

# Sedimentary Characteristics of the Holocene Tsunamigenic Deposits in the Coastal Systems of the Cadiz Gulf (Spain)

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## 1. Introduction

From a depositional point of view, tsunami deposits can be defined as high-energy event sequences, generated by highly energetic dynamic processes involving a high degree of erosion and transport of sediments. Tsunamis are waves induced either by plate tectonics or by the impact of meteorites or large underwater landslides. They are characterized by a wavelength of dozens of kilometers and by their high speed. Interest in the study of tsunamigenic deposits has increased in recent times, with numerous works published in the last few years on tsunamites generated by documented events, such as the Hokkaido-Nansei-Oki earthquake in 1993 (Nanayama et al., 2000; Sawai, 2002), the Okoropunga tsunami in New Zealand in the 15<sup>th</sup> century (Goff et al., 2004) or the one associated with the famous volcanic eruption of the Krakatoa in 1883 (Van den Bergh et al., 2003).

In coastlines protected from swell, such as bays, estuaries or coastal lagoons, tsunamis usually generate complex but easily recognizable deposits (tsunamites) clearly differentiated from storm deposits, as storms cannot reach these environments. In the inner areas of these protected coastal systems the arrival of the tsunami wave takes place after dispersion of the initial energy, which occurs through friction with the bottom when the wave crosses a shallow tidal system. The innermost limit of the tsunamigenic layer is simply evidenced as a fine but continuous level of plant fragments that may also contain a variable amount of small soft boulders (Bondevik et al., 1997; Dawson and Smith, 2000). In the most open areas of these systems, other surface deposits characteristic of high-energy events and linked to geomorphological features characteristic of storms, such as cheniers or washover fans, develop. These features can also be generated during tsunamis, and in this case it is difficult to distinguish the depositional mechanisms of both phenomena.

Criteria in favor of the action of tsunamis in this coastal sector are the tectonic setting and the rich historical record of earthquakes and tsunamis. Specifically, the zone is near an

active tectonic area, located SW of Cape Saint Vincent (Fig. 1), the Gorringe Bank, where recent geophysics studies show the existence of active faults (Udias et al., 1976; Ribeiro, 1995; Baptista et al., 1996, 1998; Terrinha et al., 2003; Gutsher, 2005 and 2006), which could be the focus of several well-documented earthquakes and tsunamis (Galbis, 1940; Udias et al., 1976; Martínez Solares et al., 1979; Levret, 1991; Ribeiro, 1995; Dawson et al., 1996; Luque et al., 2001; 2002; Silva, 2002; Silva et al., 2005; Gutierrez-Mas et al., 2009a and b). The best known is the tsunami that followed the Lisbon earthquake (1<sup>st</sup> November 1755 AD), which produced catastrophic effects on the coast of the Algarve and West Andalusia, as well as significant morphological changes in the coastal systems (Udias et al., 1976; Campos, 1992; Ribeiro, 1995; Luque et al., 2001 and 2002). The magnitude of this earthquake was 8.3 and its intensity at the epicenter was XI-XII. The earthquake generated large tsunami waves, which razed the coasts of Portugal, Atlantic Andalusia and Morocco. Another documented tsunami in the area occurred on 26<sup>th</sup> January 1531, and was caused by an earthquake of magnitude 7.7 and intensity IX. Earlier, on 10<sup>th</sup> June 881 another earthquake caused a large tsunami in the area, while still earlier, in 395, an earthquake followed by a tsunami destroyed the ancient Roman town of Baelo Claudia, on the Coast of Cadiz (Bermúdez and Peinado, 2005).

Evidence of deposits generated by the tsunami that followed the Lisbon earthquake in 1755, similar to those found in the South of Portugal (Andrade et al., 1994; Dawson et al., 1995; Hindson and Andrade, 1999), in the Bay of Cadiz (Dabrio et al., 1998; Luque et al, 2002), or the accumulations of large blocks on the coastal platform of Cape Trafalgar (Whelan and Kelletat, 2005; Gracia et al., 2006), have been found in the study area. Some washover generated by the 395 tsunami has also been documented in the Coast of Cadiz (Luque et al., 2001) and a sedimentary record of all historic tsunamis has been characterized in the Odiel and Tinto Estuaries (Morales et al., 2008) and the Bay of Cadiz (Gutierrez Mas et al, 2009 a and b). A record of older tsunamis has been documented at the mouth of the Guadalquivir River (Ruiz et al., 2005).

Previous works conducted in the Huelva estuaries, Guadalquivir estuary and the Bay of Cadiz have described the presence of coarse grain-sized surface layers and macroforms generated by high-energy events (Dabrio et al., 1998; Luque et al, 2002; Ruiz et al., 2005; Gracia et al., 2006; Morales et al., 2008, Gutiérrez Mas et al., 2009 a and b). Some of these works have focused on proving that some of these layers correspond to the action of tsunamis and, using radiometric dating techniques, they associate the layers with corresponding well-documented events which occurred in the historical period. Once this fact has been proved, there is evidence of variety in the typology of surface deposits and forms which have not been properly characterized. Thus, a methodology has been established to achieve a sedimentological description and characterization of these deposits, as well as to determine the factors responsible for their spatial distribution.

## 2. Lithofacies characteristic of tsunami deposits

Composition, grain size and area of tsunamigenic deposits are as variable as the height and intensity of incident waves, the configuration of the coast and the bottom, the type of sedimentary substrate in the bottom, the availability of sediments, and the path of the tsunami wave. Nevertheless, there are common features which characterize tsunamites and which have been described by numerous researchers. These are: 1) erosive base, 2) coarser sediments than in the overlying and underlying beds, with a fabric characterized by a

remarkably bad internal arrangement, 3) presence of exotic sedimentary particles from environments external to those where they are deposited, and 4) abundance of alien marine organisms such as foraminifera, diatoms, and even mollusk shells.

Fujiwara et al. (2000) distinguish three main types of tsunamites:

1. Massive accumulation of shells and shell fragments with sandy or muddy matrix. These deposits usually have an erosive base and present a common characteristic: a specific high diversity with a mixture of open marine species and others typical of protected low-energy environments. These shell deposits can also contain a variable percentage of alien lithoclasts, which can be associated with the most energetic zones of restricted environments, such as the bottom of estuarine or deltaic channels.
2. Fining-upwards successions which start with shell accumulation on an erosive base, and a muddy sandy or sandy gravel ceiling with muddy matrix. Shell accumulation usually includes a mixture of whole organisms (2 valves), disarticulated valves and shell fragments. This deposit also contains a large number of species, mixing shells from different environments. The upper sandy part of the succession usually shows bioturbation and may frequently present convolute bedding. These tsunamigenic sequences are indicative of a lower energy than the previous deposit and are usually associated to restricted environments such as tidal plains and channel margins or deeper channel zones. Other times they appear in the same environments as the deposit described above, although they are generated during lower energy events.
3. Sand layers with erosive bases. They usually appear in the form of decreasing grain-size sequences with shell and plant fragments and soft boulders. Very often they present internal arrangement structures characteristic of bidirectional currents like herringbone cross-stratifications and convolute bedding. Marine microorganisms are also present, especially diatoms (Sawai, 2002) and ostracods (Smoot et al., 2000).

Nichol et al. (2003) describe the tsunamite in the Whangapoua Bay (New Zealand), as being made up of coarse sands and gravels with sub-rounded pebbles from local lithologies of nearshore rock outcrops. The minor remains of marine organisms generally appear among lithoclasts. Deposits of this kind are smaller in size and exclusive to barrier-island environments, especially in the zone of the backshore, although they can also appear in cliffs. With regard to these deposits, other authors (Whelan y Kelleter, 2005; Gracia et al., 2006) have described large block deposits on cliffs or dune systems located behind abrasion platforms. In these cases the blocks also correspond to the lithologies present in the submerged rock outcrops in front of the coastal system.

Hindson and Andrade (1999), Goff et al. (2000) and Nanayama et al., (2000) have described facies variations in the sedimentary record along coastal systems originating in known events. All of them agree on a decreasing grain-size distribution of facies landwards, where coarse sand and gravels are located around closure barriers, while shell accumulations are distributed along the channels and intertidal zones of estuaries, especially in marsh areas and supratidal deltaic plains.

Goff et al. (2000) observed enrichment in heavy metals such as Pb, Cu, Ni, Fe and Cr in these deposits due to the accumulation of particles selected by high-energy currents following extraction from adjacent formations in coastal areas. Van der Bergh et al. (2003) also observed this event in the tsunamite of the Krakatoa eruption. In this case, the energetic layer is also accompanied by an increase in magnetic susceptibility.

The only agents able to generate the studied deposits are great storms or tsunami waves (Dawson *et al.*, 1988; Dott, 1996; Nott, 1997, 2003; Bryant and Nott, 2001; Goff *et al.*, 2001;

Kennedy *et al.*, 2007; Kortekaas and Dawson, 2007). Due to the similarity of the facies, both deposit types are sometimes confused (Bryant and Nott, 2001; Shanmugam, 2006). Nevertheless, some differences can be established (Nanayama *et al.*, 2000; Dawson *et al.*, 1988, 1996; Dawson, 2005; Kortekaas and Dawson, 2007). Tsunamites extend much further inland than storm deposits, have an erosive base, are poorly classified and often contain soil and vegetable remains (Paskoff, 1991; Dawson *et al.*, 1988, 1996; Nanayama *et al.*, 2000; Dawson, 2004).

Nanayama *et al.* (2000) and Goff *et al.* (2004) use distance, shoreline, topographic height of deposits and clast size as differentiation criteria. Three main features may be considered as essential distinctive characteristics: 1) Tsunamites almost always reveal an erosive base, while storm layers sometimes present net, though depositional, limits; 2) grain size in storm layers is usually coarser than in tsunamites, while the latter present a lower internal arrangement; 3) tsunamites extend inland or towards estuarine or deltaic areas much more than storm layers.

Goff *et al.* (2004) analyze the differences between storm and tsunamigenic deposits, comparing storm deposits on Easter Island in 2002 with those of the Okorocumba tsunami which occurred in the 15<sup>th</sup> century. The differences are evident in the area, thickness, and grain size. The tsunamigenic deposit diminishes sharply at the margins and inland, is better selected, coarser and does not present an erosive base with vegetation and buried soil. In addition, the storm deposit extends landwards up to 40 m, as opposed to the tsunamigenic deposit, which extends up to 200 m.

However, sometimes those features are not sufficient to establish the depositional mechanism. Other criteria may be necessary to distinguish the dynamic agent that generated the deposits (Cita and Aloisi, 2000; Shanmugam, 2006).

### 3. The study area

The Gulf of Cadiz forms a coastal sector in the SW of the Iberian Peninsula which extends from Cape Saint Vincent in Portugal to the Strait of Gibraltar. From a physiographic point of view, the coast of the Gulf of Cadiz can be divided into several sectors according to its topographical configuration and its erosive or depositional nature. As a result, we can distinguish low sandy sections of coast which extend along the Portuguese Algarve coast in the form of barrier-island systems, and along the Huelva coastline in the form of long beaches developed on the basis of a quaternary paleo-cliff system (Fig. 1).

To the South, in the coast of Cadiz and the western part of the Algarve, rocky coast and bottoms prevail, with good examples of cliff systems. The rectilinear configuration of the shoreline is broken at the mouths of the Guadiana, Piedras, Tinto-Odiel, Guadalquivir and Guadalete rivers, which are protected from the direct action of swell and in whose interior tidal sedimentation prevails.

The zone is affected by a mesotidal regime, where the mean tidal range is 2.2 m. In spring tides the highest range reaches 3.7 m and in neap tides the lowest range is 0.65 m (Benavente *et al.*, 2000). Tidal range varies along the coast, reaching maximum values at the mouth of the Tinto and Odiel rivers, whereas it decreases in the coasts of Portugal and Cadiz. The speed of the tidal current is highly variable, with the highest values reached inside the Bay of Cadiz, where the highest speeds have been determined along the Strait of Puntales (Alvarez *et al.*, 1999), and in the Punta Umbria channel (Odiel-Tinto Estuary), reaching values over 1.5 m/s during spring tide ebbs.

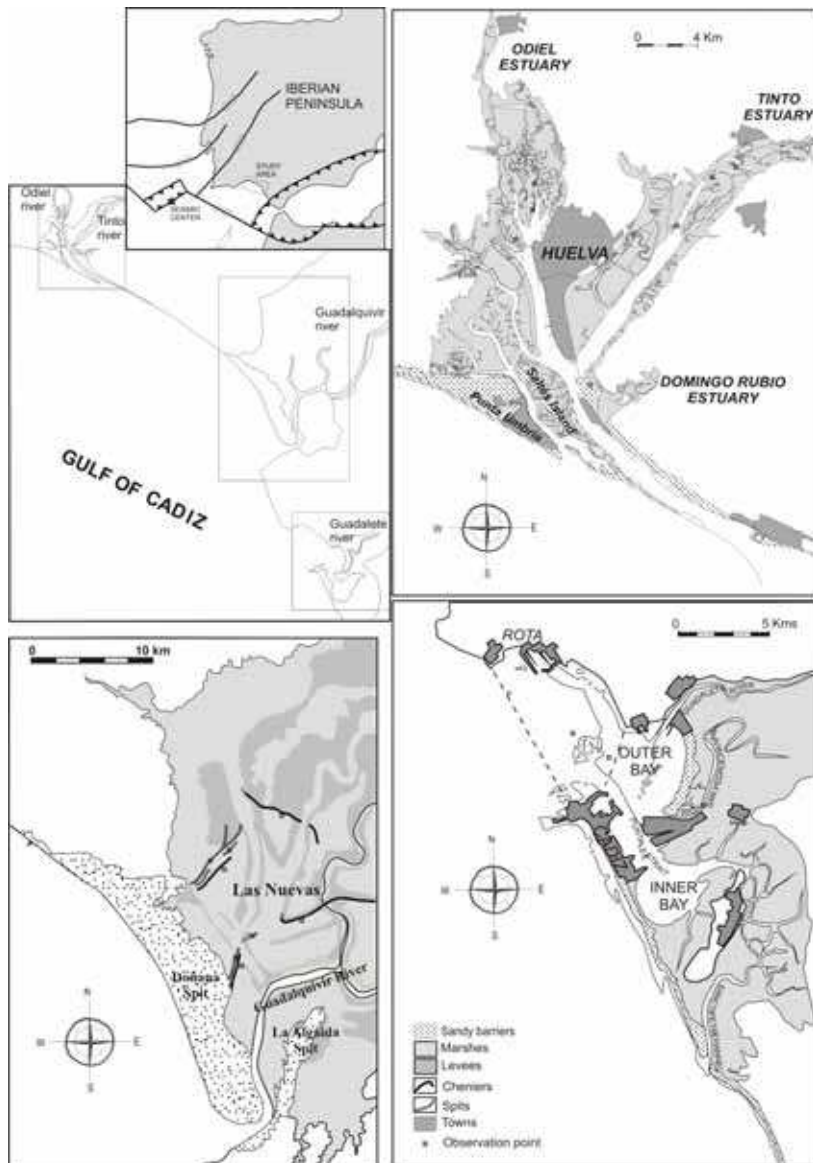


Fig. 1. Location of the seismic center and the study areas.

The prevailing swell is from the west. The data from the point WANA 1051048, in the WANA network, show that the waves from the SSW, SW and WSW represent 49.19% of the time for the period from the end of 2005 to the end of 2007. Mean significant wave height ( $H_{1/3}$ ) is 0.69 m, and the period is 5.04 seconds.

Storm waves are related to southwest Atlantic storms. Mean values of  $H_{1/3}$  reached during storms are 2.20 m. with periods of 6.24 s (Rodríguez-Ramírez et al., 2003).

The infilling in the subtidal zones of the inner systems are made up of estuarine accretion bodies (Frey and Howard, 1986). In the central and inner domains of estuaries in this coast, as well as in the Bay of Cadiz, where swell influence is scarce, sedimentary bodies generally present muddy lithology with scarce sand content and are usually highly bioturbated by the activity of annelids (*Arenicolides ecaudata*), bivalves (*Scrobicularia plana*, *Crassostrea angulata* and *Mytilus galloprovincialis*), and gastropods (*Cymbium olla*, *Murex brandaris* and *Cerithium rupestre*).

In estuarine accretion bodies within the marine domain of the above-mentioned tidal systems, muddy sand lithologies prevail, also with a high percentage of bioturbation by annelids, (*Nereis diversicolor* and *Arenicolides ecaudata*), bivalves (*Cerastoderma edule*, *Cerastoderma glaucum*, *Ruditapes decussatus*, *Solen marginatus*, *Crassostrea angulata* and *Mytilus galloprovincialis*) and gastropods (*Murex brandaris* and *Cerithium rupestre*).

The sedimentary infilling of the linear coast exposed to swell presents noticeable differences between the Huelva sector and the Cadiz sector. The subtidal zone of the Coast of Huelva under the influence of waves presents a sandy and sandy-muddy nature, with the rocky substrate being covered by several meters of sediments in the zone closest to the coast. On the other hand, the equivalent zone in the coast of Cadiz presents large rock outcrops in the form of rock slabs or beach rock composed of quartzitic-bioclastic conglomerates only partially covered by a decimetric layer of sandy sediments in the deepest zones of rock outcrops.

#### 4. Approach and methodology

The presence of coarse-grained surface layers and macroforms generated by high-energy events has been described in previous works carried out in the Odiel-Tinto Estuaries, in Guadalquivir river mouth and in the Bay of Cadiz (Rodríguez Ramírez et al., 1996; Dabrio et al., 1998; Luque et al., 2002; Ruiz et al., 2005; Gracia et al., 2006; Morales et al., 2008; Rodríguez Ramírez and Yañez 2008; Gutiérrez Mas et al., 2009 a and b). Some of these works have focused on proving that these layers correspond to the action of tsunamis and, by using radiometric dating techniques, on associating the layers with corresponding events which occurred in well-documented historical periods. Once this fact has been proved, variety is clearly seen in the typology of surface deposits and forms, which has not been properly characterized yet. As a result, a methodology has been established with the aim of describing and characterizing the sedimentology of these deposits, and also of determining the factors responsible for its spatial distribution.

##### 4.1 Field work

This involved observation of outcrops and trenches. Both in the Odiel-tinto and Guadalquivir estuaries and in the Bay of Cadiz, there are zones where the lateral erosion of tidal channels has excavated previous deposits, generating taluses of over one-and-a-half meters in height, uncovering some of the most recent tsunamites and allowing direct observation of the facies and the morphology of sedimentary bodies. The campaigns involved direct observation and exploration of the terrain, uplifting representative facies sequences, trenches excavations and drilling to extract sediment samples. Guide measurements of shell levels present in the sandy deposit were conducted to determine the relationship of these shell accumulations with flow directions. Several lacquer peel tests were performed to determine the sedimentary structures present in the deposits. Some sea samplings were also carried out to determine the existence of mollusk species similar to

those present in the analyzed deposits. Orientation and position data were carried out using GPS and a compass.

Surface geofoms, attributable to the action of high-energy events (cheniers and spits), were also described in the Odiel and Guadalquivir estuaries. The facies of these events were also studied by making trenches about one meter deep using a shovel.

#### **4.2 Core logging**

A study of the tsunamigenic facies in the sedimentary record was conducted in order to characterize the oldest tsunamites that do not crop out in the trenches. This study was carried out by obtaining sediment cores using different techniques.

A total of 73 vibracores (VH, VT, VB and VR) obtained using the method described by Lanesky et al. (1979) and with a maximum length of 6.40 m were analyzed in the Odiel-Tinto Estuary. This same method was used to a lesser extent in the Bay of Cadiz, where only 4 of these cores were studied, although another type of vibracore (Asther-2) was recovered in the subtidal zone, obtaining a total of 35 cores with a maximum length of 4 m.

Elsewhere, manual logging was conducted using an Eijkelkamp Beeker-type hand core sampler, which allows other sediment sequences with a maximum length of 2 m. to be obtained. A total of 57 cores were obtained using this method in the Ria of Huelva and 20 in the Bay of Cadiz.

#### **4.3 Texture analysis**

Grain-size analyses were conducted at different levels of the tsunamigenic sequences using a Malvern Mastersizer 2000 laser diffraction particle analyzer which allows precise grain-size distribution between 2-mm and 2- $\mu$ m sizes to be determined, so that each of the types of sediments differentiated by the Udden-Wentworth scale (1972) is in turn divided into 6 types, with measurements obtained for each one. A conventional sieving method was used for sizes bigger than 2 mm. The results were represented on grain-size distribution histograms in order to characterize the different types of sediments.

For grain-size distribution analysis and classification, we used the scale presented in Tucker (1988), based on data by Folk (1974) and Folk and Ward (1957), along with data on high-energy littoral deposits by Visher (1969), Dawson (2005), Dawson et al. (1988; 1996), Long et al. (1989a and b), Nanayama et al. (2000), Nichol et al. (2003) and Paskoff (1991).

#### **4.4 Facies analysis**

This allowed us to establish depositional features distinguishable among relict and functional sedimentary environments present in the study zone, evidenced through small variations in the textural and compositional characteristics of the deposits. These small variations, unnoticeable by routine observation, were very useful when distinguishing the deposits corresponding to environments which present similar sedimentological characteristics, but which have been generated by different depositional processes, such as, for example, sediments in environments or subenvironments affected by reworking, limited transport and almost immediate resedimentation. As part of the facies analysis, a microscopic analysis was conducted, involving determination of the sand-fraction components by first separating the different size fractions present in the sediment by sieving them mechanically and then observing them with a binocular magnifying glass. Determination of microfossils and other components was made by counting 1500 grains per

fraction. Subsequently, the percentage content of each component and its proportions in the whole of the sample were determined.

The different facies and sequences considered tsunamigenic in nature in the study zone were described and distinguished. The facies description was performed according to the criteria suggested by Frey and Howard (1986) for facies identification in tidal systems. In each facies deposit the following were described: texture, mean grain size, composition, color, physical sedimentary structure, bioturbation type and degree. The macrofauna species present were also identified in order to establish possible source areas for the sediment.

## 5. Results

Different sedimentary sequences, whose characteristics vary according to the acting depositional mechanisms and the energy of the processes, were characterized in the sedimentary record observed:

### 5.1 Bioclastic sand and microgravel sequences

The finest grain-size sequence among those observed is that made up of sandy sediment, ocher in color, with a large amount of coarser material of a different typology, dominated by bioclastic fragments of sea mollusk shells, although quartz boulders, large shell-marble fragments and soft boulders are also frequent. The most abundant identifiable species in these deposits are the bivalves *Cerastoderma glaucum*, *Cerastoderma edule*, *Crassostrea angulata*, *Solen marginatus*, *Chamelea gallina*, *Ruditapes decussatus*, *Glycimeris variabilis* and *Chlamys sp.* Some gastropod individuals, *Turritella communis* and *Cerithium rupestre*, were also observed. Only a few specimens of *Cerastoderma glaucum* were found complete with their valves disarticulated. In the estuaries of the Coast of Huelva the shells are accompanied by quartzitic particles rounded to sub-rounded clasts with sizes ranging from a few mm to 3 cm in diameter and corresponding to hydrothermal quartz. Shell-marble fragments are the biggest clasts, reaching 10 cm in diameter and are made up of the whole remains of immature bivalve individuals belonging to the *Cerastoderma glaucum* and *Crassostrea angulata* species. In Huelva, shell-marble fragments are bound together by goethite cement (Fig. 2A), while it is carbonate cement in Cadiz.

This sequence was observed in the Odiel estuary on high marsh bodies, above the level of extreme equinoctial spring tide. The deposit is organized in successive grain-fining-grain-coarsening sequences, always starting from erosive bases. Each sequence is organized showing sedimentary structures which go from parallel lamination to cross stratification, with sets of decimeters in size and herringbone beddings, although those inclined towards the mouth prevail (Fig. 2B). The deposit total power is over 1.5 m.

This kind of sequence was also observed alternating with subtidal deposits in the external sector of the Bay of Cadiz. In this case, the thickness of the sequences is much smaller, hardly reaching 20 cm, and apart from quartzic clasts, Pleistocene-old oyster rock clasts are also observed.

Strong subsurface levels mainly composed of sands with shell fragments appear in the supratidal areas of the Bay of Cadiz (Fig. 2C). These levels present sand content higher than 97%, which vary slightly in the vertical sense. Gravel content is always lower than 1% and mud content is between 1 and 3%. Mean grain size is 0.22 mm (fine sand), and sorting is 0.63 (moderately well classified). A characteristic feature of these levels is their relatively high mean content in foraminifera found in current sand deposits in different environments of



the Bay of Cadiz. Among foraminifera, the high content of miliolida is remarkable. This high content in foraminifera reaches maximum values of up to 14.34%, contrasting with the results obtained in other nearby coastal environments such as current dunes (with a foraminifera content of 2.8%) or nearby beaches (where total foraminifera content is 3.8%).

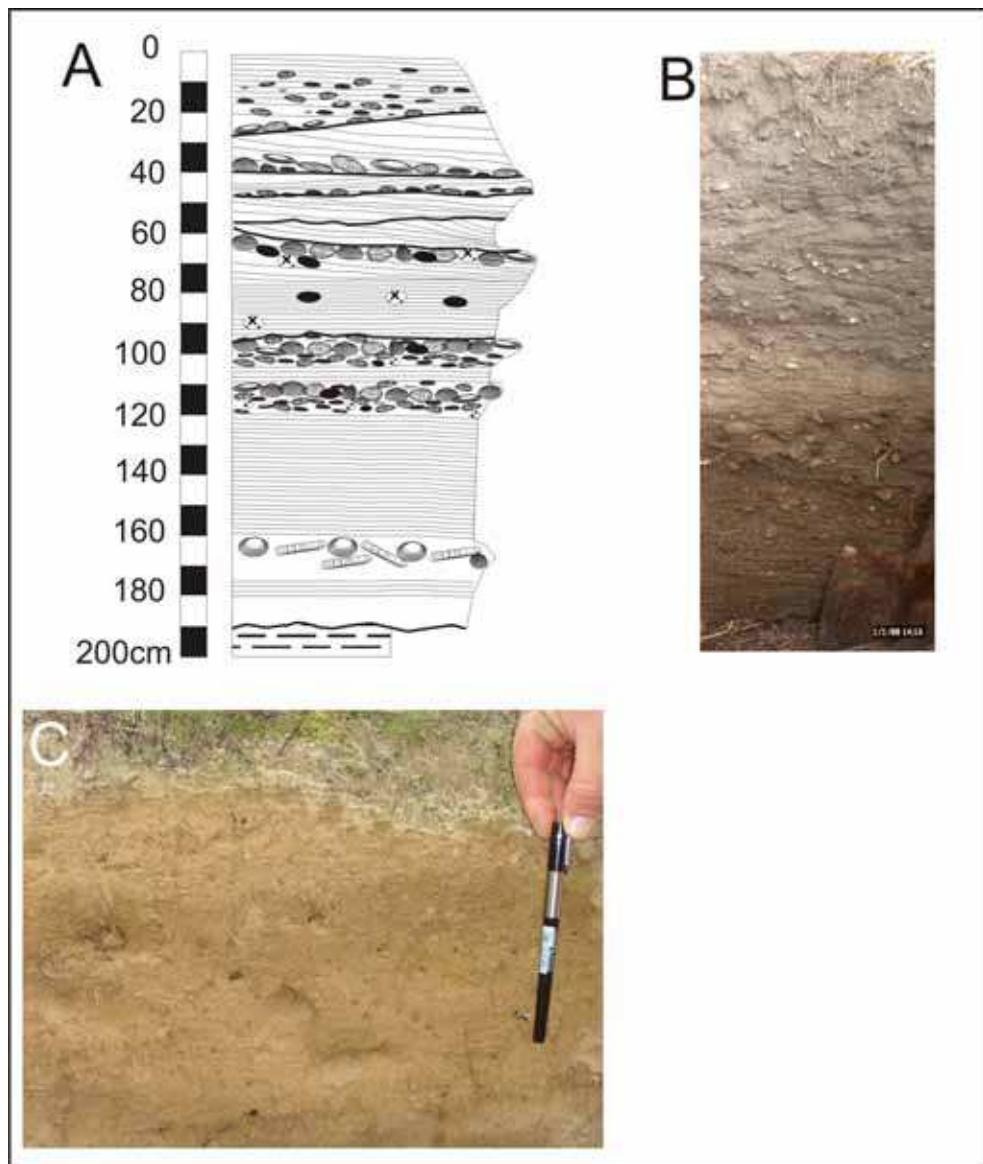


Fig. 2. Sand and bioclastic microgravel sequence (A). Photograph of the sequence studied on the Odiel Estuary (B) and photograph of the facies studied on the Bay of Cadiz (C).

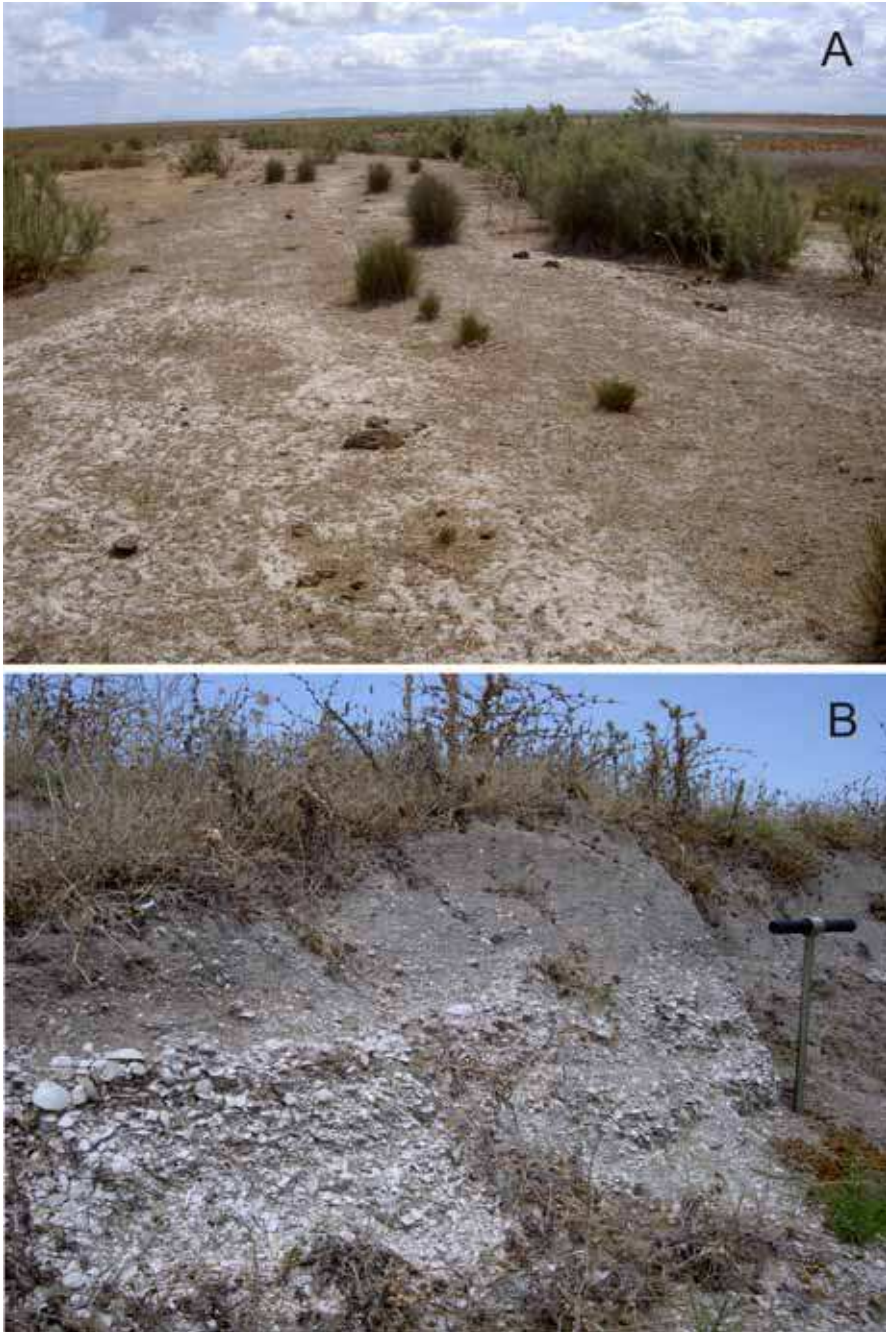


Fig. 3. Sand and bioclastic gravels studied on the Guadalquivir River mouth.

On top of the Guadalquivir estuarine marsh muddy deposits (Fig. 3) we find a series of sandy surface formations basically composed of the abundant remains of molluscs, which have recently been characterized as cheniers (Rodríguez Ramírez and Yañez 2008). This deposit is characterized by sandy and shelly material, which runs roughly parallel to the paleocoast and is isolated from the shore by mudflats. They form a sharp contrast to the silty or clayey lower deposits. The sediment's succession starts with a slight erosional unconformity with the underlying deposit. The internal structure of the sedimentary build-up is characterized by a gentle landward-dipping lamination, interrupted by large-scale cross-bedded sets with some mud debris in the base. In general the macrofauna is strongly dominated by the disarticulated valves of *Cerastoderma edule* and *Crassostrea angulata* accompanied by other marine bivalves (*Tellina* sp., *Glycymeris glycymeris*, *Chlamys* sp., etc.) which evidences the varied origin of the contributions.

### 5.2 Shell and sand fining-upwards sequences

The most frequently observed sedimentary sequence consists, in broad terms, of a mixture of disarticulated valves, shell fragments and whole bivalves in a dark gray sandy-muddy matrix (Fig. 4A). The shells and fragments include typical marine species, but also species typical of the inner estuary (Fig. 4B), although these species are different in the different layers that could be identified. On these layers of shells, the sequence ends with a very bioturbated decimetric muddy sand package, on top of which a number of dispersed valves and shells in life position accumulate (Fig. 4C).

In more detail, the base of the sequence is usually composed of a first level of shells 5-8 cm thick, with an erosive base and made up mainly of whole bivalve shells from *Cerastoderma edule*, *Cerastoderma glaucum*, *Mytilus galloprovincialis*, *Solen marginatus* and *Scrobicularia plana* and the gastropod *Murex brandaris*, accompanied by the disarticulated valves of mature specimens of *Cerastoderma edule*, *Crassostrea angulata* and *Cerastoderma glaucum*. In the Odiel estuary, the erosive base of the layer is covered by a goethite crust and the surface of the shells also appears covered in a patina of Fe oxides (Fig. 4D).

On this shell level there is another muddy sand level, 10 to 15 cm thick and black to dark gray in color, with progressive grain-size fining. This is usually a bioturbated level, so that in the internal zones of estuaries it usually presents vertical galleries of *Scrobicularia plana*, which start from the lower shell level and finish with the shell itself in life position. In other zones, muddy sands are bioturbated only by a dense network of galleries of the annelid *Arenicolides ecaudata*. The upper part of the sequence is composed of a fine layer of mud with parallel lamination.

Layers of this kind were observed in erosive trenches along the tidal channel margins of the Tinto and Odiel river estuaries, more than 15 km away from the open coast. Continuity in these layers is usually very high towards the interior of the continent in low zones, keeping the same topographic level for distances from several hundred meters to several kilometres, but in the coast longitudinal direction continuity is lower and the layer adapts to the already existing topography.

### 5.3 Massive shell strata

These are shell deposits with non-articulated whole valves and muddy, sandy or microgravel matrix, which can even be absent or subsequently entered the pores after percolation. Sometimes the sandy-gravel matrix is made up of smaller bioclastic fragments

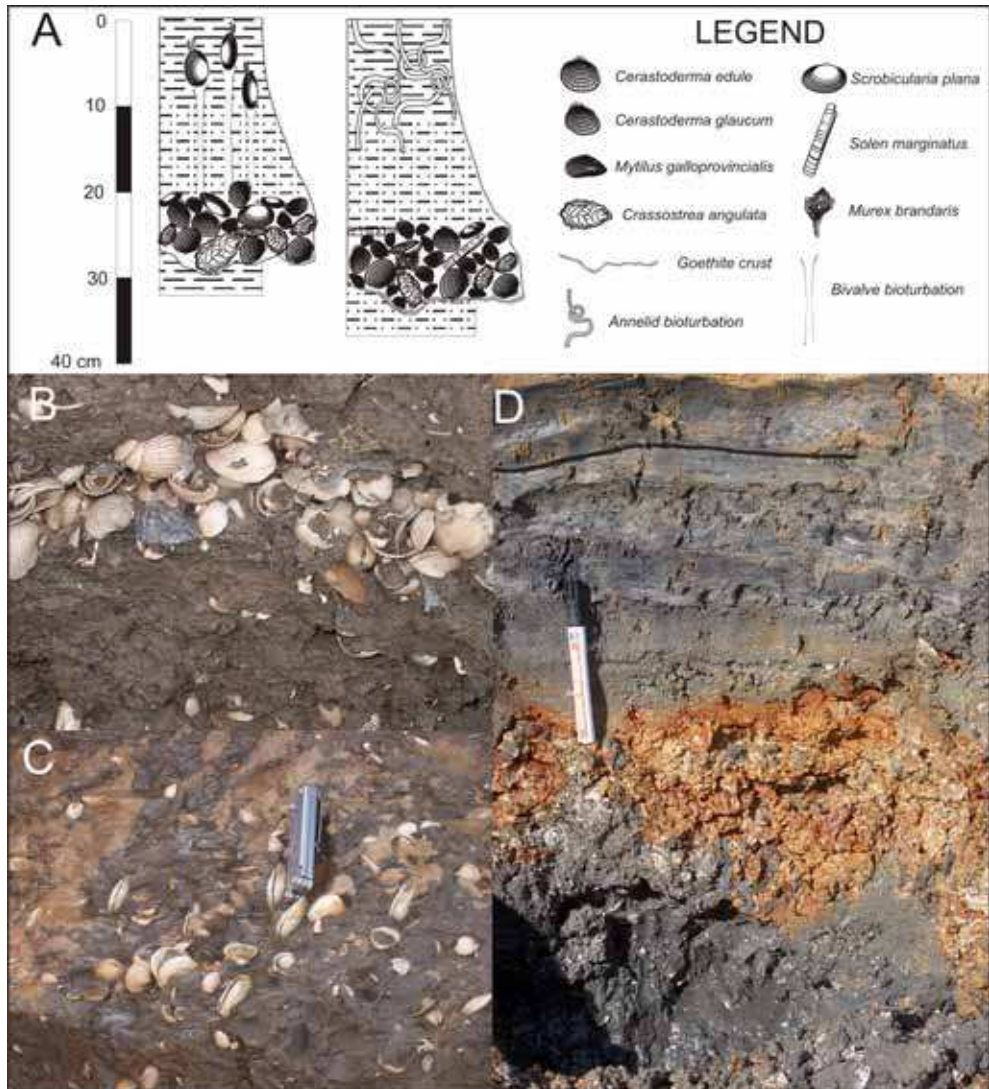


Fig. 4. Shelly sands fining-upwards sequence (A). Detail of the erosive character and species variability constituting the base of the sequence (B). Detail of the living position estuarine molluscs in the top of the sequence (C). Complete ferruginized sequence in the Odiel Estuary (D).



(Fig. 5A). The shells and clasts present strong imbrication in some deposits, as in the Bay of Cadiz (Fig. 5B), while in others, internal arrangement is observed or both horizontal and cross lamination can be slightly seen. Thickness in the deposits varies from 0.2 to 0.5 m. In many points the deposits are intersected by the present relief, while shells appear disperse forming shell pavements (Fig. 5C). In most cases, the shells present in these accumulations are of a monospecific nature and the species present in these packages are different from one place to another and from one topographic location of the deposit to another. In the Tinto and Odiel river estuaries the most abundant species are *Crassostrea angulata*, accompanied on occasions by immature individuals of *Mytilus galloprovincialis* (Fig. 5A), while in the Coast of Cadiz layers are more usually made up of *Glycymeris variabilis*. (Figs. 5B and C).

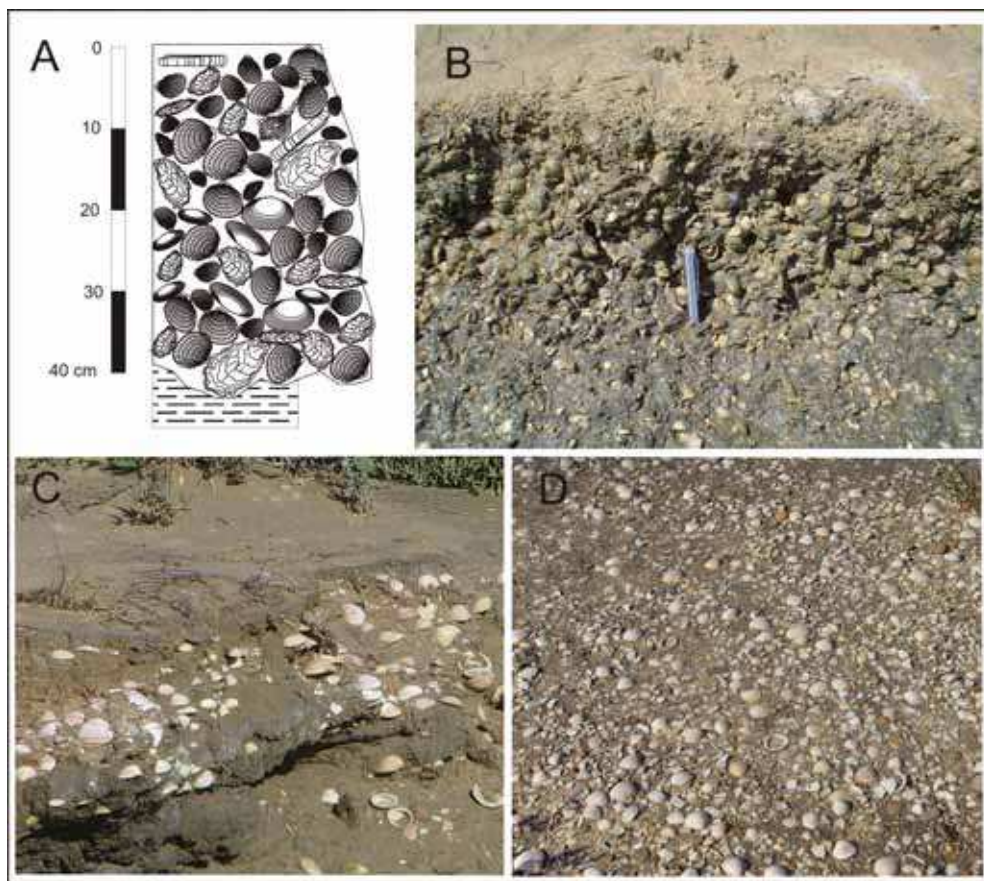


Fig. 5. Massive Shell sequence (A). Detail of the facies present in the Tinto Estuary (B). Massive strata of *Glycymeris* with muddy matrix in the Bay of Cadiz (C). *Glycymeris* pavement on a marsh in the Bay of Cadiz (D).

In the Tinto river mouth, massive ostreid packages were always observed in drillings and located under the Mean Spring Tide level, while in the Coast of Cadiz *Glycymeris* packages appear both in the intertidal and supratidal zones. These last deposits are usually accompanied by gastropod shells such as *Murex* and *Ocenebra*. *Glycymeris* valves are from 3 to 5 cm in size, although some of them reach up to 7 cm. They do not show defined orientations, although they generally appear in a subhorizontal position and concavity downwards. In some levels, valves appear in an oblique position and show a significant degree of imbrication.

#### 5.4 Layers of mixed shells-and-pebbles

In some cases, shell accumulations appear mixed in variables proportions with quartzitic clasts which may even reach 5 cm in diameter (Fig. 6A). In this case, species are usually also of highly resistant shells, the most abundant being *Glycymeris variabilis*, *Crassostrea angulata*, *Chamelea gallina* and *Ruditapes decussatus* (Fig. 6B). These facies were observed in the lower levels of the cores in the central zone of Odiel and Tinto Estuaries.

In the Bay of Cadiz, in some outcrops, well-rounded clasts of quartz, quartzite, calcite and other rocks, such as sandstones and calcarenites, appear along with mollusk shells. The deposits are made up of siliciclastic sediments, mainly quartz, mica, quartzite pebbles, limestone and rock fragments, with abundant mollusk shells, especially bivalves of the *Glycymeris* species and some gastropods which appear complete and fragmented. There are also fragments of wood or trunk pieces of plants swept from the continent. In these cases, the deposits usually display a high degree of imbrication of the whole clasts and mollusk remains. Facies of this kind appear in the lowest intertidal and subtidal levels. Subtidal levels make up the basis of the emerged sections of the San Pedro creek.

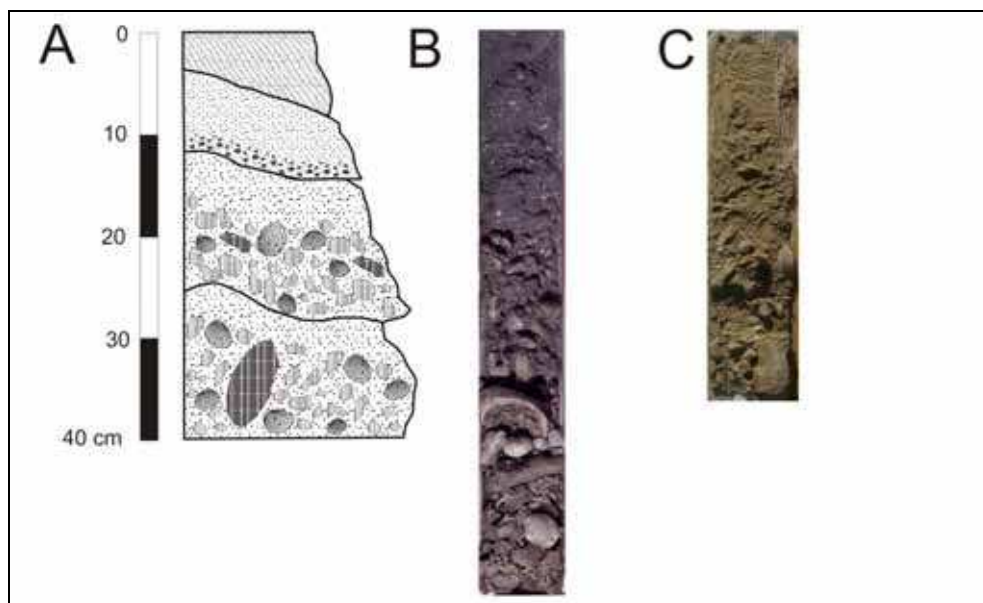


Fig. 6. Mixed shell-and-lithoclast sequence (A). Detail of the sequence in a core of the Tinto Estuary (B). Detail of a core of the subtidal area of the Bay of Cadiz (C).

The sections are grain-fining in nature, with frequent internal erosion surfaces. On the base there is a level of gravels made up of rounded blocks of rock fragments, mollusk remains, especially whole and fragmented valves of *Glycymeris* and quartzite pebbles, both with a large degree of imbrication and heterometric grain size and low classification. The sand fraction has mean contents over 78 %, gravel 13.4%, and fines 13.4%, while sorting value is 1.6, corresponding to a poorly classified sediment.

### 5.5 Pebble layers

The presence of quartz, quartzite and oyster rock included in deposits where the majority coarse elements are shells, has been described in the levels above. However, there is a type of high-energy deposit made up almost exclusively of pebbles of the above mentioned lithologies (Fig. 7A), clasts variable in size, but exceeding 1 cm in diameter. These facies were observed in cores in the central zone of the Odiel Estuary (Fig. 7B and C), over 20 meter deep and could be easily confused with fluvial facies were it not for the presence of some disperse fragments of seashells. The power of these packages does not exceed 30 cm and by correlation between different cores, these packages are known to display a certain lateral continuity and a morphology adapted to the bottom of tidal channels, extending landwards and severar kilometers into the interior of the estuaries.

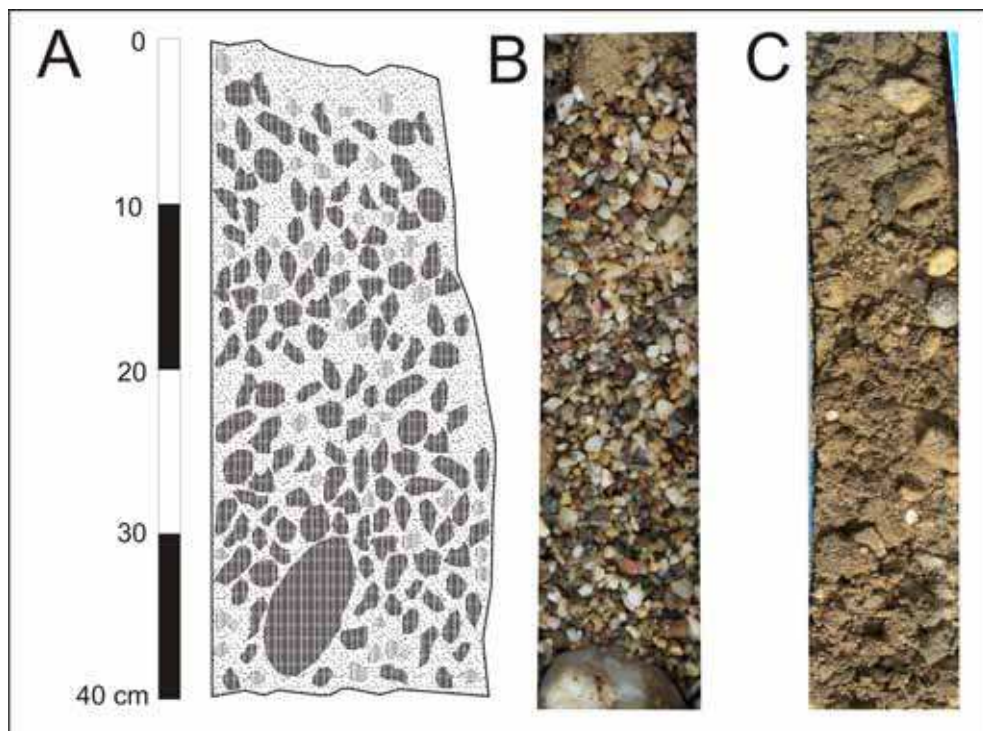


Fig. 7. Lithoclastic sequence (A). Detail of a core showing clean clast supported gravel (B). Detail of a core showing gravel with sandy matrix (C).

## 6. Discussion

In present coastal environments it is relatively common to find old littoral deposits such as aeolian dunes, beach ridges or washover fans, formed in the not-too-distant past by wind, waves or tidal action, in a climatic and hydrodynamic regime that was somewhat different from the present. These deposits, which at present display a relict character and are found fossilized among the estuary sediments or on the surface, anchored under the vegetation, appear at a different height and distance from the line of the present coast and, due to their morphology and facies, it generally proves easy to recognize the agent and environment in which they were deposited.

In the case of the estuary of the Odiel and Tinto rivers the succession of five sequences of bioclastic sands and microgravels separated by erosive surfaces with a total thickness of approximately 2 meters is clearly tsunamigenic (Morales et al., 2008). The sequences of bioclastic sands and microgravels are similar to the third type of tsunamites described by Fujiwara et al. (2000) and can be interpreted in different ways according to their location.

These sequences would represent the action of successive run-up and run-down currents (ebbs and flows) in the upper part of the estuary. The orientation of the internal cross-stratification is predominantly inclined towards the sea, which would indicate the action of an erosional flood followed by a depositional ebb. This body of sand was interpreted by Morales et al. (2008) as the sedimentary result of the dissipation of the tsunami wave over the high mud flats following the Lisbon earthquake of 1755, based on  $^{14}\text{C}$  data, and excluding other possibilities since the topographic height is greater than that reached by extreme tides and the 16-kilometer distance to the coast prevents storms reaching this zone.

Very similar facies also appear in the surface formations in the Bay of Cadiz (the Algaida sand sheet). The deposit extends along the bank of the tidal channel of the San Pedro Creek, reaching a height of roughly 8 m above the average level of the present low tides. It is composed of fine and very fine sand, with insertions, at different heights, of various shell levels of variable thickness. This sand sheet had been interpreted differently by previous authors: its granulometry, morphology and orientation parallel to the coast made Fernández-Palacios et al. (1988) think that it was formerly a coastal aeolian sheet, while Zazo et al. (1994) considered it a former spit bar, abandoned at present, which formed part of the barrier-island system located to the south of the mouth of the Guadalete river. Given the character of the deposit, fine and very fine sand, and its position on a barrier-island system, thinking that it is a former sand dune deposit is one of the easiest hypotheses to accept. These sediments present very similar granulometry and texture to coastal aeolian deposits. However, in spite of the similarity in the facies, there are very significant differences. The main difference is the foraminifera content of these sands and the planktonic/ benthic indices, both of which are much higher than those of present eolian and intertidal formations, as they present similar values to sediments which are characteristic of deeper zones away from the coast (Gutiérrez Mas et al., 2009b).

Very similar sequences, although of coarser granulometry, have also been identified in subtidal zones in the Bay of Cadiz. In this case the high-energy facies appear in a sub-recent (terminal Holocene) littoral deposit which is relict in character, however, due to their location in zones which are easily reached by storms, it cannot be stated categorically that these facies were deposited by tsunamis.

The cheniers described in Doñana National Park (Guadalquivir river mouth) are also composed of sequences of this type, but in this case their genesis is related to the moments



following high-energy events, which caused the breakthrough of large littoral spits and the interruption of the progradation of muddy formations. These events carry sand and shells towards the interior of the estuary. Subsequent wave-winnowing produced by the dynamics of the estuary concentrates the sand and shells forming a longshore bar or ridge (chenier) which is driven shoreward with intense landward migration. Below these facies are found other coarser facies, which would indeed correspond to higher-energy events that are possibly tsunamigenic in origin.

In the last two cases the dating coincides more or less with the date of certain historical tsunamis, however, these could have broken the sandy formations which closed off the tidal systems, allowing storms to enter inner sectors of these and making possible the subsequent deposition of cheniers.

The fining sequences of shells and sands display clear similarities to the tsunamigenic layers described in the literature (Fujiwara et al., 2000): 1) erosive base, 2) accumulation of a mixture of articulated and disarticulated valves and shell fragments, 3) the mixture of a large number of species from different domains in the tidal systems, 4) the inclusion of many immature bivalve and gastropod individuals, 5) the large area of the deposit without any significant modification of the topographic position but with adaptation to a previous topography. These points of agreement allow us to state that the sequences of shells studied directly in the outcrops in banks in the interior of the estuary are tsunamigenic in origin, with a similar sedimentary record to the second type of tsunamites described by Fujiwara et al. (2000). The presence of disarticulated valves is explained by the uplifting of already dead bivalves from the bottom, while complete organisms with articulated valves were dragged up by the flow while they were still alive on the bottom. Some of the organisms with finer, lighter shells, such as *Scrobicularia plana* survived the transport, producing vertical escape tunnels to continue living buried close to the bottom.

The massive sequences of shells observed in the sediment sample cores from the Odiel-Tinto estuaries or in the trenches in the supratidal zones of the Bay of Cadiz are also very similar to the first type of tsunamites described by Fujiwara et al. (2000) and can also be interpreted as the result of tsunami action. In this case, the massive size of the deposit may be interpreted as the result of low efficiency in the selective capacity of the currents, either because the high energy of the process is maintained at all times, or else due to the unavailability of finer material. With regard to the massive levels of *Glycymeris* observed in the Bay of Cadiz, there is no evidence of these in previous studies, except in those carried out recently by Gutierrez-Mas et al. (2009 a and b). These levels may be related to storm overwash processes, however no washover-fan-type morphologies are observed in the zone, rather the shells appear as continuous or scattered paving in varying degrees. In this case the sequences were simply interpreted as the result of high-energy events; it was not possible to state categorically that they were generated by tsunamis, due to their location in zones which are easily reached by extreme storms.

These massive layers of shells and pebbles are very similar to those described by Nichol et al. (2003) in Whangapoua Bay (New Zealand), although in this case gravel with sub-rounded edges come from the reworking of fluvial deposits from the Upper Pleistocene which are widespread in the area, both in terrestrial outcrops and under the sea. As in the case described by Nichol, deposits of this type are small in area and are exclusive to the zone behind sandy formations which close estuaries.

The sedimentary record studied in the logs of the vibracores in the Huelva estuaries shows wide distribution of each tsunamigenic layer under the muddy estuarine accretion bodies. The tsunamigenic deposits of the deeper zones consist of massive coarse shell accumulations with a sandy matrix and are indicative of higher energy than the deposits of shallower zones, which typically consist of fining-upward sequences with finer shells. Each layer can be observed in different topographic positions along the estuaries, because the deposit is adapted to the existing topography.

This fact may be interpreted as the result of the estuaries' sedimentary infilling. Thus, the first tsunamis arrived in a deeper, much more open estuary with less energy dissipation when entering it, while the last waves arrived in an evolved estuary with a well-developed tidal channel network and large salt-marsh bodies. In this surface environment, the tsunami wave is dissipated, hindering propagation to more internal zones of the estuaries.

In the case of the Bay of Cadiz, on the other hand, the coarser layers are found at the highest levels. This fact can be interpreted as the action of tsunamis in a more open coast oriented in the direction of the origin of the tsunami waves, so that energy dissipation is lower and the wave can reach higher levels more efficiently.

## 7. Conclusions

This work presents a summary of the different high-energy facies studied in previous works in different protected systems (estuaries and bays) located along the Gulf of Cadiz. These works carried out in the Odiel, Tinto and Guadalquivir estuaries and the Bay of Cadiz described the presence of layers and superficial macroforms with coarse grain size, generated by high-energy events. Some of these works have emphasized the existence of a relationship between these layers and the action of historically documented tsunamis. These papers used radiometric dating techniques to demonstrate that the age of each layer corresponds to a well-documented event which occurred in the historical period. Once this fact is demonstrated, a variety of facies and surface forms are evidenced. The nature of these different deposits still stays uncharacterized. Among these sequences the following have been identified: a) sequences of sands and bioclastic microgravels, b) fining-upwards sequences of shells and sands, c) massive levels of shells, d) levels of shells with pebbles and e) levels of pebbles. Each of these sedimentary sequences presents different features, which vary according to: a) the energy of the event, b) the distance to the open coast and c) the depth of the sedimentary record.

All the sequences described are similar to the tsunamigenic sequences defined by other authors in coasts with a high frequency of tsunamis. The position of these high-energy sequences in the interior part of estuarine systems dozens of kilometers away from the action of storms or in topographical levels where storms cannot reach eliminates the possibility of these being storm deposits. However, in other cases such as subtidal facies in the Bay of Cadiz, the possibility that these facies were formed by very large storms may not be discarded. In the case of the Doñana cheniers, in the Guadalquivir River estuary, the high-energy levels found in the record are related to lower-energy surface formation. In this case, it is interpreted that the action of the tsunamis broke the estuary closure barrier on different occasions, and that this tsunami was responsible for the depositing of layers which have appeared in the record, but not for the surface formations, which would be formed by the action of storms, once the system remained open after the tsunami action.

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## **The Tsunami Threat - Research and Technology**

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Submarine earthquakes, submarine slides and impacts may set large water volumes in motion characterized by very long wavelengths and a very high speed of lateral displacement, when reaching shallower water the wave breaks in over land - often with disastrous effects. This natural phenomenon is known as a tsunami event. By December 26, 2004, an event in the Indian Ocean, this word suddenly became known to the public. The effects were indeed disastrous and 227,898 people were killed. Tsunami events are a natural part of the Earth's geophysical system. There have been numerous events in the past and they will continue to be a threat to humanity; even more so today, when the coastal zone is occupied by so much more human activity and many more people. Therefore, tsunamis pose a very serious threat to humanity. The only way for us to face this threat is by increased knowledge so that we can meet future events by efficient warning systems and aid organizations. This book offers extensive and new information on tsunamis; their origin, history, effects, monitoring, hazards assessment and proposed handling with respect to precaution. Only through knowledge do we know how to behave in a wise manner. This book should be a well of tsunami knowledge for a long time, we hope.

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