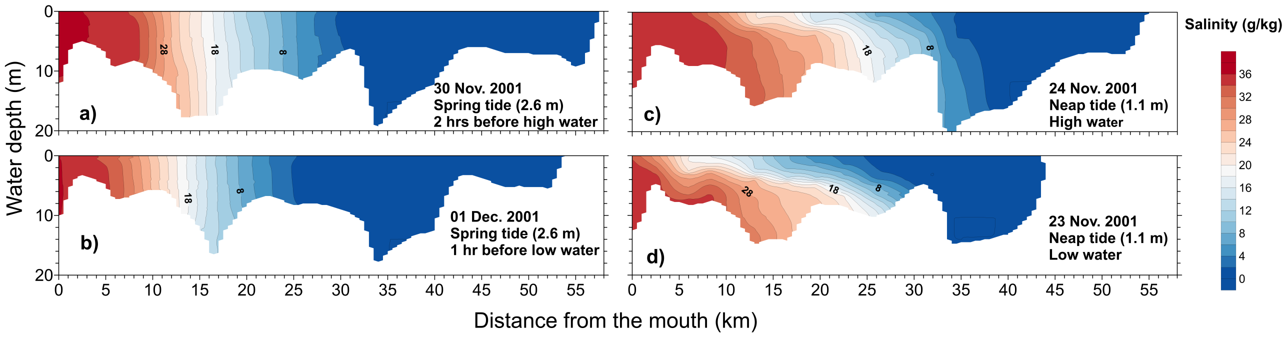

Figure 1.14.
Axial salinity at spring (a, b) and neap (c, d) tides, around high and low water. The river discharge is <10 m^3/s for all cases. The isohaline contour interval is 2 g/kg (except for salinities from 34 to 35 g/kg).

Vertical salinity profiles vary noticeably within the estuary between spring and neap tides (Figure 1.14). At spring tide, the tidal velocities are large and produce boundary turbulences of significant magnitude. As a result of turbulent mixing, the salinity does not change much along the water column, as represented by the vertical isohaline contours in Figures 1.14 (a, b). The estuary is classified as well-mixed under these conditions (see Box 1.8). At neap tide, the turbulence produced by the relatively weaker flow is not sufficient to mix the entire water column. The salinity increases towards the bed, as saltwater is denser thus heavier than freshwater (Figure 1.14 c, d). Under these stratified conditions, ebb flows are promoted near the surface and flood flows are promoted near the bed.

The strength of stratification is affected by tidal velocities (as described above), but also by the water depth. For similar flow magnitude, bed friction and thus mixing is enhanced at shallow areas. Consequently, significant variations in stratified conditions may be observed both along and across the channel. For instance, in Figure 1.14c and d, the strongest vertical density gradient is located at the deeper portion of the channel axis between km 10 and km 15. It has also been documented that the deep channel can be partly stratified at the lower estuary, while the bordering shallow areas are well-mixed. These distinct mixing conditions may induce spatial variability in the magnitude and direction of the residual circulation (see section 1.5).

1.4.3. Effects of moderate to high river inflows

A moderate increase in the river inflow enhances the strength of stratification and affects drastically the flow along the entire estuary. This is an essential feature of the Guadiana estuary, due to its constricted morphology, making this estuary very different from other systems with a large watershed such as coastal plain estuaries (where only extreme floods may produce similar effects). For example, highly stratified conditions (characterised by a homogeneous layer of salty water near the bottom, see box 1.8) have been reported at the lower estuary for moderate river discharge of 400 m^3/s. In this case, seaward flows are promoted near the surface where the ebb phase is longer and faster than for low river discharge

Box 1.8. Estuary classification based on vertical mixing

A convenient way of classifying estuaries is based on vertical variations of salinity. This classification considers the mixing between (more dense thus heavier) seawater and (less dense thus lighter) freshwater, and provides important information about the water circulation within the estuary. Four types of estuaries are typically identified: well mixed, weakly stratified (also partly stratified or partially mixed), highly (or strongly) stratified, and salt wedge estuaries. Well mixed estuaries have typically a large tidal range and a weak river discharge. The mean (tidally-averaged) salinity profiles are uniform along the water column and mean flows are unidirectional with depth. Weakly stratified estuaries have moderate to strong tidal range and weak to moderate river discharge. The mean salinity profile increases more or less regularly from surface to bottom. The mean flow is seaward near the surface and landward near the bed. This water circulation results from the enhancement of density currents and is referred to as the "estuarine (or gravitational) circulation". Highly stratified estuaries result from weak to moderate tidal range and moderate to large river discharge. The mean vertical salinity profile is relatively constant near the surface (fresher water) and near the bottom (saltier water), the transition occurring across an intermediate layer of water in which the salinity rapidly increases with depth. This stratification remains during the entire tidal cycle. The mean flow features strong surface outflows and weak bottom inflows. Salt wedge estuaries display similar stratification than strongly stratified estuaries, but during the flood tide, only. The stratification results from a large river discharge and weak tidal forcing. Seawater enters the estuary during the flood tide, in the form of a wedge at the bottom. The wedge migrates downstream during the ebb, and might be expelled out of the estuary which is then merely similar to a river, with unidirectional seaward flows and no vertical density gradients (only freshwater). Many systems may evolve from one type to another according to significant changes in the river discharge or to location along the estuary (see also Gomes & Camacho, chapter 3 in this book).

conditions. Flood flows are restricted to the bottom water layer and are observed during a large part of the tidal cycle to compensate for the long ebb phase at the surface. Hence, downstream- and upstream-oriented flows are commonly observed at the same time near the surface and bottom, respectively.
For high discharge events, roughly above 1,000-1,500 m^3/s (depending on the tidal range), the entire estuary is filled up with freshwater during most of the tidal cycle. If the river discharge is not too strong, a salt wedge may propagate upstream during the flood tide due to seawater advection near the bed and reduced mixing by weak flood currents. During the ebb tide, the salt wedge is displaced seaward and riverine characteristics are observed, with a fast unidirectional (downstream) flow of freshwater along the entire water column.

1.5. Residual circulation

Residual (also subtidal or net) flows represent the mean water circulation after one or several tidal cycles. They govern the transport of material (e.g., suspended sediment, contaminant, pollutants) along the estuary and the net exchange with the adjacent coastal area, and are therefore of great importance for the health of estuarine ecosystems. The axial residual circulation in estuaries often results from the competition between tidally-induced and density-induced flows (in particular when other forcing agents such as wind or river discharge are unimportant). Thus, this circulation is generally strongly dependent of stratified conditions.

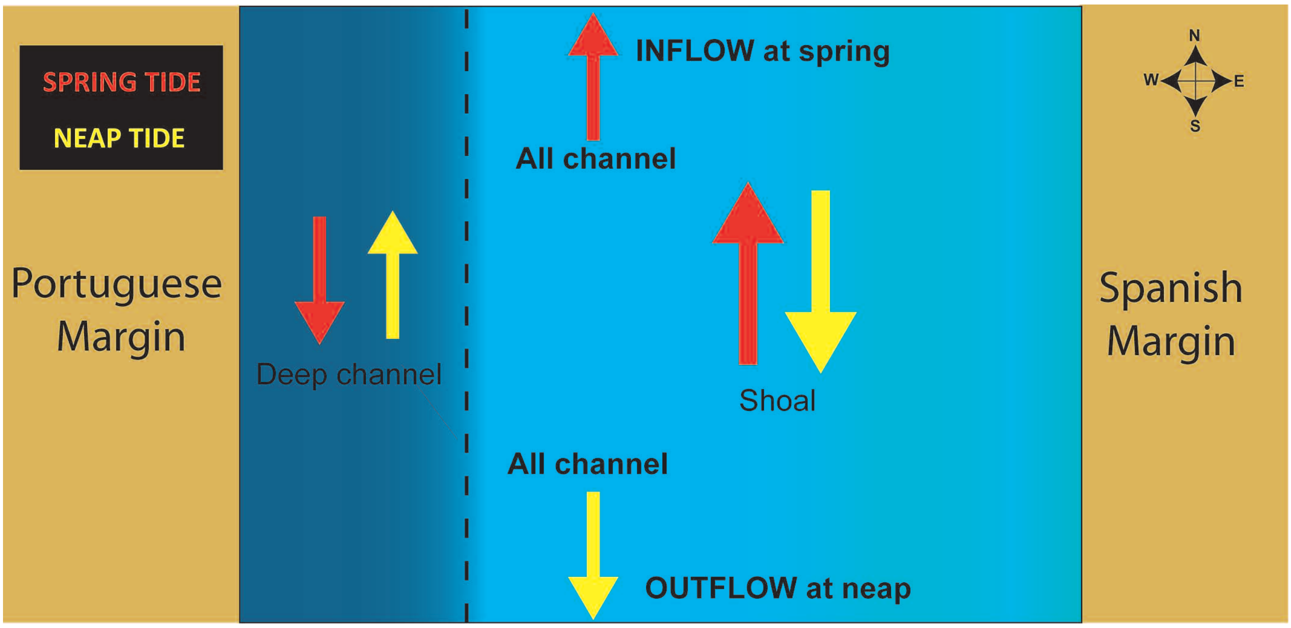

Figure 1.15.
Sketch of the residual circulation at spring (red) and neap (yellow) tides over the deep channel, over the shoals and for the entire cross-section at the lower estuary.

For low river discharge, the overall residual circulation (averaged over the channel width) at the lower Guadiana estuary is upstream at spring tide and downstream at neap tide (Figure 1.15). Albeit a narrow channel, these flow directions vary laterally with the water depth. The residual flows over the shoals are consistent with the channel width-averaged circulation, with inflows at spring tides and outflows at neap tides. By contrast, the tidal asymmetries at the deep channel (described in section 1.3) produce an opposite residual circulation, with inflows at neap tides and outflows at spring tides.
The switch in the net transport direction between spring and neap tides occurs for a tidal range of about 2 m, the average tidal range in the area. For tidal range > 2 m, the estuary is well mixed (see Box 1.8); the residual velocity profile over the deep channel is unidirectional and oriented seaward (green line in Figure 1.16). For a range < 2 m, the deep channel is partly stratified and estuarine circulation develops (see Box 1.8), with a residual flow oriented up-estuary near the bed and down-estuary near the surface (red line in Figure 1.16).

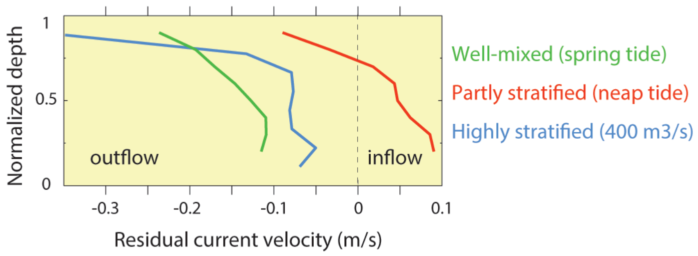

Figure 1.16.
Residual velocity profile at the deep channel for low inflow conditions at spring tide (green) and neap tide (red) and for a moderate river discharge of 400 m^3/s (blue).

The change in residual water circulation between spring and neap tides is determined (at least partly) by the combination of the Stokes transport and compensating return flow, which varies laterally with the bathymetry (see Box 1.9). The Stokes transport is strong at spring tide over shallow areas and produces an upstream transport of water. At neap tide, the Stokes transport is weak (because variations in water elevation are small), and the return flow is reinforced, producing a downstream residual flow. This flow might be further enhanced by density-induced outflows related to the increased stratification at the deep channel.

Comparison of subtidal water level variations at the mouth and near the head illustrates the fortnightly tide produced by the Stokes transport mechanism (Figure 1.17). At the mouth, water level variations are

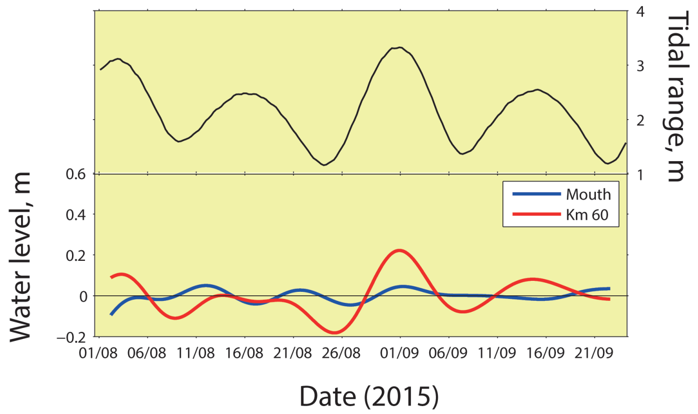

Figure 1.17.
Upper: tidal range at the mouth; Lower: residual water level at the mouth (blue line) and at km 60 upstream (red line).

Box 1.9. What is the Stokes drift in estuaries?

The Stokes drift arises because the discharge of water near to high water is greater than the discharge near low water. This mechanism relates to the progressive component of the (generally mixed) tidal wave (Box 1.5), which induces the transport of more water upstream around high water than downstream around low water (for a purely standing wave, the discharges near high and low water are equal). The Stokes transport is generally stronger over shallow than deep areas because of non-linearity between friction and velocity (enhanced friction – thus reduced velocity – around low water increases the net difference in water transport between low and high water levels). Likewise, the Stokes transport is also stronger at spring tide when the differences in water levels between high and low tide are larger. The net transport of water upstream produces a gradual increase of the mean water level towards the estuary head resulting in a water level gradient by which a return flow is driven. The interplay between upstream Stokes transport (larger at springs) and downstream return flow (larger at neaps) typically results in water level oscillations at the upper estuary over the spring - neap cycles, referred to as "fortnightly tides".

small and uncorrelated with the tidal range. By contrast, at upstream locations the water level is generally higher than the mean water level at spring tide, as water is transported towards the estuary head by the Stokes mechanism. At neap tides, the water level decreases and tends to be lower than the mean water level with the transport of water downstream by the return flow. The difference in mean water elevation can be 20 cm (and more) between the mouth and the head (e.g., 01/09/2015 in Figure 1.17).
With increasing freshwater inflows, residual velocity profile at the highly stratified estuary is unidirectional, oriented downstream, with strong velocities near the surface (Figure 1.16, blue line). The seaward directed residual velocities get larger with increasing river discharge (or with increasing upstream distance from the mouth).

1.6. The transport of sediment

1.6.1. Bedload transport

The bedload sand transport rate is mainly dependent on the tidal current magnitude near the bottom. For low river inflows, maximum velocities at neap tide are too weak to remobilise bed sediment. Significant bedload transport occurs principally at spring tide, when tidal currents are comparatively larger (Figure 1.18). At the lower estuary, the net sand transport is down-estuary due to the tidal asymmetries reported in section 1.3 (ebb longer and faster at spring tide). Most of the transport occurs at the deep channel where peak velocities are significantly larger than over the shoals. A few near bed measurements also suggest that downstream bedload transport may episodically predominate in the deep channelpredominates at the middle and upper estuary reaches (see section 1.3). In such situations, the deep channel serves as a conduit to export sediment during low inflow conditions. Presently, the estuarine export of sand to the sea is weak, estimated to be about 5,000 m^3/yr.

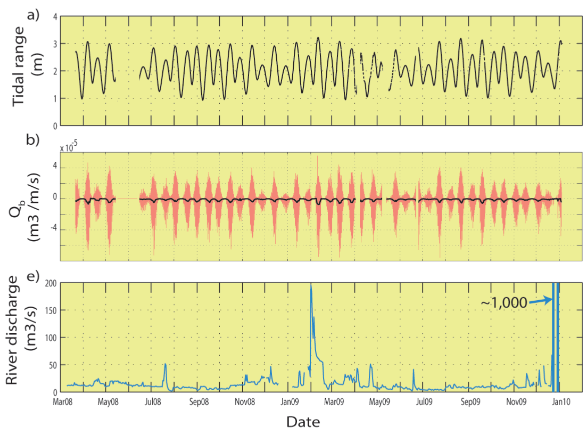

Figure 1.18.
a) Tidal range (m, MSL); b) Tidal (red) and residual (black) bedload transport rate (Qb, m^3/m/s); c) river discharge (m^3/s). Significant net bedload transport occurs at spring tide, only, when the river discharge is low. The transport rate is not enhanced during the periods of increased discharge in Feb. 2008 and Dec. 2009, due to water stratification (discharge < 1,500 m^3/s).

For enhanced river inflows, the estuary can be stratified or filled up with freshwater (during part or totality of the tidal cycle) depending on the discharge magnitude and location within the estuary (see section 1.4.3). In the presence of stratification, near bed flows are favoured in the upstream direction by density currents, resulting in long flood phases. There is therefore no significant downstream bedload transport under these stratified conditions (e.g., Figure 1.18). In other words, an increase in river discharge magnitudes does not necessarily enhance the bedload sand transport towards the sea. Downstream transport rather occurs when freshwater occupies the entire water column during at least a part of the tidal cycle. Such riverine conditions occur for moderate inflows at the middle and upper estuary, supplying bed sediment downstream. At the lower estuary, freshwater is observed for discharge > 1,000 – 1,500 m^3/s (very approximately). Although relatively moderate, these discharge magnitudes are rarely reached due to dam regulation (Figure 1.13). It has been estimated that the potential for sand export from the estuary to the nearshore has been reduced by 1 or 2 orders of magnitude since the construction of the Alqueva dam.

1.6.2. Suspended sediment

The fine sediment in suspension within the estuary is dominantly composed of phyllosilicates, represented principally by illite (> 50%), kaolinite and chlorite. Typically, fines are suspended in the water column by tidal currents and deposit at slack water. At spring tide, tidal currents are larger than at neap tides and marginal areas which are usually dry may be inundated. Consequently, the suspended sediment concentration (SSC) varies at a 15 days period (being higher at springs and lower at neaps) when freshwater inflows are weak. This variability is illustrated by turbidity records – a proxy for SSC - from the SIMPATICO Station (see Box 1.4) at the lower estuary (Figure 1.19). The SSC may also display important variations during a tidal cycle. For example, maximum surface SSC is observed at the end of the ebb (and minimum during the flood) when the seawater is less turbid than estuarine water (such as in Figure 1.19). Occasionally, the seawater can be more turbid than estuarine water leading to maximum SSC values during the flood and minimum values during the ebb.

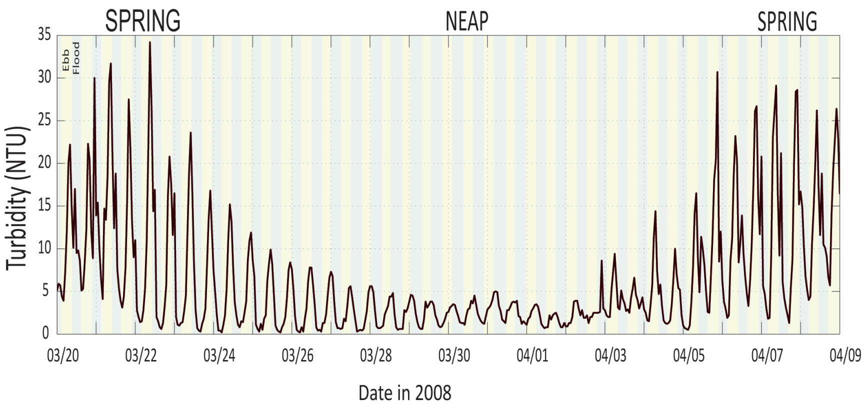

Figure 1.19.
Turbidity (NTU) records from the SIMPATICO station illustrating variability at the fortnightly and tidal time scales. Periods of ebb and flood tides are in green and blue, respectively.

For low inflows, the SSC ranges usually between less than 10 mg/l at the mouth, up to an estuarine turbidity maximum (ETM) of ~ 500 mg/l located near the haline front, at the middle/upper estuary. At spring tide, the ETM is well expressed and extends along the entire water column (Figure 1.20a, b). At neap tide, it is relatively weaker and restricted to the bed (Figure 1.20c, d). The 2nd ETM in Figure 1.20a is

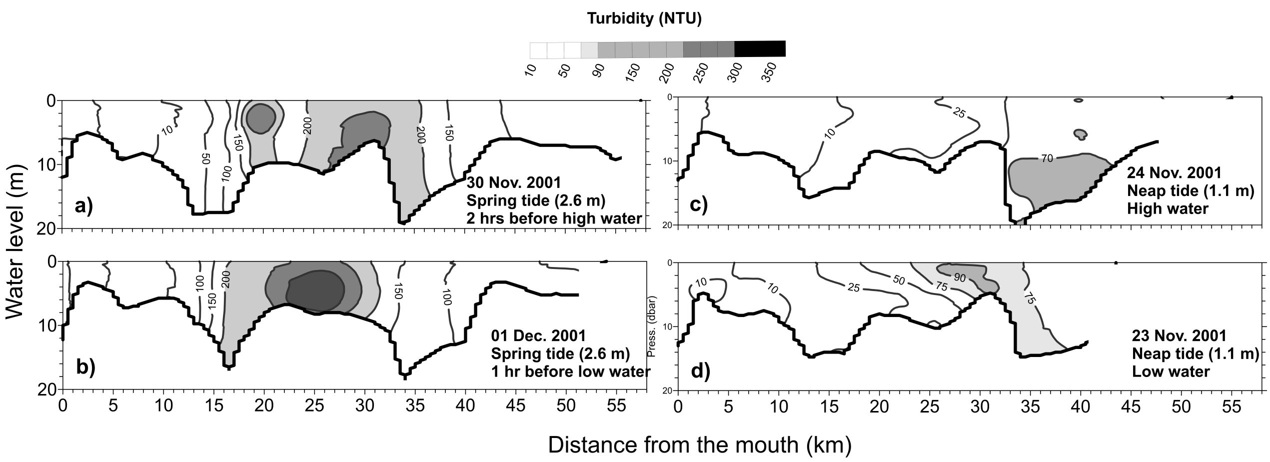

Figure 1.20.
Axial turbidity (mg/l) at spring (a, b) and neap (c, d) tides, around high and low water. The river discharge is < 10 m3/s for all cases. The filled contours show high turbidity areas.

attributed to tributary discharge after an intense rain event. With increasing river flow, the SSC within the estuary might be one order of magnitude larger. For example, a concentration of about 1,000 mg/l was observed near the mouth for a discharge of 2,000 m^3/s.
The exchange of suspended sediment between the estuary and the sea is governed by the residual water circulation. Hence, for low river discharge, suspended sediment tends to be imported at springs and exported at neaps (see Section 1.5). Over several weeks, the import and export of fines seem relatively balanced. Significant export takes place during moderate to high river discharge events. The ETM maintains its position for river discharge up to 250 m^3/s (at least) due to increased stratification. For higher flow, the ETM is displaced downstream and can be expelled out to the shelf. Freshwater plumes of high turbidity are typically observed on the inner shelf during such periods of high river inflows (e.g., Figure 1.21).

Figure 1.21.
Satellite image of the Guadiana estuary during a high river discharge event in December 2001 (source: ISS, NASA).

1.7. Morphodynamics of the ebb delta

The sand deposits that form the Guadiana ebb delta originate from the littoral transport and river export. The littoral transport is eastward in the region (due to the predominance of waves from the Southwest) and estimated about 100,000 m^3/yr. The river export is weak during low freshwater inflow conditions since Alqueva dam closure (about 5,000 m^3/yr) but might be one order of magnitude larger in the occurrence of large flood events (see section 1.6.1).
Before 1972, the (historical) ebb delta was constituted by a broad platform asymmetric towards the East, which included a large sand bank in front of the mouth (the O'Bril bank). Over the course of decades, the bank underwent large morphological changes. Those were accompanied by pronounced modifications in the position and geometry (length, width, water depth) of the inlet channel, making boat access to the estuary hazardous and intricate. To improve navigability, the mouth was stabilised in 1972-74 by a pair of parallel jetties (the eastern jetty being submerged except at low spring tide). This intervention has markedly affected the morphodynamics of the ebb-tidal delta.
In response to jetty construction, the historical delta has been severely eroded under the action of waves. A large part of the eroded material has been transported to the Spanish beaches of Isla Canela, resulting in a significant overall advance of the shoreline. The same mechanism produced accretion of the Portuguese beach of "Ponta da Areia", and resulted in the rapid accumulation of sand against the western jetty. A new (modern) delta of smaller dimension has formed off the mouth, characterized by an outer shoal and lateral bars (Figure 1.22). The erosion of the historical delta (and in particular of the O'Bril bank) provided a very large local sand supply which has promoted the rapid development of these

morphological features. At present (2017), the ebb delta is accumulating sand at a reduced pace and migrating seaward at an average rate of about 7 m/yr.
The vertical development of the outer shoal has reduced locally the depth of the navigation channel to less than 3 m (referred to the hydrographic zero; see box 1.3), justifying dredging operations performed in 1986 and 2015. In 2015, a sand volume of 0.063 Mm^3 was dredged in the channel to reach a minimum target depth of 3.5 m, for a total cost of 850,000 €. The recovery of the dredged area has been extremely rapid, challenging the efficiency of these dredging operations.

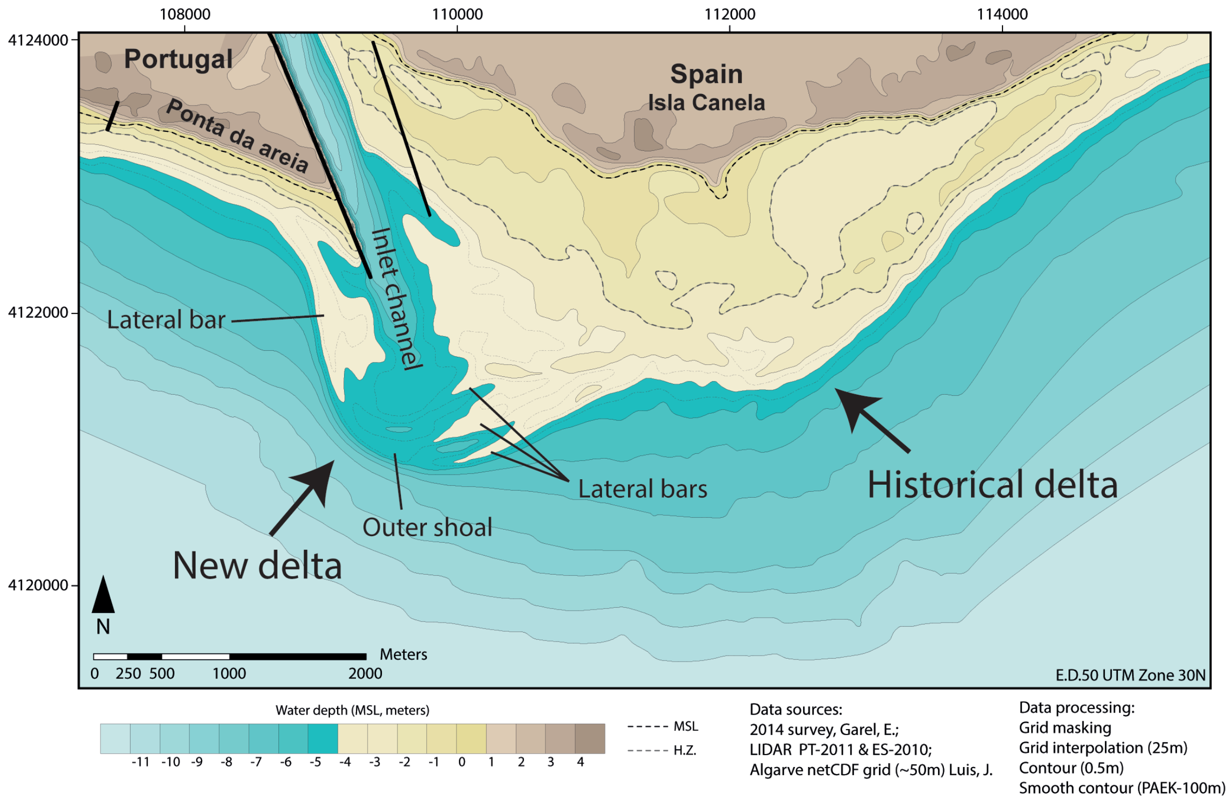

Figure 1.22.
Bathymetry of the ebb delta of the Guadiana estuary in 2014.

1.8. Final remarks

Studies conducted at the Guadiana estuary over the last decades have featured many typical physical processes that have been described at other systems. Yet, various particularities related principally to its (long and narrow) morphology and large watershed should be accounted for to correctly apprehend the dynamics of the Guadiana.
In particular, while estuaries are generally considered as sediment traps due to the infilling of sediment, the Guadiana estuary - as other Rock-Bound Estuaries - exports sediment over time scales of years and more. Weak sediment export associated to low inflows can become substantial for river discharge above 1,000-1,500 m^3/s, when the entire estuary is filled up with freshwater for at least a part of the tide. These high discharge events are however relatively rare and limited in magnitude (up to about 2,500 m^3/s) under the present regime of strong flow regulation.

At most estuaries submitted to average (i.e., non-extreme) conditions, the residual water flows results from the predominance of one physical driver, related for example to the tide or water density stratification. The magnitude of the residual circulation is in general modulated by the tidal range, being for example weaker (or stronger) at spring tide than at neap tide, but its direction remains constant. By contrast, at the lower Guadiana estuary (and may be upstream), the spring-neap cycle is associated to opposed residual water transport direction during periods of low inflows. These inversions have been rarely described in mesotidal estuaries and suggest a remarkable switching of residual flow drivers at a 15-days period. Some studies have linked this unique behaviour to the variations in stratified conditions observed between spring (well mixed) and neap (partly stratified) tides.
The mean tidal range varies little along most of the Guadiana estuary (from the mouth to ~km 60). This pattern is common at the extensively described large alluvial estuaries, which are then qualified as "ideal". However, the constant tidal range at alluvial estuaries is produced by a balance between damping (due to friction) and shoaling (due to morphological convergence) of the tidal wave as it propagates upstream (see Box 1.69). By contrast, the constant tidal amplitude along the Guadiana estuary also results from wave resonance, making it different from typical "ideal" systems. As such, the concept of ideal estuary may entail incorrect assumptions when applied to the Guadiana estuary.
Future studies regarding the dynamics of the Guadiana estuary should quantify precisely the water circulation and mixing process along the entire channel for various river flow conditions. This task must account for the variability of the flow across the channel which has been observed (so far) at the lower estuary. Considering its extreme range of stratified conditions (from well-mixed to salt-wedge) and its relatively simple morphology, the Guadiana is an exceptional natural laboratory (with moreover a beautiful natural setting) where these studies should be relevant for a wide range of other systems.

Acknowledgements

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2. Guadiana estuary– present state, past evolution and prospects for the future

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2.1. The Guadiana watershed

The Guadiana catchment extends over an area of 66 889 km^2, between the catchments of the Tagus and Guadalquivir rivers, of which 11 525 km^2 are in Portugal. Its upper part in Spain corresponds to what is called the Western La Mancha province (Figure 2.1) (see Box 2.1).

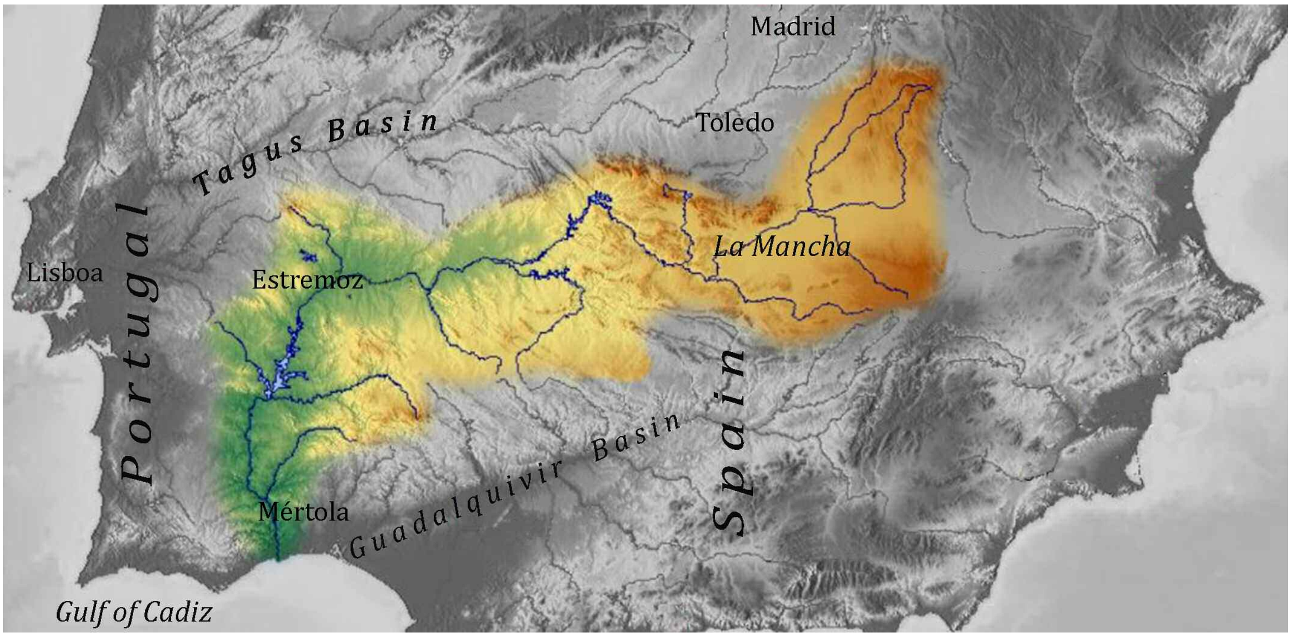

Figure 2.1.
The Drainage Basin of Guadiana River

Box 2.1 Do you know that

La Mancha province is an arid highland of Central Spain, south of Madrid, bordered on the North by Alcarria and to the South by the Sierra Morrena mountains. The lack of correspondence of the term La Mancha to any special signification in Spanish, besides "stain" or "spot", points the etymology to Moorish term al-mansha i.e. wild dry land. Indeed, the scarce precipitation and large thermal oscillations have always severely limited agriculture, which historically could not take the full advantage of predominantly very fertile soils. Due to intensive irrigation these limitations were overcome in the 20th century. Windmills have probably become the most identifiable symbol of the La Mancha region, after Miguel Cervantes immortalized the fight of Don Quixote against them.

To the North the watershed is limited by alignments, of the Sierra de Altomira (http://www.castillalamancha.es/sites/default/files/documentos/paginas/archivos/altomira_liczepa_fich.pdf) with heights between 700 and 1,000 meters and the Mancha de Toledo, with profusion of endorheic lagoons between 600 and 800 meters above sea level. The origin of the Guadiana was historically placed in the area of Campo de Montiel under the name Rio Pinilla. The drainage in this area is mostly underground through the dissolution voids within the karstified calcaraeous rock substratum (Figure 2.2 and annex V) and therefore has no permanent character. So, the actual river source is either placed in the Lagoons of Ruidera (natural park), fed by the waters from the springs that drain the aquifer of Campo de Montiel (http://cvc.cervantes.es/literatura/cervantistas/coloquios/cl_IX/cl_IX_19.pdf) or in the Wetlands of Daimiel (natural park), which are fed by the rivers Ciguela and Záncara.

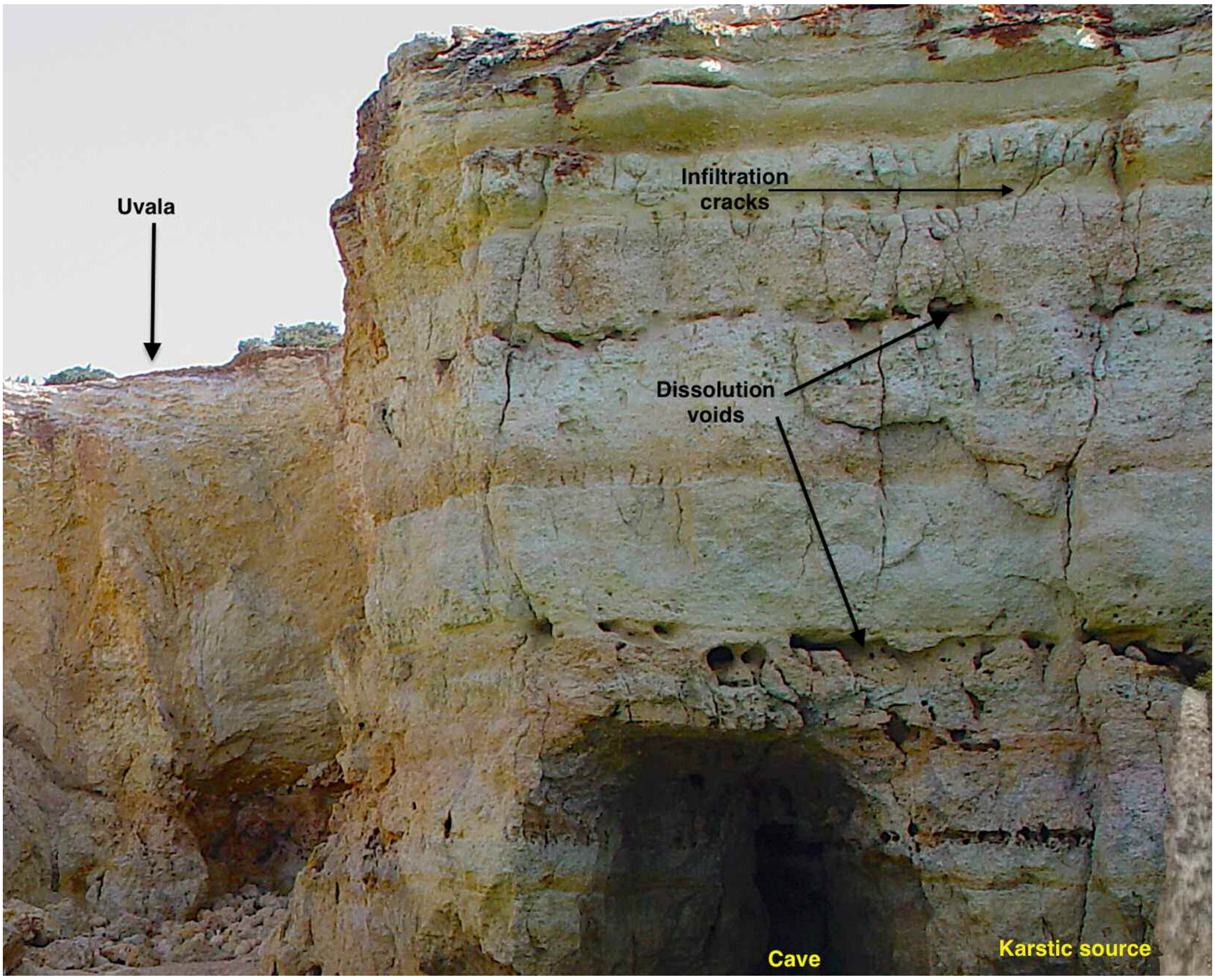

Figure 2.2.
An example of karstic dissolution features and underground drainage developed in calcareous rocks. On the left hand side the scarp cuts the collapsed cave termed uvala (photo by T. Boski, 2007).

Whatever its exact origins, the river runs through the southern Iberian plain in a direction east to west and after 578 km, it begins to turn to the south near the town of Badajoz, approaching the frontier with Portugal. From the mouth of the Caia River to the confluence with the Cuncos River, the Guadiana River marks 40 km of the international boundary between Portugal and Spain. It flows in Portuguese territory for 142 km and once more becomes the natural border for the last 60 km of its course between its confluence with the Chança River and the estuary mouth in the Gulf of Cadiz.

The climate of the Guadiana watershed is characterized by hot and dry summers and cold wet winters. The annual thermal oscillations between +50°C and -10°C in the inland part of the watershed create conditions for potential evaporation of 800 mm/yr – 1000 mm/yr, what is substantially higher than the precipitation, whose typical values vary between 450 mm/yr and 700 mm/yr. Consequently there is very strong demand for water in the whole basin, resulting in the construction of 62 permanently monitored dams (25 in Portugal and 37 in Spain) and countless other water retention structures across smaller tributaries (http://snirh.pt/index.php?idMain=1&idItem=1.3&sbaciaid=23). More than 75% of water demand is for irrigation. Damming of rivers in SW Iberian Peninsula was initiated probably by Romans for the purpose of rural and urban supply. It continued to support the rural economy for two millennia and in the 19th Century was applied for the purpose of mineral processing in the Iberian Pyrite Belt (see also Morais & Domingues, chapter 6 in this book).

Notwithstanding its importance for supporting the socioeconomic systems in Portugal and in Spain, artificial water retention by man did not substantially affect the flow of water and sediments to the ocean until the end of the 19th century. Over the 20th century water storage capacity in the drainage basin grew almost exponentially from nil to ca. 15000 hm^3 in 2002 when the Alqueva dam enclosed the largest artificial lake in Europe, with a total retention capacity of 4200 hm^3 (see also Morais & Domingues, chapter 6 in this book). The last figure is in fact very close to the annual discharge of the Guadiana measured at the hydrographic station at Pulo de Lobo.
(see Box 2.2).

From the above cited figures we may conclude that in the conditions of average discharge (4200 $hm^3/year^{-1}$) it will be necessary to wait more than 3 years in order to fill the river dams of the Guadiana that are operational at present. Despite the maintenance of so called "ecological discharge" assuring the delivery of 20 – 40 m^3/s^{-1} of water to the estuary, river dams have very drastically altered the transfer of water to the coastal ocean, and at the same time the transfer of sediments and nutrients essential to maintain the coastal zone of Gulf of Cadiz in equilibrium (see also Garel, chapter 1 in this book).

Box 2.2 Do you know that

Pulo do Lobo rapids and waterfall (Portuguese meaning wolf's leap) are situated in a narrow gorge of Guadiana, with a total height difference of 30 m, 17 km N from Mértola. The river gorge is a spectacular erosional feature cut into the folded and fractured Variscan schists and quartzites. This magnificent natural site is situated within the Lower Guadiana Natural Park (http://www.icnf.pt/portal/ap/r-nat/rnscmvrsa). The narrowness and the depth the river bed provide perfect conditions for the measurement of river discharge to which contributes 91% of the watershed. The highest discharge of ca. 8000 m3/sec was recorded in 1947, while the annual average is ca. 80 m^3/s^{-1}.

Figure Box 2.2.
O Pulo do Lobo.

2.2. The Guadiana estuary

In physical terms the Guadiana estuary extends from its mouth between the localities of Ayamonte and Vila Real de Santo António (Figure 2.3) and Mértola 60 km to the North where tidal changes in water level may still be observed. In chemical terms, i.e. of the chlorine ion limit 0.1‰ Cl^-, the estuary extends only 8 - 20 km inland or to the localities of Castro Marim and Alamo. Thus the chemical definition embraces either lower or both lower and middle estuary depending on very variable river discharge and mixing with marine water.

Figure 2.3.
Map showing some localities of the lower estuary. Source image: Google maps. This reproduction is according the the google terms and conditions (fair use).

2.2.1. Geology

At the Algarve-Andalusia regional scale the primary geological domains are:

a) The Variscan (Old) Massif rocks, represented by the Baixo Alentejo Flysch group and by the Southwest Domain;
b) The Meso-Cenozoic Algarve sedimentary belt;
c) The Guadalquivir river basin sediments;
d) Pleistocene and Holocene fluvial and estuarine deposits.

Usually, these four geological domains are separated according to their respective ages and lithologies. The first group (a) corresponds to Palaeozoic formations (see annex I: Geological Time Table), being composed mostly of schist and greywacke, although in the Southwest Domain there are also quartzite rocks. The Meso-Cenozoic belt (b) extends along the Algarve coast, presenting varied carbonated lithologies that range from dolomites to marls or even sandstone. In turn, the Guadalquivir river basin sediments (c) belong to the Cenozoic (see annex I: Geological Time Table) and are composed of sediments with variable grain sizes. The youngest, (d) Pleistocene and Holocene sediments (see annex I: Geological Time Table), mostly silts, sands and gravels were deposited during the last glacial cycle in the incised river palaeovalleys and along the littoral zone in general. Of special interest are the valley infills because they form the true geological archives of environmental changes, which occurred regionally and globally over the last fourteen millennia. The Guadiana sedimentary archive will be discussed in section 2.4 of this Chapter.

2.2.2. Geomorphology

Continental domain

In the Continental domain surrounding the Guadiana estuary it is possible to observe numerous geomorphological features, some identifiable on both margins but others on only one. Older rocks belonging to the Variscan Serra Algarvia are more representative on the Portuguese side. On the Spanish side, younger Mesozoic and Cenozoic sedimentary rocks are predominant; these are characterized by absence of large elevations, and gentle slopes without a strong incision of the drainage network. An intermediate unit called the Barrocal that only exists in the Portuguese territory separates the Variscan mountains from the littoral domain.

Littoral domain

In the Littoral domain contiguous to the Guadiana estuary, the relief morphology is more homogenous than in the continental domain, with flat areas as well as some small elevations. Sandy beaches are dominant, although dunes are also present. The inner part of the estuary, is formed by salt marshes and intertidal mud flats which are separated from the highly energetic land – ocean interface by elongated and continuous bodies of coastal sand like: particularly dune ridges, sand spits, barrier-islands, tidal deltas and terraces and also submerged deltas.

Salt-marshes and mud flats

The structure of salt marshes is characterized by the presence of creeks, pools and small embankments. The creeks are the principal routes by which the tidal waters enter and leave the marsh as the tide rises and falls. They are important for the different habitats that they create, and for the exchange of materials as well as organisms between the marsh and the rest of the estuary. Salt-marshes are areas sheltered from wave action and where water flows are moderated so that organic material, muds and other sediments can settle out. The sediments include tiny fragments of shells, sands (mostly derived from the sea) and finer silts and clays (creating muddy sediments, mostly derived from the rivers).

The presence of salt water is the main factor which distinguishes salt marshes from the other types of wetland that one finds in the more interior zones of an estuary and that are more influenced by fresh water. In reality there is not a clear delimitation between the two regimes, but rather a gradual transition. The ecological importance of salt marshes arises from the diversity of habitats that they support. Owing to the specific characteristics of salt marshes the diversity of plant species to be found is relatively low. This reflects the hostile conditions for plant life generally– few species and groups are adapted to live in these demanding environments. These plants show some similarity in their form, being generally small plants, fleshy and hairless, with small, glaucous leaves with shiny surfaces. The diversity of the plants increases as one goes up a salt marsh. In the upper marshes the specialists, which are called 'halophytes', become mixed with others, the non-halophytes, and a more varied topography generally creates a wider range of niches encouraging the co-existence of a greater diversity of plants. Salt marshes undergo continuous changes, with some areas undergoing growth, and others degradation and retreat even on an inter-annual scale.

Sand spits and littoral ridges

When the sediments carried by the Guadiana River reach the coastline, they are integrated into the littoral longshore and cross-shore transport due to the action of waves and tides, giving rise to large sandy coastal units, like sand spits and littoral ridges (see box 2.3). Littoral ridges are sand accumulations, developed along the coastline, that remain connected to land throughout their whole length. Sand spits are similar to littoral ridges, being also sand accumulations, but are not always connected to land. Sand spits are connected to land at one extremity and continue as a tongue of sand through the sea. In the Guadiana estuary, sand spits are only developed on the Spanish margin, and they partially block the mouth of the estuary (see Box 2.3.).

Dune ridges

Wind action over beach sand is responsible for sand being transported and then deposited where obstructed by the presence of objects. The resulting accumulations of sand can grow and give rise to sand dunes. These dunes continue to rise with the sand transported by wind and become stabilized by vegetation that helps dunes to be further developed. Whilst the dunes grow and become even more vegetated, new dunes arise at their front, creating a series of dune ridges oriented according to the primary wind direction. In the Guadiana estuary, dune ridges are particularly developed on the Portuguese margin. Monte Gordo pines has been planted on these dune ridges.

Box 2.3.

Since its construction in 1974, the groin of Vila Real de Santo António interrupted the longshore drift of sandy sediments. On one hand this intervention prevented the shoaling of navigation channel but the another drastically decreased the transfer of sand to the Spanish side of the estuary and provoked local beach erosion.

Barrier-islands

Sandy formations that are completely separated from land are designated as barrier-islands, because they form elongated sand bodies in front of the mainland and are separated from it by aquatic surfaces and intertidal zones. Nowadays, there are no barrier islands at the Portuguese margin, although it is very probable that, in the recent geological past they may have actually existed. In the Spanish margin it is still possible to identify barrier-islands, although they are already deeply altered by human action.

Tidal shoals and terraces

Close to the main river channel and to the inlets that separate barrier-islands, there are a series of sand accumulations termed flood and ebb tide deltas (see also Garel, chapter 1 in this book). Protected from intense wave action, flat and low lying plains composed of fine sediments, normally mud and clay, called tidal terraces have developed. There are two types of tidal terraces. The first type has very little or even no vegetation at all and is located in the lower areas. The second type develops in the higher lying terraces and presents a well-developed vegetation cover. This latter type makes the transition to the salt marsh areas, being sometimes designated as lower salt marsh.

2.3. Socio-economic characterization

During the last decades, the Guadiana River basin has undergone a significant demographic change due to rural depopulation and parallel (compensating) development of tourism activities in the coastal zone. The latter is most significantly seen in the summer with the arrival of countless numbers of tourists which leads to a considerable increase in the seasonal population of the estuary.
The resident population of the Guadiana estuary, especially in the cities of Vila Real de Santo António, Castro Marim, Ayamonte and Isla Cristina, has always been connected to the exploration of the land and the sea, but also taking advantage of the privileged location as a centre of commerce between the two nations.

Commerce

The navigability of the Guadiana River, together with its location on the border between Portugal and Spain, has driven the development of the Ayamonte and Vila Real de Santo António ports. These ports have then contributed to the development of commerce and the growth of the local economy.

Agriculture

A considerable part of the Guadiana estuary is used for agriculture, practised either on the dryer slopes or on the land reclaimed from the estuary. Irrigated agriculture has been developed in the lower and marshy areas, while on the dryer soils and on the slopes there are traditional dry land tree crops such as carobs, olive trees and almond trees, or even cereals such as wheat, barley or oats.

Salt production

Salt production, described in Chapter 5, is one of the oldest activities in the Guadiana estuary area, being an a fast growing component of the local economy. There are both traditional and industrial, or semi-industrial, salt explorations in the Guadiana estuary.

Aquaculture

The development of fish farms in the Guadiana estuary has been undertaken mostly by conversion of older salt pans into fish tanks. There are fish farms on both margins of the estuary, where fish species are produced either in an intensive or semi-intensive regime. Although they create richness and employment for the estuarine populations, these farms have a strong impact on the environmental quality of the estuarine waters.

Cattle rearing

Cattle rearing is an economic activity currently in decline in the Guadiana estuary region. However, it is still possible to find bovine or caprine cattle grazing on the degraded salt marshes or the slopes where extensive agriculture is practiced. This activity often complements the primary farming system based on crop cultivation.

Tourism

Nowadays, economic activities related to tourism, recreation and leisure are the most important in terms of revenue for the Guadiana estuary. Besides sun and sea tourism, clearly dominant in Isla Canela, Isla Cristina, Vila Real de Santo António and Monte Gordo, there are new developments more related to cultural tourist activities, mainly in Ayamonte and Castro Marim, but also nature-based tourism in the areas with high natural heritage value on both sides of the estuary. That kind of activities, based on unspoiled natural values of waters and of the estuarine and river valley margins should be developed and promoted

Hunting

Hunting is practised only in restricted areas around the estuary, as in the protected areas it is forbidden. Hunters seek mostly hares, rabbits, partridges and turtle-doves. As the estuarine area has important communities of aquatic birds, hunting around such areas creates a considerable impact for the estuarine avifauna.

Fishing

Fishing is legal in the main river channel only if practiced with lines and fish-hooks. It is forbidden in the salt marshes and tidal creeks. Nevertheless, illegal shrimp and bivalve fishing occurs in almost the whole estuary. This illegal fishing is an important source of revenue for fishermen that live in the Guadiana estuary region.

Open sea fishing is done by many fishermen, mostly from Isla Cristina and in lower numbers by fishermen from Ayamonte and Vila Real de Santo António. Although these fishermen do not fish in the estuary, they land their catches here and as a result there is an important local industry of fish processing and marketing.

Nature Conservation

The high natural heritage value of the Guadiana estuary is clearly demonstrated by the extensive salt-marsh areas, salt steppes, salt pans (both traditional and industrial), lagoons, tidal creeks, barrier island, and many other locations and habitats of great ecological value (http://www.cima.ualg.pt/MEGASIG/). All these habitats support plant and animal communities that not only increase the estuary's natural value, but also make it unique and irreplaceable. Because of such variety and richness, it was soon realized that it would be necessary to safeguard some areas from urban sprawl and industrial growth. The Sapal de Castro Marim and Vila Real de Santo António Nature Reserve was thus created in 1975 (http://www.icnf.pt/portal/ap/r-nat/rnscmvrsa). This was the first nature reserve to be created in Portugal. Some years later, in 1989, the Marismas de Isla Cristina Natural Landscape was created on the Spanish side of the estuary. These two protected areas have been key for maintaining the ecological diversity of the Guadiana estuary. Today, with the ongoing development of tourist facilities and consequent urban growth, the importance of these protected areas has become even greater.

Recently, the creation of the European network of areas with high nature conservation value, the NATURA 2000 network (http://ec.europa.eu/environment/nature/natura2000/index_en.htm), has reinforced and increased the areas dedicated to nature conservation in the estuary. Due to the important bird communities that use the estuary, two Special Protection Areas (SPA) have been created, one on each margin of the estuary (Castro Marim Saltmarshes SPA and Isla Cristina SPA). Besides these areas dedicated to birds, three Special Areas of Conservation (SAC) were created to protect specific habitats (Lower Guadiana SAC, Isla Cristina Saltmarshes SAC and Isla de S. Bruno SAC).

Pollution

The Guadiana estuary still shows a high environmental quality, without persistent pollution problems (see also Bebianno et al., chapter 7 in this book). During the MEGASIG Project, the organic fraction of sediments collected along the tidal creeks and estuarine channels was analysed in order to detect possible pollution sources. The lipid fraction of the organic matter was subjected to specific studies and the analyses done led to the identification of some types of molecules that indicate the presence of industrial plastic. Nevertheless, generally speaking, no concentrations or evidences typical of persistent pollution resulting from human activities were found.

2.4. Past and future environmental changes in the Guadiana estuary

2.4.1 Reconstruction of the last 14 thousand years in the Guadiana estuary

Due to the tectonic fracturing and impervious character of rocks, the Guadiana valley was deeply incised into the shale and greywacke substratum of the Old Massif. Over the Quaternary period (the last 2.4 million years- see annex I- Geological Time Table) and in particular during the last 700 thousand years when the Northern Hemisphere experienced glacial periods, the mean sea level lowered to 120 – 140 meters below that presently observed. These periods, termed marine lowstands corresponded to the expansion of North American and Scandinavian ice caps locking thousands of cubic kilometres of water. They were witnessed all over the world, a strong incision of the river beds and export of the sediment to the sea, whose limits here were some 30 kms to the south of the present coastline. In the following period of climate warming, the retreat of melting ice caps occurred and the ensuing sea level rise led to a progressive inundation of the continental shelf. Marine waters have penetrated deeply into the valley of Guadiana creating a new space that accommodated new sediments, which contain the record of accompanying environmental changes. Assembling of geophysical, geotechnical and geological data enabled to create the digital reconstruction of terminal tract of deeply incised Guadiana paleovalley, which corresponds to the present estuary. The 3D diagram based on tens of thousands interpolated depth points is depicted in Figure 2. 4

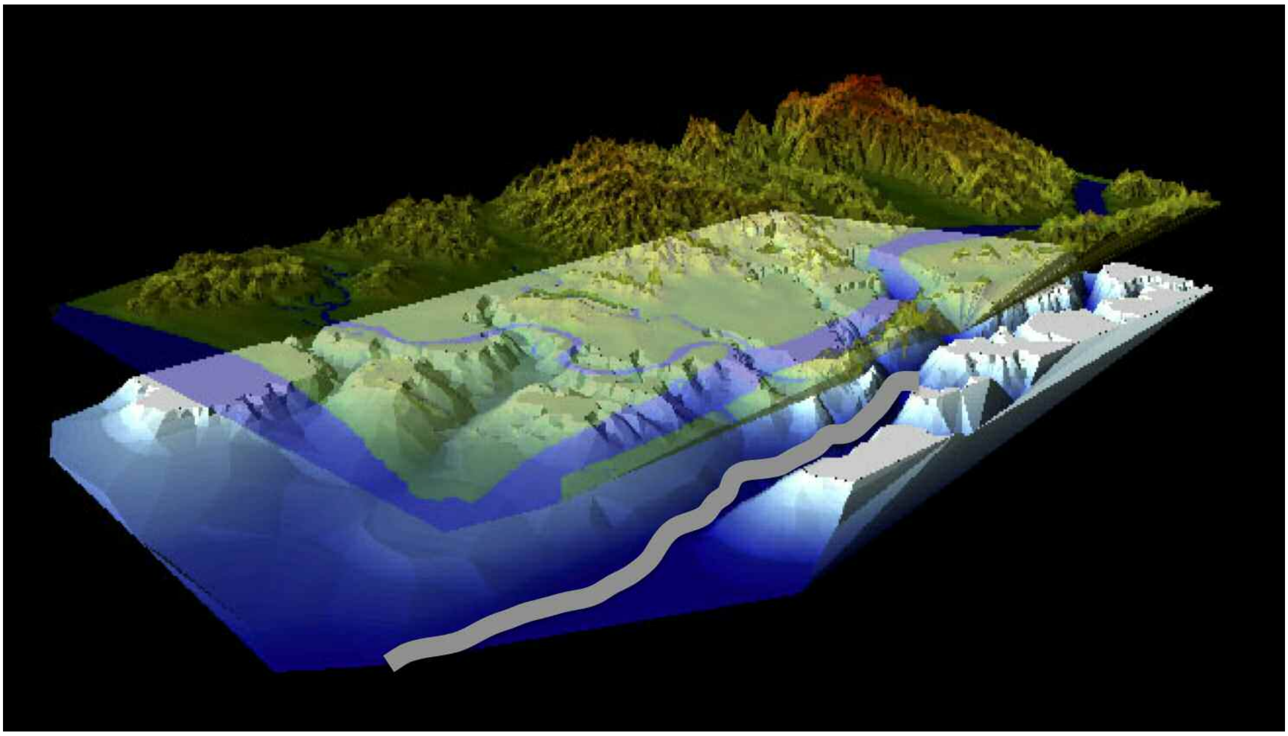

Figure 2.4.
Digitally reconstructed land surface of Guadiana palaeovalley some 18 000 years ago. The upper image layer shows present topography and the river course. The projection is vertically exaggerated 50 times.

To study the complex history of sedimentation and obtain the information on the past environmental conditions, the CIMA team carried out several mechanical drilling campaigns, which produced six continuously cored boreholes (Fig. 2.5). The mechanic drillings were further complemented by tens of shallower hand drilled boreholes. The deepest of the boreholes (CM6 in Figure 2.5), drilled on the Spanish side of the river, ca. 2 kms north from the International bridge reached a depth of 62.5 m and is the longest sediment profile of that type in Europe.

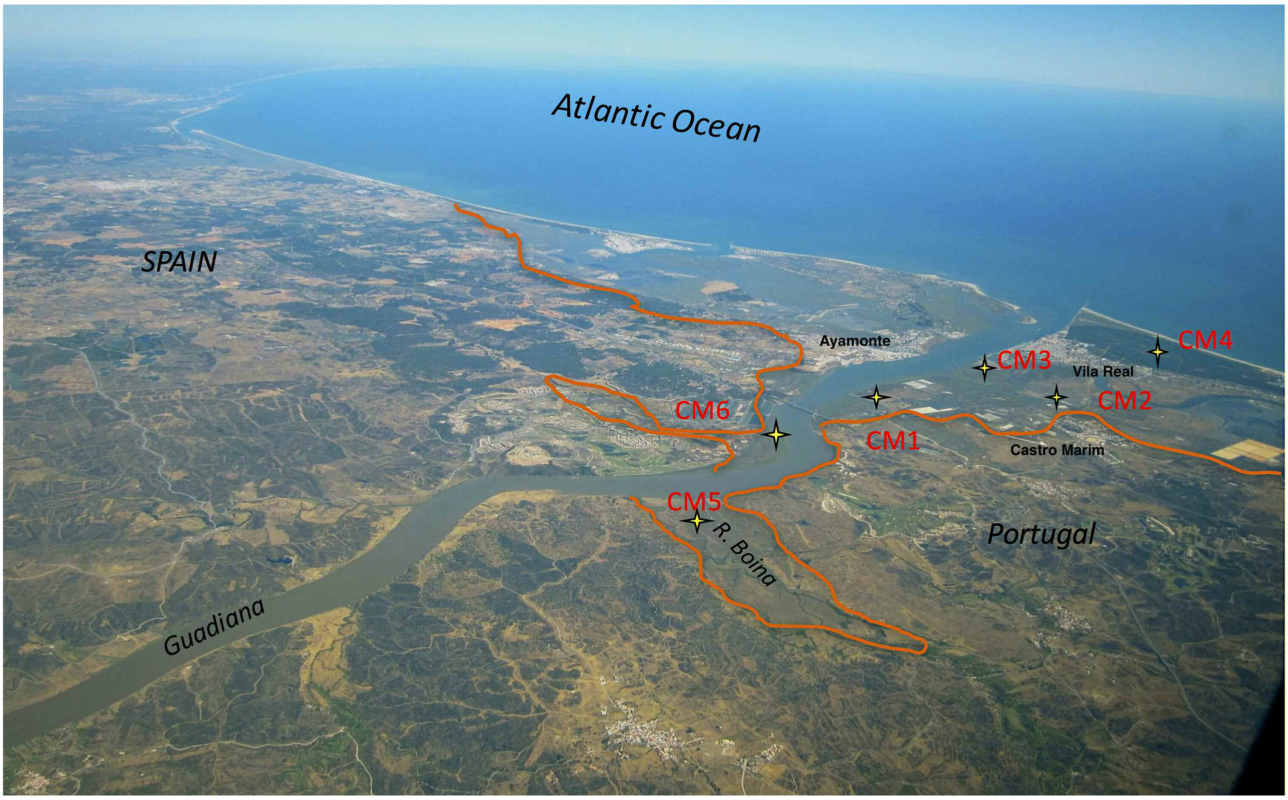

Figure 2.5.
Oblique view of Guadiana River estuary showing the localization of boreholes which permitted the reconstruction of regional sea level changes during the past thirteen millennia. Orange line indicate the limits of maximum sea transgression ca. 7500 yrs before the present (photo by T.Boski, 2013).

The initially observed fast (8 – 10 mm/yr) sea level rise (see the first segment of the curve in Fig. 2.6) laid sediments whose pollen inventory indicated the predominant forest flora of pines and oaks. Marine waters stopped rising ca. 12.5 thousand years ago during the cold period of Younger Dryas when the flora became more shrubby, including junipers, artemisia and ephedra. This colder and dryer climatic period terminated some thousand years afterwards, at the beginning of Holocene period (see annex I- Geological Time Table), with the sea level resuming its rise at a rate of 7-8 mm/year. That accelerated marine transgression culminated (see Figure 2.6) with a major jump of 4-5 meters during just two – three centuries. It transformed the whole estuarine area, some 7.5 thousand years ago, into a vast embayment completely open to the Atlantic Ocean.
The climate was mild at that time and the regional landscape was covered by oaks, olive and pine trees in decreasing order of abundance, as dominant arboreal species. Since then, the marine advance progressed at 1.2 mm/rate until the 20th century. The first signals of human presence in the SW Iberian Peninsula were detected indirectly through pollen analysis around 5 millennia ago, when a conspicuous deforestation is detected in parallel to the expansion of shrubs. The anthropic activities were also detected since 4500 years ago (beginning of the Copper Age), by a higher content of chemical elements like Pb, Co, Ni, and Mn, and to a lesser extent to Zn, Cu, and Ni, which were introduced by early mining activities at the beginning of the Copper Age. Mining activities became particularly intensive between

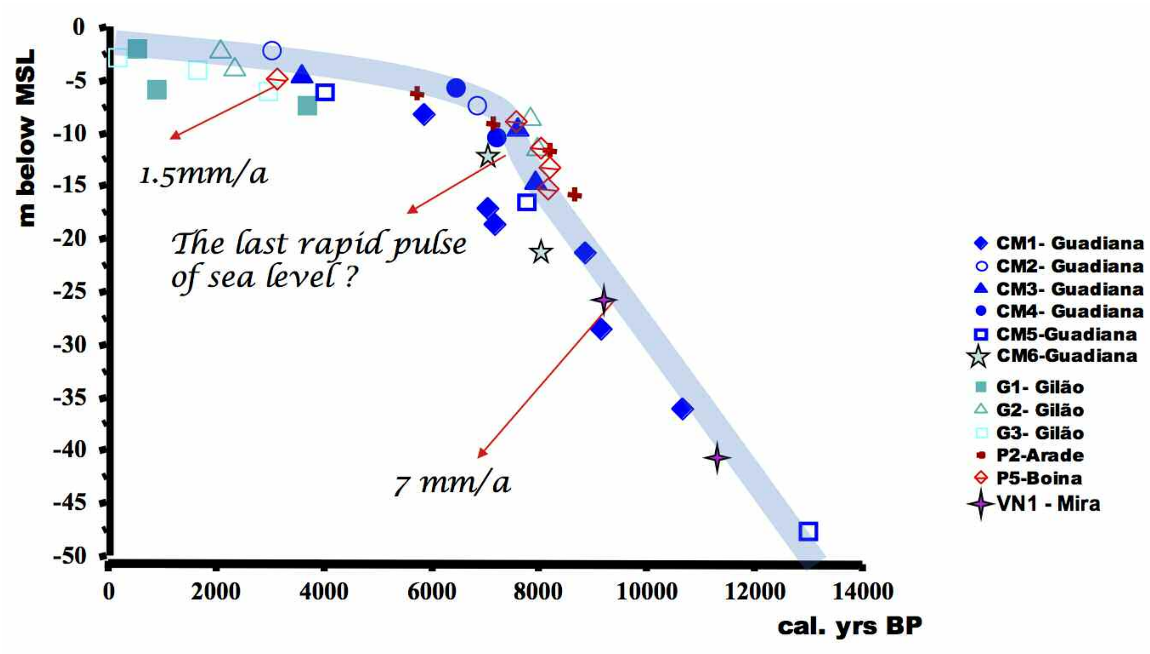

Figure 2.6.
Sea level curve of Southern Portugal based on borehole data mostly from Guadiana estuary and complemented by information from Gilão, Arade, Boina and Mira Estuaries. The time scale is expressed in calibrated years before present.

the late Bronze Age and the Roman period (3000-1500 yrs before present), when higher than previous levels of metal pollution were detected. Roman times saw the Lower Guadiana estuary as a vast swampy salt marsh area, drained by several channels used for navigation. In general, the intensification of human occupation during Moorish domination and medieval epochs led to the higher sediment input from land where wood cutting and agricultural practices lead to an increased soil erosion. During Roman times, Castro Marim was an important commercial harbor and maintained this function until 1774. The progressive shoaling of the channels aggravated by the impact of 1755 Lisbon tsunami imposed the necessity to move the port closer to the main inlet. The new facility became a part of the infrastructure of Vila Real de Santo António, an example of modern urban planning ordered by Marques de Pombal. It provided shelter to the fishing fleet exploring the fertile waters of Guadiana shelf and in the second half of 19th century to the transport of minerals mined in the Iberian Pyrite Belt (San Domingos Mine being the most prominent) and exported to the United Kingdom. Shoaling by continuous deposition of sands, transported by the western coastal drift current and pushed into the estuary by tides, continued to be a severe problem for navigation in 20th century. It led to the construction of a jetty by Portuguese authorities in 1974, which contributed to the accretion of more than 200 hectares of the new land on the Western side, during the next 10 years.

2.5. The future evolution of the Guadiana estuary

Two main factors that define the morphology of an estuary or delta are changes of the sea level and changes in supply of sediments. Assuming that the present rate of sea-level rise estimated at 3 mm/yr will continue or more probably will accelerate during the 21st Century and beyond, the reduction of fluvial sediment supply due to the regulation of river discharge represents a major challenge for the management of estuarine ecosystems. In contrast to the Holocene period of sediment input accommodated into the new unrestricted space created by sea level rise, coastal systems including saltmarshes will retreat because reduced river flow and reduced terrestrial sediment input. Both phenomena are caused by river damming, which is particularly intensive in the Guadiana watershed. Saltmarshes thriving on both sides of the main estuarine channel under the Nature Reserve protection, rely on a continuous fine grain sediment delivery from fluvial sources, and it is exactly for that reason that river discharge is critical for sustaining the saltmarsh ecosystems. The present estimations of minimum environmental flow do not take into consideration the fluvial discharge required to maintain saltmarshes under the pressure of the rising ocean waters. The CIMA team accepted the challenge of filling this gap in knowledge and carried out decadal time scale modelling of estuarine response to the sea level rise foreseen in the IPCC (http://www.ipcc.ch) scenarios for the end of 21st century. From this exercise, it appears that for the upper limit scenarios (probably the most realistic), the expansion of intertidal zone limits at the Spanish and Portuguese margins is visible on the banks of most of secondary tidal channels. Under the worst sea level rise scenario, the low and mid marsh will be forced to migrate into a new higher setting. However its establishment will be successful if the biogeochemical conditions for halophytic plant development are appropriate and there is no man made spatial constraints like roads, building or any hard artificial land cover. Submerging of saltmarshes due to sea level rise and sediment starvation may be avoided by implementing a multi-dimensional and integrated approach that consists of: (1) Determination of minimum ecological flow based on a full spectrum of natural flows, in terms of temporal and spatial variability; (2) possible removal of the unnecessary coastal structures to allow the natural sedimentation process to take place within the system; (3) bypassing the dams to enhance the fine fluvial sediment needed to sustain the marshes to be delivered to the estuarine system; and (4) a possible transplanting of the dominant marsh species or development of a back-barrier perimarine wetland.

Acknowledgements

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EVEDUS funded by the Portuguese Science and Technology Foundation, MEGASIG and SPICOSA projects funded by the European Union under Interreg IIB and 6 Framework Programs. Carlos Loureiro, D. Ruwan Sampath and Carlos Sousa provided invaluable help in creating the digital terrain models.

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3. Habitats of the Guadiana River estuary

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The Guadiana River estuary is the most important estuarine system in southern Portugal. The estuary's variety of habitats supports a great diversity of species. Some of these species have only recently been discovered and are found nowhere else on Earth. This chapter details the current state of knowledge of the estuary's habitats, with a particular focus on the unseen microscopic flora and fauna that support the entire food chain – and many economic activities – in the estuary.

3.1. Ecological zones of the Guadiana estuary and their environment

The Guadiana River estuary has two major environmental gradients, in which several important ecological zones occur. One such gradient is defined along the main axis of the estuary, as a result of the distance to the river mouth (a balance between tidal inflow and river outflow). The other gradient is set along an axis perpendicular to the estuarine channel, and relates to changes in elevation and their interaction with the tidal range.

The gradient defined along the main axis of the estuary divides it into three zones (Figure 3.1): (i) upper estuary (with tidal influence and salinity close to zero); (ii) the middle estuary (where salinity varies between 0.5–25 g/kg); and (iii) lower estuary (where the salinity is higher to 25 g/kg). The salinity of the Bay of Cadiz is, on average, 36 g/kg (see also Garel, chapter 1 in this book).

The gradient set along an axis perpendicular to the estuarine channel is classified into three zones (Figure 3.2): (i) subtidal (below the mean low tide level - always covered by the water); (ii) intertidal (between the mean low and high tide levels - flooded twice a day) and (iii) supratidal areas (above the mean high tide level, only flooded during spring or storm tides). Each of these zones has characteristic landforms and vegetation. In the intertidal area, unvegetated sand and mudflats are widespread, dependent on the local hydrodynamics (Figure 3.2). Saltmarshes may also occur in this zone – these areas differ by the presence of halophyte vegetation and a shorter duration of tidal inundation. Increased exposure to the atmosphere increases evaporation and makes the soil water of saltmarshes saltier than the surrounding soils. The fine, muddy soils of saltmarshes trap the organic matter from the halophyte vegetation and algae. The organic matter decomposes rapidly due to greater exposure to the atmospheric oxygen, making the soil water more acidic. In areas where saltmarshes remain inundated for longer, organic matter may be trapped in the soils for long periods of time, contributing to what is called 'blue carbon'. Disturbance of these blue carbon deposits through dredging or drainage can cause the carbon to be released as a greenhouse gas. Sulphuric acid may be released into the waterway at the same time, leading to problems for aquatic species. It is therefore important to avoid disturbing saltmarsh soils to keep our atmosphere, waterways and ecosystems healthy. Salt water is heavier than fresh water, so the water in estuaries like the Guadiana may become 'stratified' into layers, with salty water occurring near the bottom of the channel and fresh water sitting at the surface. During periods of low river flow, the water column is (i) well mixed during spring tides and (ii) partially stratified in neap tides. When the river flow is high, the water column is highly stratified. A feature called a 'salt wedge' appears in the estuary during these periods. The wedge is thickest at the estuary mouth and gradually becomes thinner further upstream (see also Garel, chapter 1 in this book).

It is this complexity of the estuary that creates the basis for the existence of a great diversity of habitats. As well as ecological diversity, along the estuarine margins there are: (i) urban areas (Vila Real de Santo António, Ayamonte, Castro Marim, Costa Esuri, Foz de Odeleite, Guerreiros do Rio, Laranjeiras, Alcoutim, Sanlúcar de Guadiana, Puerto de la Laja, Pomarão and Mértola), (ii) salt and aquaculture pans, (iii) agricultural areas and (iv) pinewoods (Figure 3.1) (see Box 3.1.).

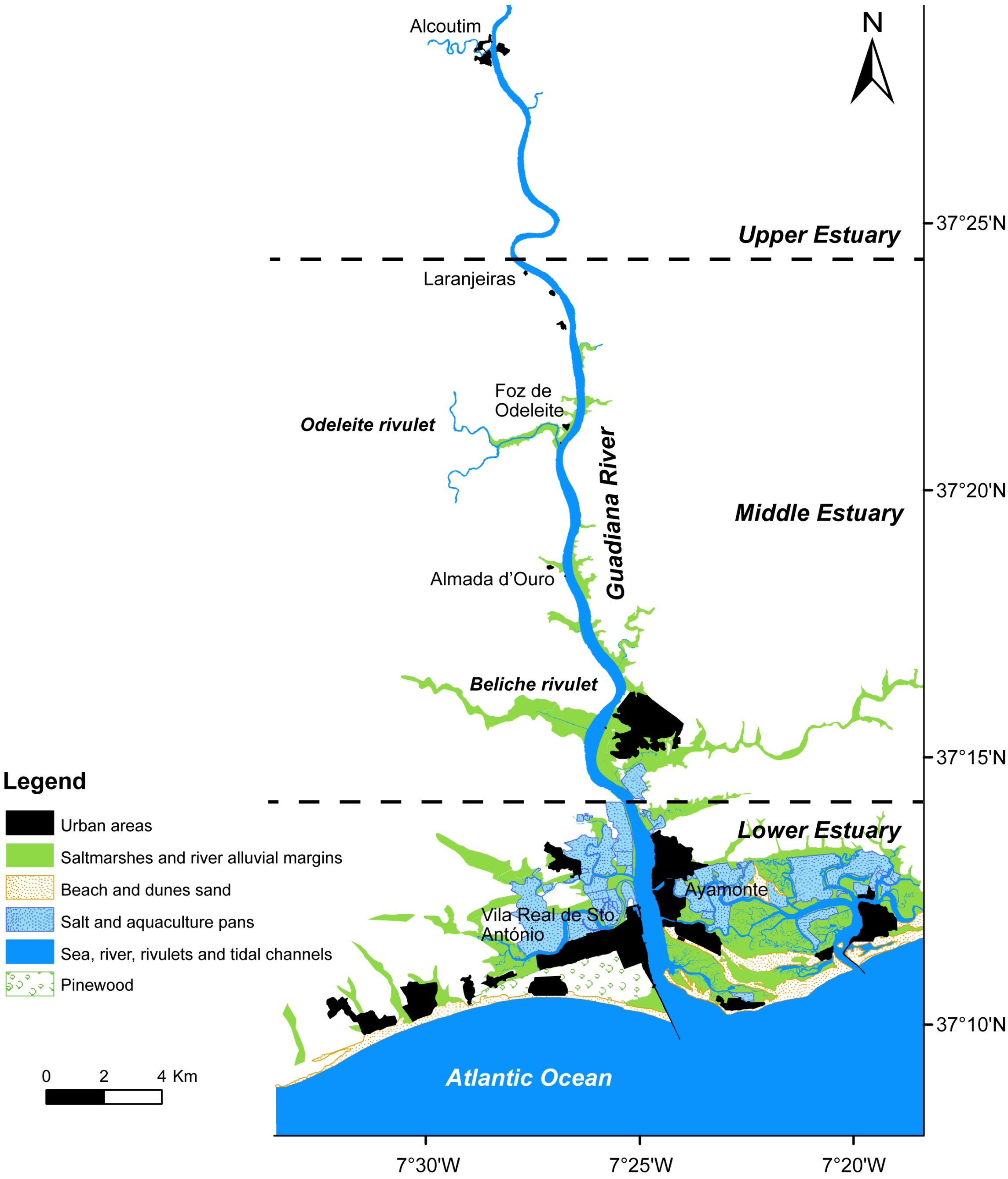

Figure 3.1.
Guadiana River estuary, showing the three main zones that are the result of distance to the river mouth (see also Garel, chapter 1 in this book).

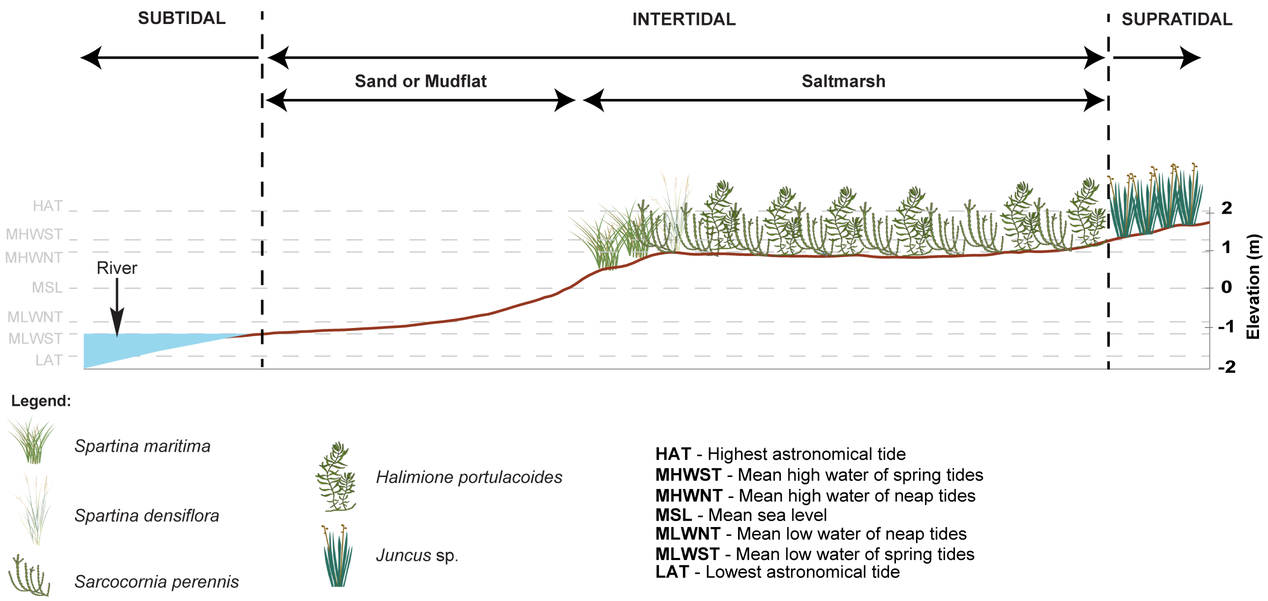

Figure 3.2.
Guadiana River estuary zonation as a result of tidal range. Note how each of the plant species inhabits a distinct zone along the gradient.

3.2. Biological communities

The various ecological zones in the Guadiana estuary are constantly changing as they respond to changes in the tides, river flows, climate and other aspects of the environment. Over the longer term, Guadiana estuary's ecosystems have also responded to large changes in sea level. These constant changes create highly diverse habitats hosting several groups of macro and microorganisms. In this section we will present some of the organisms that have been studied in the Guadiana estuary. We have chosen to focus on organisms with high scientific, ecological and economic value (see Box 3.2.).

Box 3.1. Do you know that...?

...the saltmarsh area located at the Portuguese margin of the Guadiana River estuary is part of the first Natural Reserve created in the Portuguese mainland (additional information available at http://www.icnf.pt/portal/icnf/organica/apc-alg). The natural importance of this area is related to various ecological, botanical, ornithological, ichthyological, archaeological and economic aspects (e.g. fishing, salt production and tourism). For several birds (e.g. flamingo, *Phoenicopterus roseus*), fish (e.g. anchovy, *Engraulis encrasicolus*) and crustaceans (e.g. shrimp, *Crangon crangon*), this area assumes a special role during the nesting period and during subsequent migrations.

Box 3.2. What are macro and microorganism?

Macroorganisms are all the organisms whose size is equal or higher than 0.5 mm, that is, the ones that are visible to the naked eye. On the other hand, microorganisms are ones that we can only see using a microscope (Figure 3.3).

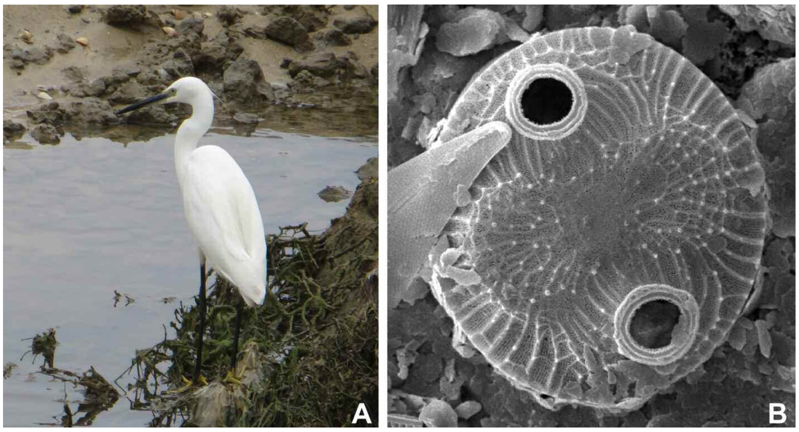

Figure 3.3.
Examples of a macroorganism (A – an egret, *Egretta garzetta*) and a microorganism (B – a diatom, *Auliscus sculptus*). Photographs by Ana Gomes (2012/2015).

3.2.1. Flora

In this section we will present some of the Guadiana macro and microflora. We understand as flora all the vascular plants, bryophytes, fungi, algae and lichens that grow up in this area.

Macroflora

In the area of the Guadiana River estuary there are at least 462 registered species of plants. Between them it is important to highlight *Picris algarbiensis and Picris willkommii* (species endemic to the Iberian Peninsula), as well as *Limonium diffusum*, *Beta macrocarpa and Melilotus fallax,* for their and their habitats' state of conservation. All these species are considered vulnerable or threatened (species images and additional information available at http://flora-on.pt/ and http://www.icnf.pt/portal/ap/r-nat/rnscmvrsa/flora).
In the saltmarshes, we found a diversity of halophyte species such as *Spartina maritima*, *Sarcocornia perennis*, *Halimione portulacoides*, *Arthrocnemum macrostachyum, Suaeda vera*, *Frankenia laevis* and *Spergularia salina* (Figure 3.4 and http://flora-on.pt/). All of these species have remarkable adaptations to living in an environment of high salinity, intense sunlight and changing water levels. Upward in the estuary, it is also possible to find *Spartina densiflora, Elymus* cf. *repens, Juncus* cf. *subulatus* and some riparian vegetation typical of freshwater habitats, such as *Scirpus maritimus* and *Phragmites australis* (Figure 3.4 and http://flora-on.pt/).
In the surrounding forest areas, *Quercus suber* (cork oak) or mixed stands of *Quercus suber* and *Pinus pinaster or Pinus pinea* (pine trees) predominate, with an undeveloped undergrowth composed *Genista hirsuta, Ulex parviflorus, Lavandula luisieri, Cistus crispus* and *Cistus monspeliensis* (species images and additional information available at http://flora-on.pt/ and http://www.icnf.pt/portal/ap/r-nat/rnscmvrsa/flora). These habitats are typical of the Barrocal and Serra landscapes that characterize the Algarve region. Landscapes nearer the coast have been highly modified by economic development, including towns, saltpans, wharves, bridges, tourist facilities and other infrastructure.

Why is the study and conservation of the macroflora so important?

The study and conservation of the macroflora is essential, because it provides many things that are vital to sustaining life – these are called 'ecosystem services' and include the primary production of energy from sunlight, nutrient cycling, production of food and medical resources, climate regulation, Green Tourism, and

Figure 3.4.

Macroflora from the Guadiana River estuary: (A) *Spartina maritima* (closer to the river water, top right) and *Spartina densiflora*; (B) close up of *Spartina maritima*; (C) *Sarcocornia perennis*; (D) *Halimione portulacoides*; (E) *Elymus* cf. *repens* (see arrow); (F) *Phragmites australis*. Photographs by Ana Gomes (2010/2011).

environmental education. All of these ecosystem services are vital for the region's economic activities. Furthermore, the large macroflora diversity existent in and around the Guadiana River estuary must be preserved and valued, since this natural heritage is essential as habitat for other species. Many of these species may also give us early-warning signals to detect environmental changes caused by human pressures, climate change and sea-level rise (see Box 3.3.).

Box 3.3. Did you know that...?

...*Sarcocornia perennis* produce succulent shoots suitable for human consumption which are used in gourmet cuisine, due to their salty taste and nutritional properties. *Arthrocnemum macrostachyum* is also edible and is used in the pharmaceutical industry and in the functional foods industry, because of its high concentration of polyunsaturated fatty acids and antioxidants.

Microflora

Guadiana River estuary microflora is very diverse. However, this book will only focus on diatoms.

What are diatoms?

Diatoms are single-celled algae that have cell walls of silica (called frustules). Each frustule is made up of two valves (Figure 3.5). As algae, diatom cells contain pigments (carotenoids) that give them a brownish/golden colour (Figure 3.6). They can vary in size between 2 – 500 µm and belong to the Chromista Kingdom, which includes all algae (additional information available at http://westerndiatoms.colorado.edu) (see Box 3.4.).

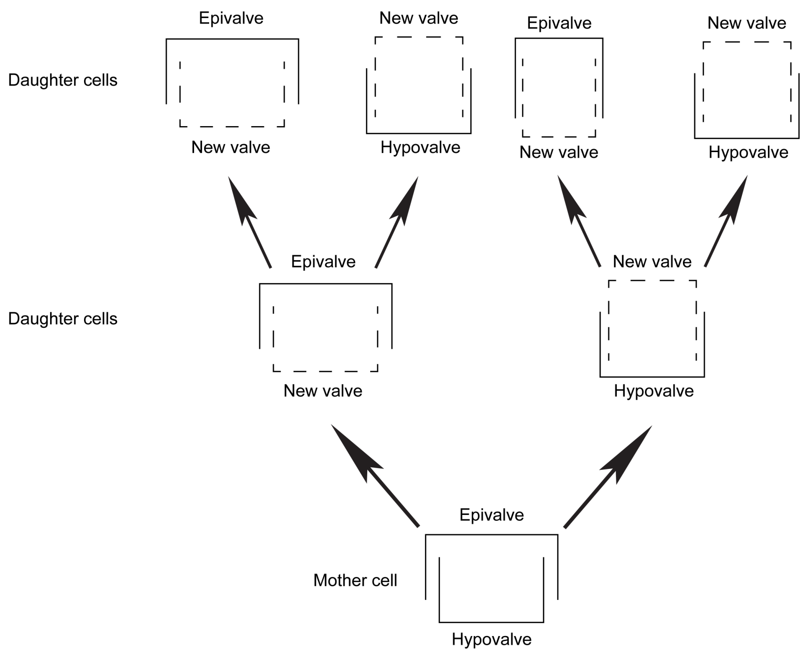

Figure 3.5.
Schematic representation of asexual reproduction of diatoms. Mother and daughter cells are composed of two siliceous valves (epi- and hypovalve).

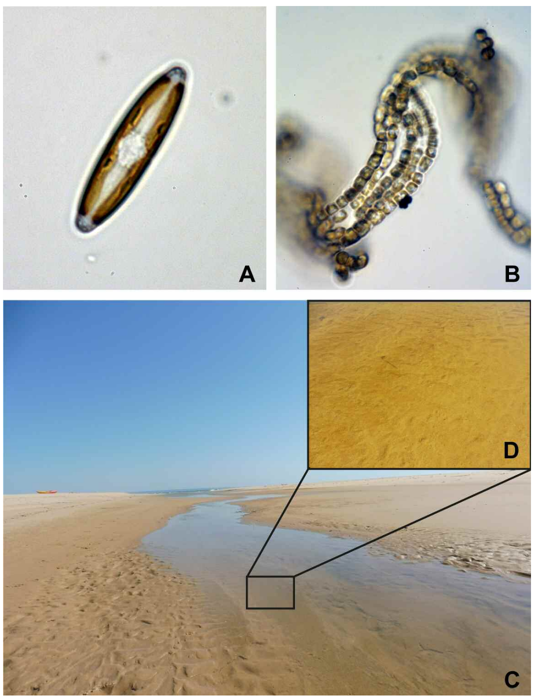

Figure 3.6
Diatom cells brownish/golden colour given by the carotenoids: (A) solitary diatom under a light microscope (*Navicula* sp.); (B) diatom colony under a light microscope (*Nanofrustulum* sp.); (C) tidal channel covered by diatom cells; (D) close up of the bottom of the tidal channel. Photographs by Ana Gomes (2012/2016).

Box 3.4. Did you know that...?

...diatoms were first described by an English gentleman in 1703. Due to their small size, it was only possible to visualize them after the invention of the microscope. Diatoms are so finely patterned that they were later used by German manufacturers to calibrate microscope optics.

How can we identify different diatom species?

Diatom identification, to the species level, is based on the analysis of its valve shape, size and ornamentation. Diatoms are traditionally divided in two groups based on shape: (i) the centric diatoms (which have a circular, bi- or multipolar shape and a radial perforation pattern) and (ii) the pennate diatoms (which are bipolar and have a sternum or a raphe - Figure 3.7).

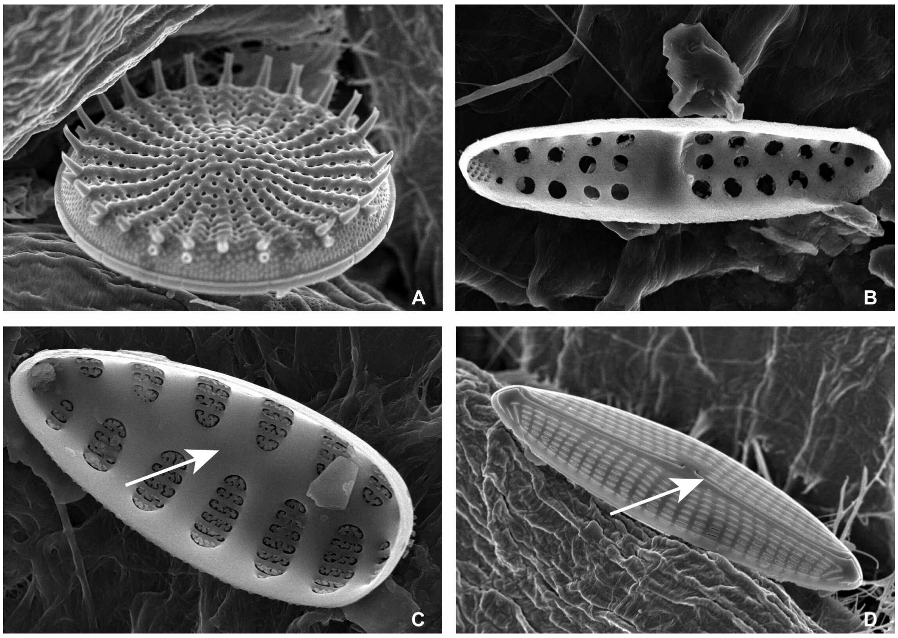

Figure 3.7
Examples of diatoms of different morphological groups: (A) centric diatom with a circular shape (*Stephanodiscus alpinus*); (B) centric diatom with a bipolar shape (*Plagiogrammopsis minima*); (C) pennate diatom with a sternum (longitudinal siliceous structure indicated by the arrow; *Opephora guenter-grassi*); (D) pennate diatom with a raphe (fissures positioned through the valve face - see arrow; *Navicula erifuga*). Photographs by Ana Gomes (2011).

When did diatoms appear in the history of the Planet Earth?

Centric diatoms were the first to appear in the geological time scale. That happened during the Jurassic Period, ca. 190 million years ago, which is a period better known for its dinosaurs than for its diatoms (see the geological scale at http://www.stratigraphy.org/index.php/ics-chart-timescale). The appearance of the bi- or multipolar centric diatoms occurred during the Cretaceous, ca. 100 million years ago, a time when flowering plants were overtaking conifers in the world's land vegetation. The pennate diatoms with a sternum were detected in the fossil record 65 million years ago and the pennate with a raphe appeared ca. 30 million years ago. The appearance of the raphe in diatoms allow them to greatly expand their ecological niches and probably had a major impact in their diversification (see Box 3.5.).

Box 3.5. How do diatoms reproduce?

Diatoms reproduce mainly by asexual reproduction (Figure 3.5), which are infrequently interrupted by sexual events. During the asexual reproduction, diatom cells continuously decrease size, because each daughter cell has a valve that belong to the mother cell and forms a new valve inferior to this (Figure 3.5). Thus, only sexual reproduction allows diatoms to reestablish the maximum dimensions of the cells. Diatoms have very short generation times which enables the rapid development of algal blooms, increasing the number of cells in many orders of magnitude in only a few days. In a gram of saltmarsh soil from the Guadiana estuary, there can be many thousands of diatoms.

How many diatom species exist in the world?

Diatom species may number in the tens of thousands globally. This number arises, most probably, from the variety of environments that diatoms can colonize. In the Guadiana River estuary there are hundreds of diatom species. Among those are a new diatom genus (*Syvertsenia*) and two new species recently described: *Syvertsenia iberica* and *Simonsenia aveniformis* (Figure 3.8). Additionally, there are still some diatom species in the Guadiana River estuary that are yet unknown to science.

Where can diatoms live?

Diatoms can live in salt, brackish and freshwater environments and they have different life-forms. They can be planktonic (they float in the water column), tycoplanktonic (they spend part of their lives associated with some kind of substrate and the other part floating in the water column) or they can be benthic (they live attached to a substrate). Benthic diatoms can colonise several substrates, including: plants or other algae, rocks, sand, mud and animals. Diatoms may also live solitarily or form colonies (Figure 3.6).

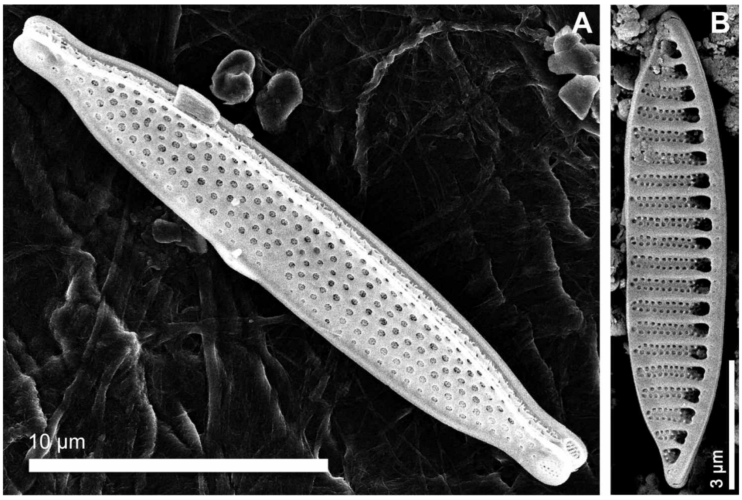

Figure 3.8.
Images from the diatom species found and recently described in the Guadiana River estuary: (A) *Syvertsenia iberica*; (B) *Simonsenia aveniformis* (figure adapted from Gomes et al., 2013 and Witkowski et al., 2015).

Why are they so important? What can they be used for?

Diatoms are responsible for 1/5 of the Earth's photosynthesis and they are the key players in the carbon, nitrogen, phosphorous, silica and iron cycles. Additionally, diatoms are an important component of the phytoplankton and microphytobenthos, which are the basis of the food chain in aquatic systems. Moreover, they are highly sensitive to changes in environmental variables such as salinity, sediment type, duration of tidal inundation, nutrient levels and pH. These characteristics, along with their short generation time, allow diatoms to quickly respond to environmental changes. Thus, since the begin of the 20th century they have been often used to study the evolution of estuaries, like the Guadiana River estuary, in relation to sea level and climate changes. Particularly in the Guadiana estuary, diatoms were a determinant indicator to identify climatic events of short time duration and reconstruct in detail the estuary's evolution after the Last Glacial Maximum. Recently, diatoms have also started to be used as indicators for environmental quality in freshwater and coastal systems . Diatoms have proven to be very sensitive to changes caused by increasing human pressure on natural systems and are therefore useful in pollution monitoring. On the other hand, some diatoms or the toxins they produce represent a threat to fisheries, aquaculture and public health. The ingestion, for example, of shellfish during periods of these harmful diatom blooms may cause diarrhea, amnesia or even death. Better knowledge and understanding of diatoms can allow us to value and preserve our natural heritage, ecosystem services and our health.

Diatoms may also be used in forensic and archaeological research. Diatoms are useful, for example, to determine where a homicide/suicide took place (e.g. if a death by drowning occurred in a swimming pool, in a river or in the sea) or to determine if a person was at the crime scene (e.g. comparing diatoms of a garden pond with the diatoms attached to the wet jeans of a suspect who could have gained access to a house through the garden, after the suspect stated that the jeans were wet because he had been in the sea). In archaeological research, among other applications, diatoms can tell us about clay sources for pottery and provenance of finished pottery.
Finally, other economic gains associated with diatoms are: (i) the exploitation of diatomite (rock formed by are large concentrations of diatom frustules) and (ii) oil and gas exploration. Diatomite is used, for example, to make bricks (good insulator), dynamite, polishers and filters. Diatoms are useful tools in oil and gas exploration for age dating and for correlating rocks that form in different aquatic environments. Such information is important to understand the geological history of the basin and determine the prospects of the basin for hydrocarbon production.

3.2.2. Fauna

In this section we will present a group of organisms that belong to the Guadiana microfauna.

Microfauna

This category includes all animal, protist and chromist organisms with size less than 0.2 millimeters that can only be observed with the help of a microscope. In estuarine sediments, the microfauna is mainly constituted by single-celled eukaryotes, which are autonomous living beings.

Can such microorganisms be important in science, especially in the study of an estuary?

Indeed, all eukaryotic estuarine species play a role in the base stages of the food chain and participate actively in the carbon cycle. They have short lifecycles and react quickly to changes, which makes them very sensitive to environmental impacts and, thus, excellent bioindicators in the assessment of the ecological quality of a given place. In these environmental studies, eukaryotes that possess a hard test (testate eukaryotes) that preserves in the sediment have some advantages compared to those called naked eukaryotes, which do not preserve well (Figure 3.9). By leaving a permanent record in the sediment, the testate eukaryotes enable the reconstruction of the environmental history of a site in the absence of the original physico-chemical baseline data. So the better we know them and their relations with the surrounding environment in the present, the better we can interpret their occurrences in the past and make reliable predictions for the future (see also Mendes and Rosa, chapter 4 in this book).
Despite the great diversity of single-celled eukaryotes we may find in the sediments, in this section we will focus on one special group of testate chromists, the foraminifera, and how their study has been contributing to the understanding of Guadiana estuary, both present and past.

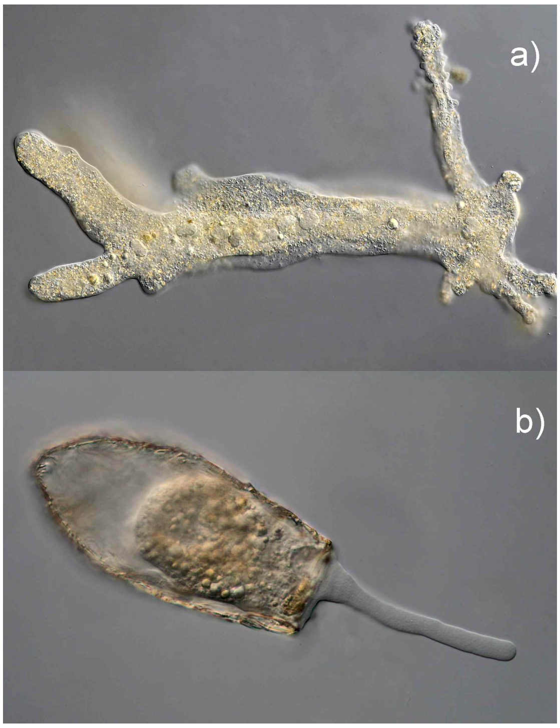

Figure 3.9.
Difference between a (a) naked amoeba (Genus *Chaos*) and a (b) testate amoeba (Genus *Difflugia*) (courtesy of Prof. Ferry Siemensma – http://www.arcella.nl/).

What are foraminifera?

Foraminifera are testate chromists that occupy a great diversity of habitats, from the deepest oceanic environments to the upper limits of the tidal zones in coastal wetlands. Most foraminifera possess a hard shell which, after death, remains in the sediment where it may eventually fossilize (Figure 3.10) (see Box 3.6.). Whereas metazoans evolved organs and other specialized features through the multicellularity, the foraminifera, as other eukaryotes, specialized by diversifying subcellular components or organelles to perform their vital functions.

Box 3.6. Did you know that...?

The foraminifera were first described and illustrated in the sixteenth century, but were not studied systematically until the latter part of the nineteenth century following the remarkable voyage of HMS Challenger which began in 1872 (Figure 3.11). The discovery of living foraminifera in deep-sea waters occurred during that expedition, alongside fossil remains in sediments that were dredged from the sea floor.

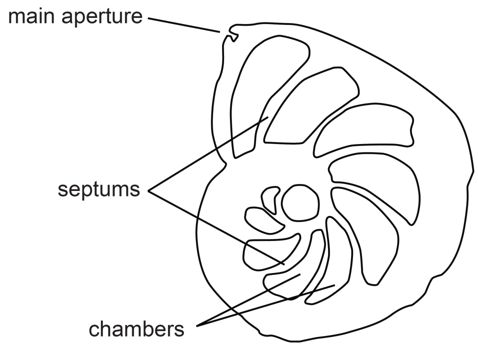

Figure 3.10.
Schematic thin section of a foraminifer test. The foraminifer shell is often distinctively coiled resembling that of a gastropod or a cephalopod. Illustration by Sarita Camacho (2017).

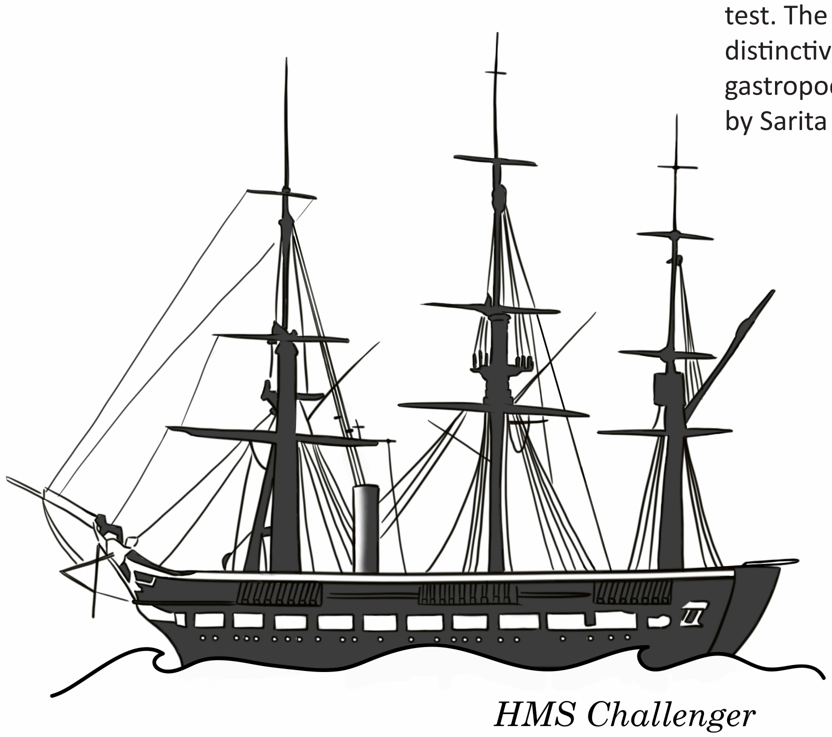

Figure 3.11.
HMS Challenger was a steam-assisted corvette built for the British Royal Navy in 1858. In 1872 she undertook the first global marine research expedition. The Challenger Expedition was a grand tour of the world, covering 68,000 nautical miles (125,936 km) organized by the Royal Society in collaboration with the University of Edinburgh. Illustration by Sara Encarnação (2017).

Two broad physical features characterize the foraminifera:
They possess *granuloreticulopodia*, which are fine, thread-like, pseudopodia ('false feet') that anastomose and have a granular texture when viewed under a microscope (Figure 3.12).
Nearly all foraminifera possess a *test* or shell that contains the organism and separates it from the surrounding environment. The test may be organic (not mineralized), agglutinated (constructed of foreign particles cemented together by the foraminifer), composed of calcium carbonate or, in rare cases, silica.
There are considerable variations in the dimension, morphology, composition and microstructure of the foraminifera tests. Those features are of great taxonomic importance for being intimately related with physiological differences, habitat, ecological niche and various types of reproductive strategies, each with repercussions in their life cycles.

Figure 3.12.
Light microscope micrograph of a *Lacogromia cassipara* exhibiting its distinctive 'granuloreticulopodia' (courtesy of Prof. Ferry Siemensma - http://www.arcella.nl/). The granuloreticulopodia emerge from one or several orifices existent in the test (known as 'foramina', a term from which the name of the group is derived) existent in the test, and are used in the captures of prey, to hold onto surfaces, to remove waste, to travel and in test construction.

The agglutinated forms, which are very common in estuarine sediments, collect organic and mineral matter from the sea floor and bind it together with an organic, calcareous or ferric oxide cement. Like the better-known caddisfly larvae, agglutinated foraminifera carefully select the sediment grains for their size, texture and composition when building their homes (Figure 3.13). The type of cement and composition of bonded particles provide information about the type of sediment and environmental conditions at the time when the foraminifer was building its test. Some genera, however, are not selective and use, indiscriminately, every type of material available on the seafloor.
The calcareous forms come in two main types: porcelaneous and hyalines (also called glassy), according to

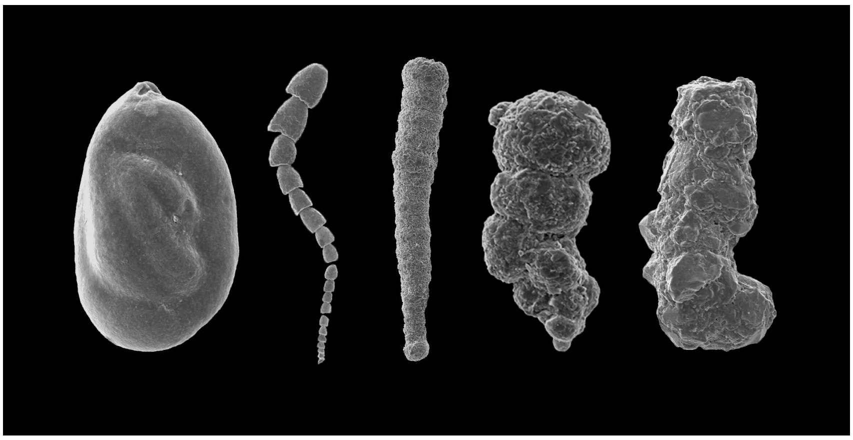

Figure 3.13.
Sequence of different species of agglutinated foraminifera, with increasing test roughness from left to the right. Micrographs by Sarita Camacho (2011).

their appearance under transmitted light. The porcelaneous types are opaque, reflecting all the light, while the glassy types, as the name suggests, are translucent (Figure 3.14).

Porcelaneous tests have a solid surface with a milky or amber aspect and are constructed by the secretion of tiny needles of high magnesium calcite within tiny vesicles in the cytoplasm, which are then exported

Figure 3.14.
Foraminifera stained with Rose Bengal, a vital stain for differentiating the living from the dead individuals (the fuchsia-stained specimens were alive at collection time). The porcelaneous ones (white circles) have a semi-opaque test, avoiding the observation of the vividly stained protoplasm as is visible in the translucent test of the glassy forms (black circles). Photography by Sarita Camacho (2011).

to the outer margin of the cell. In the hyaline (glassy) forms the test is built by a bio-mineralization process which takes place outside the protoplasmatic body. This type of wall has numerous perforations (pores) of very small diameter – foraminifers of this kind are known as "calcareous perforate" (Figure 3.15). Together with the aperture, the pores function as passages for the cytoplasm to carry food or waste products between the interior and the exterior of the test (see Box 3.7.).

Box 3.7. What are the foraminifera feeding mechanisms?

Most benthic foraminifers are opportunistic omnivores. They have adopted a broad range of feeding mechanisms including herbivory, bacterivory, suspensivory, detritivory, carnivory and parasitism, allowing them to access a wide range of nutritional resources. Some large calcareous and planktic forms can carry naked photosybionts in their endoplasm, especially diatoms and dinoflagellates which aid in supplying energy to the foraminifera.

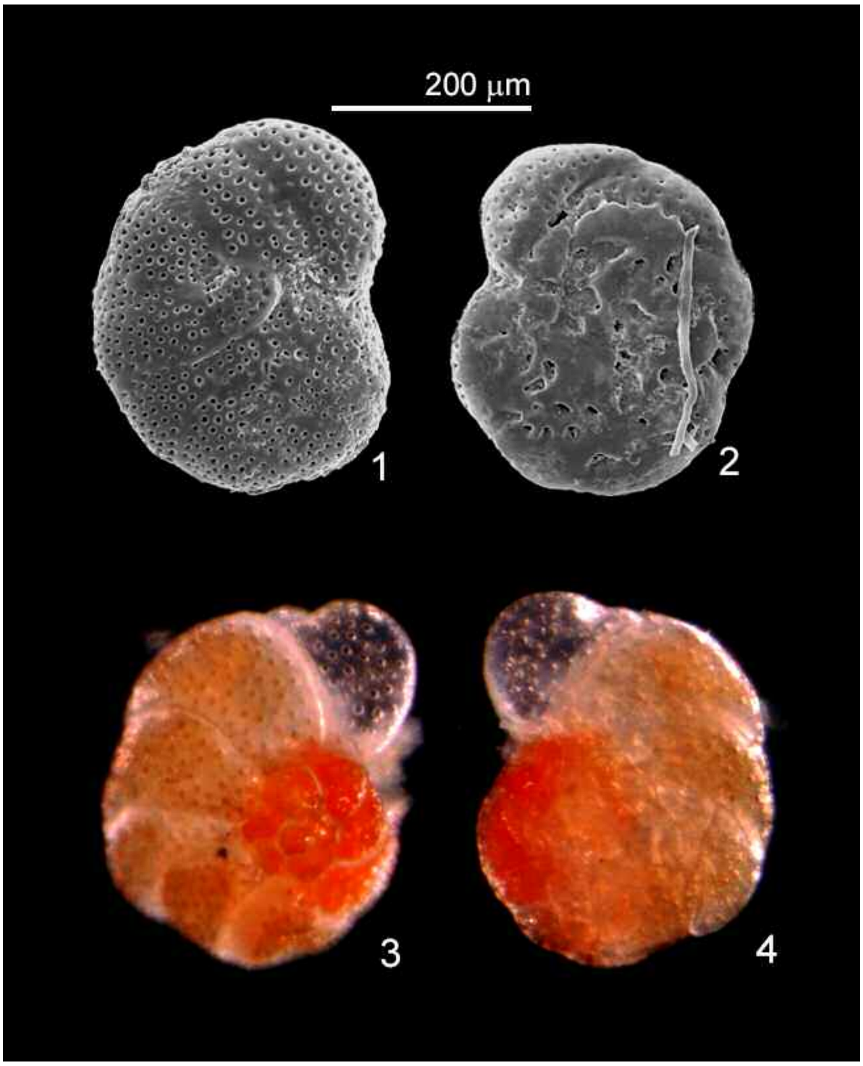

Figure 3.15.
The well visible pores of *Discorinopsis aguayoi,* a hyaline, epiphytic species: 1) dorsal view, and 2) ventral view, of a specimen photographed at scanning electronic microscope; 3) dorsal view and 4) ventral view, of a living specimen photographed at light microscope (natural colours). Stereoscope micrographs by Dr Maria Holzmann and scanning electron microscope (SEM) micrographs by Sarita Camacho (2011).

How can we identify different foraminifera species?

The test is the best studied element of foraminifera as the shape of the test serves as the basis of its classification. More recently, the analysis of ribosomal ribonucleic acid (RNA ribosomal) sequences has been applied in the identification of the foraminiferal species, providing a new taxonomic criterion, independent of the morphologic characteristics of the test. Molecular analysis also enables an evaluation of the ecological significance of the different morphologic characteristics and helps to determine the subtle morphological differences within the species avoiding erroneous and superfluous taxonomic subdivisions.

When did foraminifera appear in the history of the Planet Earth? How many foraminifera species exist in the world?

Stratigraphically, the foraminifers appear in the Early Cambrian (see the geological scale at http://www.stratigraphy.org/index.php/ics-chart-timescale) (the first unambiguous ones are from the lowermost Cambrian of West Africa), at about the same time that the metazoans with skeletons. Foraminifers began differentiating into countless species which adapted to all marine environments, from the surface to the deepest oceanic depths. At the moment, around 4000 species of foraminifera are estimated to exist in the world.

Where can foraminifera live?

The benthic species live on the seafloor, where they can be free or sessile, epifaunal (attached to the substrate - sand, stones, rocks, animal shells, etc.), epifaunal epiphyte (attached to algae or sea-grass) or infaunal, living within the sediment. The planktic forms float passively in the water column, moved only by currents but capable of vertical migration (Figure 3.16).

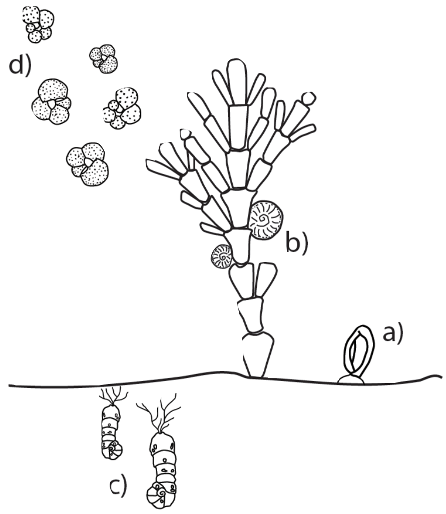

Figure 3.16.
The different life positions of foraminifera: a) epifaunal; b) epiphyte; c) infaunal; and d) planktic.
Illustration by Sarita Camacho (2017).

How helpful can the foraminifera be in the study of an estuary?

Inferences about the evolution of estuaries are possible through the study of sediments that progressively accumulate, preserving ancient bioclasts and organic matter. The presence of fossil assemblages that represent the live communities in the moment of deposition can be used to make reconstructions of the past environment with greater accuracy than can be achieved from studying the sediment alone. This type of palaeoenvironmental reconstruction is based on the principle of uniformitarism, which states that "the present is the key to the past" and assumes that the natural processes that operate in the present are the same as the natural processes that operated in the past. Foraminifera are particularly useful in finding out about changes in sea-level in saltmarsh environments. The zones in which the foraminifera are found on the present-day surface of the marsh are surveyed. They are so sensitive to subtle environmental changes that in an huge marsh, where the physical-chemical parameters are constantly changing, we may find many different assemblages. This modern analogues assemblages which ecological meaning is known serve then as a base for identification and interpretation to the fossil sequences.

Foraminifera have been used as reliable bioindicators as they provide information about both modern and historical contexts, their biological and ecological features are usually well known, they are easily identifiable and may be sampled in great quantities in small sediment volumes, providing ideally reliable statistical results. The better the foraminiferal modern assemblages and the ecological conditions which determine their spatial and temporal abundance are known, the better scientists' palaeoecological interpretations will be (see also Mendes and Rosa, chapter 4 in this book).

In Portugal, most ecological studies based on estuarine foraminifera have been performed in order to establish modern databases through which fossil foraminiferal assemblages can be compared and interpreted. But they are also successful used to identify the different ecological provinces, to detect environmental stress conditions and to monitor pollution. Before foraminiferal assemblages can be used as stress and pollution indicators in the marshlands which mark the transition between the continent and the sea, a precise understanding of their response to varying environmental conditions is necessary in order to distinguish between the stress promoted by human activities and natural environmental changes. This requirement is particularly critical in estuaries and coastal lagoons that are subject to a complex interaction of numerous physico-chemical parameters, each presenting spatial and temporal variability, and because these environments are often exposed to various human impacts, such as chemical pollution, industrial effluent and agricultural pesticides. Explaining foraminiferal distribution patterns thus requires consideration of a broad range of environmental factors. Species will be able to survive and potentially prosper as long as conditions remain within their tolerance limits. Once conditions move beyond the tolerance limits for any limiting factor, the species is likely to disappear (see Box 3.8.).

Box 3.8. How to study the foraminiferal ecology of an estuary?

Observing foraminifera is much simpler than we think. A short walk through the marsh, a spatula, a small bag, a magnifying glass and a pinch of luck will be enough to observe hundreds, if not thousands of foraminifera. The complexity of the sampling plan will vary according to the objectives we want to achieve. But whatever study we want to achieve, for example, variation and distribution of species, diversity analysis, assessment of the health of the ecosystem, there are two trends in the spatial distribution of foraminifera that should be considered: 1) most foraminifera prefer to live in marine environments, and so in coastal areas species richness (biodiversity) is generally high, gradually decreasing as we move upstream where the waters are brackish, and eventually ending up with just one or two species, or disappearing in the areas where the salinity is close to zero; 2) foraminifera need moisture to survive and therefore their distribution is strongly dependent on the tides. Because of this, it is expected that greater diversity of species and evenness will occur in the lower zones of the marsh where the time of tidal inundation is greater. As we move upslope into the marshland towards land, diversity tends to decrease. These higher zones of the marsh, flooded only at high tide, are exposed to the atmosphere for longer periods and consequently more exposed to variations of the elements. Also in these higher stages of the marsh there is a greater accumulation of organic matter, which causes the pH to drop (that is, become more acidic), which is not compatible with the carbonate shells of the foraminifera. In these extreme conditions, only a few agglutinated species, with greater osmoregulation capacity, are able to survive. In the upper stages of the marsh, it is therefore common to find only one or two species in assemblages of agglutinated foraminifera.

The study of the Guadiana's microfauna

Detailed scientific study of the Guadiana's foraminifera began in February 2010, conducted by Dr Sarita Camacho and a team of researchers at the University of the Algarve. Several field trips were carried to Guadiana estuary in order to analyse variations of the foraminifera communities in the two periods of the year with the greatest environmental contrast – summer and winter. The sampling area extended over 34 km of the river's length, from Alcoutim to the mouth of the Guadiana, thus covering the entire salinity gradient of the estuary. Several samples were collected along profiles at each sampling site, usually perpendicular to the course of the river. The exact location of the samples was related to the zonation of the halophyte (salt-adapted) vegetation, sampling the different stages of marsh, from the non-vegetated mudflats to the highest areas, which are covered with water only during periods of spring tides (Figure 3.17).

Figure 3.17.
Edited photograph of the river margin highlighting the different intertidal zones. Photography by Sarita Camacho (2010).

Samples for analysis of the foraminifera were collected at the sediment surface (~0-1 cm depth) where most of the living foraminifera are found (Figure 3.18 a). Simultaneously sediment samples were collected for analysis of organic matter and grain size. The salinity, temperature and oxygen dissolved in the water, as well as the pH of the sediment, were measured in each campaign (Figure 3.18 b and c).

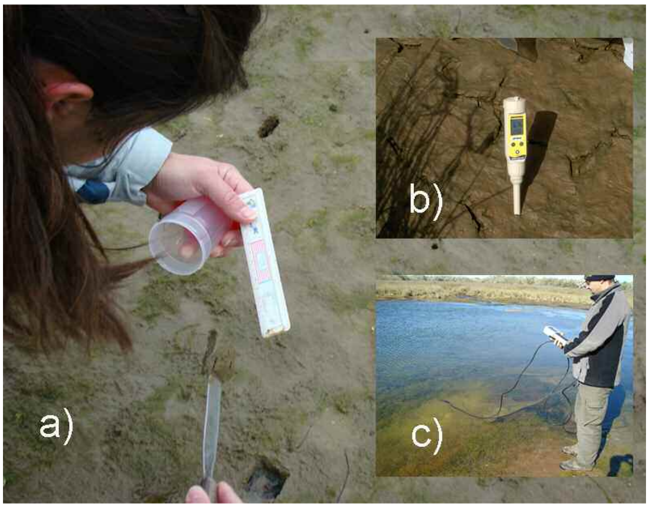

Figure 3.18.
Field sampling procedures: a) collection of the first centimeter of sediment; b) sediment pH measurement; and c) water parameters measurement. Photography by Sarita Camacho (2010).

Through this research, it was possible to identify 52 different species of foraminifera in the Guadiana estuary. Their distribution mirrored the seasonal variation of environmental factors, whose relative importance depended on environmental differences in the estuary. Elevation above sea level proved to be the most important parameter in the distribution of foraminifera, since it combines the effect of a series of other variables, such as organic matter and fine sediment, which tend to increase as elevation increases, and the pH of the sediment, coarse sediment and temperature, which tend to decrease as elevation increases. The salinity gradient of the fluvial–marine transition has also proved to be important in microfauna distribution, however, showed little significance in species distribution along the elevation gradient in the intertidal zone, probably due to the high osmoresistence reported for marsh species.
In the most elevated marsh areas, where environmental conditions are usually more severe, only some agglutinated species were able to survive. In the lower areas of the marsh, where the duration of air exposure is diminished and environmental conditions are generally more uniform, there was dominance of more diversified faunas, mainly composed of calcareous species. During winter, when fluvial processes are dominant, agglutinated species of the highest stands of saltmarsh proliferate, constituting more than 80% of the total individuals counted. In summer, when marine conditions prevail, calcareous species become more competitive, increasing their faunal densities and expanding into higher marsh areas and areas further upstream.
Based on the dominant species, on their interrelationships and their relation to the environmental parameters, it was possible to define three main foraminiferal assemblages in the Guadiana estuary:

i) The *Miliammina fusca* assemblage, was the most common in the mid-low elevation zones of the upper reaches of the lower estuary up until the sampling northern limit (Alcoutim), usually in unvegetated areas. *Miliammina fusca* was the dominant species, associated with *Ammonia aberdoveyensis* and *Elphidium oceanensis* (Figure 3.19 a);
ii) The *Jadammina macrescens* assemblage occurs in the most elevated and highly vegetated marsh stands (or lower, in sheltered environments) of the lower estuary, where the sediments are very fine, pH is low and organic matter is high. *Jadammina macrescens* was the dominant species but *Trochammina inflata* was also very common. Occasionally, significant occurrences of *Miliammina obliqua*, *Polysaccamminaipo halina* and miliolids were observed (Figure 3.19 b);
iii) The *Ammonia aberdoveyensis* assemblage was observed in the lower elevation zones of the lower estuary, where marine influence is high and the sediment is sandy. *Ammonia aberdoveyensis* was the dominant species, associated with *Haynesina germanica*, *Polysaccammina hyperhalina* and *Elphidium oceanensis*. In winter, *Bolivina ordinaria* is co-dominant with *A. aberdoveyensis* (Figure 3.19 c).

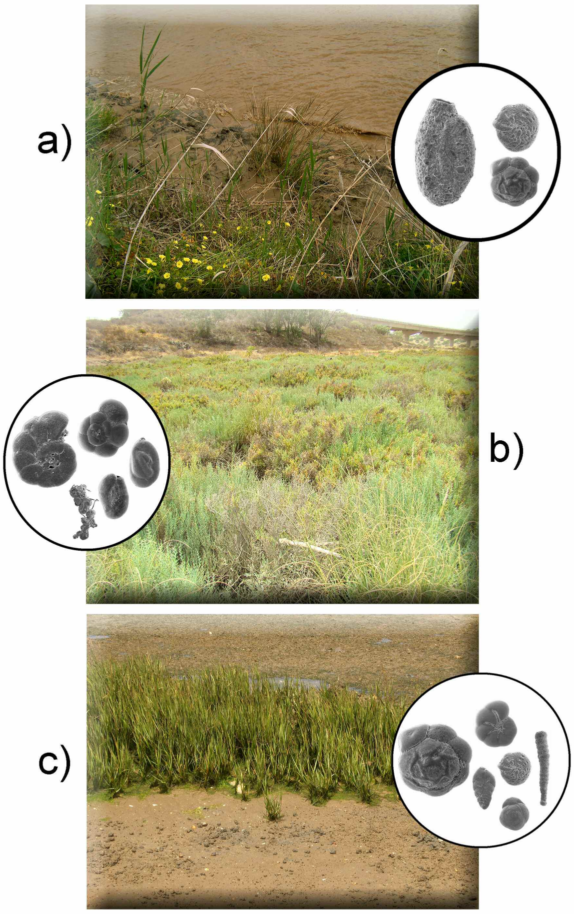

Figure 3.19.
The three main foraminiferal assemblages in Guadiana estuary: a) *Miliammina fusca* assemblage, most often found in the upper reaches of the lower estuary; b) *Jadammina macrescens* assemblage, found mainly in the most elevated, strongly vegetated marsh stages; and C) *Ammonia aberdoveyensis* assemblage, found primarily in the lower elevation zones of the lower estuary. Infography by Sarita Camacho.

When compared to other estuarine systems in the north of Portugal, the foraminiferal distribution in the Guadiana estuary shows slight differences, pointing to a dominance of warmth-preferring species, resembling more the ecological distributions typical of the Mediterranean climatic zone than those of the North Atlantic climatic zone. This trend seems to make sense considering the Guadiana's geographical position which grant it both North Atlantic and Mediterranean climatic characteristics.
These results bring new insights into foraminiferal distribution and are expected to improve their value as bioindicators, providing a benchmark for future environmental quality assessments and to improve the ecological interpretation of palaeoenvironmental data on the southern Iberian Peninsula and related bioclimatic zones.

Acknowledgements

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4. The Continental Shelf off the Guadiana estuary

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4.1. What defines and characterizes the continental shelf off the Guadiana estuary?

4.1.1. Geographic location

The Continental shelf is the seafloor area around a large land mass where the sea is relatively shallow compared with the open ocean. This major physiographic domain is comprised between the shoreline and the shelf break located at variable water depths (generally, around 200 m water depth) and variable extensions (average width of about 80 km).

The continental shelf off the Guadiana estuary is the area in front of the Guadiana River mouth, which is influenced by the discharges of the Guadiana River Basin. This area is located in the southern border between Portugal and Spain, in the middle part of the northern Gulf of Cadiz continental shelf, southwestern Iberian Peninsula (Figure 4.1).

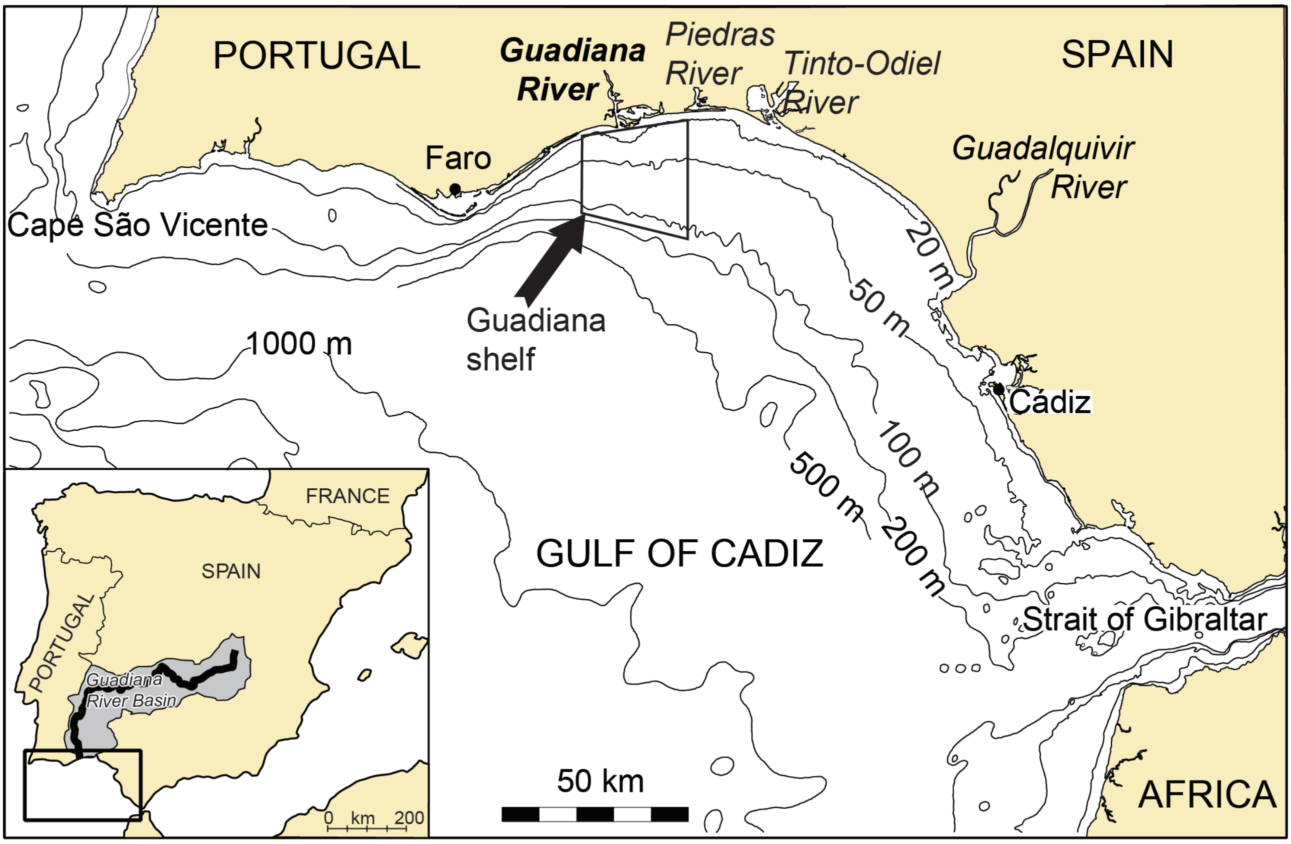


Figure 4.1.
Location map of the continental shelf off the Guadiana River, in the northern Gulf of Cadiz.

4.1.2. Shelf Geomorphology

The maximum extent of the northern Gulf of Cadiz continental shelf occurs on the middle part, and decreases laterally both towards Cape São Vicente and the Strait of Gibraltar. The shelf has a minimum width of 5-7 km off Cape Santa Maria, increases to 20-25 km off the Guadiana River and attains a width of more than 30 km off the Guadalquivir River mouth (Figure 4.1). Accordingly, the mean slope of the Portuguese shelf is 0.5°, decreasing to slopes of less than 0.3° on the Spanish shelf. The average Guadiana shelf slope is 0.32°.

The shelf break lies at varying water depths in concordance with shelf width and slope changes. Off the Guadiana River, the shelf break lies at around 140–150 m water depth. The shelf can be divided here into three main morphological provinces, namely the inner shelf (from approximately 0 to 30-50 m water depth), the middle shelf (from 30-50 to 90-100 m water depth) and the outer shelf (from 90-100 to 140-150 m water depth) (Figure 4.2).

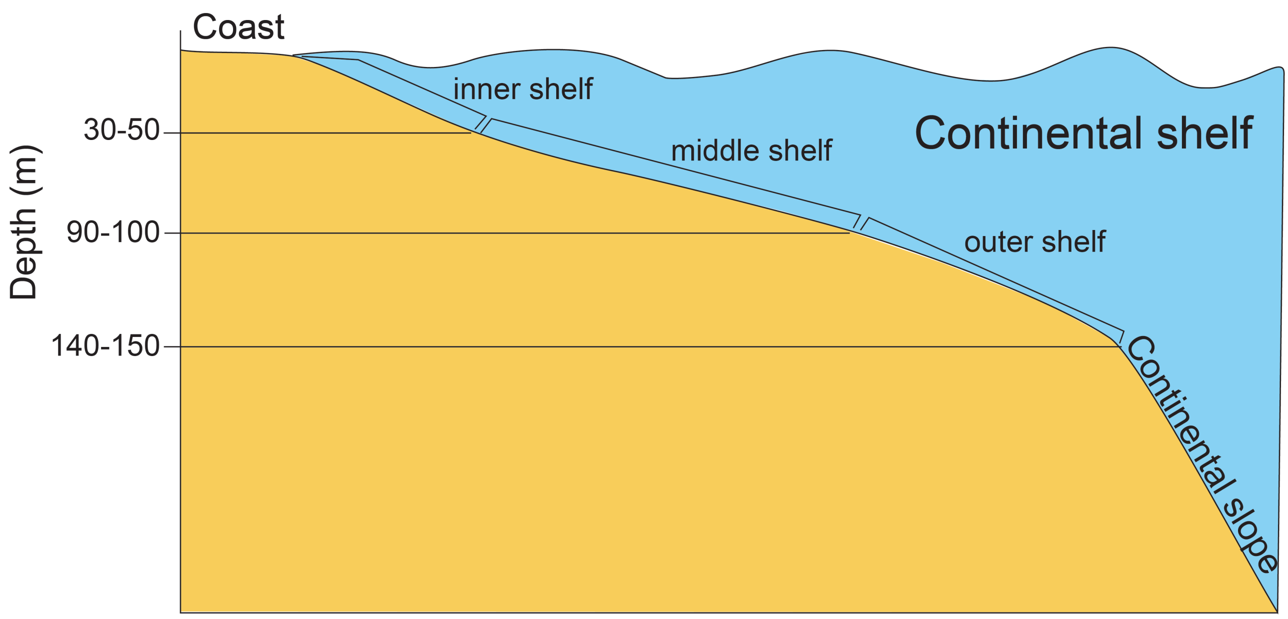


Figure 4.2.
Schematic morphology of the continental shelf off the Guadiana estuary, with the identification of the morphological zonation, inner, middle and outer shelves.

4.1.3. Climatic characteristics

What are the main characteristics of the climate in the Guadiana Valley region?

The Iberian Peninsula is located in a transitional climatic region where Atlantic and Mediterranean influences meet and imprint specific low-frequency variability patterns to the regional climate.

The climate that characterizes the Guadiana Valley is however of strong Mediterranean influence, as the Guadiana River drains a semi-arid region and its runoff shows high intra- (i.e. seasonal) and inter-annual variability. The mean annual rainfall along the hydrological year is distributed by three different periods: rainy (October-February), transitional (March-May) and dry (June-September).

What is the North Atlantic Oscillation (NAO) and how does it influences the regional climate in the Guadiana Valley?

The general climate trends in the region are strongly determined by the North Atlantic Oscillation (NAO), which is the leading pattern of climate and winter surface variability over the North Atlantic (Figure 4.3).

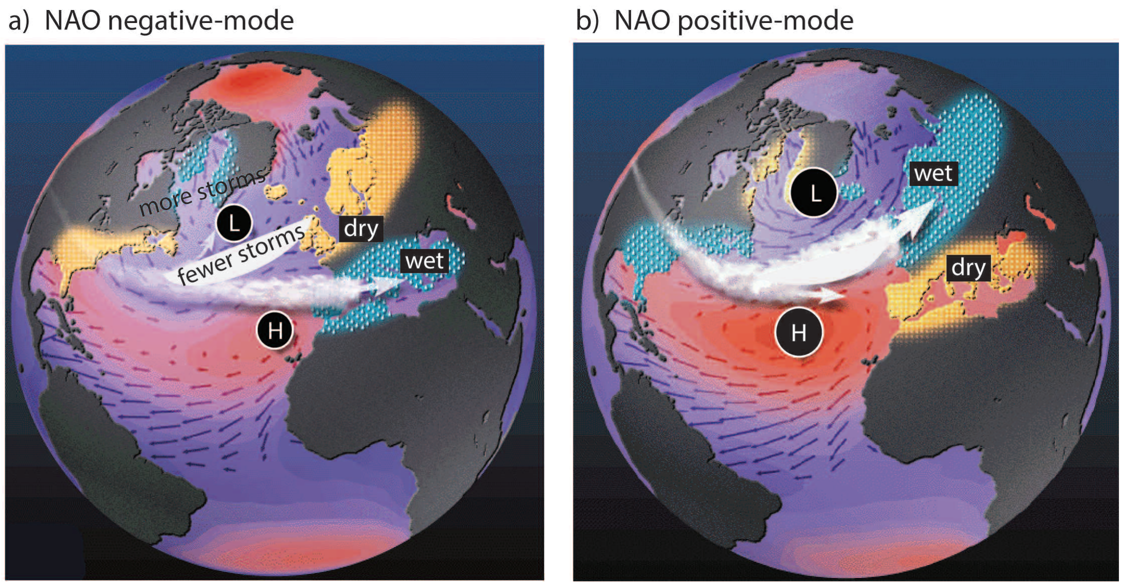


Figure 4.3.
Model of the two modes of the North Atlantic Oscillation (NAO), associated storminess activity and distribution of moisture over the North Atlantic: a) negative and b) positive NAO index phases. H – Subtropical High Pressure Centre, L – Icelandic Low Pressure Centre (adapted from http://www.ldeo.columbia.edu/res/pi/NAO/).

In general terms, the NAO refers to a redistribution of atmospheric masses between the Arctic and the subtropical Atlantic basin, and shifts from one phase to another, positive and negative, producing large changes in surface air temperature, winds, storminess and precipitation over the Atlantic (Figure 4.3). Positive values of the NAO index are typically associated with stronger-than-average westerlies over the middle latitudes, and wetter/milder weather over western Europe, whereas negative index values usually associate with stronger westerlies and enhanced moisture over low-latitudes and the Mediterranean (Figure 4.3).

4.1.4. Oceanographic regime

Tides and waves

The continental shelf off the Guadiana River is considered mesotidal with a mean tidal range of 2 m. Wave energy is moderate with an average annual significant offshore wave height of 1.0 m and average peak period of 8.2 s. The offshore waves are predominantly incoming from the west-southwest (71% of occurrences) to east-southeast, but easterly "Levante" winds frequently generate short-period waves incoming from the southeast (23% of occurrences) in direction to northwest-west. Storm events in the region have been defined as events with offshore wave heights superior to 3 m, between 1986 and 1993, storm events accounted for 1% of the offshore wave climate.

Shelf current patterns

In the Gulf of Cadiz the shelf circulation patterns are complex, showing different behavior in the open sea and on the continental shelf. The general surface circulation is anticyclonic, which is quasi-permanent in the open sea but interrupted on the continental shelf on a seasonal basis. Thus, the surface spring-summer circulation is governed by a branch of the larger-scale Portuguese-Canary Eastern Boundary Current (core N2), which moves around a cyclonic eddy off Cape San Vicente (SVE) and moves further east towards the Strait of Gibraltar to feed the Atlantic inflow into the Mediterranean. To the east, the shelf is dominated by a cyclonic circulation bounded by a shelf-break front (core N1) at the south and a warmer

coastal countercurrent (CCC) in the northern area (Figure 4.4). During the late autumn-early winter flow reversals and the eastward current replaces the cyclonic circulation (core N1). A likely closure of the cell could occur as the inflow from to the Strait of Gibraltar from the interior of the Gulf of Cadiz.
The dynamics in this area is also strongly dependent on wind regime. Westerly winds enhance the upwelling off Cape São Vicente (an almost-permanent phenomena in this area), creating a second intense core of upwelling off Cape Santa Maria and extending the upwelling along the southern Portuguese coast. Easterly winds favor the warm coastal countercurrent that is observed in the eastern shelf and may invade the western shelf connecting both shelves in an east to west direction. The relaxation of the large-scale upwelling favorable wind also drives the development of this coastal countercurrent.

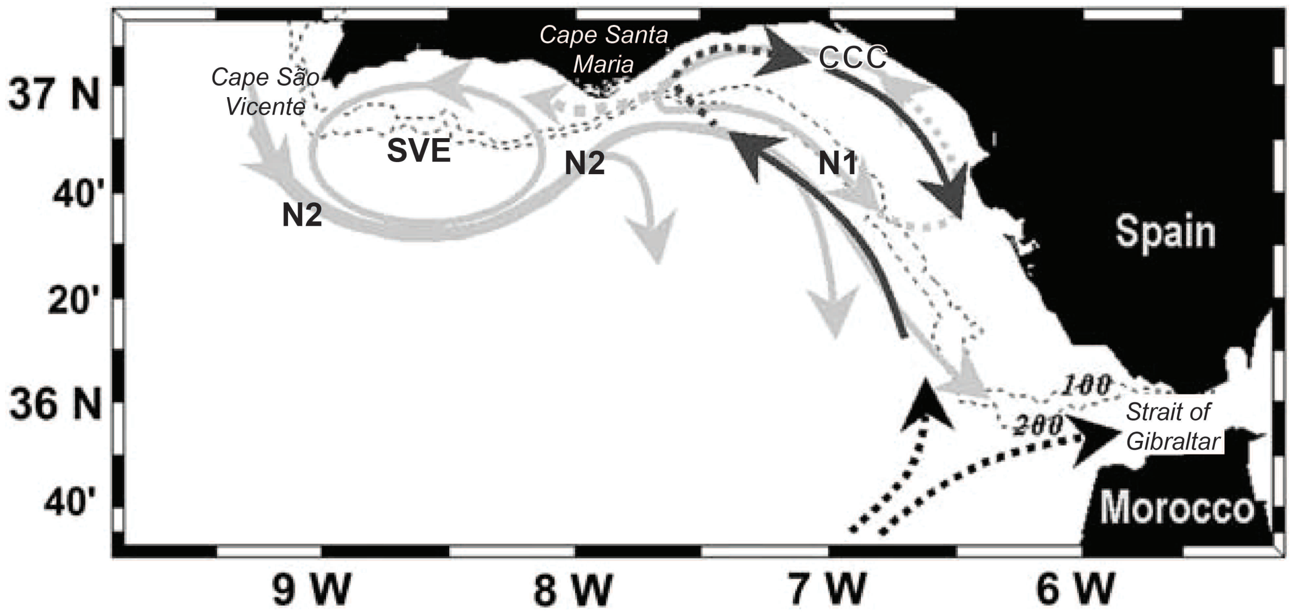


Figure 4.4.
Schematic surface circulation on the Northern Gulf of Cadiz. Grey lines correspond to the spring-summer circulation (adapted from García-Lafuente et al., 2006). Black lines indicate the open sea autumn-early winter circulation (adapted from Criado-Aldeianueva et al., 2009). Legend: N2- branch of the larger-scale Portuguese-Canary Eastern Boundary Current; SVE- cyclonic eddy off Cape san Vicente; N1- cyclonic circulation bounded by a shelf-break front; and CCC- coastal countercurrent.

4.1.5. Sediment supply and main sources

Sources of sediment to the Guadiana Continental Shelf

The main regional sediment source is the Guadiana River. The sediment supply from the river basin is dominated by suspended load relative to bed load material, and shows strong seasonal and inter-annual variability. The river discharges more sediment (both coarse- and fine-grained) onto the shelf during winter floods generated by intense rainfalls. On the contrary, persistent drier years mean less precipitation during winter seasons and less amounts of sediments being transported from the river basin to the shelf. The second most important regional source to the shelf is the littoral drift, a mechanism of bed load transport. The longshore transport of sandy sediments is eastward-directed under the predominant influence of the south-eastward Atlantic currents, which move along the southern Portuguese coast towards the eastern sector of the Gulf of Cadiz.

What do we know about the current distribution patterns of sediments on the Guadiana shelf and the main mechanisms behind it?

Most of the river's bed-load sediment that is exported to the shelf is deposited in the inner shelf at around 15 m water depth. The exported sediments constitute a submerged sandy delta with some patches of sandy muds, reflecting the combination of both fluvial and littoral drift sources. The fine-grained fluvial sediments tend to be re-suspended on the inner shelf by currents and storms.

Sands dominate the surficial sediments on the inner shelf down to water depths of ca. 25 m (Figure 4.5). The middle shelf is dominated by very fine silt and clay deposits that form the Guadiana mud belt, extending from ca. 30-40 to 90-100 m water depths (Figure 4.5). This deposit is mainly fed by the resuspension of inner shelf fine-grained sediments.

East of the Guadiana River Mouth, these muddy deposits are interrupted by an N-S oriented coarse-grained (i.e., muddy gravelly sands) deposit of transgressive origin (transgressive buldge) stretching from ca. 20 to 100 m water depth (Figure 4.5).

In the outer shelf the surficial sediment distribution exhibits a complex mosaic of sands and silty clays, with patches of sand and gravelly sands near the shelf edge (Figure 4.5).

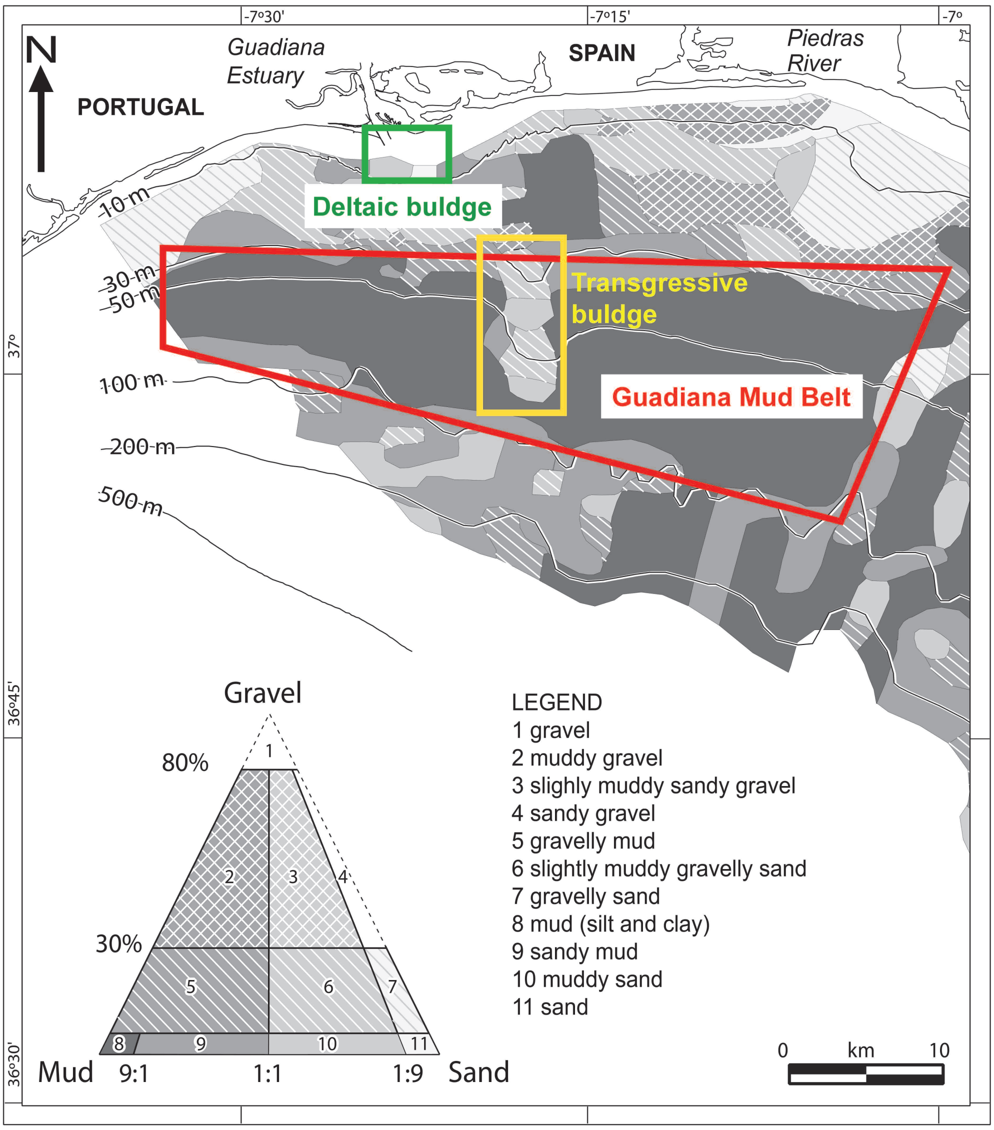


Figure 4.5. Modern distribution of surficial sediments on the Guadiana Shelf (sediments of type 1 and 4 do not occur on the mapped area). Classification of sediments according to Folk (1954) (Adapted from González et al., 2004).

Distributional patterns of the mineralogical and biogenic components of sands: clues to understand the origin of the shelf sediments

Most of the inner shelf sands are dominated by terrigenous/mineralogical components, largely quartz. Bioclasts (e.g. mollusc and gastropod shells, foraminifera, echinoids) can form large accumulations locally. In the vicinity of the Guadiana mouth, fluvially-supplied terrigenous particles and mollusk shells settle down up to ca. 5 m water depth whereas micas (mineral) settle around 10-15 m water depths. Other terrigenous particles such as fluvially-derived metaschists and greywacke (rock types) grains are very abundant on the deltaic bulge (deposits composed of a mixture of sands and mud that accumulate on the inner shelf, just in front of the Guadiana River mouth) (Figure 4.5).

Most of the middle and outer shelf sands are composed of bioclastic grains. Foraminifera dominate but locally, on the outer shelf, large amounts of mollusc shells are present, particularly in the transgressive bulge. Quartz is the dominant component of the sandy fraction in the mud belt in front and east of the Guadiana River mouth, down to ca. 90 m water depth (see Box 4.1.).

Box 4.1. Did you know that…

The Measurement of average Guadiana River flows at Pulo do Lobo Hydrographic Station (Lower Alentejo), which covers 91% of the Guadiana River drainage basin, have witnessed a dramatic reduction in the second half of the 20th century, decreasing to nearly half the values.

The main reason behind this change in the water-flow volume in the river basin was the construction of several dams and the development of intensive irrigation schemes, both on the Spanish and Portuguese sides of the border.

4.1.6. Anthropogenic impact

The impact of anthropogenic land-use activities on the environment has been widely investigated throughout Europe in recent years; a relationship between human forcing mechanisms and the transformation of the natural systems has been evidenced.

In southern Iberia, the influence of human activity on the landscape has been detected as far back as ca. 5,500 cal. years B.P. Particularly, the onset of exploration of the Iberian Pyrite Belt is dated around the third millennium B.C.

The first indications of human modification of the vegetation cover and of mining exploitation in the Guadiana Valley also date back to around 4,500-4,000 cal. years B.P. Subsequent transformations were driven by the emergence of a semi-forested cultural landscape and the intensification of mining practices after ca. 3,300 cal. years B.P.

Major landscape changes were brought by the Roman Rule of Iberia (ca. 200 years B.C. to 500 years A.D. – ca. 2,200 to 1,450 cal. years B.P.). Indeed, historical and archaeological sources record an increased exploitation of vegetation and woodland resources during this period, for agricultural, domestic and larger-scale mining purposes. These activities favoured widespread soil erosion; which was contemporaneous with a climate change to wetter conditions, thus producing an increase of the sediment flux to the coast.

The Medieval Islamic Rule of Iberia, after the 8th century A.D. (ca. 1,200 cal. years B.P.), constituted the second major pulse of human intervention in the Guadiana River Valley.

An unprecedented population growth let to an extraordinary maximization of the natural resources of the region, which eventually exacerbated the ongoing erosional processes.

Throughout the Middle Ages and beyond, the human-induced transformations persisted to some extent, although another significant increase of such activities only occurred during the last ca. 200-150 years. The reactivation and expansion of several important mines along the Iberian Pyrite Belt during the 19th century A.D., including the São Domingos Mines in the south of the Alentejo region, and new agricultural developments such as the Wheat Campaign during the 1930s, contributed to the enhancement of the long-term anthropogenic impacts in the region. Consequently, soil erosion increased along the watersheds and the sediment supply from the river basin to the coast and shelf increased.

4.2. How can we learn about the evolution of the continental shelf?

4.2.1. Knowing the present conditions

Present-day environmental conditions must be understood in order to reconstruct the ancient evolution. Microfossils, such as the benthic foraminifera, occur in sediments of all ages and under all environmental conditions, because of their capacity to fossilize and to preserve their tests (shells) in the sediment record. Their abundance and distribution are highly dependent on environmental conditions, which make them excellent environmental indicators (*proxy*), as long as their ecological requirements are determined. Thus, any analysis of distribution patterns and abundances of organisms needs to take into account the interaction between individuals, species, and the physical-chemical environmental parameters. Only studies of living (stained) fauna can be used for ecological interpretations and be used to infer past habitats, to ensure that benthic foraminifera reflect the surrounding environment. This knowledge is also important to predict future climatic and oceanographic change trends.
On the continental shelf off the Guadiana estuary the distribution of living benthic foraminifera was studied and related with several present-day environmental parameters, as an example of an ecosystem model as a basis for paleoenvironmental interpretations.

How to select and treat the surficial sediment samples in the laboratory?

Sediment samples on the continental shelf were collected in order to investigate the different fluvial inputs, the seafloor physiography and surficial sediment distribution. Three different areas on the continental shelf were selected, namely the areas under the influence of the Guadiana, the Tinto-Odiel and the Guadalquivir river discharges.
Samples were collected using a Smyth McIntyre grab sampler. The surficial layer (0-1 cm sediment thickness) was sampled and stained with a solution of ethanol and Rose Bengal to distinguish the living and dead benthic foraminiferal assemblages (Figure 4.7 a-c). The samples

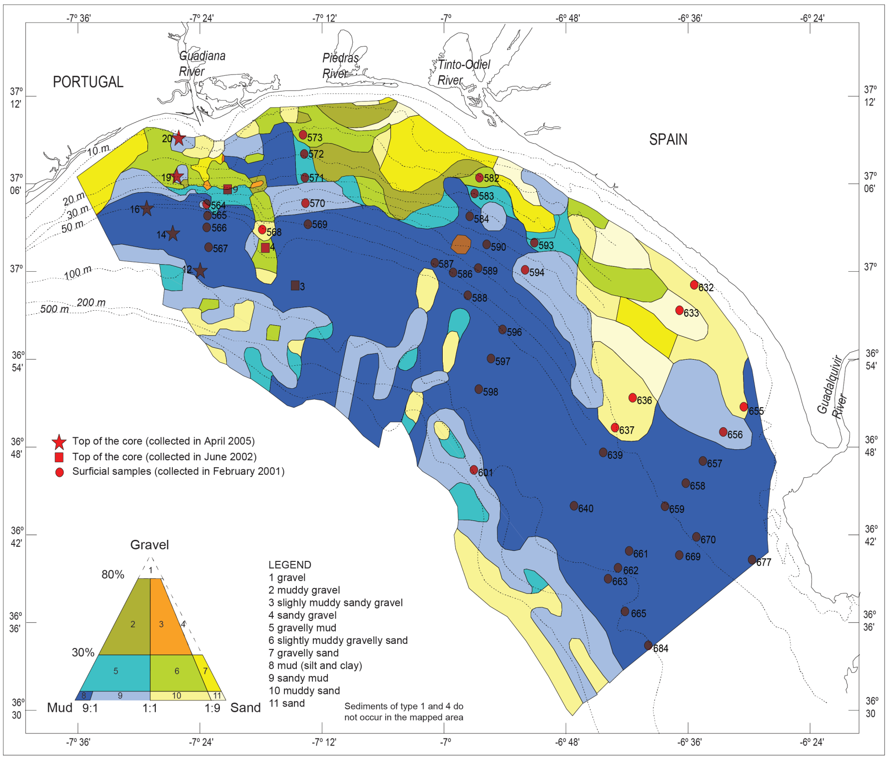


Figure 4.6.
Location of the samples collected to investigate benthic foraminiferal faunas and surface sediments on the continental shelf between the Guadiana and the Guadalquivir rivers (adapted from Gonzalez et al., 2004).

were washed with tap water using a 63 m sieve. The size fractions retained on each sieve were dried, spread on a picking tray and analysed under a binocular microscope with a maximum zoom magnification of 110X. Whenever possible, at least 300 stained tests of benthic foraminifera were collected, mounted on lightly glued carbon slides, identified and counted (Figure 4.7 d-f). Benthic foraminifera were identified on the basis of bibliographic descriptions. The most abundant species were documented using scanning electron microscope (SEM) and camera photographs (Figure 4.8). Statistical analysis were performed using the number of individuals counted in each species per sample.

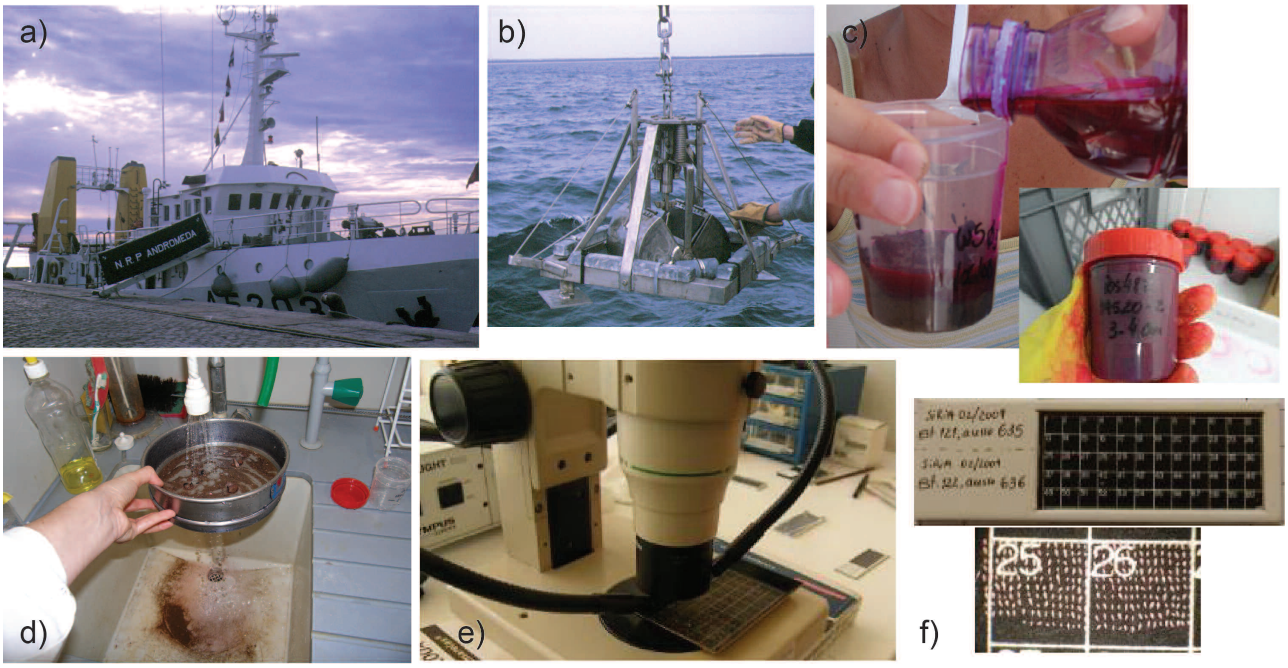
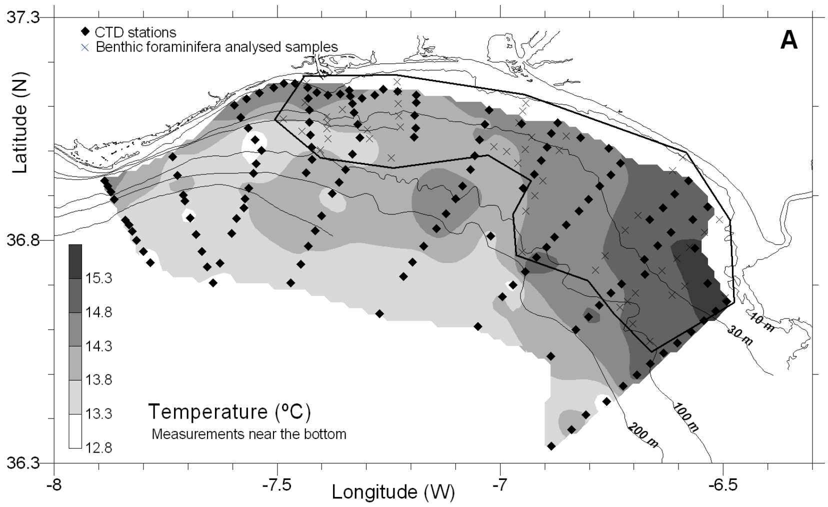


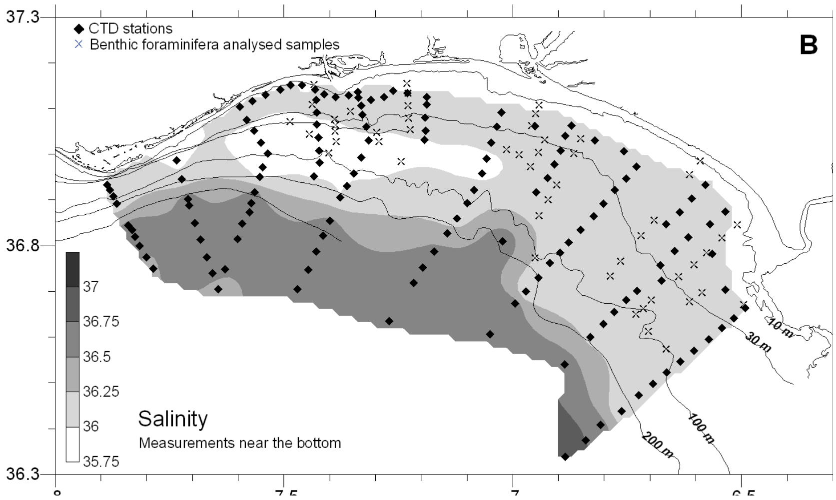
Figure 4.7.
Material and methods used to collect and treat the surficial sediment samples for benthic foraminiferal analyses: a) Smyth McIntyre grab sampler (Photo by Ramon González, 2001); b and c) Staining a sediment sample with a solution of ethanol and Rose Bengal; d) Wash a sample with tap water using a 63 μm sieve; e) Dry sample spread on a picking tray analysed under a binocular microscope; f) Tests of benthic foraminifera mounted on lightly glued carbon slides, each square represent a different species (Photos by Isabel Mendes).

Figure 4.8.
Photographic exemples of the most abundant living benthic foraminiferal species. In grey, photographs documented using a scanning electron microscope (SEM) and in pink microscope photographs taken with a camera (Photos by Isabel Mendes, 2007).

Water temperature, Salinity and Suspended Particulate Matter

Hydrological data were collected on the continental shelf in order to investigate environmental parameters variation. Data were recorded at 148 locations at water depths ranging 9–764 m. At each location, water column vertical profiles were obtained using a CTD (Conductivity, Temperature, Depth) profiler, coupled with a Rosette equipped with a dozen Niskin water bottles (Figure 4.9). Temperature, salinity and Suspended Particulate Matter (SPM) data were mapped in the northern Gulf of Cadiz (Figure 4.9).





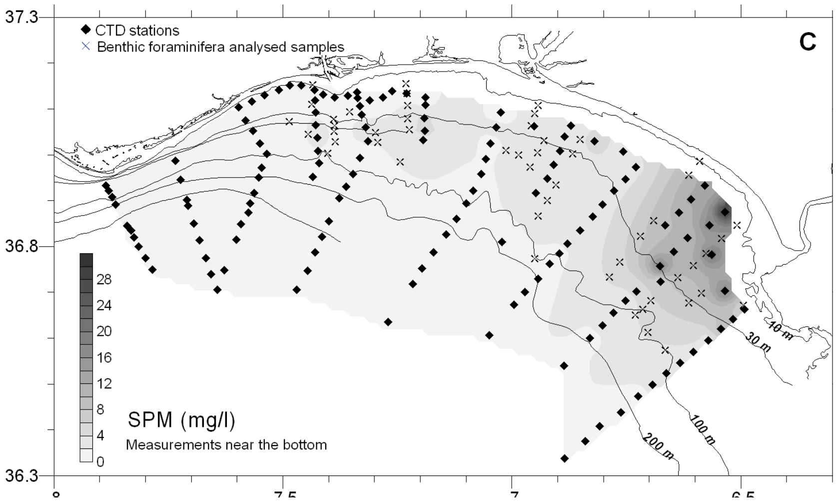


Figure 4.9.
Example of a CTD profiler, coupled with a Rosette with Niskin water bottles (Photos by Francisca Rosa, 2006). A, B and C, distribution of environmental parameters obtained near the sea floor: A. Temperature (°C); B. Salinity (g/kg); and C. Suspended particulate matter concentrations (mg/l) (adapted from Mendes et al., 2012).

Distribution of living benthic foraminifera

The higher densities, defined as the number of living benthic foraminifera per 10 cm^3, occur in different areas of the continental shelf (Figure 4.10A) and seem to be influenced by the river outflows, with maximum values observed in muddy sediments. In shallow waters off the Guadalquivir River, foraminiferal density seems also to be influenced by suspended particulate matter; however, other samples collected in the same area with the same sediment type had lower population densities. This implies that other factors (e.g., water depth, sediment type) were also influencing the densities of living benthic foraminifera. Species richness (as the total number of species per sample) generally decreases with water depth (Figure 10B) and seems to be highly influenced by sediment types. The higher number of species at shallow water depths in muddy substrates with mixtures of sands and/or gravels would be indicative of relatively stable conditions that allow accumulation of fine suspended material derived from river discharges and more abundant niche space compared to the surrounding areas. On the other hand, the low number of species in muddy sediments only allow a restricted number of specialized and dominant species to inhabit this area.

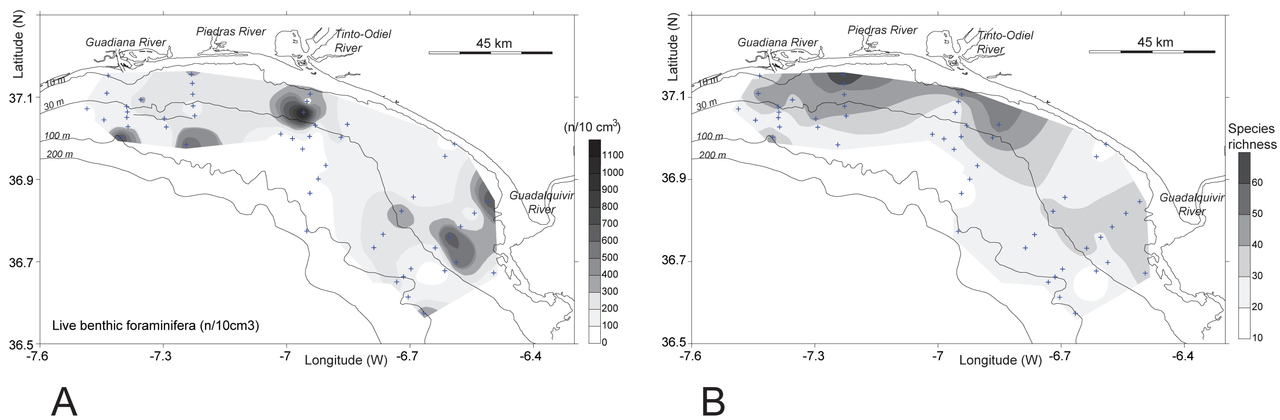


Figure 4.10.

Distribution of the: A. number of living benthic foraminifera per 10 cm3; and B. number of species per sample (as species richness), on the continental shelf between the Guadiana and Guadalquivir rivers (adapted from Mendes et al., 2012).

The data obtained in samples containing species with relative abundances higher than 5% in at least one sample were used to perform multivariate statistical cluster analysis. This analyses allow to group samples according with their degree of similarities and enabled the distinction of four clusters (Figure 4.11A). The spatial distribution of these clusters across the continental shelf (Figure 4.11B) showed that: Cluster A, with 10 samples, is located at shallow waters near the Guadiana and Tinto-Odiel river mouths and exhibits a more extensive distribution near the Guadalquivir mouth; Cluster B included the highest number of samples, located between 25 and 100 m in the southeast part of the study area and from 20 to 60 m in the northwest; Cluster C, an intermediate group with four samples, was present in 3 samples off the Tinto-Odiel mouth below 60 m water depth, and in one sample at 79.5 m depth off the Guadiana mouth; and Cluster D occurs in the southeast in one deeper sample and northwest in three samples, all below 80 m water depth. Depth and sediment type in the shallowest cluster seem to be the main factors controlling samples spatial distribution.

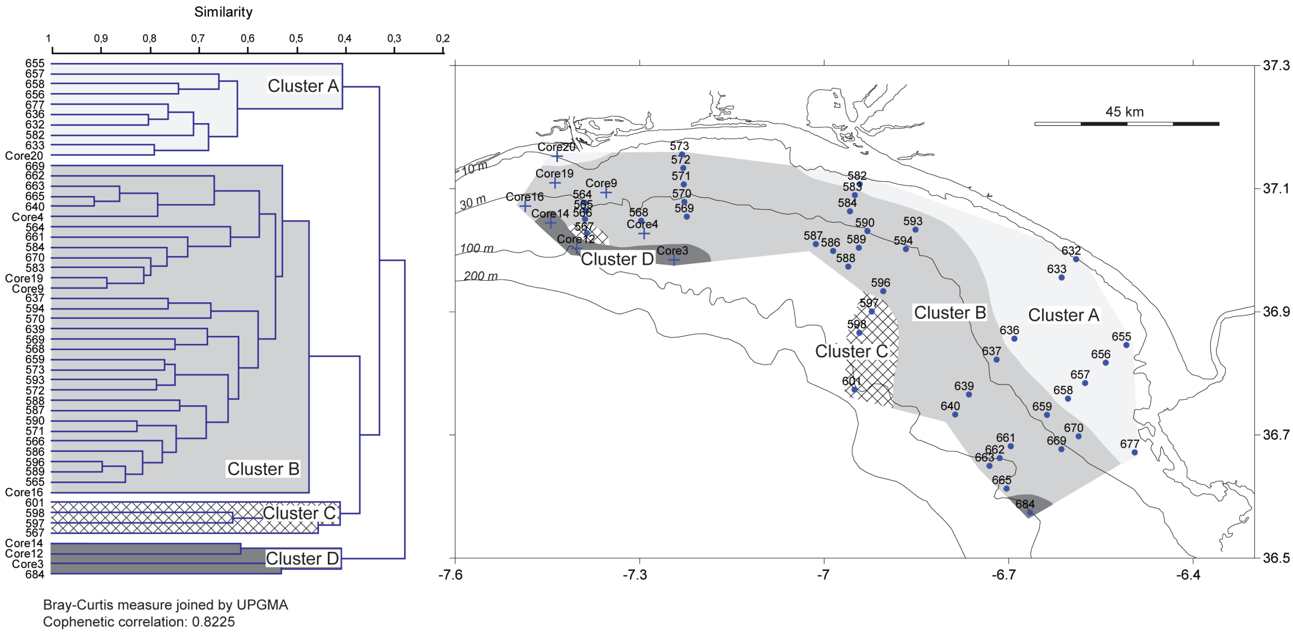


Figure 4.11.
Four clusters obtained by cluster analysis (A to D) and their spatial distribution across the continental shelf (adapted from Mendes et al., 2012).

The individual distribution of each of the most abundant living benthic foraminiferal species also infers the separation in 4 general groups. These groups were closely linked to those obtained by cluster analyses and their spatial distribution. For example, species *Bolivina ordinaria* included in Group 1 showed the higher abundances in the vicinity of rivers outflow from the inner to the outer shelf; the same trends were observed for *Eggerelloides scaber* from Group 2 which showed the higher abundances in shallow waters associated with river discharge; for *Epistominella vitrea* from Group 3 was mostly distributed between 40 and 100 m water depth. In Group 4, the same tendency was observed; however, it was also possible to relate the individual distribution of *N. iridea*, for instance, which showed higher abundances off the Guadiana River, to an area with high productivity related with local upwelling filaments, with lower temperature and salinity values (Figure 4.12).

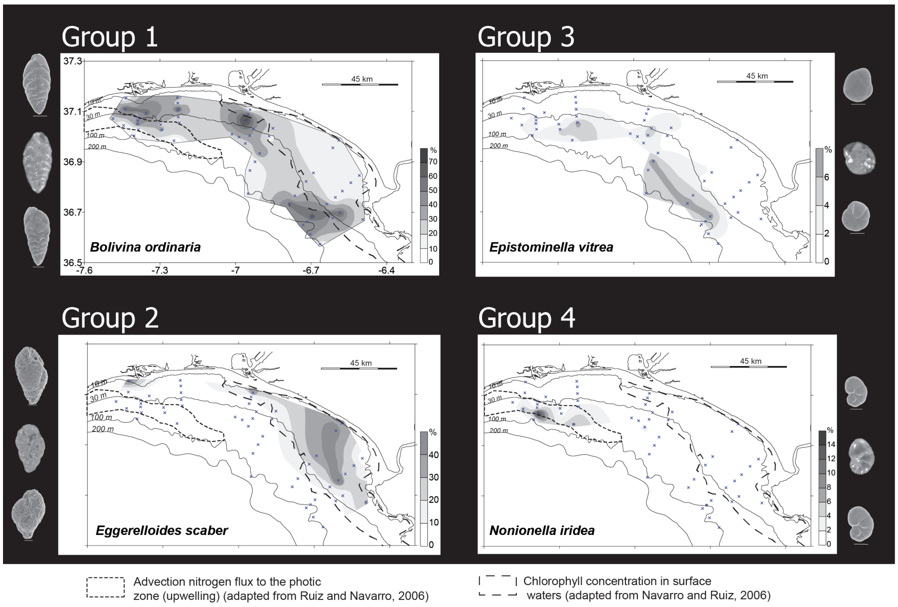


Figure 4.12.
Examples of the individual distribution of species separated in four general groups, closely linked with cluster analyses and biofacies spatial distribution. Species photographs taken by SEM and a camera (adapted from Mendes et al., 2012).

The results obtained based on cluster analyses and on the individual distributions of the most abundant species allow to divide the living benthic foraminiferal fauna into four general groups (Figure 4.13) accordingly with sediment type, influence of river discharges, water depth, water temperature, salinity, turbidity, and primary productivity.

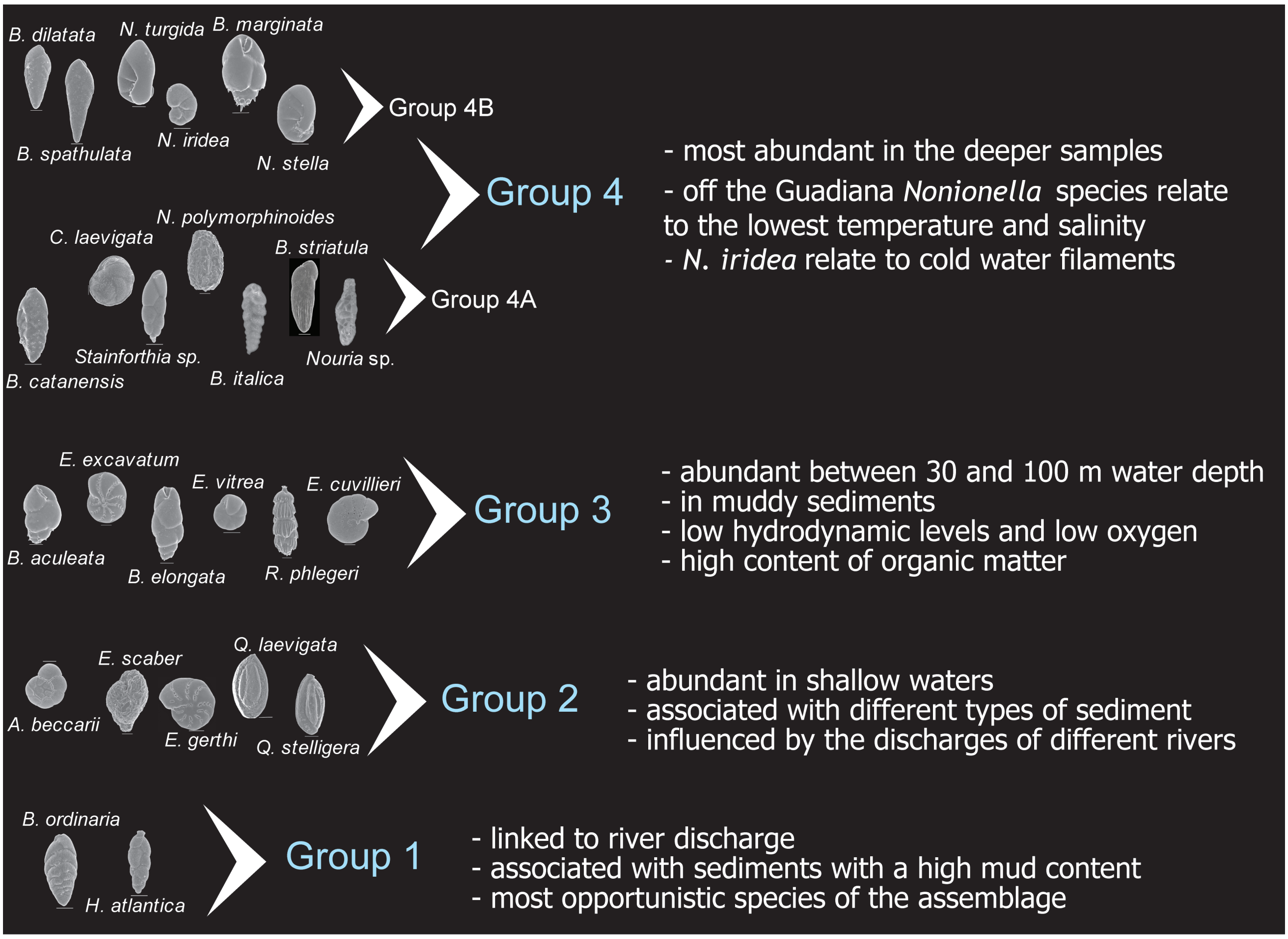


Figure 4.13.
Resume of the four general groups obtained, using the most abundant living benthic foraminiferal species and their associated environmental parameters.

Group 1 is represented by *Bolivina ordinaria* and *Hopkinsina atlantica*. These species were directly linked to river discharges and large amounts of organic matter input. These species were also generally associated with muddy substrates, and considered the most opportunistic of the assemblage.
Group 2 comprises species that were abundant in a variety of shallow-water substrates. The species distribution is also influenced by fluvial discharge and associated with different types of sediments.
In **group 3**, the most abundant species occur between 30–100 m water depths. They prevail in muddy sediments associated with low levels of hydrodynamic energy and oxygen, and high contents of organic matter.
Group 4 includes species that are generally more abundant in the deeper parts of the continental shelf. This group was divided into two subgroups. Subgroup 4A contains species with higher abundances in the selected samples and subgroup 4B species with patchy distributions on the continental shelf. High abundances of *Nonionella* species off the Guadiana River may be related to lower temperature and salinity near the seafloor. The abundance of *Nonionella iridea* could also be related to cold-water filaments (upwelling).

4.2.2. Understanding past environmental conditions

Age of sediment deposition

Learning about the tools used in geology to determine the age of sedimentary deposits

Researchers use sediment cores to investigate sedimentary deposits: these are vertical records (time record) obtained from the seafloor with specialised equipment, in which each layer (depth) of sediment represents a different age and depositional environment within the continental shelf deposits. Each layer is sampled and the sedimentological and micropalaeontological content is analysed with several techniques that allow us to know how the deposits formed and evolved through time.

The science that studies the age of rocks, sediments and fossils is designated by Geochronology and uses various types of signatures inherent to the rocks themselves in order to date their formation. One of the most common types of rock signatures used in Geochronology are radioactive isotopes. Radiocarbon dating (^{14}C) is the most widely used technique to date sediments. Radiocarbon dating measures the amount of radioactive decay of the radioactive isotope carbon-14 (with a known half-life) in organic material and can be best applied to samples younger than 60,000 years.

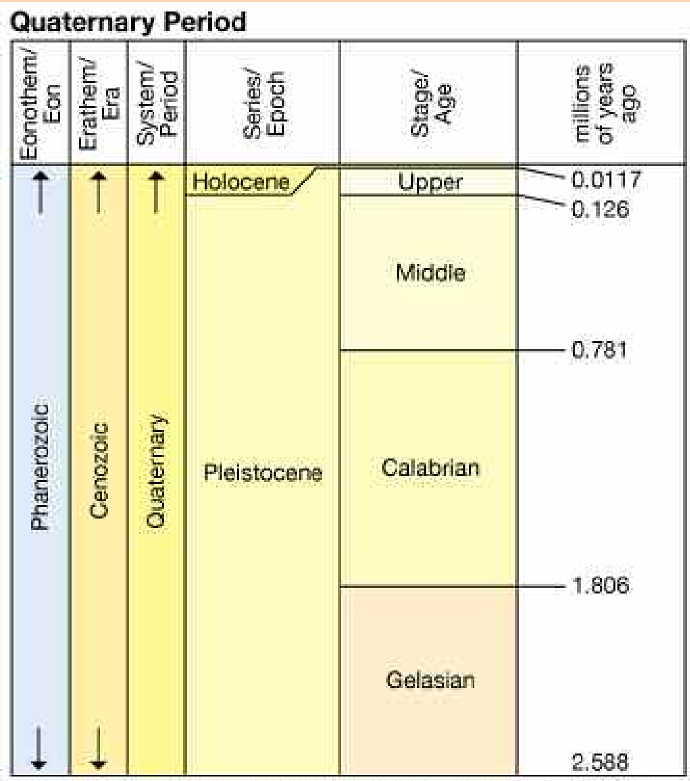
In the deposits of the Guadiana Shelf, radiocarbon dating has been applied using the fossilised calcareous tests of benthonic foraminifera found within the sediments (see Box 4.2.).

What do we know about the climate changes that occurred throughout the Quaternary and their link with the sea-level change?

The climate of the last glacial period was extremely unstable, ranging from full glacial to interglacial conditions. Within these glacial-interglacial periods, shorter

Box 4.2. What is the Quaternary Period?

Subdivision of the geological time which covers the last 2.6 million years up to the present day. It is further subdivided into two epochs; the Pleistocene (up to about 11,700 years ago) and the Holocene (about 11,700 years ago to the present day). The Quaternary has been one of extraordinary changes in global environment as well as the period during which much of human evolution took place. https://www.qra.org.uk



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Source: 2012 International Stratigraphic Chart produced by the ICS.

Figure Box 4.2

The Quaternary Period: Series/Epochs and Stages/Ages, in millions of years. Source: 2012 International Stratigraphic Chart, published by the International Commission on Stratigraphy, http://www.stratigraphy.org/

climatic cycles characterised by alternating colder and warmer conditions, occurred. These cycles are named as Dansgaard–Oeschger (D–O) Stadials and Interstadials, corresponding to cold and warm phases, respectively, and having a periodicity of ca. 20,000 years, as illustrated in figure 4.14. Some of the D–O Stadials were related to episodes of massive iceberg discharges into the North Atlantic Ocean, named Heinrich events (HE) that occurred with a periodicity of ca. 7,000 years (Figure 4.14).
Since then, during late Pleistocene, the Northern Hemisphere was marked by a succession of major deglacial climatic events that preceded the Holocene period. These events were named as the Oldest Dryas (ca. 18,000-14,700 cal. years B.P.; the Bølling/Allerød warm period (ca. 14,600 to 12,900 cal. years B.P.) and the Younger Dryas cold event (ca. 12,900 to 11,700 cal. years B.P.) (Figure 4.14).

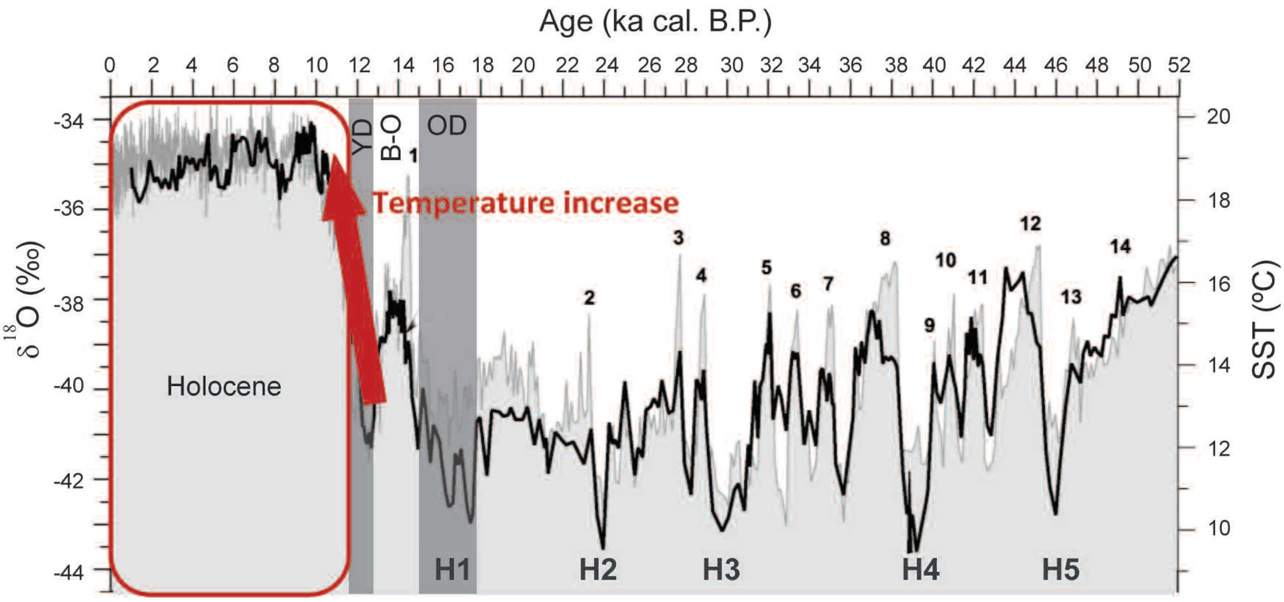

Figure 4.14.
Climate variability since the last glacial period: grey line marker is the atmospheric temperature record of the Greenland ice core GISP2 reconstructed from oxygen stable isotope data. Interstadial cycles correspond to the numbers on top of the grey line marker, Heinrich events are signalised on the bottom. YD – Younger Dryas, B-O - Bølling/Allerød, OD – Oldest Dryas (adapted from Cacho et al., 2002).

The Holocene was also a time of abrupt, cyclic climatic changes in the North Atlantic. The early- to mid-Holocene was characterized in the Iberian Peninsula (including the Guadiana Valley) by wet conditions, in a warm climate known as the Holocene Thermal Maximum. From the mid-Holocene onwards, a shift in insolation and the installation of the present-day atmosphere circulation in the northern hemisphere occurred, with the progressive instauration of drier conditions. Along the Mediterranean Basin, a regional response to these global climatic oscillations forced the establishment of an arid, Mediterranean-like, climate. During the late Holocene, the NAO has influenced major climatic and environmental changes across Europe, such as the Medieval Warm Period and the Little Ice Age periods.

How did the sea level evolved during the Quaternary?
During the Quaternary, the main control on sea-level change was the exchange of mass between ice sheets and oceans, with cold periods inducing ice sheet growth and sea-level eustatic lowstands (phases of lower sea level regarding the present). In the course of the Last Glacial Maximum (LGM) the sea level was around 125 +/- 5 m lower than the present day. An initial slow, postglacial rise lasted from ca. 21,000

to 17,000 cal. B.P., followed by an increase in the rate of rise for the next 10,000 years, until the decay of most of the large ice sheets was completed by 7,000 cal. B.P.
In agreement with the worldwide sea-level datasets, sea-level reconstructions for the western European margin point to persistent sea-level rise throughout the early- to mid-Holocene, including different areas along the Iberian Margin and the Bay of Biscay (Figure 4.15).

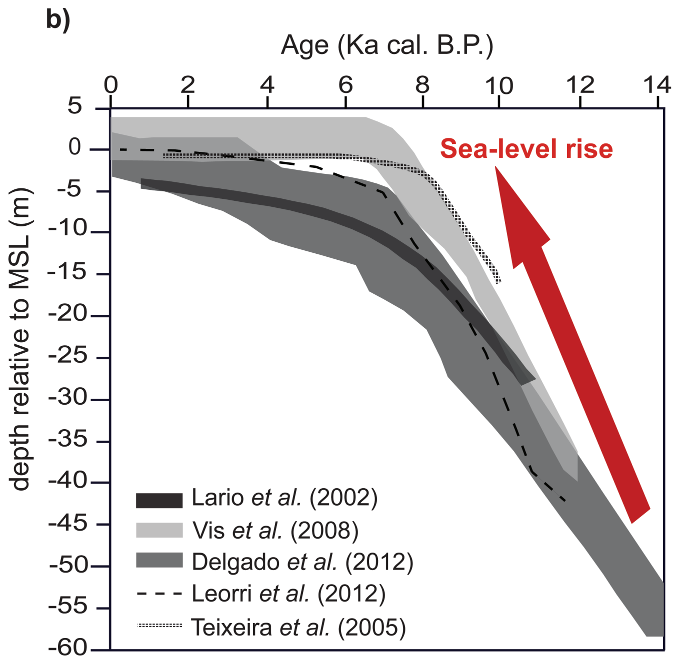

Figure 4.15.
Examples of Sea-level curves for the Eastern North Atlantic during the late Pleistocene and Holocene periods (MSL – Mean Sea Level). The model curves correspond to data from: southern Spain estuaries, Tagus River valley, Guadiana estuary, Bay of Biscay and Algarve beaches.

The most recent data concerning the infilling of the Guadiana estuary further indicated that since ca. 7,500 cal. years B.P. the sea level has continued to oscillate with a slow rate of rise until present-day conditions.

Sediments

Linkage between the evolution of sediment deposition on the Guadiana Shelf and the infilling of the Guadiana estuary

Shelf depositional patterns throughout the late Pleistocene and Holocene have been influenced by the evolution of the Guadiana estuary and its infilling. A first phase of accelerated infilling and trapping of clays occurred between ca. 13,000 and 7,500-7,300 cal. years B.P., when the sea-level rise was fast. The second phase was driven by a much slower sea-level rise between ca. 7,500-7,300 and 5,700 cal. years B.P., when mostly sands began to accumulate in the estuary. When sea level stabilized in the region after ca. 5,500 cal. years B.P., the estuarine infilling continued with deposition of sand bodies and salt marshes on both the western (Portuguese) and eastern (Spanish) margins. Consequently, the estuary acted as a major sediment sink.

Learning more about how did the sediment components of the Guadiana Shelf deposits evolved through time: clues to understand past environmental changes

The deposits of the Guadiana continental shelf have been extensively studied during the past years using sediment cores, in particular the fine-grained sediments of the middle shelf composing the Guadiana mud belt. Calm hydrodynamic conditions, set beyond the influence of storms, tides and coastal currents, favoured a continued deposition and the creation of a complete sedimentological record through time, without remobilisation of sediments and consequent hiatus/gaps in the depositional succession. Grain size trends are also detected, as the sediments become finer from the bottom (deeper, older sediments) towards the top (younger sediments, located closer to the sea floor surface). Sediments became particularly dominated by fine material after around 2,000 cal years B.P. (Figure 4.16).

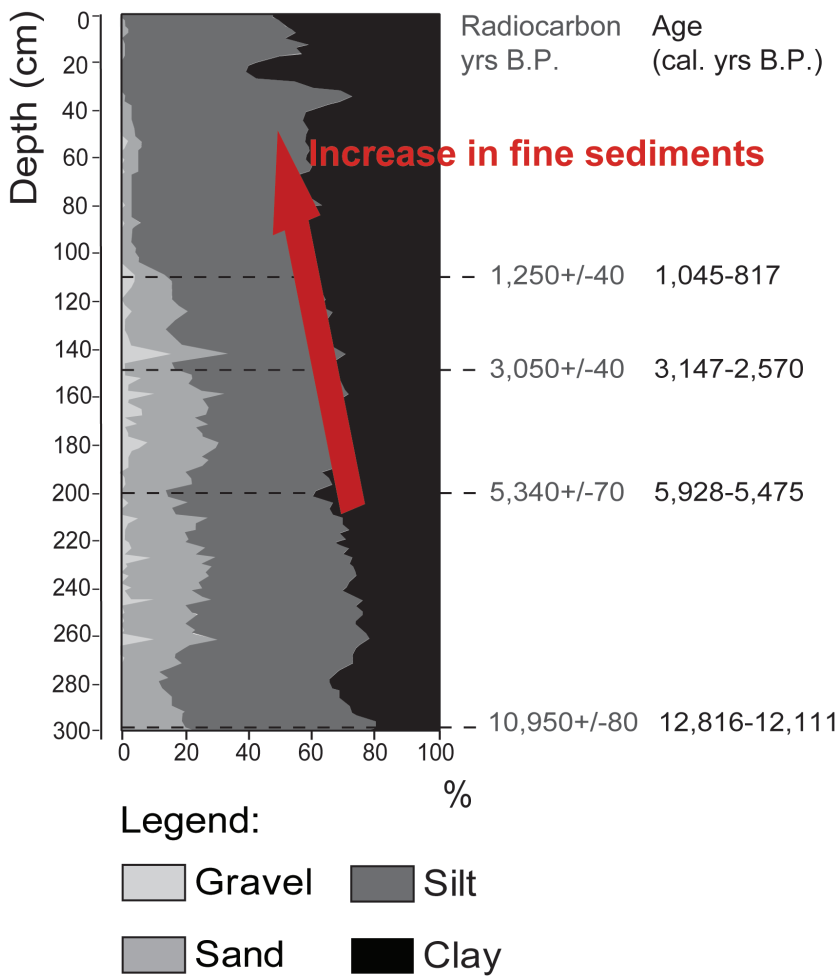

Figure 4.16.
Depth (cm), size-types of sediment (gravel, sand, silt and clay) and depth levels selected for radiocarbon dating (ages are given in radiocarbon years B.P. and calibrated ages - cal. years B.P.) along a sediment core obtained from the Guadiana middle continental shelf (adapted from Rosa, 2014).

The distribution of the components of sandy sediments along time reveals the dominance of the terrigenous/lithologic material and an increase in the diversity of the bioclasts (marine-derived) towards the top/more recent part of the depositional successions (Figure 4.17). Within the bioclasts, shallower forms (namely mollusc shells), that are associated with more energetic/coastal conditions, were more abundant in the lower/older part of the sequences, whereas towards the top/more recent deposits, foraminifera, which are much smaller and with preference for deeper and calmer marine habitats, became more abundant (Figure 4.17).

These main changes in the sediment grain size and in the composition of the sand-sized material along time are used as indicators, or proxies, of past environmental changes that occurred in the continental shelf and allow reconstructing the history of deposition driven by sea level and climate changes and the more recent human impacts.

At current deep locations of the middle shelf, shallow-marine environments were developed during the Late Pleistocene, inferred by the grain size heterogeneity and the dominance of fluvially-supplied particles (mostly the OT – other terrigenous/lithoclastic and mica particles). It would have been set in

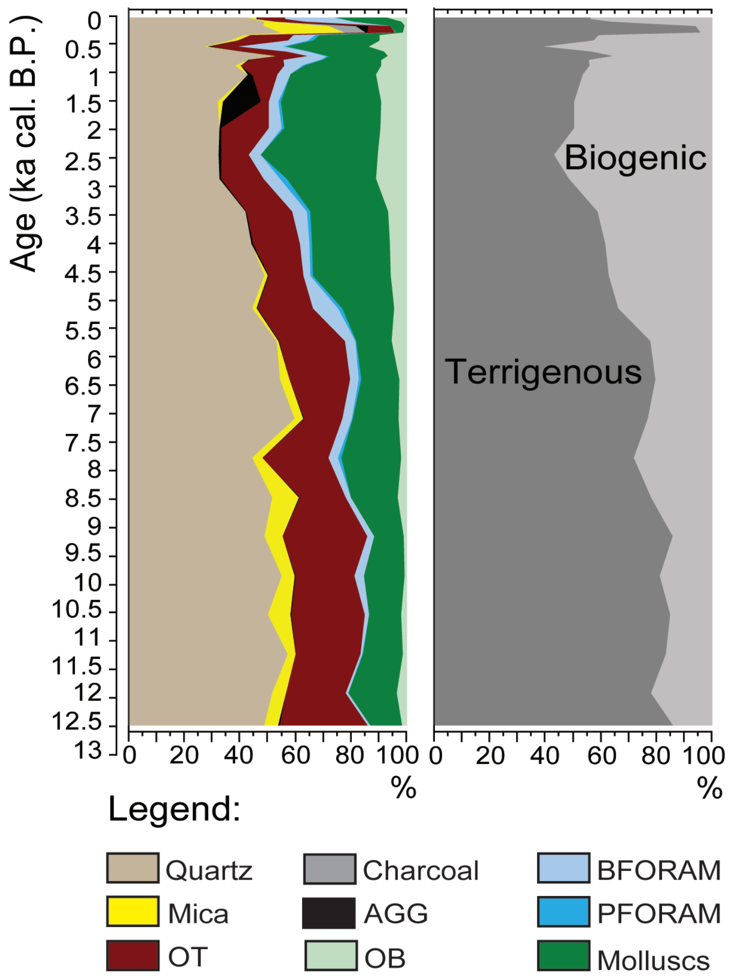

Figure 4.17.
Relative abundances (%) of sand components and proportion (%) of terrigenous versus biogenic content on the mud body deposits. Legend: OT – other terrigenous particles than quartz, AGG – aggregates, S/G – schist/greywackes, SANDST – sandstones, CARBLIT – carbonate lithoclasts, BFORAMS – benthic foraminifera, PFORAMS – planktonic foraminifera, OB – other bioclasts (adapted from Rosa, 2014).

close proximity to the Guadiana River mouth and the river discharges, when the sea level was several meters below its present day position and the river mouth was located further offshore, in present-day deeper areas of the shelf.

The fast sea-level rise decreased the river export-capacity due to the infilling of the Guadiana estuary, as part of the sediments transported by the river were being trapped inside the estuary by the rising waters in the transition of the Late Pleistocene and the Early Holocene periods.

When the sea-level rise decelerated, between the Early and the Mid Holocene, a prevailing influence of the Guadiana sediment inputs was persistently detected. The increase of clays and of benthic foraminifera within the sands shows the progressive establishment of these shelf areas in a deeper marine environment as the sea continued to rise.

After the sea level was nearly stabilised in the region in the Mid Holocene, at ca. 6,000 cal. yrs B.P., the disappearance of fluvial-supplied particles at more distal shelf locations points to a gradual decrease of the impact of the fluvial inputs, as the depositional environments evolved to become progressively better established at deeper depths, within a middle shelf setting.

In the Late Holocene, after ca. 2,500 cal. yrs. B.P. and until present-day, depositional patterns across the shelf were characterised by enhanced fine sedimentation and sedimentation rates, associated with further increased fluvial supplies. The first major human impacts in the Guadiana River Basin caused by the Roman and Islamic Rules of Iberia, coupled with the climatic shifts of the North Atlantic Oscillation (NAO), are believed to have been the main cause for the onset of the most recent chapter in the depositional history of the Guadiana continental shelf.

Benthic foraminiferal faunas

Learning more about the evolution of the Guadiana Shelf microfossil assemblages of benthic foraminifera: clues to understand past environmental changes

The study of the benthic foraminiferal microfossils is based on the identification of the most abundant species present in the sediments, and the variations of their distribution and diversity through time. Knowing their environmental constraints and habitat preference, as was explained previously in Sub-chapter 4.2.1, it becomes possible to use them as indicators, or proxies, of the environmental changes occurred in the continental shelf in the past. Hence they support the sedimentological information in the task of reconstructing the depositional history of the shelf.

The evolution of benthic foraminiferal communities in the Guadiana middle shelf

The interpretation of the fossil benthic foraminiferal assemblages that colonised the Guadiana middle shelf deposits through time, proved to be a valuable tool to reconstruct the past shelf depositional environments (Fig. 4.18).

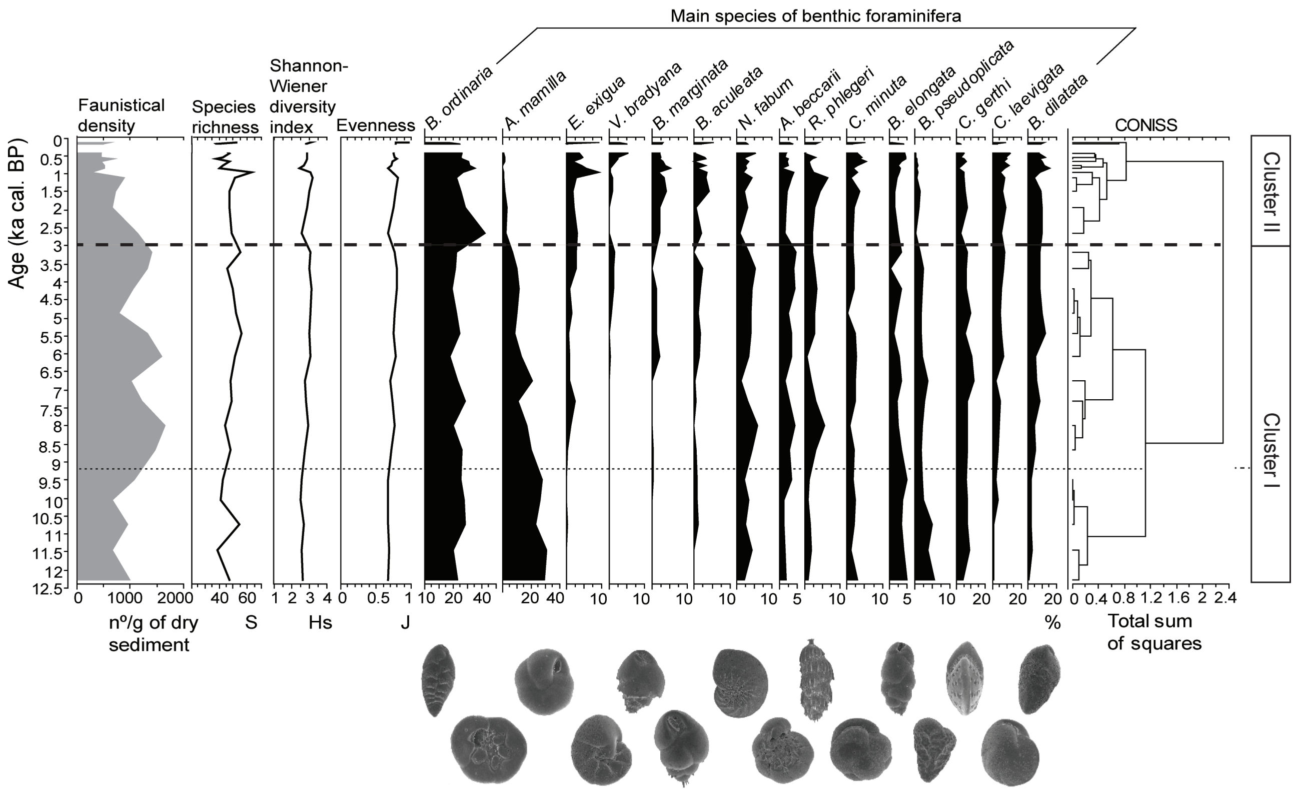

Figure 4.18.

Faunistical density (number of foraminifera per gram of sediment), species richness (number of species), diversity indices Shannon-Wiener and Evenness, abundance (%) of main benthic foraminiferal species, main benthic foraminiferal species in a sediment core from the Guadiana middle shelf (adapted from Rosa, 2014).

Combining all the micropalaeontological data obtained for the Guadiana middle shelf, the foraminiferal species were gathered in different sets with the help of multivariate statistics to improve their palaeoenvironmental interpretation. Each of these sets, Groups and Biofacies, has a specific environmental significance: Groups refer to groups of species that show a similar evolution trend in their abundance along time; Biofacies refer to the specific species composition of the benthic assemblages for a given period (different combinations of Groups) along the depositional/geological record (Fig. 4.19).

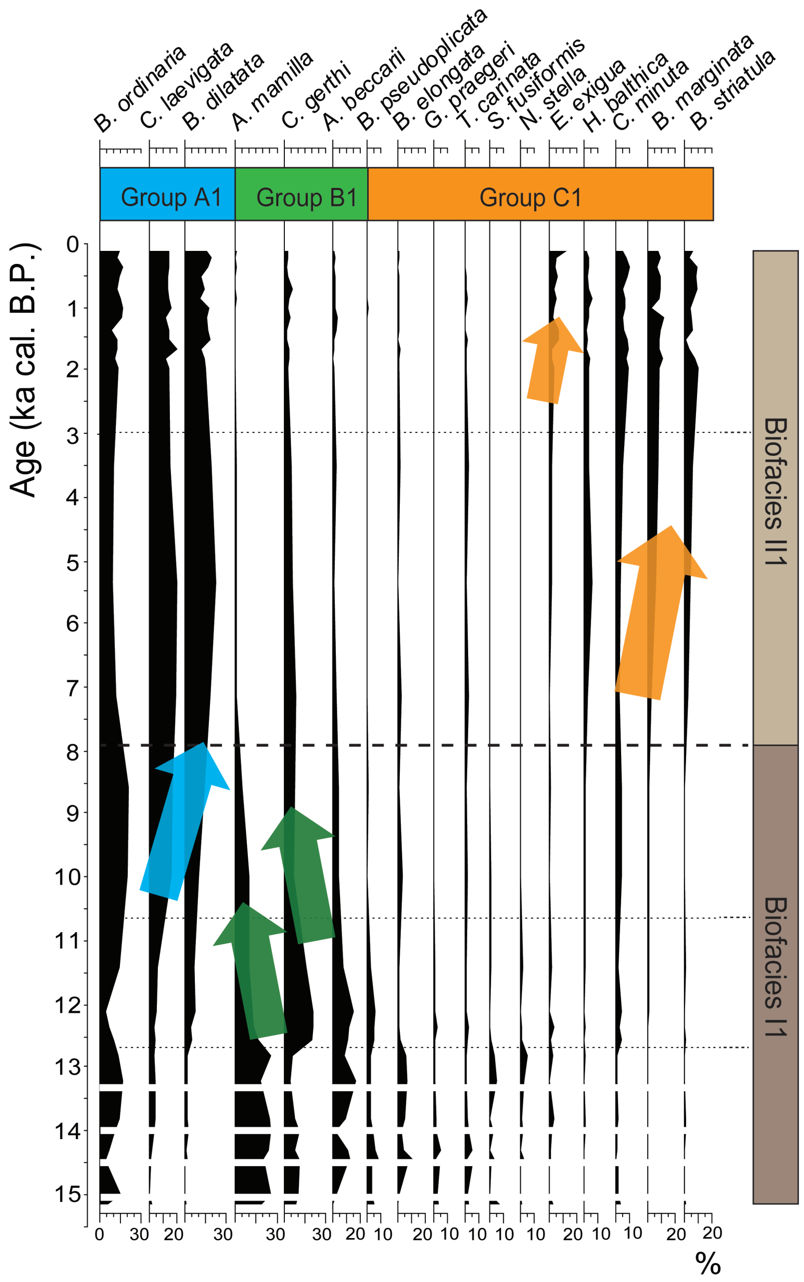

Figure 4.19. Abundance (%) of main benthic foraminiferal species in a sediment core from the Guadiana middle shelf. Colored arrows represent the main shifts in abundance observed for several species along time (adapted from Rosa, 2014).

In the Late Pleistocene, the benthic foraminiferal groups were dominated by coastal species that inhabit the surface of the bottom sediments and adapt better to strong currents. They are consistent with a shallow marine depositional environment that was set on the under direct fluvial influence, when the sea level was well below its present day position.

During the Latest Pleistocene and Early Holocene the increase of faunistical densities and a change in the dominant species, with species better adapted to quieter, deeper marine domains, becoming increasingly more abundant indicate the gradual increase of water depth as the sea level continued to rise fast during this period.

The evolution of the benthic foraminifera towards the Mid Holocene is consistent with the continuous deepening of the depositional shelf environments during the last phases of the Holocene sea-level rise that eventually lead to the establishment of water depths very identical to modern ones. Simultaneously, prevailing river nutrient influxes to the shelf assured continuous organic-rich conditions in the area, favourable to the development of the benthic communities.

The last ca. 2,500 years were marked by several abundance/diversity peaks of the benthic foraminiferal assemblages. The significant presence of species with preference for organic matter-enriched fine sediments were associated with particularly high inputs of nutrients derived from enhanced supplies of the Guadiana River onto the shelf. Moreover, the appearance of specific taxa that had been absent from the shelf environment until this time, was symptomatic of new ecological conditions being established in the area. These overall changes within the benthic foraminiferal population are consistent with the information obtained with the sedimentological study of the deposits, in the sense that the Roman and Islamic Rules of Iberia played a major role in the most recent evolution of the depositional environments on the shelf.

Acknowledgements

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5. Salt harvesting

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5.1. Salt harvesting

Saltworks (other terms: salterns, saltponds, solar ponds) are man-made hypersaline systems where table salt or halite (NaCl, sodium chloride) is harvested. Salt production in the Guadiana River estuary is based on solar evaporation of sea water. In other areas, salt is obtained from solid state or brine mining.
Saltworks using sea water are usually located in low coastal areas, allowing gravitational filling of ponds during the high tides. Evaporative salt production is restricted to geographical areas where this process is favoured by combined action of wind, solar radiation, low rain rates, and high temperatures. Hence, the Mediterranean and part of the European Atlantic coastal areas fulfil these conditions, particularly during the summer months where the evaporation greatly exceeds precipitation.
Salt production is one of the few economic activities legally permitted in the estuary of the Guadiana River, which is under protection of several international, national and regional legal instruments that were implemented to preserve the ecosystems and promote a sustainable development in the áreas (Figures 5.1.A; 5.1.B).

Figure 5.1. A
Sea salt warehouse in Isla Cristina, Spanish Guadiana River estuary (photo by Noa Sainz, 2010)

Figure 5.1. B
Salinas landscape from Castro Marim Castle, Guadiana River estuary (photo by Noa Sainz, 2015)

5.2. History

In Europe the technology of progressive sea water evaporation to obtain salt goes back about 4000 BP. In the Guadiana River estuary, salt harvesting has been taking place since Phoenician times and was recorded in several manuscripts (Figure 5.2). This millennial activity experienced a severe decrease for the last century due to competition of mined, industrial salt and the ensuing loss of markets. In the first decade of the XXI century most of the solar ponds were abandoned with a negative impact on the landscape (Figure 5.3). Only 10 production units were active in 2010 in the Guadiana River estuary (Figure 5.4) with only marginal importance for the local economy (see Box 5.1.)

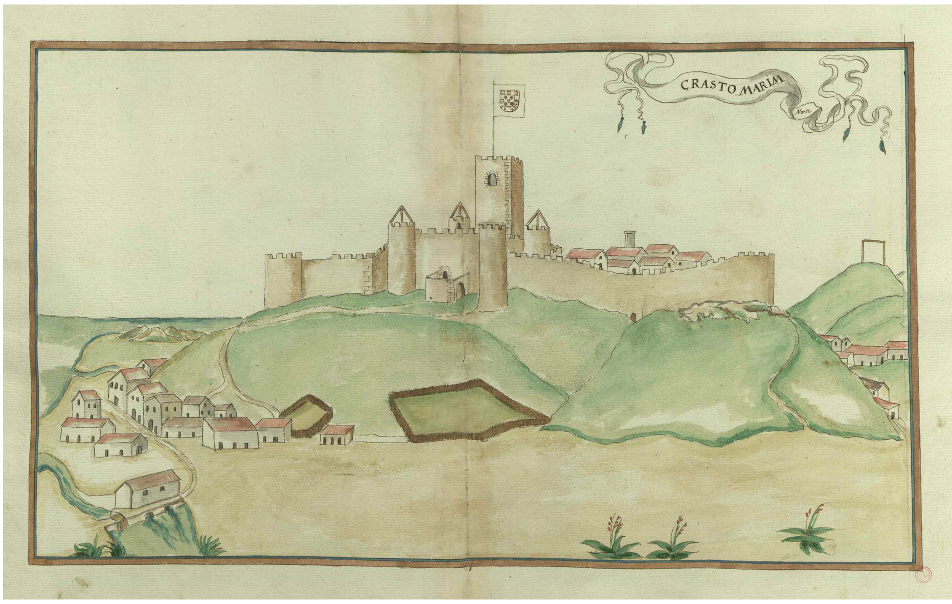

Figure 5.2.
Castro Marim, early XVI century, reproduction of a manuscript at *Fronteira de Portugal fortificada pellos reys deste Reyno* (Armas d´, 1642). On the back, next to the castle hill heaps of salt can be observed indicating the existence of active salt ponds.

Figure 5.3.
Abandoned salt ponds in the Guadiana River estuary (photo by Noa Sainz, 2015).

Box 5.1. Did you know that…?

Salt production has traditionally played an important role in the livelihood of Mediterranean societies, as salting was a principal method of preserving food, and enhancing its taste. The word that illustrates best the importance of salt as a vital commodity is "salary", coming from Latin "*salarium*" or salt-money or monetary equivalent of salt portion, paid to the roman soldiers. Solar ponds are part of the cultural and industrial heritage showing a sustained increase in economic output over the last decades.

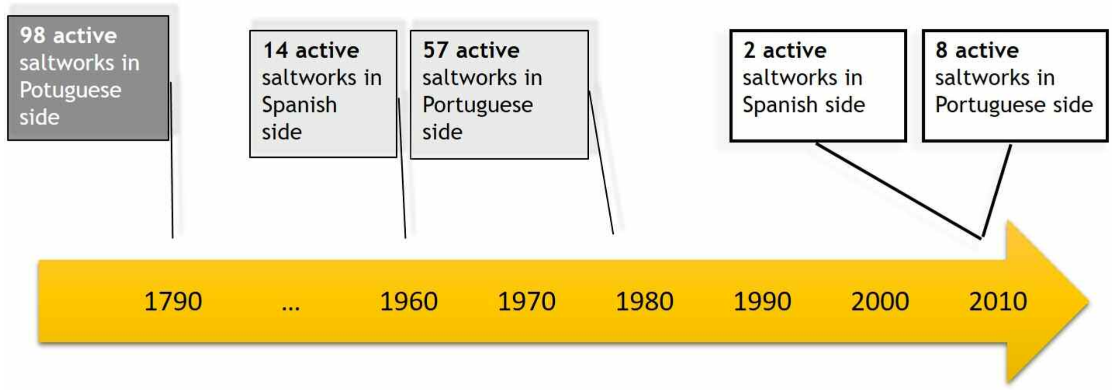

Figure 5.4.
Number of saltworks active in the Guadiana River estuary during the last 2 centuries (adapted from Menanteau et al., 2006).

The decreasing trend observed during the last century was recently reversed as a consequence of new environmental policies formulated in the Management Plan for the Nature Reserve of the Saltmarshes of *Castro Marim and Vila Real de Santo António* (http://www.icnf.pt/portal/ap/r-nat/rnscmvrsa), approved in 2008. The latter considers artisanal salt production as an important activity that should be promoted in the context of sustainable use of resources, and diversification of natural habitats for birds and other species of flora and fauna. In the past few years a slow recovery of several saltworks has been observed.

5.3. Saltworks configuration

Saltworks size can vary in the Guadiana estuary. The artisanal salt production units can occupy 1 hectare, while the industrial saltworks occupy 250 hectares. Nevertheless, all saltworks are organized by a successions of shallow (20-80 cm depth) evaporation ponds leading to the crystallization of sea salt at the end of the circuit. Water gets "saltier" and warmer as it goes through the circuit (see Figure 5.5). This water circuit can be differentiated into the main following compartments with different mean temperature and salinity:

- Marine water of salinity close to 35 PSU enters the sedimentation & storage ponds through the sluice which is opened during the spring high tide. Here, most of the suspended matter is deposited and temperature increases.
- The evaporation/pre-concentration area is divided into the evaporators, the heaters, and the reservoirs. Here the temperature further increases to 35-45ºC and salinity reaches, stepwise, 160-180 PSU. Less soluble salts like $CaCO_3$ and $CaSO_4$ are precipitated.
- In the crystallizers (*talhos* in Portuguese or *tajos*, in Spanish) the brine reaches the state of oversaturation, most commonly 220-250 PSU, and precipitates halite either as *fleur de sel* on the surface from which it is collected daily or as coarse salt collected usually every month, depending on the weather conditions.

Figure 5.5.
Water circuit in an artisanal saltworks (area: 1 hectare) in the Guadiana River estuary. Arrows indicate the direction of the water flow and are placed where water flow can be controlled with sluice gates (photo adapted from Google Earth).

Before harvesting season, the evaporation area and the crystallizers undergo a cleaning process in order to remove the excess of accumulated sediments, organic matter and algae.

5.4. Types of salt

Industrial saltworks and artisanal saltworks can be found at the Portuguese side of the estuary. On the contrary, at the Spanish side it can only be found artisanal saltworks.
University of Algarve-CIMA's research is focused on the formation of *fleur de sel* (or *flor de sal* in Portuguese/ Spanish) which is a kind of sea salt harvested by hand. *Fleur de sel* is formed (Figure 5.6.A) and collected from the surface of the crystallizers brine. Its collection is done with a skimmer (Figure 5.6.B), and immediately after its collection it is placed in perforated plastic boxes for draining of residual brine (Figure 5.6.C) and in the last stage it is sun dried on plastic nets (Figure 5.6.D).

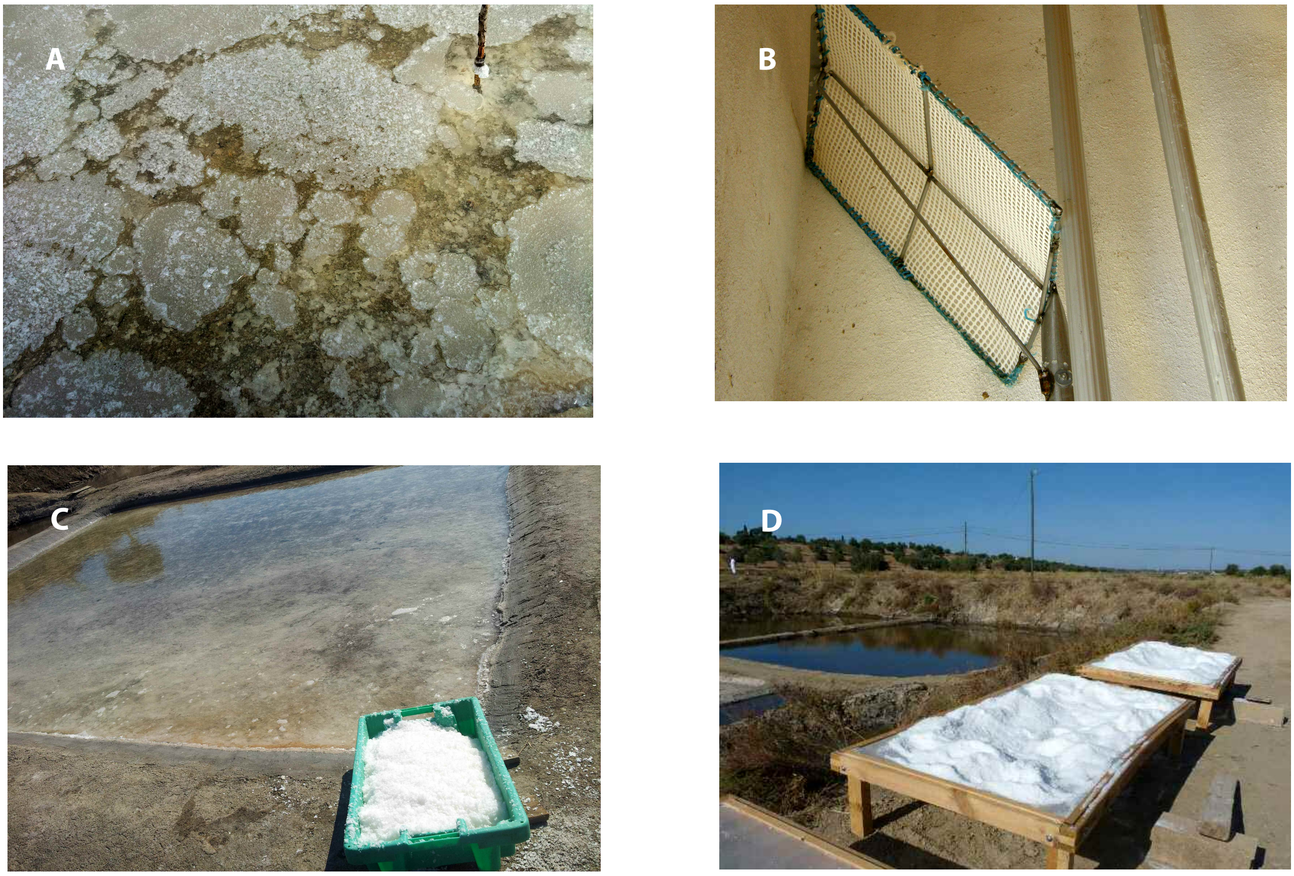

Figure 5.6.
Figure 5.6: (A) Fleur de sel formed at the surface of the brine; (B) tool for collection of fleur de sel; (C) fleur de sel draining box; and, (D) fleur de sel drying nets (photos by Noa Sainz and Tomasz Boski, 2014/2015).

Coarse salt, which accumulates in the bottom of the crystallizers is harvested when its crust is too thick to admit enough new liquid or in the other words when the brine lamina is too thin for collecting *fleur de sel*. This happen after 1-2 months depending on prevailing weather conditions and quantity of *fleur de sel* collected. Before removal of coarse salt, the brine left in the crystallizer is evacuated, and the salt is pushed onto the dikes separating the crystallizers (Figure 5.7.A), forming small heaps of salt for its final natural drying before packaging (Figure 5.7.B).

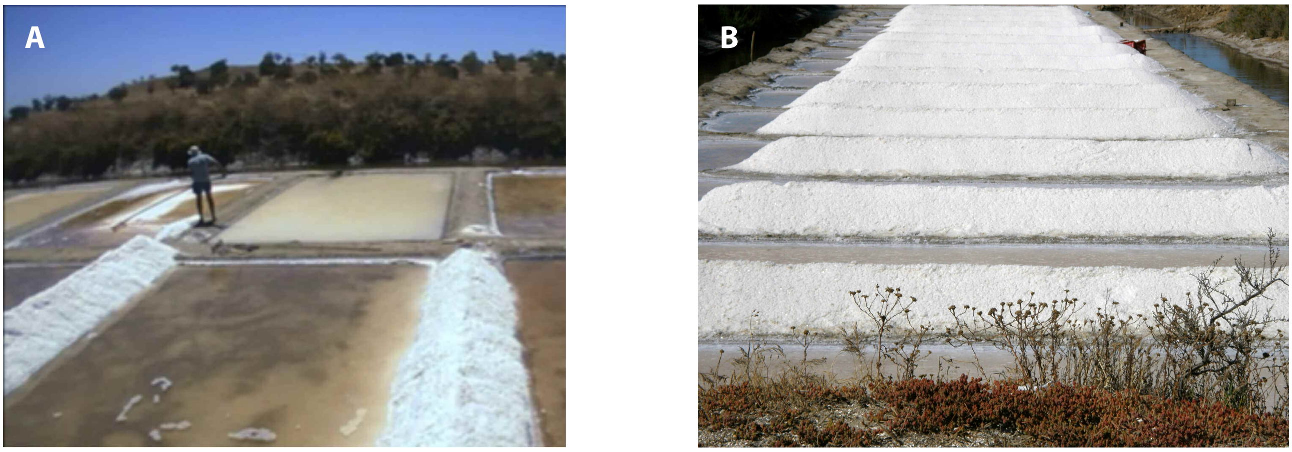

Figure 5.7.
(A) Raking coarse sea salt; and, (B) coarse sea salt heaps drying up in a traditional solar saltworks at the Spanish side of the Guadiana River estuary (photos by Noa Sainz, 2015/2010).

Variables that affect artisanal salt formation are: strength of solar radiation, air humidity, wind speed and direction, atmospheric temperature, and salinity and temperature of the brine (Figure 5.8), which jointly determine the rate of evaporation. Salt formation can also be influenced by the microorganisms found in the brine. For instance, red halophilic bacteria aid solar energy absorption and, hence, brine evaporation. While atmospheric conditions are beyond human influence the physical-chemical variables of the solutions may be partially controlled by managing the circulation of brine in the evaporations - crystallizations circuit.

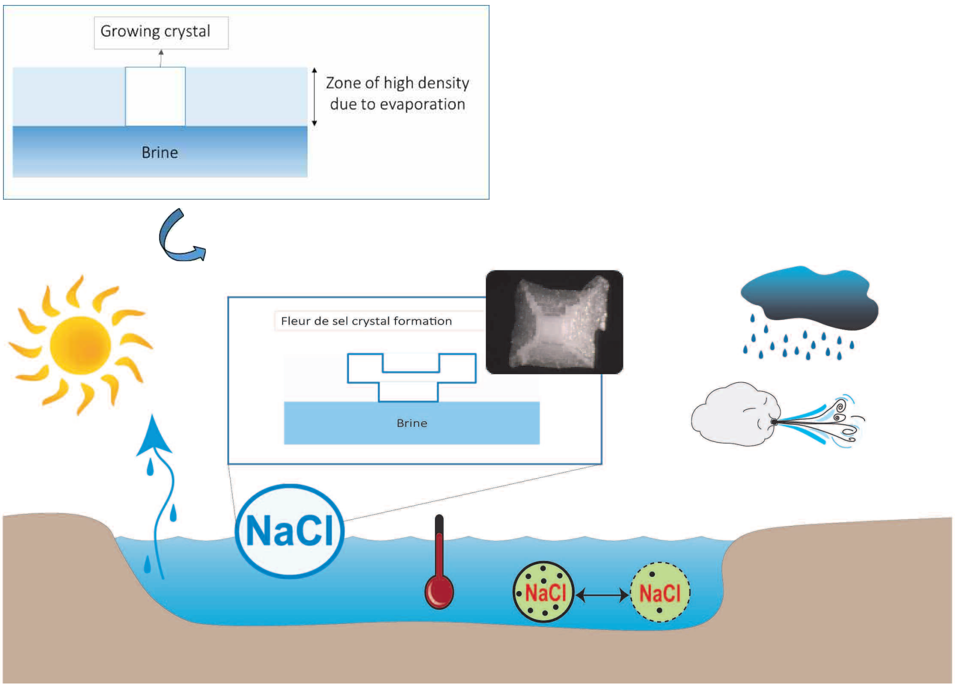

Figure 5.8.
Cross section of a crystallizer showing how fleur de sel crystals are formed. Microscopic picture of a crystal of *fleur de sel* (from top of the pyramid).

Fleur de sel, which is formed on surface of oversaturated brine, appears initially as quasi-two-dimensional floating, centimetric size flakes which through an in-depth growth assume the geometric form of hopper pyramids (see Figure 5.9).

Figure 5.9.
Lateral macro picture of a crystal of *fleur de sel* (photo by Noa Sainz, 2014).

Fleur de sel is composed in ca. 96% of sodium chloride, the remaining being calcium, potassium and magnesium (see Table 5.1) which together with the adsorbed organic matter are responsible for its appreciated specific flavour. The origin of organic matter is attributed to the algae which can support the high salinity. (see Box 5.2.)

Components		Fleur de sel	Coarse sea salt
Sodium chloride	g/kg	966	968
Humidity	g/kg	45.7	37.1
Insoluble matter	g/kg	0.1	0.2
Sulphates	g/kg	14	10.9
Calcium	g/kg	2.4	0.6
Potassium	g/kg	0.9	1.8
Magnesium	g/kg	6.1	7
Iodine	mg/Kg	0.51	0.552
Copper	mg/Kg	<0.05	<0.05
Iron	mg/Kg	0.06	0.12
Lead	mg/Kg	<0.05	<0.05
Mercury	mg/Kg	<0.01	<0.01
Arsenic	mg/Kg	<0.02	<0.02
Cadmium	mg/Kg	<0.02	<0.02

Table 5.1.
Composition of artisanal sea salt collected in Castro Marim saltponds in 2015 harvest season.

Box 5.2. There is still life in there

High salinity can be the perfect environment for some organisms. Some algae, like *Dunaliella*, are rich in β-Carotene responsible for the roe/reddish tint of salt and of the pond shrimps.

Box 5.2 Figure
Dunaliella bloom in a sea salt crystallizer (photo by Noa Sainz, 2015).

Industrial sea salt after collection by heavy machinery must be transported to the specialized industrial units for the purpose of re-dissolving, drying and grinding prior to human consumption. It differs substantially from artisanal sea salt (see Table 5.2) as it is an almost pure sodium chloride containing only small amounts of Al_2O_3 added as anti-agglutinating agent . The Portuguese company Salexpor occupies around 250 hectares of industrial saltworks in the Guadiana River estuary. They can produce 30,000 tonnes of coarse salt in one harvest season.

Purified salt composition	
Sodium chloride	Min. 98%
Humidity	Max. 1%
Insoluble matter	Max. 0.2%

Table 5.2.
Physicochemical characteristics of purified crystal sea salt composition after washing, drying and grinding for human consumption (1 Kg) from the company that utilises the industrial saltworks in the Guadiana River estuary.

5.5. Economy

Portuguese Official National Statistics showed that in 2010 the production of coarse sea salt on mainland Portugal declined by 38.4 % compared to 2009. The main reason for this sharp decrease is that many producers have re-oriented their production because of higher revenues that may be obtained from commercializing *fleur de sel*, when compared to coarse sea salt (see Box 5.3.)
Fleur de sel in some of the traditional saltworks in the Guadiana River estuary has a certified quality by the international associations *Nature et Progrès* (http://www.natureetprogres.org) and the Portuguese *Sativa* (http://www.sativa.pt/default.asp), both specialised in organic farming. The European certificate of "Protected Geographical Indication" has been awarded to a *fleur de sel* produced as well in other locals of the Algarve region, but the Guadiana *fleur de sel* has not been registered under this designation. Obtaining this certification and matching international standards of labelling, would contribute to an increased competitiveness of *fleur de sel* from the Guadiana River estuary. Moreover, the Guadiana *fleur de*

Box 5.3. Coarse sea salt vs *fleur de sel*

Artisanal *fleur de sel* (also known as flower of salt) from Algarve, whose price may be two order of magnitude higher than traditional coarse salt found its way to several markets, and greatly improved the financial output of local producers. Technological improvements like more precise control of the brine's flux, weather forecasting and evaporation enhancing may play a role in further improvements of the process and its profitability.

Box 5.3 Figure
Fleur de sel for sale in Portugal (photo by Noa Sainz, 2014).

sel could be promoted and could protect its name by registering under other quality schemes, such as the "Protected Designation of Origin" (PDO) and/or "Traditional Speciality Guaranteed" (TSG) (https://ec.europa.eu/agriculture/quality_en): PDO covers agricultural products and foodstuffs which are produced, processed and prepared in a given geographical area using recognised know-how; and, TSG highlights traditional character, either in the composition or means of production of the product.
In 2006, in the area of the Nature Reserve of the Saltmarshes of *Castro Marim and Vila Real de Santo António* ca. 30 ha were occupied by active saltworks, while 200 ha were still abandoned but considered as recoverable. The abandonment trend is now reversing and for example, in 2016, 1 ha of saltworks was recovered an started to produce *fleur de sel* and coarse salt. Lately, there has been a product diversification from saltworks, and for instance, in 2015 an approximately 1 ha of saltworks focused its activity on tourism and offered floating baths in one pond and beauty treatments with mud as an outdoor spa for skin exfoliation. This has been observed in other saltworks in Europe, for instance salina mud from Secovlje salina (Slovenia) composed of quartz, carbonates and clay minerals and containing variable amounts of sulphides, is used in health resorts of that area.
Recently, some tourism-oriented activities have been developed in active saltworks at the Guadiana River estuary, such as offering the possibility to tourists of experience the profession of *marnoto* (salt harvesting worker, in the local jargon) for some hours, encouraging traditional knowledge dissemination. Moreover, another activity focusing on visitors directly link to the saltworks is bird watching, attracting every year more tourists. Other activities promoted in European salinas relying on the exploitation of the Mediterranean's salt heritage are guided tours and school visits, although they should be accompanied with other activities to be economically profitable. In the case of the Guadiana saltworks, the University of Algarve - CIMA has been working in the area for the last two decades and it has produced materials for education and management.
Although experiences on farming *Artemia spp* in saltworks in Asian countries have reported increased incomes for families, no similar practices are taking place in the Guadiana River estuary. The former is probably due to the fact that large quantities of *Artemia spp* are required to make this a profitable business and mainly because there is no industry already established on this product in the area. Nevertheless, it should be mentioned that research on this issue is currently being carried out in abandoned saltworks in another part of the Algarve. So, this activity could be considered as well for the Guadiana River estuary, after an appropriate research and development period.
There is only one industrial sea salt producer company in the Guadiana River estuary and it is at the Portuguese riverside (Figure 5.10). It produces most of the coarse salt, accounting for 25-30,000 t/yr.

Figure 5.10.
Salt heap at industrial saltworks in Castro Marim (Portugal) (photo by Noa Sainz, 2015).

5.6. Biodiversity/ Ecosystem

Saltponds are recognized as ecosystems that hold an important biodiversity and are considered as important conservation areas with unique food webs, directly link to the salinity gradient. Saltponds are known for holding a wide variety of resident and migratory birds (Figure 5.11.A and 5.11.B).

Figure 5.11.
(A) *Phoenicopterus roseus* (flamingo) at the industrial saltponds of Castro Marim and, (B) Footprints of *Himantopus himantopus* (black-winged stilt) in one pond of the traditional saltworks in Castro Marim (photos by Noa Sainz, 2015).

Saltponds provide a series of ecosystem services, such as: food, biological regulation, hydrological balance, atmospheric and climate regulation, flood/storm protection, erosion control, cultural amnity, recreational, aesthetic, education and research.

5.7. Weaknesses and threats of artisanal salt production

Although protected under several treaties/legislation, saltworks are currently under different threats. The estuary of the Guadiana River is under several low and medium pressures which affect as well the saltworks indirectly:

- Some areas of the saline ecosystems have been converted to hold tourism infrastructure, such as golf courses and marinas, especially at the Spanish side. Apart from land reclamation, urbanization can represent a source of pollution, particularly as solid waste reaches abandoned saltworks, converted into illegal dumpsites. Since 2008 financial crisis, urbanization has stopped sharply in both countries.
- Agriculture and aquaculture have replaced salt harvesting in some areas, especially at the Spanish river side, where several aquaculture companies occupy former saltworks due to a conversion trend that took place in the 1980s when there was no nature protection policy in place. On the contrary, the Portuguese side accounts for only one installation, a 32 ha semi-intensive fish farm, as well placed in former saltworks. Due to environmental regulations, no more aquaculture units are allowed to operate in the Guadiana River estuary, since large scale aquaculture leads to the impoverishment of saltpans landscape, it can aggravate conflicts with farmers, and it can cause environmental impacts, such as:

decrease of available emerged area for birds and other species; increase of nutrient concentrations; diminish dissolved oxygen levels; and introduce hormones, antibiotics, pesticides and various compounds, affecting the rest of the ecosystem. However, the conversion of saltworks and wetlands into aquaculture ponds is considered an activity that increases economic output from coastal areas, as declared in the Strategic Plan for Aquaculture of the Portuguese Government for 2013-2020.

One matter that can be a threat to the estuary, can also be an opportunity for the saltworks; this is salinization, as it can help on the recovery of abandoned saltworks by means of reducing the minimum required time for salt harvesting and make the activity more efficient. The revitalization of saltworks would create jobs and preserve biodiversity of this ecosystem. Salinization of the Guadiana River estuary is due to the excess number and capacity of upstream river dams that limits freshwater reaching the river mouth (the biggest dam, closed in 2002, can retain 4,150 hm^3 of water 60 km upstream, in the council of Alqueva). Moreover, climate change will affect the saltmarshes, especially at the Spanish margin of the estuary where there will be risk of flooding due to sea-level rise together with lack of sediment supply, partially caused by upstream damming that causes sediment retention.

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6. A brief journey along time in the Guadiana estuary

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The physical characteristics of the Guadiana estuary and the richness of its adjacent territories were essential in defining the historical and cultural context of the entire region. The extended navigability of the estuary was fundamental to establish trade routes with the Mediterranean civilizations, namely with the Phoenicians, Greeks, and Carthaginians. These civilizations created several commercial harbors along the Guadiana, namely in Mértola, Alcoutim, Castro Marim and Ayamonte. In these locations the human presence dates back as far as the Neolithic (12,000 to 4,000 BCE) and the Chalcolithic periods (4,000 to 3,100 BCE). Later, the Romans (II BCE to V CE), the Alans (V to VI CE.), the Visigoths (VI to VIII CE), and the Arabs (VIII to XIII CE) successively settled in this Iberian region, until the borders of the continental Portuguese territory were set in the 13th century. The predominant North-South direction of the estuary is intrinsically linked with the definition of the Portuguese and Spanish territories, as it serves as a natural border in its last 50 km.

Ore extraction and cereal production in the surrounding areas of the estuary turned Mértola into the most important trading center, up to the Portuguese conquest in 1238 (Fig. 6.1). Copper, iron, and manganese were the main ore resources, but silver and gold were exploited as well. With the Portuguese conquests, the economic importance of the Guadiana estuary decreased sharply. In the 15th and 16th centuries, cereals were shipped to the Portuguese forts of northern Africa, but it was only in the late 19th century that all the regions around the estuary had a new economic burst.

Figure 6.1.
The castle of Mertóla viewed from the Ribeira de Oeiras valley in April 2004 (Photography by Pedro Morais).

In the late 18th century, the Portuguese Prime-Minister, Marquês de Pombal, ordered the construction of a new city, Vila Real de Santo António, located near the river mouth. The main goals were political, economical and strategic-related, but primarily to face the economic boom of the Spanish city of Ayamonte, in the opposite margin. Ayamonte's prosperity derived from an intense fishing activity targeting sardine in the Gulf of Cadiz and Bay of Montegordo, which attracted Spanish and Portuguese fishermen. However, Vila Real de Santo António only prospered in the late 19th century, due to a strong development of ore extraction, fisheries, canning and shipyard industries (see Box 6.1.)

Box 6.1. Marquês de Pombal

Sebastião José de Carvalho e Melo (Lisbon, May 13, 1699 – Pombal, May 8, 1782), mostly known as Marquês de Pombal, was the prime-minister of King D. José I. Marquês de Pombal was a controversial political personality during the 18th century, and he is recognized for commissioning the reconstruction of Lisbon after the 1755 earthquake. Marquês de Pombal tried to improve the country's economic status by developing the agriculture, industry and commerce. The city of Vila Real de Santo António, was built with the purpose to divert part of Ayamonte's fisheries profit, which is a city located in the opposite margin to Castro Marim and Vila Real de Santo António.

Ore extraction, specifically of copper, began in 1858 in re-discovered Roman mines at Minas de São Domingos (Fig 6.2). Ships transported the ore to the estuary mouth, where it was re-transferred to bigger ships heading England and Germany. The end of the mining activity in 1965 caused a deep economic and demographic recession. Between 1961 and 1971, the county of Mértola lost 50% of its population, which migrated either to Lisbon and surrounding cities, or abroad. Presently, the upper estuary is one of the poorest regions of the European Union.

The fishery activity developed in the late 19th century with the rise of sardine and tuna canning industry, which were promoted by Spanish, Italian and Greek entrepreneurs.

Figure 6.2.
Abandoned ore extraction facilities at Mina de São Domingos in September 2014 (photography by Pedro Morais).

Truly, Vila Real de Santo António is the birthplace of the Portuguese fish canning industry, where the first tuna canning factory was built in 1865. Canned fish soon became one of the most famous Portuguese export goods, like wine and cork, and mainly during the World War II. Fisheries started to decline in the 1960's, and today no fish canning industry remains working in Vila Real de Santo António.

From 1929 to 1937 the "wheat campaign" was imposed by the Portuguese government, as an attempt to make Portugal self-sufficient and end its reliance on US and Canadian wheat. During this period, the economic activity increased along the estuary, especially in Alcoutim, where the wheat was flowed-off, and fertilizers were received. However, the "wheat campaign" was made in poor soils, leading to their complete exhaustion,once the traditional rotation system of cultures and fallow practices were abandoned. Today, tourism is the main economic activity, not only in the Guadiana estuary but in all the Algarve, the southern Portuguese region.

Whereas from the late 19th century, mining and canned fish industries were the most harmful activities around the Guadiana estuary, presently water abstraction and retention on dams are probably those of most concern to the estuary. Since mid-1950's, the Guadiana basin has been intensively dammed, allowing the development of extensive irrigation areas, electrical production and other public and industrial demands. The Alqueva dam, located at approximately 150 km from the river mouth, was the last to be built. The floodgates closed on February 8th 2002, and river flow regulation increased from 75% to 81% (Fig. 6.3). With this dam, the Portuguese government aimed, besides regularizing the Guadiana river flow, to reinforce the capacity of hydroelectric energy production, develop the tourist potentialities of the area, promote the regional employment market, organize intervention in environmental and patrimony domains, fight physical desertification and climate change, and modify the agriculture specialization model of southern Portugal by implementing an irrigation area of 110,000 ha. (see Box 6.2.)

Box 6.2. Alqueva dam

The Alqueva dam is located approximately at 150 km from the river mouth. It forms at its maximum capacity (152 m level) one of the biggest artificial lakes in Europe, with an area of 250 km^2 (63 km^2 in Spain), a perimeter of approximately 1000 km, a total capacity of 4150 hm^3, and an useful capacity of 3150 hm^3.

Figure 6.3.
Downstream face of the Alqueva dam in July 2009 (photography by Pedro Morais).

Other significant constructions in the Guadiana estuary during the 1970's were the two jetties that stabilized the once highly dynamic river mouth, which drastically changed local sediment dynamics. The main consequence was the interruption of the predominant eastward littoral drift and sediment deposition in the river mouth. However, due to sediment retention in dams and lower freshwater flows, coastal erosion is expected to be enhanced in the future.

The company responsible for constructing the Alqueva dam monitors the reservoir's water quality . However, the impact of altered river flow on downstream ecosystems is significant. The first changes were observed on the phytoplankton community. Before the Alqueva dam construction, phytoplankton exhibited a typical uni-modal cycle, with a biomass maximum during spring, corresponding to the diatom bloom, and a summer cyanobacteria bloom. During 2002-2004, when the Alqueva dam was being filled and freshwater flowing into the estuary was tremendously reduced, cyanobacteria dominated the phytoplankton community, not only during summer months, but in the autumn and winter as well. In the post-filling period, river flow became more constant throughout the year, significantly affecting phytoplankton dynamics. The abundance of diatoms and cyanobacteria decreased in the post-filling period. The decrease of cyanobacteria represents an improvement in water quality since many species produce toxins responsible for gastrointestinal, dermatological, and neurological problems. However, the overall decrease in phytoplankton biomass and, specifically, the decline in diatom biomass may have major negative consequences for higher trophic levels that depend on planktonic food.

The impacts of the altered river flow are also evident in fish populations. The main consequence is a reduced use of the Guadiana estuary as a habitat for freshwater fishes, and as a spawning ground for marine species. Several barbells, endemic of the southern Iberian Peninsula, are today classified as threatened, and other species occurring in brackish and freshwater habitats are considered vulnerable, such as allis shad (*Alosa alosa*) and twaite shad (*Alosa fallax*). The cyprinidae *Anaecypris hispanica*, an endemism once abundant in the Guadiana basin, is today threatened with extinction. Damming, water abstraction for agriculture irrigation systems, habitat degradation, polluted effluents, and introduction of non-indigenous competitors are the probable causes of these losses. Other problems, namely overfishing and damage of spawning grounds by sand and gravel extraction, resulted in the disappearance the European sturgeon *Acipenser sturio*, an emblematic migratory fish from the Guadiana basin. The last sturgeon was caught in the early 1980's. Coastal fisheries are also affected by the Guadiana river flow (Fig. 6.4). In years of low river discharge, sardine landings decreased 69%, from 886 to 279 ton, while landings of carnivorous fish (e.g. seabreams) increased between 112% and 128% (see Boxes 6.3. to 6.5.)

Box 6.3. Migratory fish

Migratory fish species are those that need to perform regular migrations between different ecosystems (river, estuary, ocean/sea), or habitats within ecosystems, at specific stages of their life cycle. There are three main types of migratory fish: i) potamodromous fish- perform migrations between distinct freshwater habitats; i) diadromous fish- perform migrations along a salinity gradient, between rivers and/or estuaries and the ocean; iii) oceanodromous fish- perform migrations in the oceanic environment. The most emblematic migratory fish species present in the Guadiana estuary are the diadromous fish European ell *Anguilla anguilla* (Linnaeus, 1758), twaite shad *Alosa fallax* Lacépède, 1800, allis shad Alosa alosa (Linnaeus, 1758), and sea lamprey *Petromyzon marinus* Linnaeus, 1758. The emblematic European sturgeon *Acipenser sturio* Linnaeus, 1758 is extirpated from the Guadiana basin since early 1980's.

Box 6.4. Diadromous fish

Fish species that perform migrations along a salinity gradient. There are three types of diadromous fish. Amphidromous fish are those that hatch in rivers and then migrate into the ocean, but that return back to rivers still as post-larvae or as young juveniles (e.g. species of the family Galaxiidae). Anadromous fish are those that migrate from the ocean into freshwater/brackish ecosystems to spawn (e.g. shad, sturgeon, lamprey). Catadromous fish are those that migrate from rivers/estuaries to spawn in the ocean (e.g. eel).

Box 6.5. Cyanobacteria

Group of photosynthetic bacteria that live in a wide range of habitats, including marine and freshwater ecosystems. Many cyanobacteria species produce toxins that can cause gastrointestinal, dermatological, and neurological problems. Cyanobacteria that live and drift freely in the water column in aquatic ecosystems are part of phytoplankton, a heterogeneous group of photosynthetic organisms that is responsible for 50% of the world's total primary productivity.

Damming and water abstraction are not the only threats to the Guadiana estuary. Agricultural, industrial, and urban pressures are not significant in the Guadiana, compared to other Iberian estuaries. However, the lack of land use and proper management is responsible for other problems, as the increased probability of forest fires. Lack of forest management results from complex social-economical problems. The upper estuarine region is one of the poorest in the European Union, and the manpower is scarce due to the aging of local populations. Nevertheless, tourism infrastructures are still being developed in the lower Guadiana estuary. One of these is in its late stages of construction in the Spanish margin; this tourist resort will host 20,000 inhabitants and will be equipped with houses and hotels, shopping centers, golf courts, and a marina, representing an enormous change in land and estuarine use.

Figure 6.4.
Fishing boat (Princesa do Guadiana) entering the Guadiana estuary in December 2002 (Photography by Pedro Morais).

The creation of a Biosphere Reserve or the International Natural Park of the Lower Guadiana was proposed by Almargem, a local environmental organization, during the first decade of the 21st century to avoid the massive construction of tourism infrastructures and to compensate for the loss of biological diversity. Currently, the only protected landscapes around the Guadiana estuary are the Natural Reserve of Castro Marim and Vila Real de Santo António, located near the river mouth, and the Natural Park of the Guadiana Valley, occupying an area of 70,000 ha around the village of Mértola. A demosite was implemented in the Guadiana estuary, with the support of the UNESCO's International Hydrological Program, to demonstrate how it is possible to mitigate and restore the functioning of estuaries and coastal areas impacted by dam construction using ecohydrological solutions. This is a new approach to achieve sustainable water management, based on the study of functional inter-relationships between hydrology and biota at the catchment scale.

Currently, the future environmental sustainability of the Guadiana estuary has to rely on an ecohydrological approach of the Guadiana basin. The conjunction of efforts between academia, NGO's, local populations, local and regional authorities, basin managers, and even tourism entrepreneurs is compulsory to achieve the environmental sustainability of the Guadiana estuary.

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7. Chemical stressors in the Guadiana River

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7.1. What is this Chapter about?

The Guadiana River, the fourth major river of the Iberian Peninsula, represents an important aquatic system from a socio, geo and ecological point of view for Portugal and Spain. Important economic activities such as agriculture, tourism and aquaculture are present along with several economic facilities such as harbour (commercial and fishing), marina and small shipyards for construction and repair of small vessels. All these activities generate wastes some of them toxic to the aquatic environment. That is why in the river there are several aquatic species some of them endemic, rare and even threatened. Recently, the water regime of the river changed due to the construction of the Alqueva Dam (the largest artificial lake in Europe) with the capacity to store 4 150 hm^3 of water, which reduced the river flow and the sediment transport to the coastal area. This flow reduction might have an impact in the levels of the stressors present in the river.
The above referred anthropogenic activities and their technological development imply the use of a lot of materials, especially metals, which are generally obtained as a result of mining exploration. The exploration of these metals give origin to the production of acid mining waste containing high amounts of metals some of which are toxic to the aquatic species and to humans. For these reasons, metals are considered traditional contaminants to the aquatic systems. Furthermore, estuaries are also targeted for several other economic services such as harbours and marinas for receiving commercial ships, ships maintenance and nautical activities, which are another source of pollutants. Indeed, all these activities if not properly managed can introduce chemical stressors such as petroleum hydrocarbons that are highly toxic to the aquatic environment. On the other hand, the enhancement in urban development, increasing the population that lives near the coast and mainly in the vicinity of the estuaries, results in the production of significant amounts of solid and liquid wastes containing several other chemical stressors. Moreover, the increase of human life expectancy is related to the increasing use of pharmaceutical compounds that are used in hospitals or at home. Therefore, these compounds were detected with significant concentrations in rivers and coastal areas around the world. However, the available technology to treat wastewater effluents is unable to eliminate most of them in the waste treatment process reason why they can easily reach the aquatic systems, inducing a serious threat to the aquatic and human health. For that reason, chemical stressors such as these pharmaceutical compounds are considered emerging contaminants to the aquatic environment.

7.2. Sources of Stressors in the Guadiana River

In the Guadiana River the majority of anthropogenic sources of chemical stressors are metals (among the most toxic Cd, Pb and Hg), persistent organic compounds (like polycyclic aromatic hydrocarbons-PAHs, biphenyl polychlorides-PCBs), pharmaceutical and personnel care products (like UV filters and fragrances). These traditional and emerging contaminants were detected in the water and are present in the sediments where they sink and become available for the aquatic organisms, in which they are then accumulated. Once accumulated in the aquatic organisms, they can induce biological changes in their metabolism resulting, most of the time, in a threat to these organisms' health. Because most of them are important as human food source they can also represent a threat to human health. In the Guadiana River, our studies revealed metal contamination, especially regarding lead, in water, sediments and fresh and marine organisms, indicating biological effects related to these stressors and revealing an impact of the acid mine drainage from the Minas of São Domingos located in the upper part of the river. Nevertheless, an additional source of metals was also detected as the result of the impact of sewage and tourism activity in the mouth of the river. In addition persistent organic pollutants (POPs), including PAHs, PCBs, and tributyltin (TBT) used in antifouling paints and herbicides, were also detected in the same samples. The presence of these compounds is responsible for endocrine disruptor effects detected in the aquatic bivalves present in the river. Direct human impact due to personal care was also detected in bivalves through the presence of UV filters coumpounds (2-ethyl-hexyl-4-trimethoxycinnamate - EHMC, octocrylene -OC and octyldimethyl p-amino benzoic acid - OD-PABA) that are used in sun tan lotions and through two types of musk (galaxolide and musk-ketone) present in fragrances, indicating that, besides bathing activities, wastewater discharges might also be a source of these compounds. Finally several pharmaceutical compounds, from different therapeutic classes, were detected in water namely analgesics, anti-asthmatics, lower lipid agent, anti-inflammatory, anxiolytics and antidepressants revealing the inefficiency of sewage treatment. The presence of diclofenac known as Voltaren in the Guadiana River is a cause of concern due to the effects that this compound can cause to aquatic organisms. These effects led to the inclusion of diclofenac in the list of toxic substances of concern of the EU Directive known as the Water Framework Directive (WFD), which main objective is that all European Waters reach a good ecological status by 2020. Therefore, diclofenac levels as well as those of the other stressors identified in the present chapter need to be followed in future studies in the Guadiana River.

7.3. Metals detected in the water of the Guadiana River

As already referred above, economic activities induce major anthropogenic sources of contaminants, some of them being considered major point sources. This is the case for industrial effluents, wastewater discharges and waste disposal sites including historic mining exploration from the Iberian pyrite belt. The other sources are considered diffuse sources like agriculture run off, road run off, accidental oil spills, etc …
In the Guadiana River, one of the major metal point sources is the acid mining waste from São Domingos Mines (Figure 7.1).

Figure 7.1.
Photography of acid mining water from S. Domingos, showing red-yellowish colour linked to iron and other high metal contents (photograph by Ana Gomes, 2007).

The exploration of iron (Fe) and cupper (Cu), along with lead (Pb) and zinc (Zn) in this mine dates back to prehistoric times (age of iron and bronze) but the largest quantities of these metals were extracted in the 19^{th} and 20^{th} centuries. Since then, the abandoned areas of the mine had a very weak intervention with regard to environmental remediation. Therefore, the areas of un-remediated mine waste and discharge of acid mine waters are the principal sources of metal pollution in the river; the metals are transported into the river flow and then dissolved or adsorbed to the suspended particulate matter. In fact, suspended particulate matter comprises iron-rich particles, with up to 12 % in weight of Fe, that also have high concentrations of Pb (20–80 ppm) and even higher concentrations of Cu and Zn during periods of moderate flow (i.e. winter). As for the dissolved phase, the information available for the presence of metals, besides for Pb, dissolved in water is scarce and only cadmium (Cd) and cupper (Cu) have been measured in waters one mile from the mouth of the river, with concentrations up to 0.36 nM and 11 nM, respectively.

A **B**

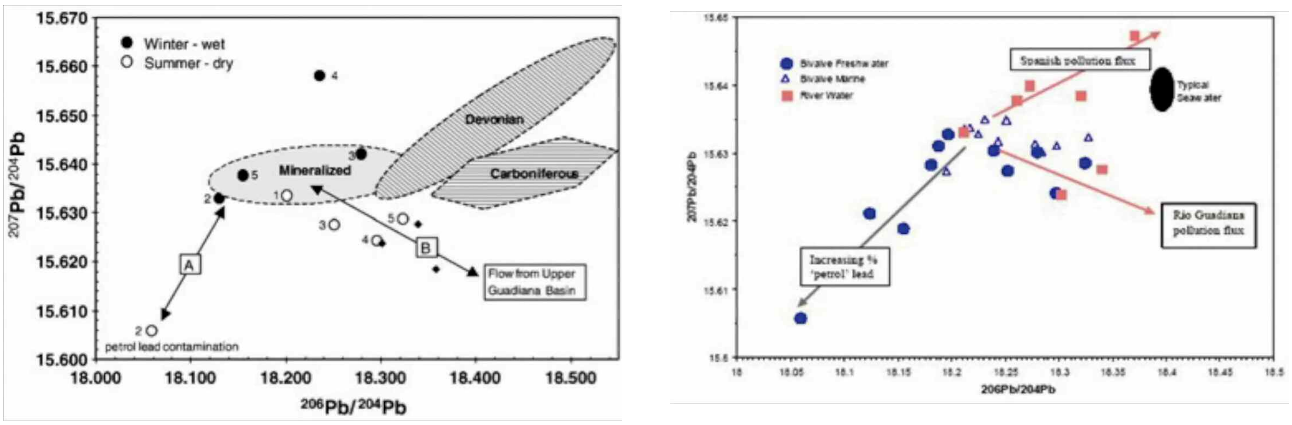


Figure 7.2.

A) Seasonal variation in the lead isotopic composition ($^{207}Pb/^{204}Pb$, $^{206}Pb/^{204}Pb$ ratios) of C. fluminea in the lower Guadiana River (sample sites as for Fig. 7.5.). Key: Summer values (○), winter (●) values. 'Devonian' defines lithogenic lead associated with volcanic and sedimentary rocks that host the Iberian Pyrite Belt (IPB) ore deposits. 'Mineralised' defines anthropogenic lead associated with mine contaminated soils. 'Carboniferous' defines lithogenic lead of unmineralised rocks south of the IPB. Small filled rhombuses (♦) are the isotopic composition of lower Guadiana River water sampled during the dry season (unpublished data provided courtesy of the Universities of Aveiro and Huelva: Surface and Groundwater Studies, UTPIA Project). B) Lead isotopic composition and anthropogenic (Company et al., 2008).

As Pb is a metal with no known biological function, it is considered as a priority substance of the Water Framework Directive (WFD). Therefore, a good environmental practice is needed to assess the impact of Pb in this aquatic system. The anthropogenic sources of Pb include burning of leaded fuels, metal smelters and mining activities. The toxic lead (Pb) effects, in aquatic organisms and mammals, are a result of Pb ability to displace other metals that are considered essential for biological functions, such as calcium (Ca), Fe and Zn.

In the Guadiana River, dissolved Pb concentrations during summer are lower than minimum detectable values by the existing analytical methods (<0.1 g l^{-1}) except in the Pomarão area where the levels are 0.2 g l^{-1}. However, in winter, levels of dissolved Pb are higher (ranging from 0.3 to 0.8 g l^{-1}) and attributed to the run-off contribution of acid mining waste and from land run-off. These Pb sources were assessed using high precision isotopic techniques to measure Pb isotopic ratios ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$), which correspond to isotopic signatures of Pb sources (see results in Figure 7.2). In noncontaminated places, lead was not present and no isotopic signature could be measured. In the other sites, results revealed diverse Pb anthropogenic sources. The dominant one was from the impact of acid mine drainage, being also traced in the river until the open marine environment. In general, the Pb isotopic ratios fall within a field defined by the Devonian volcanic formation and sedimentary rocks that host the massive sulphide ore deposits of the Iberian Pyrite Belt. However, this technique also allows to identify a mixing in the Guadiana water between streams draining Devonian rocks and streams draining areas of the Carboniferous cover rocks. The same technique applied to fresh and marine bivalves suggest marked seasonal changes in the source of mine-related pollution. During the summer, most of the pollution is from the mining area, whereas in winter, it is from the Spanish mining sources. In addition to mining sources, results also revealed the presence of a petrol-lead additive component; especially near the marina and the major highway bridge between Spain and Portugal (Figure 7.3), even if it is forbidden in both countries since 1999.

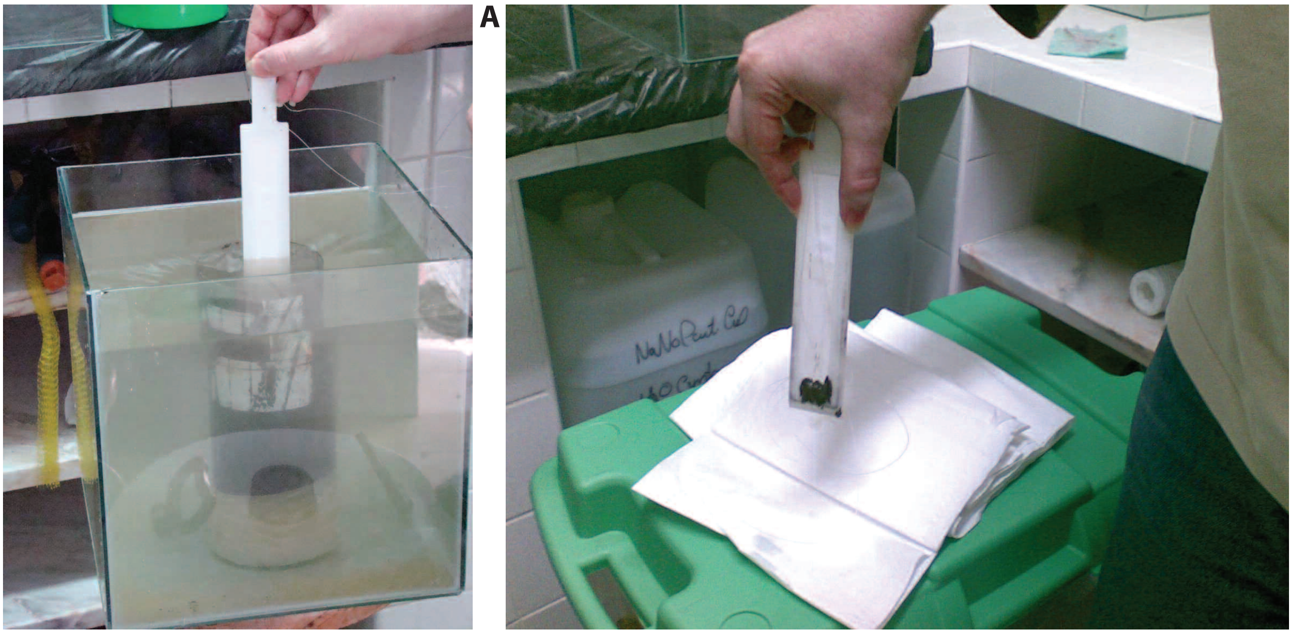
Furthermore, petrol lead was also detected in freshwater bivalves downstream of the population centres of the River Guadiana confirming that besides mining wastes there are other Pb sources in the estuary. Finally, there might be still another Pb source to be confirmed in the Guadiana linked to hunting and respective shooting activity that is significant in the area.

Figure 7.3.
The international bridge over the Guadiana River, relating Spain and Portugal (photography by Maria Gonzalez-Rey).

7.4. Metals detected in sediments from the Guadiana River

Cadmium (Cd), cupper (Cu), manganese (Mn), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) levels are particularly high in Guadiana sediments since 1999, exhibiting a site and seasonal dependence. Cd, Ni, Pb and Zn concentrations were above the established Sediment Quality Guidelines (SQG) for Effects Range Low (ERL) in more than 50 % of the samples whereas Hg concentrations were above the Effects Range

Medium (ERM). This confirms that metal levels observed in the Guadiana estuary are from anthropogenic sources but not directly linked to oil usage since PAHs concentrations in sediments were always well below the ERL values.
However, these metal concentrations represent the total amount of metals present in the sediment and not only the quantity of metal available by the organisms, referred as the bioavailable metal concentrations. Accordingly, new methodologies based on new devices were developed to assess metal levels bioavailable in sediments, which also avoid the need for sediment sampling. These devices are known as Diffusive gradients in thin (DGT) films (see Figure 7.4) and were applied to document metal bioavailability and toxicity in estuarine sediments of the Guadiana.



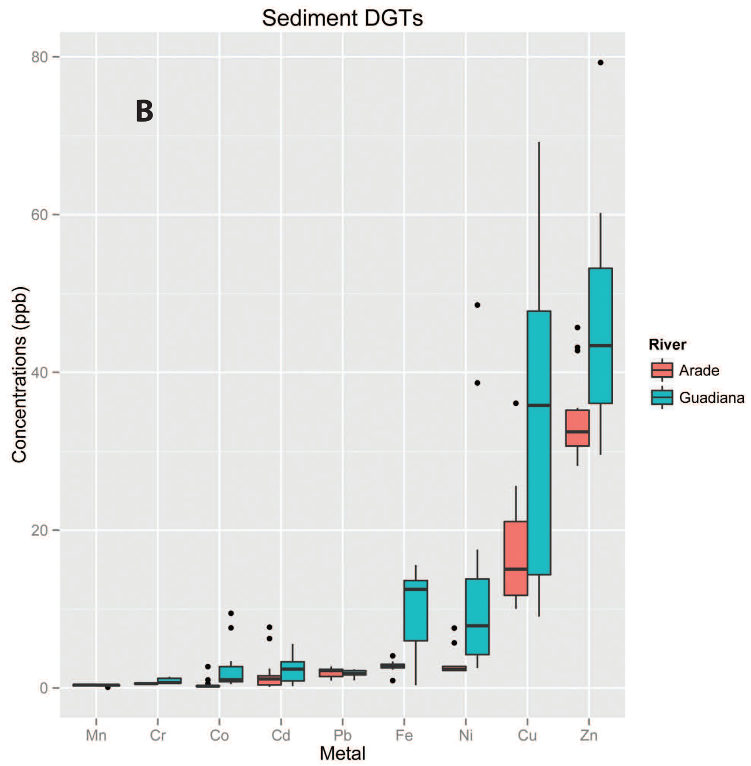


Figure 7.4.
(A) Photography of the apparatus mounted in the laboratory for using the DGTs in sediment cores (by Maria Gonzalez-Rey); (B) Concentrations of metal pollutants in sediments from Arade and Guadiana River obtained from DGTs.

For such this study, one sediment core was collected from the Guadiana estuary and another from the Arade estuary, for comparison purposes. Both cores were stored in laboratory, close-to-natural conditions, with one DGT probe placed in each of them for 15 days. The results showed the same tendency in both estuaries with metal concentrations ranging from 0.32 ppm for Mn to 46.11 ppm for Zn (Figure 7.4, Mn>Cr>Co>Cd>Pb>Fe>Ni>Cu>Zn), but with higher concentrations in the Guadiana than in the Arade, as well as higher ranges. The more important differences between the two sediments were found in the concentrations of Fe, Ni, Cu and Zn (Figure 7.4), which correspond to the main metals explored in the S. Domingos Mines exploration.

In parallel to these metal bioavailability evaluations, a sediment toxicity test was also carried out using a method known as Microtox solid phase test at two different sites from the Guadiana River. The results revealed half maximum effective concentrations (EC_{50}) of 6.9 and 21.8 mg ml^{-1} w.w. in the two sites, indicating that upstream sediments are more toxic than in the mouth of the estuary. These toxicity levels seem to be related to the levels of Cd, Hg, Pb and Ni present in the sediments that were higher than the ERL.

7.5. Metals detected in bivalve species from the Guadiana River

Freshwater clam *Corbicula fluminea* (an alien freshwater species recently introduced in the Guadiana River) and other marine species (the oyster *Crassostrea gigas*, the mussel *Mytilus galloprovincialis* and the clam *Scrobicularia plana*) are well-established indicators to assess the impact of stressors in the aquatic environment. Accordingly, these species were collected from several sites (Figure 7.5) in order to identify sources and effects of lead (Pb) in the Guadiana River.

The concentrations of Pb in the whole soft tissues of these bivalves are represented in Figure 7.6 and show that Pb concentrations in *C. fluminea* at the site adjacent to the abandoned mining area (Mina de São

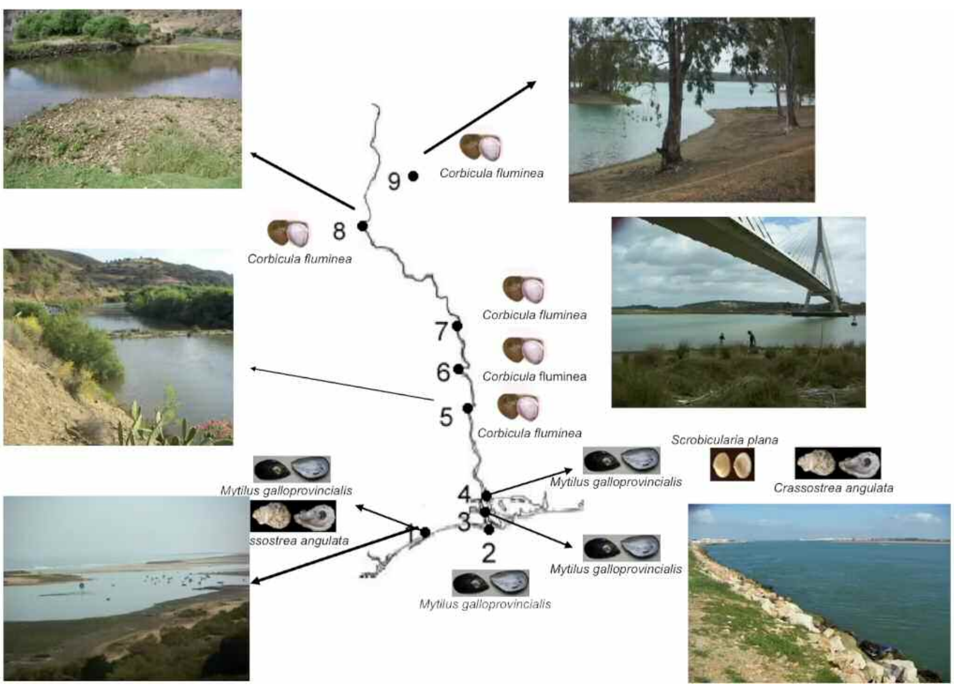


Figure 7.5.
Sampling sites of several bioindicators along a marine to freshwater gradient, from site 1 to site 9 respectively: oyster *Crassostrea gigas (*marine species), mussel *Mytilus galloprovincialis* (marine species), clam *Scrobicularia plana (*marine species) and clam *Corbicula fluminea* (alien freshwater species) (illustration by Rui Company).

Domingos) are 6-fold higher than at the main river sites (2.49 ppb compared to 0.2-0.5 ppb) (see Figure 7.5). For the marine species (mussels, oysters and clams), the highest Pb concentrations were in the deposit feeders *S. plana* (3.50 ppb) and *D. trunculus* (1.95 ppb) that are able to accumulate bioavailable chemical stressors both from water and sediments. High Pb concentrations, as well as high Cu concentrations, were also found in deposit feeder *Nereis diversicolor* (6.84 and 37.47 ppb, respectively), with levels higher than those obtained for the same species in the Southern Iberian coast. The lowest Pb levels were detected in the filter feeder species mussels (*M. galloprovincialis)* and oysters (*C. angulata)* (<0.38 ppb) showing a decreasing trend towards the mouth of the river. However, Pb concentrations in mussels (*M. galloprovincialis)* from the Guadiana estuary were the highest of the South Coast of Portugal. These results confirm the isotopic data, presented above, indicating that mining is an important anthropogenic Pb source to the Guadiana River. Besides Pb, other metals (Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb and Zn) as well as organic and organometallic compounds (polyaromatic hydrocarbons- PAHs, polychlorinated byphenyls – PCBs, trybutiltin -TBT) found in petrol, electric conductors and antifouling paints, respectively, were also detected in marine species from the Guadiana River. Metal concentrations in in the same bivalves species and sites as mentioned in Figure 7.5 decreased according to the following order: oysters *(Crassostrea angulata*), followed by clams (*S. plana)* and mussels (*M. galloprovincialis)*. However, cupper (Cu) and zinc (Zn) concentrations analysed in these species did not show any spatial or seasonal changes and their concentrations in mussels from the Guadiana River are comparable with the ones from other parts of the southern Portuguese coast (2.35 and 380±171 ppb for Cd and Zn respectively).

7.6. Biological effects in marine bivalves as a result of exposure to metallic chemical stressors

The exposure of marine bivalves to chemical stressors has different biological effects depending on their origin and chemistry, either metallic or organic, but also depending on their bioavailability both in time and in quantity. Some biological effects are so fast responding that they are considered as sentinel species for early pollution alert.

One of the early warning effects of the presence of lead (Pb) in biological species is the activity inhibition of three enzymes (aminolevulinic acid dehydratase - ALAD, coporphyrinogen oxidase, and ferrochelatase), the effects on ALAD activity being the more important. It is also why the degree of inhibition of ALAD activity on human erythrocytes is used to clinically estimate Pb poisoning in humans. ALAD levels in bivalves from Guadiana River are presented in Figure 7.6. Mean ALAD activity measured in the same bivalve species varies by an order of magnitude and is negatively related with Pb concentrations among the different species. Examples of this relationship are shown in Figure 7.6B for the fresh water species *C. fluminea* and the marine mussel *M. galloprovincialis,* confirming that this enzyme is inhibited in the presence of Pb in these bivalve species. Apart from ALAD inhibition, Pb also induces another early warning system that is the damage in cell membranes of aquatic organisms. This cell membrane damage, measured as lipid peroxidation (LPO), is negatively related with ALAD activity and directly related with some organic compounds (> 4 rings PAHs and total PAHs) concentrations along with high metal levels (Cd, Cr, Ni, Pb and Zn). In summer, LPO in *M. galloprovincialis* was higher than in winter, which suggests an additional environmental stress at this time of the year. Moreover, both summer and winter DNA damage measured in mussels haemocytes collected from the mouth of the estuary are low (10<% Tail DNA<25%) but still higher than when compared to mussels from other sites of the Southern Portuguese coast. This DNA damage is directly related to LPO, indicating that the stressors present in Guadiana promote cell membrane injuries and DNA damage in mussel's haemocytes.

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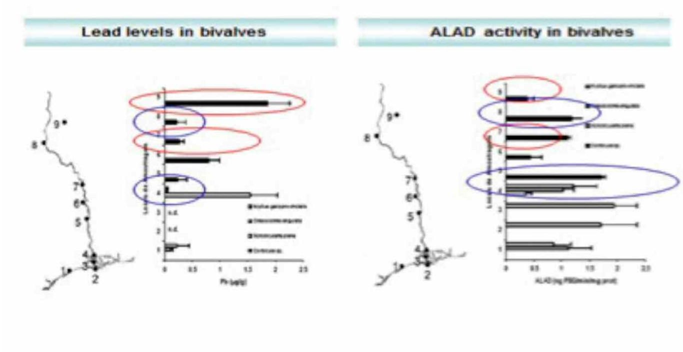

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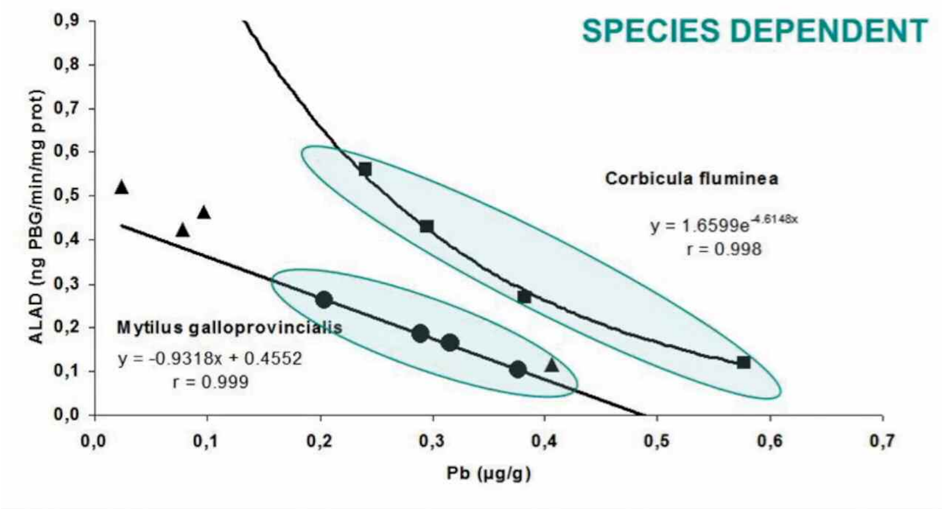

Figure 7.6.
Lead (Pb) concentration and ALAD activity along the salinity gradient (A) in *M. galloprovincialis* and *C. fluminea* (B), showing an inverse relationship between Pb concentrations and ALAD activity (see text for more informations).

Besides enzyme inhibition, there are other parameters that can assess and evaluate the biological effects of aquatic organisms to chemical stressors. For instance, histopathological parameters, a well-established general biomarker to assess the health of aquatic organisms, revealed seasonal differences and alterations in the form and volume of the hepatic cells of the mussels. The digestive gland of bivalves is an important target organ for storage of the presence of pollutants because it plays a central role in metabolizing and detoxifying stressors as well as in eliminating them. Metal levels were determined in the digestive gland of *S. plana* and revealed the presence of arsenic (As), cadmium (Cd), cupper (Cu), lead (Pb) and zinc (Zn).

Finally, nowadays, new technologies known as "omics" are presently used in order to assess the effects of the accumulation of stressors in bivalve tissues. One of these technologies is the proteomics that allows identifying protein changes in certain tissues due to the presence of stressors. Accordingly, a proteomic approach was also used to detect the effect of the metals mentioned above in the digestive gland of the marine clam *S. plana*.

In this study, twenty-one proteins were differentially expressed in the digestive gland of the clams retrieved from the Guadiana River, when compared to those of the same species from the Ria Formosa lagoon. Nine of these proteins were up-regulated, while twelve were down-regulated. These protein changes are related to toxicological mechanisms induced by some of the environmental stressors identified in the Guadiana River.

7.7. Persistent Organic Compounds (POPs)

As seen above, some anthropogenic activities are also directly or indirectly responsible for the release of organic compounds that are persistent and harmful in the aquatic environment and are thus considered as contaminants. This is the case of the persistent organic (PAHs and PCBs) and organometallic (TBT) compounds that are known to be present in tissues of several aquatic species in the Guadiana estuary. The variation of PAHs concentrations in the whole soft tissues of the mussels *(M. galloprovincialis)* are presented in Figure 7.7 and show a significant decreasing trend of PAHs levels in mussel tissues since 1997. It is important to explain here that PAHs are classified and differentiated according to their numbers of benzenic rings, an organic structure in the molecule, and that the persistent PAHs in the Guadiana River are mostly characterized by PAHs that have a high percentage of 5 benzenic rings (>79%) . Moreover, based on the values of the ratios between different PAHs, namely phenantrene/antracene and flourene/pyrene, it is clear that the origin of the PAHs accumulated in Guadiana mussels' tissues is from fuel source (see Figure 7.7)

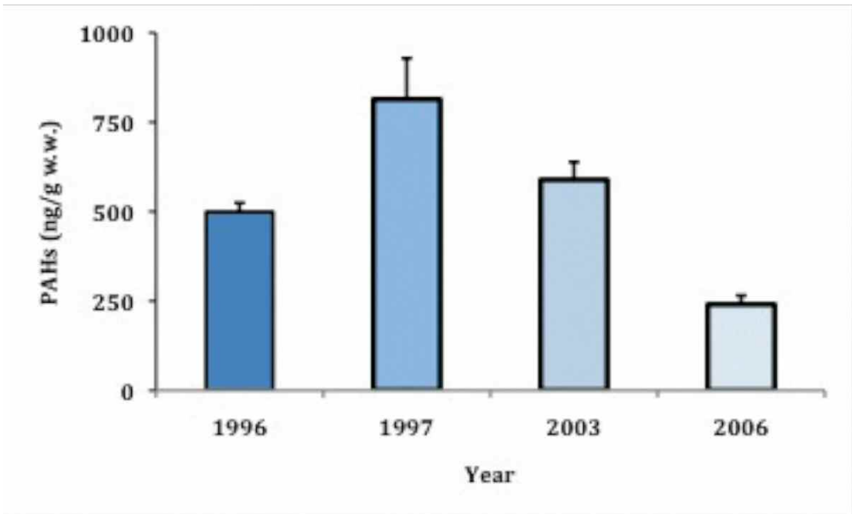

Figure 7.7.
Evolution of PAHs levels in the whole soft tissues of *M. galloprovincialis* for the last 20 years (units in nanograms of PAHs per gram of tissue in wet weight).

As already mentioned above, some chemical stressors accumulated in biological tissues are endocrine disruptors. One of these endocrine disruptors is the organometallic compound known as Trybutytin (TBT) that is responsible for the phenomenon of imposex, which is the superimposition of male characters onto the female of gasteropods, and also intersex, which is superimposition of female characters onto the male characters. This phenomenon was reported in the prosobranch gastropod *Ocenebra erinacea* present in the mouth of the Guadiana River, presenting higher levels of imposex in this species than in other places from the Southern Coast of Portugal. In addition, intersex with several degrees of intensity was also detected in the clam *S. plana* with oocites inside the male testis (ovotestis). The percentage of males affected were in the range between 6 to 71%, which can induce a decrease in the sex ratio of the future population of these species. Besides TBT, several other endocrine disruptor contaminants (EDCs) can be found in water and sediments, including already mentioned PAHs (phenantherene, pyrene, etc.), but also pesticides and their metabolites (atrazine, simazine, prometryn, among others), or herbicides (diuron and bisphenol A). These EDCs, although in small amounts, may also be directly linked with the levels of intersex and imposex detected in the clams or even with other examples of alterations of the endocrine system of marine invertebrates already detected in the Guadiana River.

7.8. New emerging contaminants

The new emerging contaminants, composed essential by personal care products (PCPs) and pharmaceutical compounds (PhACs) gained increasing attention due to their huge consumption and potentially harmful effects detected in the aquatic environment.

Levels of three UV filters used in personal care products such as sunscreens but also in food additives and two types of musk (galaxolide and musk-ketone) used in fragrances are recognized as important organic stressors in the aquatic environment due to their lipophilic properties and potential bioaccumulation. These compounds were detected in mussels *M. galloprovincialis* collected from the beach on the mouth of the Guadiana estuary. Levels of UV filters were higher than galaxolide musk while Musk-ketone, although detected in all samples, had concentrations close to the lower limit of analytical detection. It is important to highlight the fact that, once in the water, musk-ketone produces amino-musk that is another well-known endocrine disruptor compound. These results indicate that the sources of these compounds are not only from direct bathing activities but might also be from wastewater discharges.

On the other hand, other emergent contaminants, such as pharmaceutical products, are used for centuries in human health therapy and are ubiquitous in the environment. However, due to their bioactive action and presence in several types of water bodies they were classified as emerging environmental contaminants. One of the pivotal goals of the Water Framework Directive (WFD) is therefore the need to assess the concentration of these contaminants in water bodies. One of the means to detect the presence of these compounds in the aquatic environment is by using passive samplers known as Polar Organic Compound Integrative Sampler (POCIS, Figure 7.8). These passive samplers were designed to tackle the difficulty of biological data interpretation. Although designed to mimic biological uptake, they also provide a time-weighted average concentration of these pesticides and pharmaceutical compounds, which is a more holistic approach of the water quality status than spot sampling of a water body.

Figure 7.8.
Photography of three Polar Organic Compound Integrative Sampler (POCIS) within their metallic holder, retrieved after staying 30 days in water (photography by Maria Gonzalez-Rey).

With the help of these passive samplers (POCIS), the presence of eleven pharmaceutical compounds were detected in the Guadiana estuary (Figure 7.9), namely in decreasing order of concentrations: paracetamol (analgesic), theophylline and clenbuterol (antiasthmatic), carbamazepine (antiepileptic), gemfibrozil (Lower lipid agent), nordiazepam (anxyolitic), naproxen and diclofenac (anti-inflammatory), alprazolam

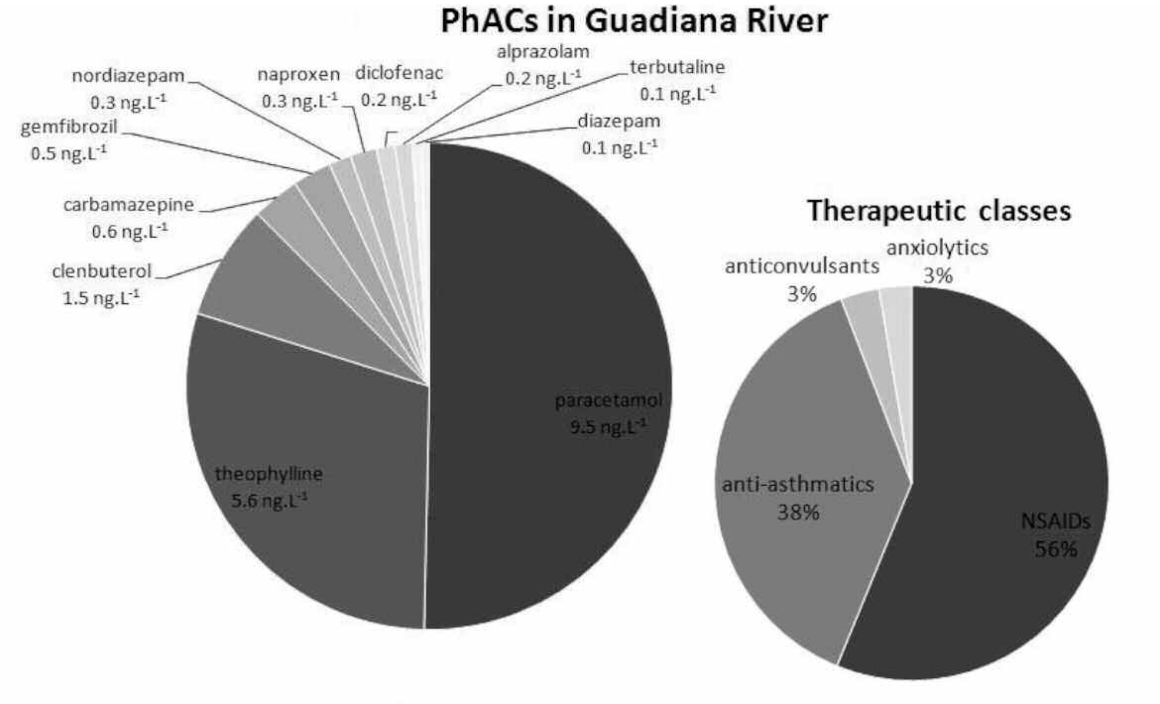

Figure 7.9.
Concentration and therapeutic classes of Pharmaceutical compounds (PhACs) in the Guadiana River.

(antidepressants), terbutaline (antiasthmatic) and diazepam (anxyolitic). Comparing the concentrations of pharmaceutical therapeutic classes obtained in the Guadiana revealed that the highest percentage represents analgesic compounds (51%), followed by the antiasthmatics (38%) and a similar percentage of antiepileptic, lower lipid agent and anti-inflammatory (3%) and lower and similar levels of anxyolitics and antidepressants (1%). Comparing these levels with those found in the same period in the Arade river, it appears that the concentrations of anti-inflammatory (naproxen and diclofenac) were 2-fold lower in the Guadiana River and that Ibuprofen, fluoxetine and bromozepam were present in the Arade and not detected in the Guadiana River. The presence of diclofenac anti-inflammatory in the Guadiana River is a cause of concern due to the known biological effects of this compound, reason why it was included , and by the European Union in the list of priority substances of WFD.

7.9. Conclusion

Although one of the major rivers of the Iberian Peninsula, the Guadiana River presents detectable, and some times high, levels of traditional contaminants (metals but also persistent organic compounds) as well as of emerging compounds (personal care products and pharmaceutical compounds), some of which are known to induce endocrine disruption contaminant (EDC) effects. In most of the cases, the detected levels are higher that in other parts of the Southern Portuguese Coast. These chemical stressor levels detected have already shown some effects in the aquatic species, which might be a cause of concern for the economy and the health of the Guadiana River.

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GLOSSARY

ADVECTION: bulk transport of a substance, heat or momentum.

ALGAL BLOOM: an algal bloom is a rapid increase of algal cell numbers in a water body. Generally such blooms have low species diversity and are associated with changed environmental conditions, such as excess nutrients. Most algal blooms are harmless and short-lived.

ALLUVIAL ESTUARIES: estuaries consisting of unconsolidated sediment originating from the river and the sea showing an upstream width reduction as an exponential function and almost no bottom slope (also called "coastal plain" estuaries).

ANTICYCLONIC CIRCULATION: (the opposite of a **cyclonic circulation**): large-scale circulation around a region, which is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

ANTICYCLONIC CIRCULATION: (the opposite of a **cyclonic circulation**): Large-scale circulation around a region, which is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

AQUIFER: underground sediment or rock saturated in water that can flow easly through them.

AXIAL VELOCITY: along-channel velocity component.

BAROTROPIC GRADIENT: difference in pressure generated by a sloping sea surface.

BARROCAL: It is one of the three geomorphological units that are present in the Algarve region. It is the zone located between the 'Serra' and the 'Litoral'. The Barrocal's rocks rocks formed during the Jurassic and Cretaceous Periods (see annex I).

BATHYMETRY: the measurement of underwater depth.

BED FRICTION: friction of the water against the bottom of the channel which contribute to reduce the water velocity.

BEDFORMS: morphological features such as dunes or ripples which result from the interaction between the flowing water and the sediment (see also sediment and annex II).

BEDROCK OUTCROP: rock exposed at the surface of the Earth with no soil cover (see also bedrock).

BEDROCK: unbroken solid rock, often overlaid by unconsolidated sediment, soil or rock fragments.

BIOCLASTS: fragments of skeleton pieces such as, shells, teeth, bone, spicules, diatom frustules (see also diatoms) and foraminifera tests (see also foraminifera).

BLUE CARBON: it is the carbon stored by the organisms and sediments of world's oceans and coastal ecosystems.

BOUNDARY LAYER: layer of fluid close to a bounding surface where the effets of viscosity are important to fluid motion.

BOUNDARY TURBULENCE: near-bed turbulence of the water (see also boundary layer).

CAMBRIAN: The Cambrian Period was the first geological Period of the Paleozoic Era and is divided in into three epochs: Early Cambrian (541 ± 1.0 to 509 ± 1.7 million years ago [mya]), Middle Cambrian (509 ± 1.0 to 497 ± 1.7 mya) and Late Cambrian (497 ± 1.0 to 485.4 ± 1.7 mya).

CHANNEL MORPHOLOGY: shape of the river channel (see also meandering channel and annex IV).

CHLORITE: mineral of the phyllosilicate group (see also phyllosilicate).

EBB TIDAL DELTA: sediment accumulation at the seaward mouth of tidal inlets due to the interaction of tidal currents and waves (see also inlet).

ECOLOGICAL DISCHARGE: minimum flow to ensure the ecological quality and the hydrological and ecological functions of the drainage networks.

EDDY: characterized by currents which flow in a roughly circular motion around a center. The sense of rotation of these currents may either be cyclonic or anticyclonic.

ENDEMIC SPECIES: it is a species that grows only in a specific region and nowhere else.

ENDORHEIC LAGOON: lagoons that retains all the water that falls in it because they have no outflow.

EROSION: set of processes acting at the Earth surface that remove the products of the rocks weathering (see also weathering).

EUKARYOTES: organisms whose cells contain a nucleus and other organelles enclosed within membranes.

EUSTATIC: sea level changes occurring due to an alteration in the volume of water in the oceans or, alternatively, a change in the shape of an ocean basin and hence a change in the amount of water the sea can hold. Eustatic change is always a global effect.

EVENNESS: is an ecological index which measures the homogeneity of species distribution. Eveness will be the highest when each species of an assemblage has the same number of individuals.

FELDSPARS: one of the most common group of the rocks minerals.

FINE SAND: particles which diameter lies between 0.125 mm and 0.25 mm (see annex III).

FLOOD TIDAL DELTA: sediment accumulation at the landward mouth of tidal inlets (see also inlet).

GEOMORPHOLOGY: science concerned with the land surface forms and processes responsible for their generation and evolution.

GORGE: strech of the river valley shoing a marked narrowing.

GRAVEL: particles which diameter lies between 2.00 mm and 4,096 mm (see annex III).

GREEN TOURISM: it is a kind of tourism that promotes the contact between people and nature, increasing the environmental education of the visitor in exchange for funds needed for the economic development and conservation of an area, with a low impact on it.

GULF OF CADIZ: wide basin located in the northeast Atlantic Ocean, west of the Strait of Gibraltar, between the Iberian Peninsula and northwest African coasts.

GULF: portion of an ocean partially enclosed by land.

HABITAT: it is the environment in which a species occurs.

HALOPHYTE SPECIES: it is a species of terrestrial plant that grows in environments with high salinities, due to the marine influence.

HYDRODYNAMIC: science that deals with the water motion and forces acting on objects moving in water.

IBERIAN PYRITE BELT: area located in the SW of the Iberian Peninsula that has been mined during more than 5,000 years. For additional information: (http://www.igme.es/patrimonio/GEOSITES/Chapter_04_SGFG.pdf)

ILLITE: mineral of the phyllosilicate group (see also phyllosilicate).

INLET: connection between a river or coastal lagoon and the ocean.

ISOHALINE CONTOUR: line connecting all points of equal salinity.

KAOLINITE: mineral of the phyllosilicate group (see also phyllosilicate).

LITHIC COMPONENTS: fragments of minerals and rocks in the sediment (see also sediment and annex III).

LITTLE ICE AGE: Was a period of climate cooling , extending from the 16th to the 19th centuries, or from about 1300 A.D. to about 1850 A.D. (A.D. = 'Anno Domini', or 'after Christ').

LITTORAL DRIFT OR LONGSHORE TRANSPORT: transport of non-cohesive sediments, i.e. mainly sand, along the coast due to the action of breaking waves and alongshore currents.

LITTORAL TRANSPORT: movement of sediment both parallel (longshore drift) and perpendicular (cross-shore transport) to the shore.

MEANDERING CHANNEL: sinuous fluvial channel (see annex IV).

MEDIEVAL WARM PERIOD: was a time of particularly warm climate in the North Atlantic region, lasting from about 950 A.D. to 1250 A.D. (A.D. = 'Anno Domini', or 'after Christ').

MEDIUM SAND: particles which diameter lies between 0.25 mm and 0.50 mm (see annex III).

MESOTIDAL REGIME: tidal range variation between 2 m and 4 m (see also tidal range).

METAZOANS: the Metazoa are a major group of multi-cellular eukaryotic organisms. Differently to the protozoans, they possess body layers, organs and a nervous system.

MORPHODYNAMIC EQUILIBRIUM: concept in which the net sediment mass of a system is balanced for example because erosion equals deposition (see also sediment).

MORPHODYNAMIC: landscape changes and processes responsible for it.

MUD: particles which size is lower than 0.063 mm (see annex III).

NEAP TIDE: a tide in which the difference between high and low tide is small, when the Sun and Moon are at right angles from the Earth.

NEARSHORE: zone extending seaward from the surf zone up to depths were longshore currents transport sediment (see also littoral transport and annex VI).

OFFSHORE: zone seaward from the nearshore (see also nearshore and annex VI).

OSMOREGULATION: capacity that a living being has to control the water content and the concentration of salts in the body, ensuring adequate conditions for metabolic activity.

PERMEABILITY: the ease of fluids to flow through the sediment or rock.

PHYLLOSILICATES: group of sillicate minerals which are disposed in sheets (see also sillicates).

PHYTOPLANKTON AND PHYTOBENTHOS: phytoplankton and phytobenthos are any group of organisms capable of photosynthesis (diatoms, dinoflagellates, green algae, coccolithophorids and cyanobacteria) that float in the upper part of the water column (phytoplankton) or live attached to a substrate such as sand and mud (phytobenthos).

POORLY SORTED SEDIMENT: sediment that contains a large range of grain sizes (see annex III).

QUARTZ: mineral formed by silicon and oxygen. Is one of the most abundant minerals in the Earh crust.

RAPIDS: steep portions of the river channel inducing an increase in the water velocity and turbulence.

RIPARIAN VEGETATION: It is the vegetation that grows around the freshwater courses (rivers or streams).

RIPPLES: sedimentary structures produced by hydraulic currenst or wind (see annex II).

RNA RIBOSOMAL: sequences of of a component of the ribosome (a cell organelle) which is responsible for the protein synthesis in the organisms.

ROSE BENGAL: is a stain. Used in solution (2 g of Rose Bengal per 1 liter of ethanol) to stain of pink the cytoplasm of the living organisms, allowing to distinct between tests that were alive or dead at the time of their sampling.

SALT MARSHES: coastal wetlands that are flooded by salt water during the rising tides.

SEDIMENT FACIES: physical, chemical and biological aspects of a sediment conferred by the environment where sediment was deposited.

SEDIMENT SORTING: distribution of the grain size in sediment (see annex III).

SEDIMENT SOURCE: In geology, sediment source is the term used to designate the mechanisms/channels through which sediments are supplied from their original source location into a specific area or depositional setting.

SEDIMENT TRANSPORT: movement of the sediment promoted by rivers, wind, waves and currents.

SEDIMENT: particles resulting from the rocks weathering (rock fragnets and minerals-lithic components). Some biological material may also be added to the lithics such as shells and wood pieces (bioclasts). See also lithic components, bioclasts and annex III).

SEMIDIURNAL TIDE: tidal regime of two high tides and two low tides each day.

SERRA: It is one of the three geomorphological units that are present in the Algarve region. It is the zone located in the Northern part of the region, where there are rocks from the Paleozoic (see annex I).

SILLICATES: dominant minerals of the Earth crust composed mainly by the silicon ion.

STRUCTURAL CONTROL: we say that some geological aspect show structural control when its genesis and evolution is mainly forced by tectonics or geometry of the rocks masses (see also tectonics).

SUSPENDED LOAD: portion of the sediment that is carried in suspension by a fluid flow, and consists of particles generally of the fine sand, silt and clay size.

TECTONICS: processes related to the structure and properties of the Earth crust such as mountain building and the displacement of the continental plates.

TIDAL CYCLE: sequence of one low tide and one high tide.

TIDAL RANGE: difference in height between the low tide and the hight tide lines.

TRANSGRESSIVE, MARINE TRANSGRESSION: geologic event/process during which sea level rises relative to the land and the shoreline moves toward inland, resulting in flooding of the emerged continental areas. It can be caused by tectonic events, eustatic changes or adjustments following removal of ice or sediment load.

TRIBUTARY: stream flowing to a larger one.

TURBIDITY: opacity of the water caused by suspended particles.

UPWELLING: upward movement of deep colder waters, normally nutrient-rich towards the ocean surface. This oceanographic phenomenon occur when the wind blows parallel to a coastline, surface waters are pushed offshore and water is drawn from below to replace the water that has been pushed away.

VALLEY INCISION: fluvial erosion into the bedrock leding to the river valley deepening. This process is favoured by the relative fall in sea level.

WATERFALL: sudden fall of water due to a change in the gradient of the river channel.

WATERSHED: area of land where all the rainwater that falls in it feed a common outlet trough a drainage net.

WAVELENGTH OF DUNES: distance between two consecutive dune crests.

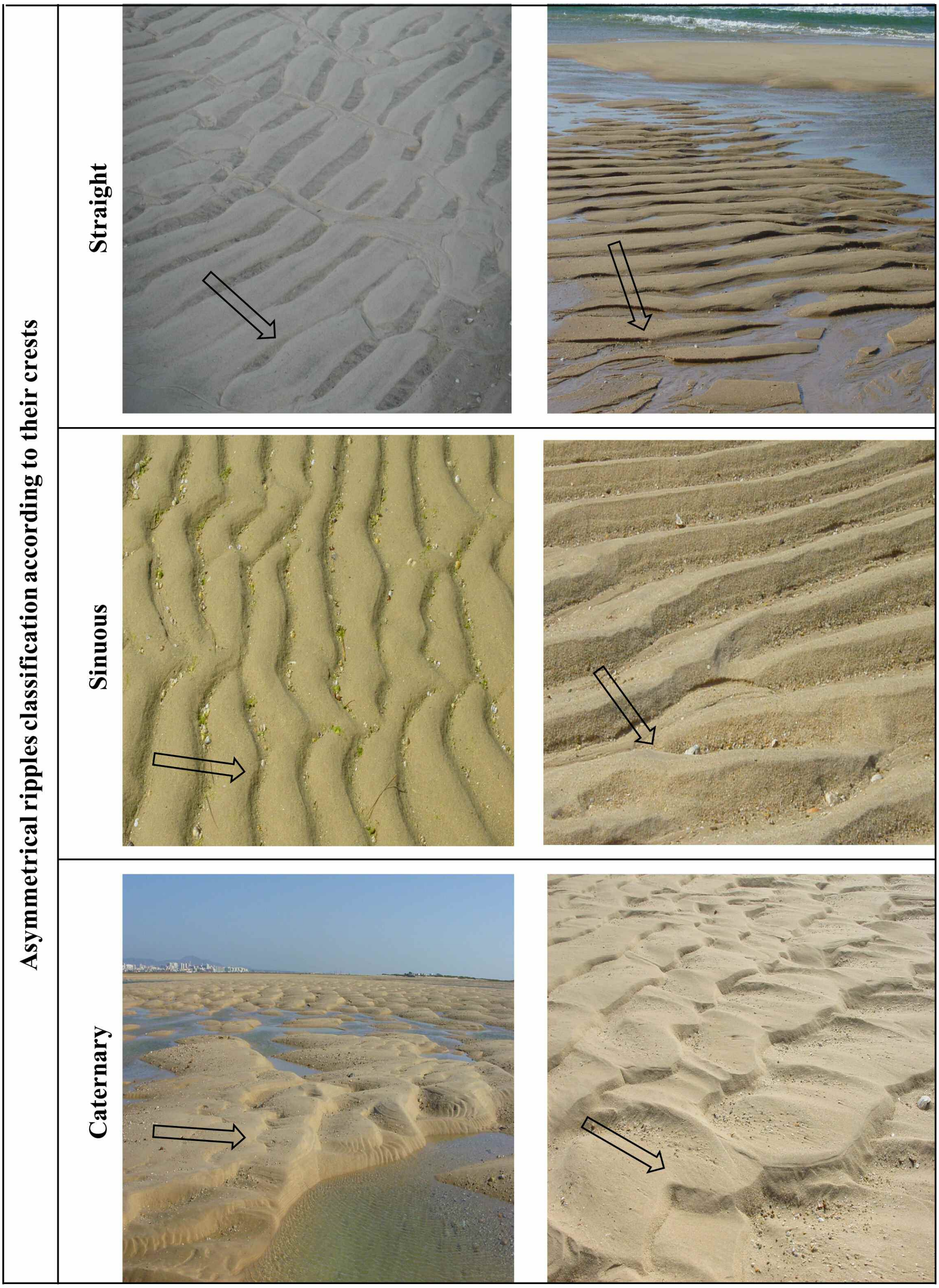
Annexes

Million years	Eon	Era	Period	Epoch	
0,011	PHANEROZOIC	CENOZOIC	QUATERNARY	HOLOCENE	From the Greek *holos* (whole) and *kainos* (new). End of the Pleistocene glaciations. Rise of Human civilization (Stone, Bronze and Iron Ages).
2,6				PLEISTOCENE	From the Greek *pleistos* (most) and *kainos* (new). Climatic instability with successive cycles of glacial-interglacial. Evolution of anatomically modern humans.
24			NEOGENE		Means "new- born" . Diversity of horses and mastodons. Appearance of *Homo habilis*.
65			PALEOGENE		Means "ancient- born". Formation of the Antarctica ice cap Appearance of several modern mammals.
114		MESOZOIC	CRETACEOUS		From chalk the rock forming the cliffs of the English Channel. Flowering plants proliferate and many types of insects.
213			JURASSIC		Jura mountains between France and Switzerland. Many types of dinosaurs. Mammals were small yet common. First birds.
248			TRIASSIC		From trias, the three phases of folding affecting the European rocks. Dinosaurs dominant on land and appearance of the first mammals and crocodilian.
286		PALEOZOIC	PERMIAN		Perm province from the ex USSR. Amphibians remain common.
360			CARBONIFEROUS		Coal deposits. First reptiles.
408			DEVONIAN		Devonshire, England. First trees and insects.
438			SILURIAN		Siluros Celtic tribe of Wales. Early corals. First vascular plants and fishes.
505			ORDOVICIAN		Ordovico Celtic tribe of Wales. Diversity of invertebrates. Early corals.
541			CAMBRIAN		Cambria was the Roman name of Wales. Major diversification of life.
4 600	PROTEROZOIC				

Annex I
Geological Time Table

This organization of the geological time since the Earth origin (4 600 million years ago) is a very simplified version. Note that the graduated scale of ages is not proportional to the lasted interval of Periods and Eras. It was a functional option to fit one page and still contain additional information.

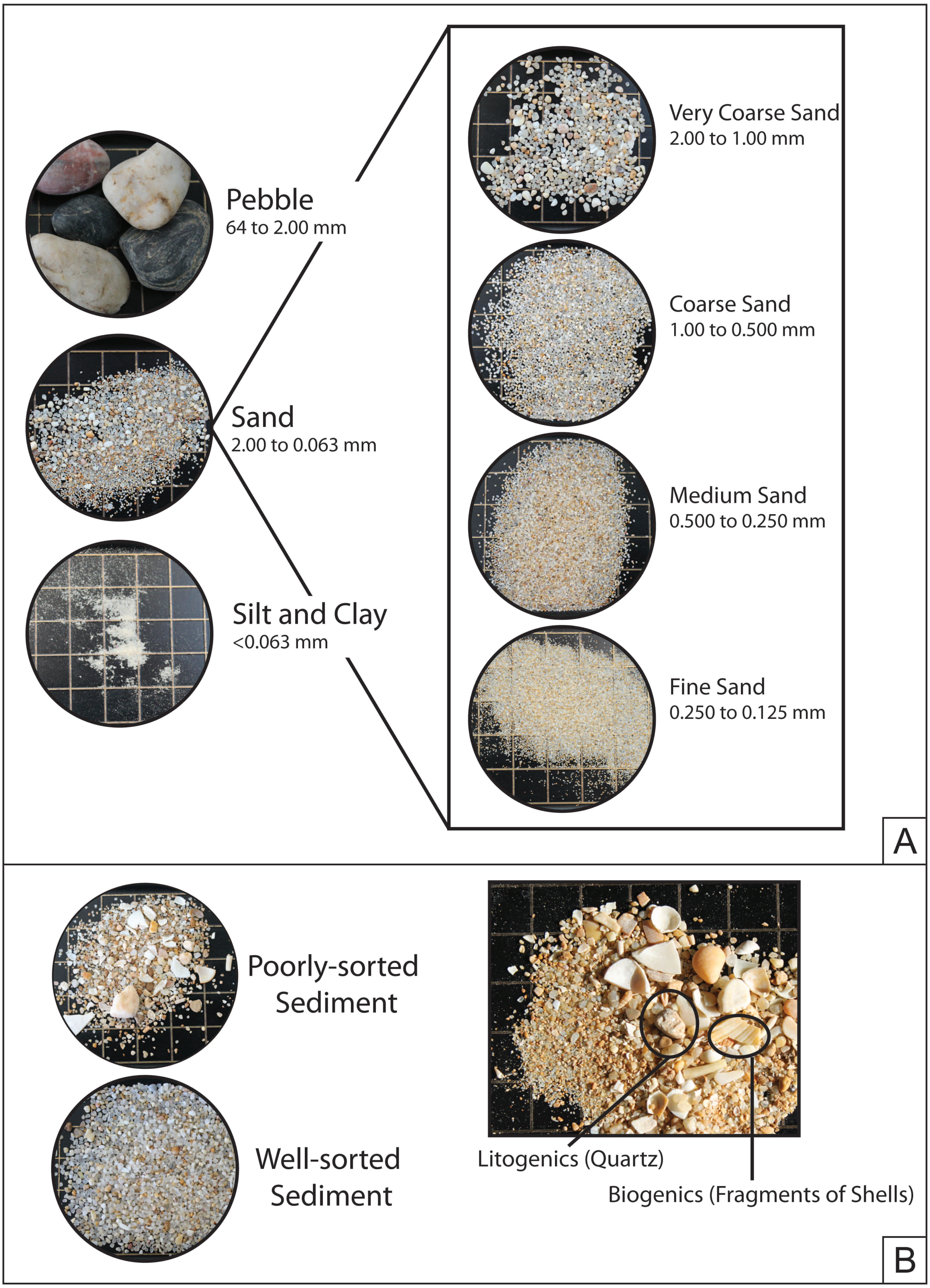
Credits: Delminda Moura & Ana Gomes



Annex II
Bedforms and current directions

The sediment moves under a flow of water and forms topographic features. This figure shows ripples moulded into the sand by the movement of water. They were photographed at low tide in several beaches of Algarve. Arrows represent the flux direction. The steeper dip of asymmetrical ripples is always downstream.

Credits: Delminda Moura

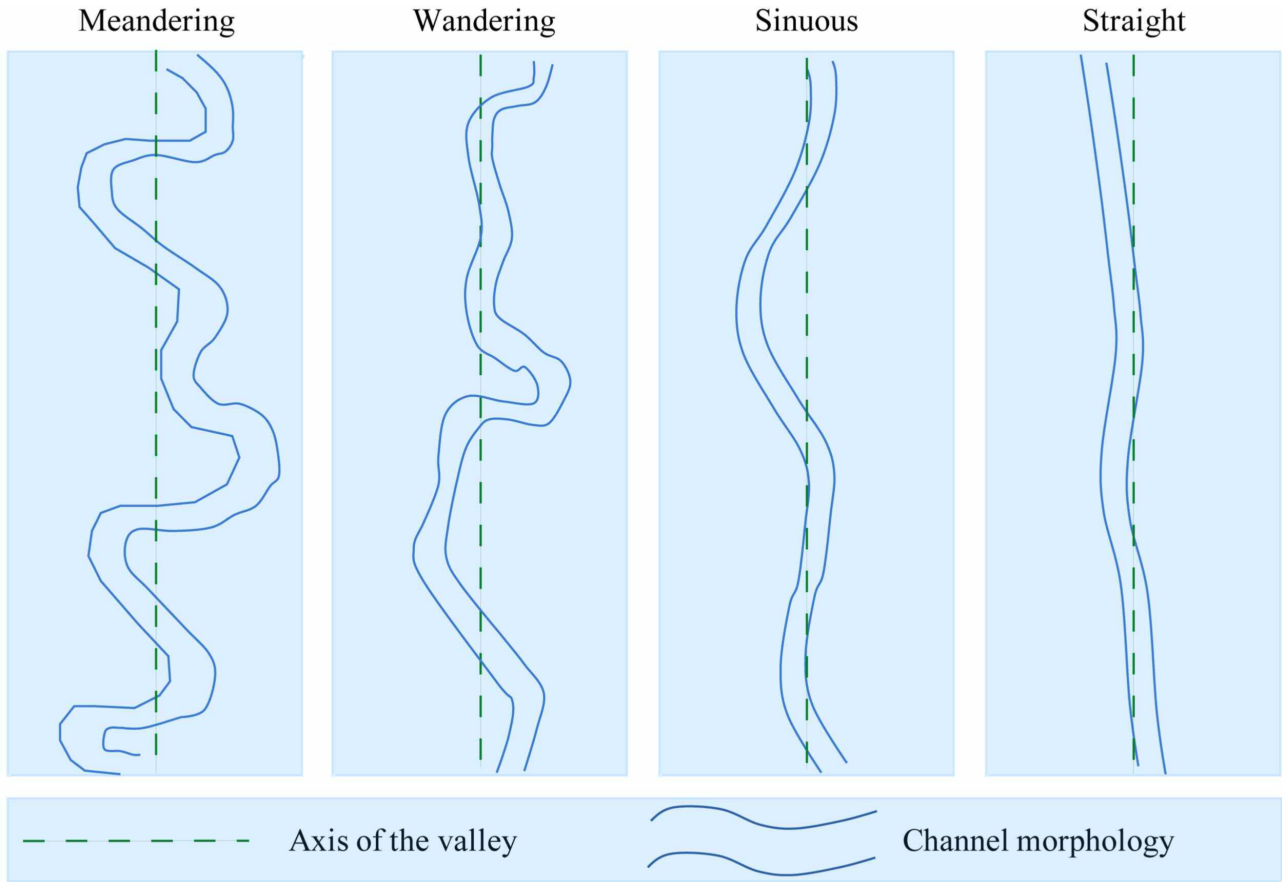


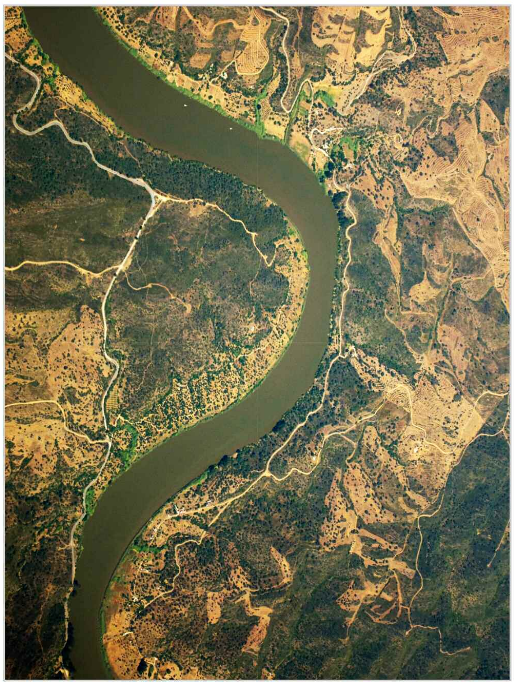
Annex III

Sediment grain size and sorting

These images represent the grain size dimensions in millimetres (mm) from pebbles to silt and clay (A) and the degree of uniformity of grain size: sorting (B).

Credits: Sónia Oliveira





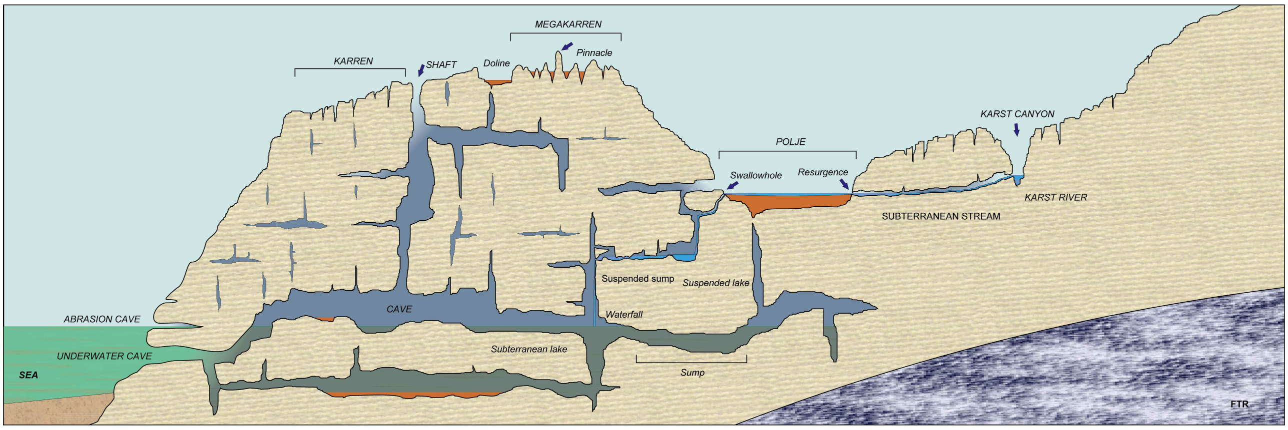
Meander in the Guadiana River

Annex IV

Morphology of fluvial channels

Rivers have a shape that depends on characteristics of the substrate, amount of the transported sediment and climate.

Credits: Delminda Moura

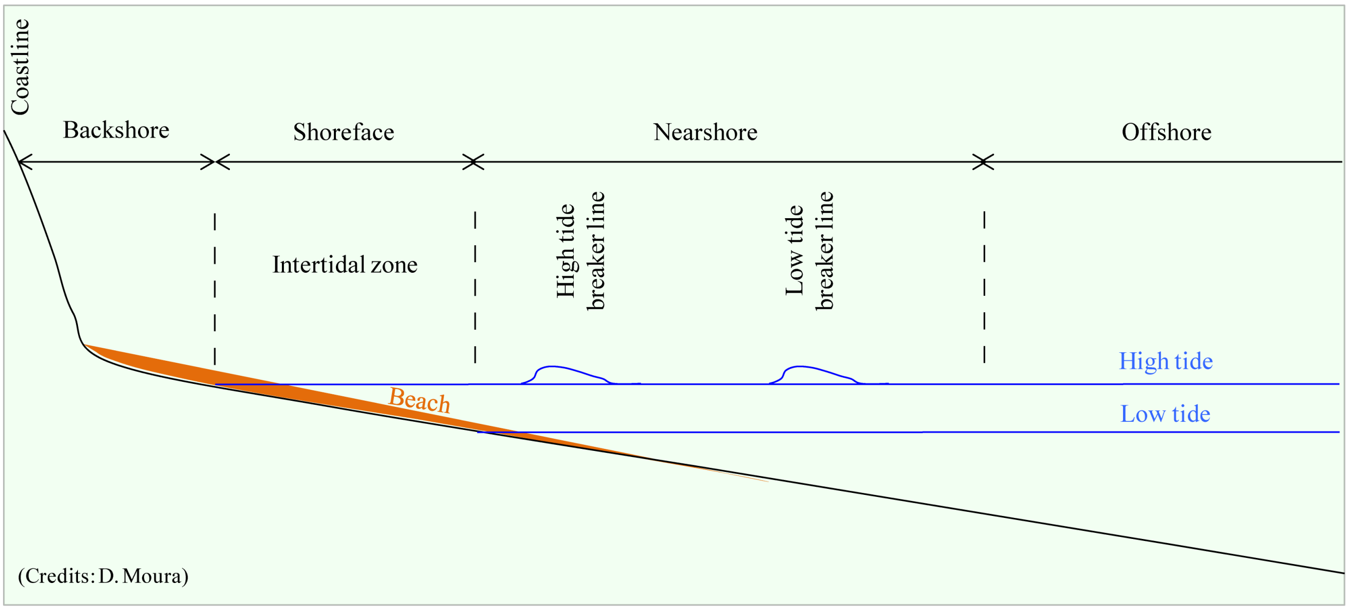


Annex V

Karst landscapes

Karst landscapes are dissolution landscapes resulting from chemical weathering in carbonate rocks: karstification. Superficial karst (epikarst) connects with a subsurface domain (endokarst) with which maintains constant exchanges of water, air and sediment.

Credits: Frederico Tátá Regala



Annex VI
Coastal terminology

UAlg CIMA
UNIVERSIDADE DO ALGARVE
CENTRO DE INVESTIGAÇÃO MARINHA E AMBIENTAL

The Centre for Marine and Environmental Research (CIMA) is one of the research centres of the University of the Algarve. Is a multidisciplinary Research Unit that develops its scientific activities in leading areas and assumes the scientific dissemination and the knowledge sharing as missions of utmost importance. This book expresses the team commitment on the scientific knowledge transference to Society.

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