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Evidence of high-energy events in shelly layers interbedded in coastal Holocene sands in Cadiz Bay (south-west Spain)

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ABSTRACT: In some present-day coastal areas, recent inactive deposits now outside the reach of sea agents can be observed. These deposits, although formed under different climatic and sea level conditions, often show similar facies to current littoral deposits. They are frequently interpreted as old dunes and beach ridges, or as abandoned spit bars, representative of previous dynamic stages. Nevertheless, in coastal areas which have been subjected to highly-energetic events similar deposits can also be found. When a dynamic event acts on several adjacent environments, the transported and re-deposited sediments can create homogeneous deposits with similar facies, that are easily confused.

In this work, shelly layers interbedded in relict littoral sands located in the *La Algaida* pinewood, on the edge of the Rio San Pedro tidal channel, in Cadiz Bay (south-west Spain) have been studied. The main constituents of the shelly beds are *Glycimeris* valves, organisms which are no longer found as live specimens in the present-day sea bed of Cadiz Bay.

From their appearance, the origin of these shelly beds could be related to sea washovers generated by tidal or storm action, but their disposition and height over the present sea level implies that even higher energy agents were involved in their formation, such as major storms or tsunami waves. The most significant process was the mobilization of the sub-tidal and littoral sediments and their dispersal and re-sedimentation, both lengthways and widthways of the coast, giving way to homogeneous sandy deposits in all littoral environments some of which are now outside the reach of current sea agents. The exception is the present-day shore of the San Pedro tidal channel, where the sediments are being reworked by tidal and small wave action.

If the proximity of the study zone to the limit of the African and Iberian plates is considered, where several historical earthquakes and tsunamis have taken place, it is possible to think that these deposits could be a consequence of sporadic and successive washovers, generated by tsunamis occurring between AD 800 and AD 1200. Sedimentological and historical data indicate an increase in seismic and tsunami activity during this period of time, while the shelly layers would be the consequence of the most intense pulses occurring during these high-energy events. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: Cadiz Bay; Holocene sediments; relict littoral deposits; tsunamites

Introduction

In present-day coastal areas, it is relatively common to find old littoral deposits formed under different climatic and dynamic conditions to those existing today. These deposits are frequently fixed by a vegetation cover, and situated at different heights and distances from the sea shore. Due to their facies and fossil content, they are normally interpreted as abandoned littoral deposits. Nevertheless, this interpretation may sometimes be imprecise, for instance, when a highly dynamic sea agent overtakes the limits of several adjacent littoral environments. Powerful events such as, cyclones and tsunamis, and the subsequent erosion, homogenization and re-sedimentation processes, can generate similar deposits to the pre-existent littoral sediments, and can easily be misinterpreted (Visher, 1969).

A relict Holocene deposit at the *La Algaida* pinewood, has been studied, on the edge of the Rio San Pedro tidal channel (Cadiz Bay, south-west Spain) (Figures 1 and 2). The sediments consist of fine and very fine sands with several intercalated shelly layers. Due to the deposit's morphology, grain size and the ease with which it can be transported by wind, some authors have interpreted this deposit as an old dune cordon (Fernández-Palacios *et al.*, 1988), or an abandoned spit bar (Zazo and Goy, 1987).

No previous studies about the shelly layers are not known to the authors. The evidence suggests that they could be the result of relatively extensive sea washovers, but their true origin is still unknown. The proximity of the study area to an active seismic region (Udías *et al.*, 1976; Campos, 1991, 1992; Ribeiro, 1995), suggests that the action of high-energy events may be the most plausible hypothesis. In addition,

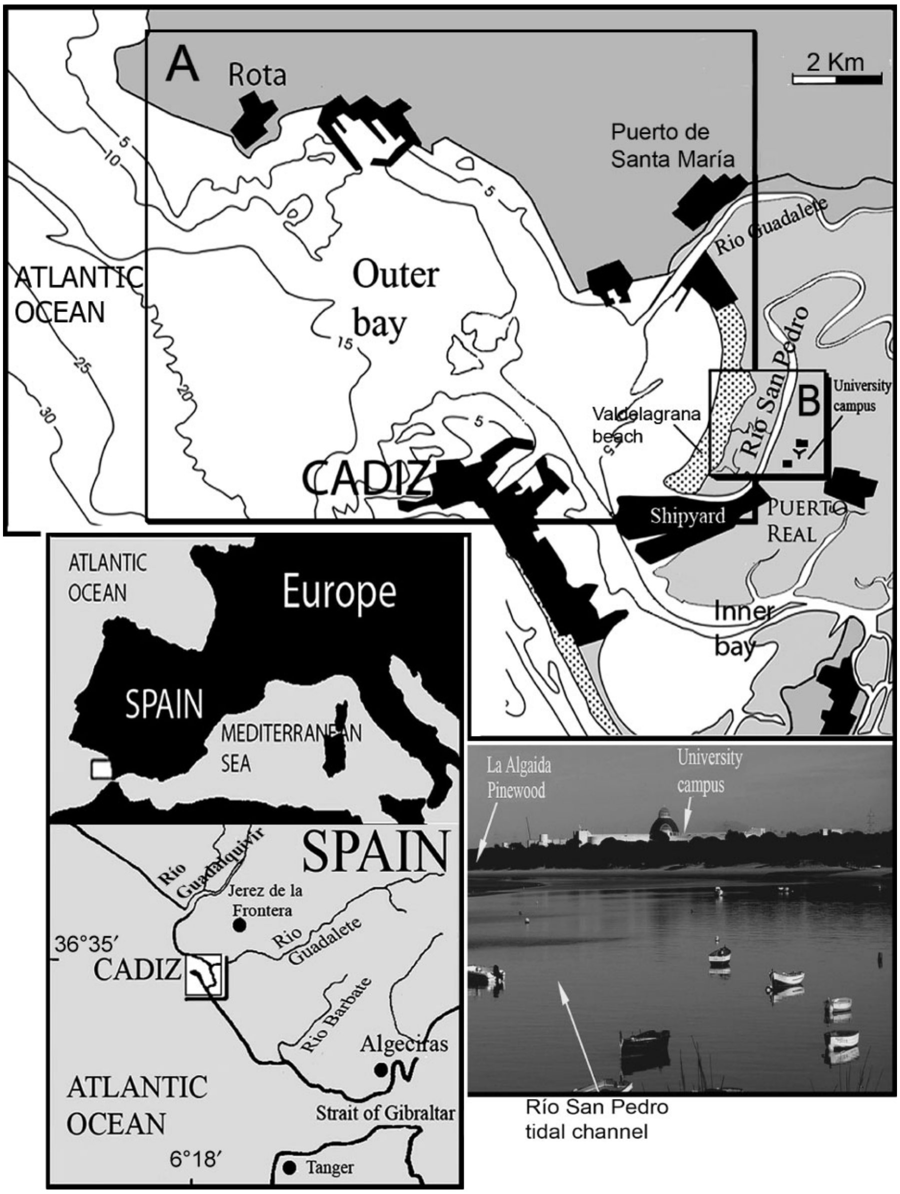

Figure 1. Maps of the study area and an image of the San Pedro River tidal channel.

tsunami deposits have been described in locations close to the zone (Dabrio *et al.*, 1998, 2000; Luque *et al.*, 2002a, 2002b; Lario *et al.*, 2002a, 2002b; Ruiz *et al.*, 2005; Whelan and Kelletat, 2005; Morales *et al.*, 2008). This paper provides sedimentary analyses which enables the interpretation of the deposit's origin and contributes to current knowledge of the sedimentary evolution of the Cadiz Bay.

Study Area

The study area is located in Cadiz Bay, between the Guadalquivir river mouth and Cape Trafalgar (Figures 1 and 2). The coast has a north-north-west (NNW)-south-south-east (SSE) orientation, with sectors facing NNW-SSE, WNW-ESE and E-W, as a result of both old and recent fractures (Baldy *et al.*, 1977; Sanz de Galdeano, 1990; Gutiérrez–Mas *et al.*, 2004).

The hydrodynamic regime is dominated by surge and tides. Tides are of a semi-diurnal character, ranging from 2·2 m to 3·7 m during the spring tide. The region is affected by two oceanic streams, Superficial Atlantic Water and Out Flow Mediterranean Water. The main littoral current flows towards the south-east, generating sediment transport in the same direction consequence of the coast orientation and the dominant wind from the west. Easterly winds also generate littoral-drifts towards the north and north-west. The dominant wind direction varies seasonally, but overall the west component prevails, with a Significant Wave Height of 0·6–1 m, although during storm weather, the maximum height reached can be 4 m. West, north-west and south-west waves prevail in the offshore zone, whereas inshore waves are refracted by the bottom.

Pre-Holocene substratum consists of Plio-Pleistocene marls, calcarenites and conglomerates (Figure 2A). Older materials are also present, such as, Triasic marls and gypsums (Gutierrez-Mas *et al.*, 2004).

Methods

Fieldwork involved several sampling campaigns and the carrying out of representative stratigraphic sections. Shelly bed orientation measurements were taken, with the objective of establishing the relationship between flow directions. Samples and drillings were also extracted from adjacent sea areas to determine the

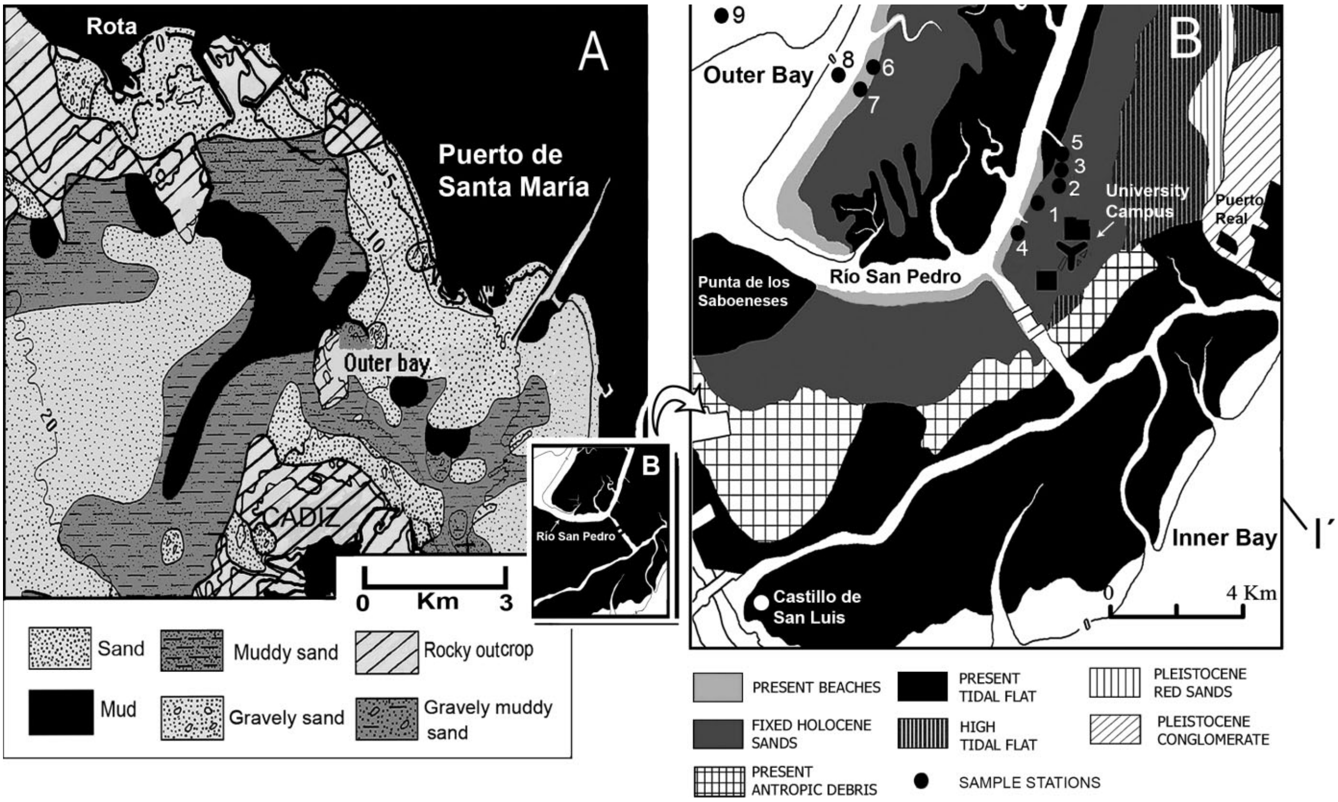

Figure 2. (A) Sediment types at the sea bed of the outer Cadiz Bay (location map in Figure 1). (B) Sampling station location and environmental map of the study area (location map in Figure 1).

sediments and other characteristics of the sea-bottom. Some lacquer-peel tests were performed in order to observe the sedimentary structures present in the deposits.

Laboratory work consisted of the textural analysis of samples and the determination of sand fraction constituents. Microfossils were determined using a binocular magnifying glass and the counting of 1500 grains by fraction. Grain-size distribution and granulometric parameters were used to describe the sediments and processes. Textural analysis has provided data on the sedimentary processes involved and helped to establish differences between deposits, recognize small depositional features and distinguish between relict and present-day deposits through textural and compositional variations. For grain-size distribution analysis, formulas by Folk (1974) and Folk and Ward (1957) were used. Other sedimentary and paleontological criteria were used to identify the depositional environments.

The dating of samples was established using the carbon-14 method (PE-03-01), and carried out by the Dating Laboratory at the Scientific Instrumentations Centre, Granada University. Calibration was carried out through the Washington University Programme (Stuiver and Reimer, 1993; Stuiver and Braziunas, 1993; Stuiver *et al*., 1998) and the Marine Curve 04 (Hughen *et al*., 2004) (CALIB Program version 5.01). The marine reservoir correction values (ΔR) used for sample age calibration were: $\Delta R = 440 \pm 84$ for samples older than 2500 years; $\Delta R = 412 \pm 45$ between 2500 and 1700 BP, $\Delta R = 304 \pm 70$ between 1700 and 1000 BP and $\Delta R = 114 \pm 90$ for samples younger than 1000 years (Monge Soares, 1993; Reimer *et al*., 2002; Morales *et al*., 2008).

Results

The *La Algaida* deposit consists of 97·7% sand, fundamentally of a fine and very fine nature. Gravel and mud are present in very small amounts, 0·74% and 1·21%, respectively. The materials exhibit massive bedding, with slight planar and tangential cross-lamination, abundant bivalves and no fossilized root remains. The main mineral component in the sediments is quartz, constituting 75% to 85%. Quartz grains have a rounded morphology, are dull and somewhat translucent, although some grains are glossy with an angular morphology. Philosilicates are present in the form of muscovite and biotite (2%). Other constituents are rock fragments such as calcarenite grains from Plio-Pleistocene outcrops. Clay fraction consists of inherited minerals, with a predominance of illite, chlorite, kaolinite, smectite and mixed layer illite-smectite clay minerals.

Sediments are very homogeneous with the dominant mode in the fine sand fraction and a secondary mode in very fine sand. Mean grain size is 0·18 mm and sorting is 0·55, corresponding to very well-sorted sediments (Folk and Ward, 1957) (Table I). Carbonates represent 15% to 30% of the deposit. They mainly consist of bioclast calcite, pertaining to bivalve and gastropod fragments, foraminifers and other biogenic remains. Macrofauna consists mainly of *Glycimeris* valves and gastropod shell, whereas the microfauna is fundamentally constituted by benthonic and planktonic foraminifers, ostracods, spicule, echinoderm fragments, bryozoa and corals, microscopic fish bones and sponge spicules.

Foraminifers are the most significant microfossils. They are well-preserved with clean caparaces and no abrasion or recrystallization marks. Chambers are hollow or with a glaucomite lining, although a pyritized specimen was also found. Benthic specimens are predominant, represented by: Miliolids, Rotalids and Anomalinids (Table II). Sub-littoral specimens are present in the form of *Lobatulus*, *Nonion pompiloides* and *Boneanum*, *Cassidulina laevigata* and *Amonia becarii*. Neríthic specimens are also present, such as *Textularia articulate* and *Sagitula*, *Uvigerina mediterranea*, *Peregrina* and *Hyalinea balthica* (Table II). The planktonic foraminifers are represented by

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Table I. Grain size parameters in *La Algaida* and in present-day littoral sediments

Environment	Gravel (%)	Sand (%)	Mud (%)	Sorting (Phi)	Mean (mm)	Median (mm)	Mode	Skewnes (Phi)
La Algaida (Upper sand bed)	0·83	98·43	0·72	0·72	0·19	0·13	Fine and very fine sand	–0·12
La Algaida (Upper shelly bed)	0·65	97·5	1·71	0·63	0·19	0·13	Fine and very fine sand	0·12
La Algaida (Average contents)	0·74	97·9	1·21	0·67	0·19	0·13	Fine and very fine sand	0
Valdelagrana beach (Active dunes)	0	100	0	0·51	0·18	0·17	Fine sand	0·31
Valdelagrana beach (Washover channels)	0	99·86	0·14	0·06	0·17	0·17	Fine sand	0·19
Valdelagrana beach (Active foreshore)	5·9	94·04	0·07	1·05	0·61	0·3	Medium and fine sand	–0·12
Valdelagrana beach (Active backshore)	0·78	99·08	0·14	0·50	0·2	0·18	Fine sand	–0·11
Cadiz Bay (Subtidal zone)	13·20	78·7	13·40	1·06	0·18	0·18	Medium and fine sand	–0·20

Table II. Foraminifer content in the *La Algaida* sands and in present-day littoral sediments

Sedimentary environment	Foraminifer Total	Benthic	Planktonic	Benthic/ planktonic (ben/plan)	Foraminifer present in sediments from Cadiz Bay and *La Algaida* sands	
					Benthic	Planktonic
La Algaida (Average)	6·3	4·47	1·44	3·35	*Cibícides lobatulus*	*Globigerina aequilateralis*
					Nonion pompiloides	*Globigerina bulloides*
La Algaida (Upper sandy bed)	7·8	5·9	1·9	3·1	*Nonion boneanum*	*Globigerina apertura*
					Cassidulina laevigata	*Globigerina concinna*
La Algaida (Upper shelly bed)	2·06	1·63	0·43	3·76	*Cassidulina obtusa*	*Globigerina quinqueloba*
					Ammonia becarii	*Globigerina sp.*
Valdelagrana beach (Active dune)	2·8	1·6	1·2	1·33	*Textularia articulata*	*Orbulina universa*
					Textularia sagittula	*Orbulina bilobata*
Valdelagrana beach (Active backshore)	3·2	1·8	1·4	1·28	*Uvigerina mediterranea*	*Globogerinoides rubber*
					Uvigerina peregrina	*Globogerinoides trilobus*
Valdelagrana beach (Active washover)	3·2	2·4	1·8	1·3	*Hyalinea balthica*	*Globorrotalia pachyderma*
						Globorrotalia truncatulinoides
Valdelagrana beach (Active foreshore)	3·8	2·6	1·2	2·17		*Glorrotalia sp.*
						Planuaria auris
Cadiz Bay (Subtidal zone)	4	2·7	1·3	2·07		

Globigerinids (globigerinae and orbulinae), although deeper-water species such as *Globorrotalia truncatulinoides* are also present (Table II).

The average foraminifer content in the *La Algaida* sands is 6·3%, of which, 4·47% corresponds to benthic and 1·44% to planktonic. The benthic/planktonic ratio (ben/plan) is 3·35 (Table II), which is high when it is compared to the present-day littoral sediments. In active dunes on the *Valdelagrana* beach (Station 7), the foraminifer content is 2·8%, of which 1·6% corresponds to benthic and 1·2% to planktonic, and the ben/plan ratio is 1·3. These values are even lower for active dune deposits outside the study zone, but still within Cadiz Bay, for instance, the *Cortadura* beach dunes, with a foraminifer content of 0·6%.

In active backshore sediments from the study zone, as the *Valdelagrana* beach, foraminifer content is 3·2% and ben/plan ratio is 1·28. In active washover channels, the content is 3·2% and the ben/plan ratio is 1·3. In active foreshore of this beach, content is 3·8% and the ben/plan ratio is 2·1. Finally, in sub-tidal areas (Station 9), the foraminifer content is 4% and the ben/plan ratio is 2·07.

Shelly layers

The *La Algaida* deposit consists of fine and very fine sands with no recognizable inner fabric, with the exception of the shelly components. The stratigraphic sections show very homogeneous and monotonous materials, presenting no substantial variations between sample stations. This monotonous disposition is only altered by the presence of shelly beds intercalated in the sand. When the shelly beds are intercepted by surface ground, they show bands from 3 to 15 m long, and 1 to 3 m wide (Figures 3 and 4), and are orientated WNW-ESE, NE-SW and N-S (Figure 4D). The shells are normally in a horizontal position with downward concavity, although in some beds, the valves are imbricated, as in the lowest shelly bed of *La Algaida* (Station 5).

The biogenic remains consist of *Glycimeris* shells (Figure 4). These have a mean size of between 3 and 6·5 cm, with a circular morphology and similar valves and crenulated borders. They are generally well-preserved, although in the lower beds, the shells have a hoary colour due to discolouration and deterioration. Furthermore, they present impact marks, abrasion and dissolution (Figure 4). In the most recent beds, valves have well-carved surfaces and their colour is greyish-brown to purplish.

The lowest shelly layer (Station 5) (Figures 2 and 5), shows a slight dip of 5° to 10° westward, specifically, towards the sea. Valves are imbricated with a westerly inclination, and show evidence of the action of flows coming from the west. The base consists of a shelly bed of *Glycimeris* valves of 5 cm in diameter and shelly matrix. Above this, there is a 1 cm-wide white-grey scab with alternating layers of mud, sand and *Glycimeris* valves.

Over the previous beds, an alternating humus and sand with *Glycimeris* is present. Above this, there is a 12 cm-wide shelly bed, consisting of imbricated *Glycimeris* valves of 6 cm

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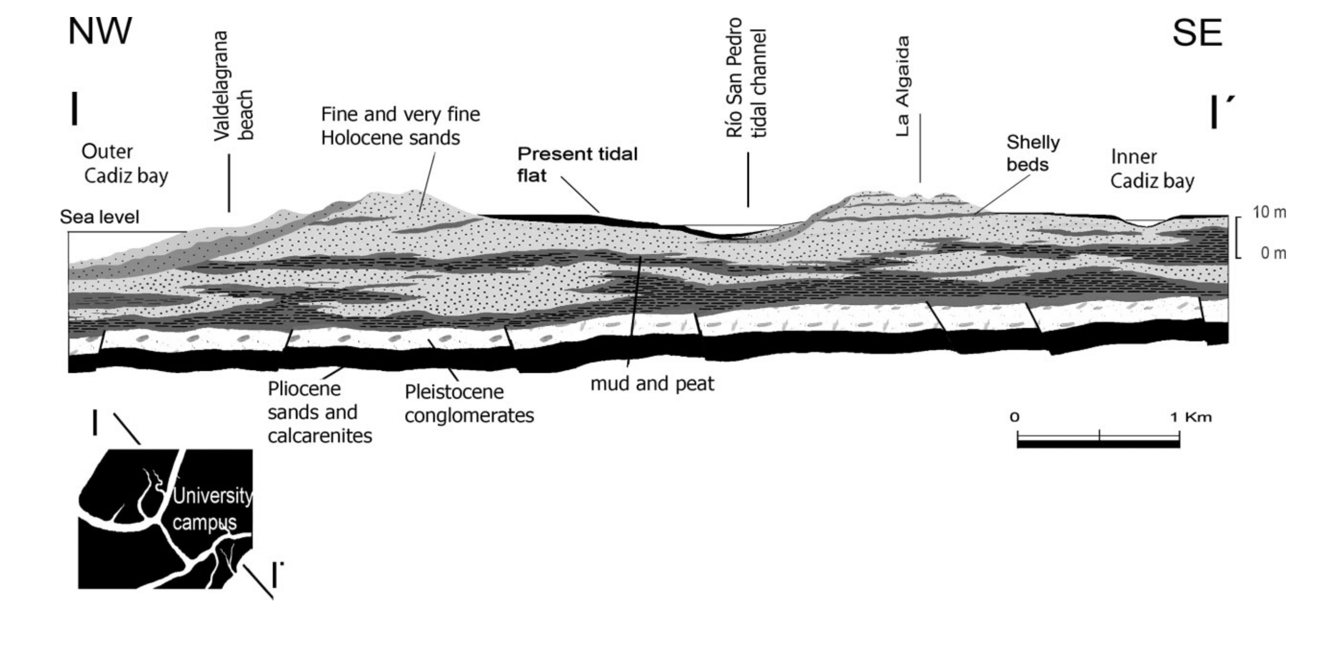

Figure 3. Schematic geological cross-section of the study area (location in Figure 2B).

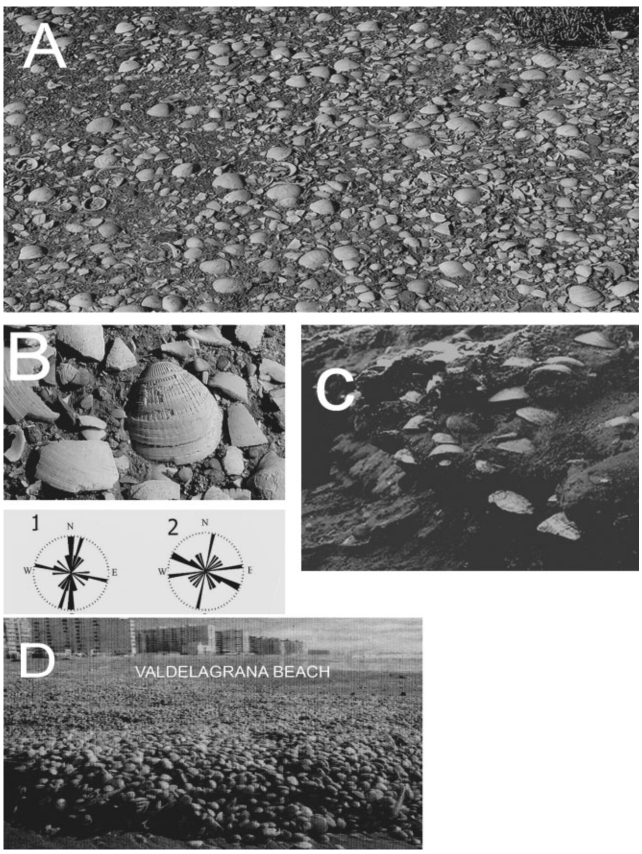

Figure 4. Images of the Holocene shelly layers in the *La Algaida* sands. (A) Upper shelly layer. (B) Close-up of *Glycimeris* shells. (C) Lowest shelly deposit: 1, predominant orientation of the shelly beds in the northern sector of the study area; 2, predominant orientation of the shelly beds in the southern sector of the study area. (D) present-day coquina deposit in the *Valdelagrana* beach.

in diameter, quartzite and sandstone pebbles and shelly matrix (Figure 5). Over the previous shelly layer, present-day tidal mud covers the outcrop (Figure 5).

The upper shelly layers are at a higher topographic and stratigraphic position (Station 3) (Figures 2, 6 and 7). They consist of imbricated *Glycimeris* valves of between 5 and 6 cm in diameter, with gastropods such as *Murex* and *Strombus*. At 25 cm over the previous bed, there is another 10 cm wide bed, constituted by *Glycimeris* valves with downward concavities.

Over the previous layers, there is a wide deposit of fine and very fine sand, well-represented in Station 4 (Figure 2 and 8), with an abundance of recent roots and humus. Sand content is 98·43% and mean grain size is 0·19 mm. Mode is in fine and very fine sand and sorting is 0·72, corresponding to moderately-sorted sediments. A characteristic of these sands is the high foraminifer content, reaching a maximum of 14·34%, and consisting mainly of miliolids (Table II).

Comparison with present-day littoral sediments

The present-day dunes are the more similar littoral sediments to the *La Algaida* sands. Eolian sediments from the study zone have a sand content of 100% (Table I), with unimodal character and mode in the fine sand fraction. Sorting is 0·55, corresponding to well-sorted sediments (Folk and Ward, 1957, in McManus, 1998). Foraminifer content is 2·8% and the ben/plan ratio is 1·3, lower than the values obtained from the *La Algaida* sands (Table I). This difference is more remarkable if the sands are compared to dune deposits outside the study area, for instance at *La Cortadura* beach, where foraminifer content is only 0·6%. Interestingly, miliolids are the most abundant, both in present-day dunes within the study area and in the higher levels of the *La Algaida* sands. Nevertheless, in small dune bodies such as sand shadows, miliolids are not present, while planorbilinidae are dominant (Table II). Sediments from present backshore and active washover also have similar characteristics to those of the *La Algaida* sands, with a sand content of 98 to 99·9%, mode in fine or very fine sand and sorting from 0·50 to 0·61, while the main difference with the *La Algaida* sands is the lower foraminifer content (3·2%).

Intertidal sediments in active beaches show the lowest sand content (94%) and a slight displacement towards a coarser grain size. The mode is in medium sand and sorting is 1·05, corresponding to poorly-sorted sediments, while the foraminifer content is 3·8%. In the sub-tidal zone (Station 9),

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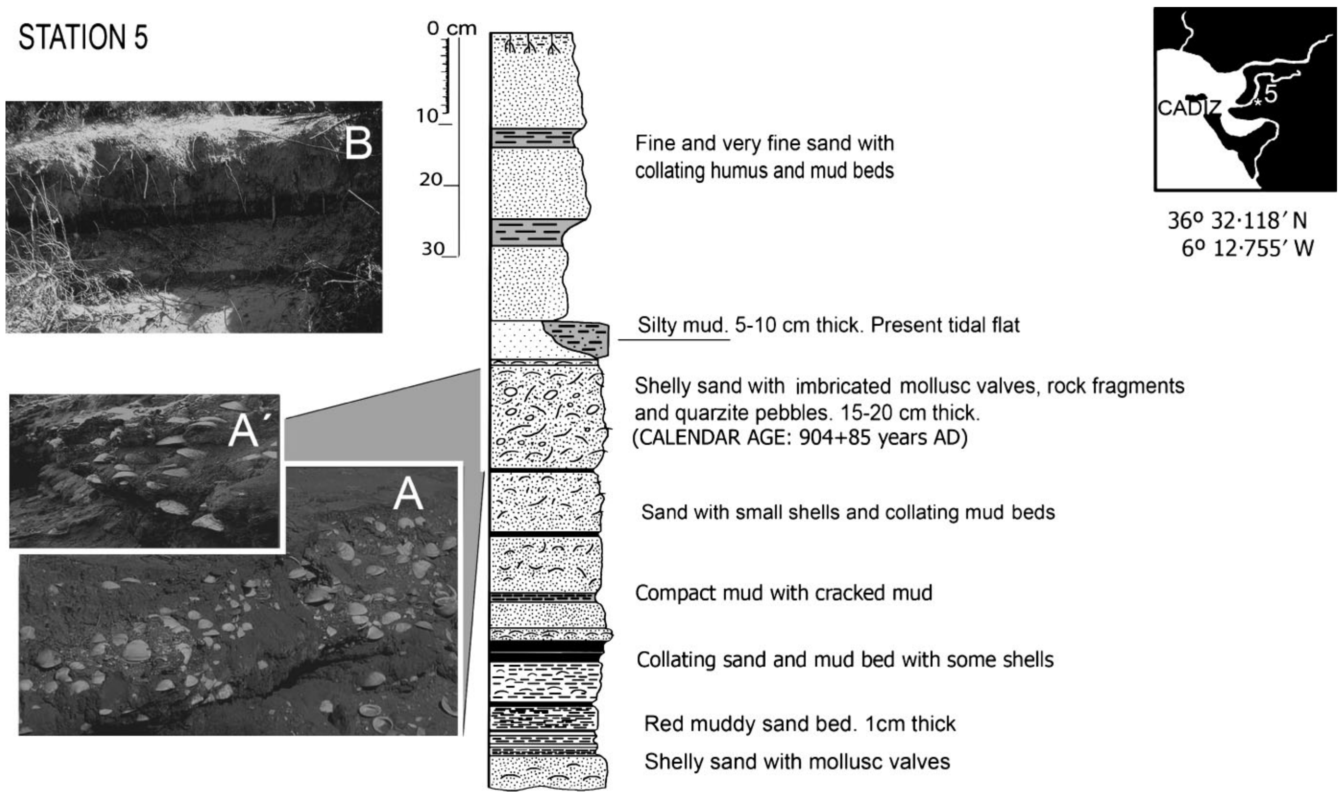

Figure 5. Corresponding section of the lowest shelly layers. (A) and (A′) Close-up of the outcrops (Station 5). (B) Overlying sandy deposit.

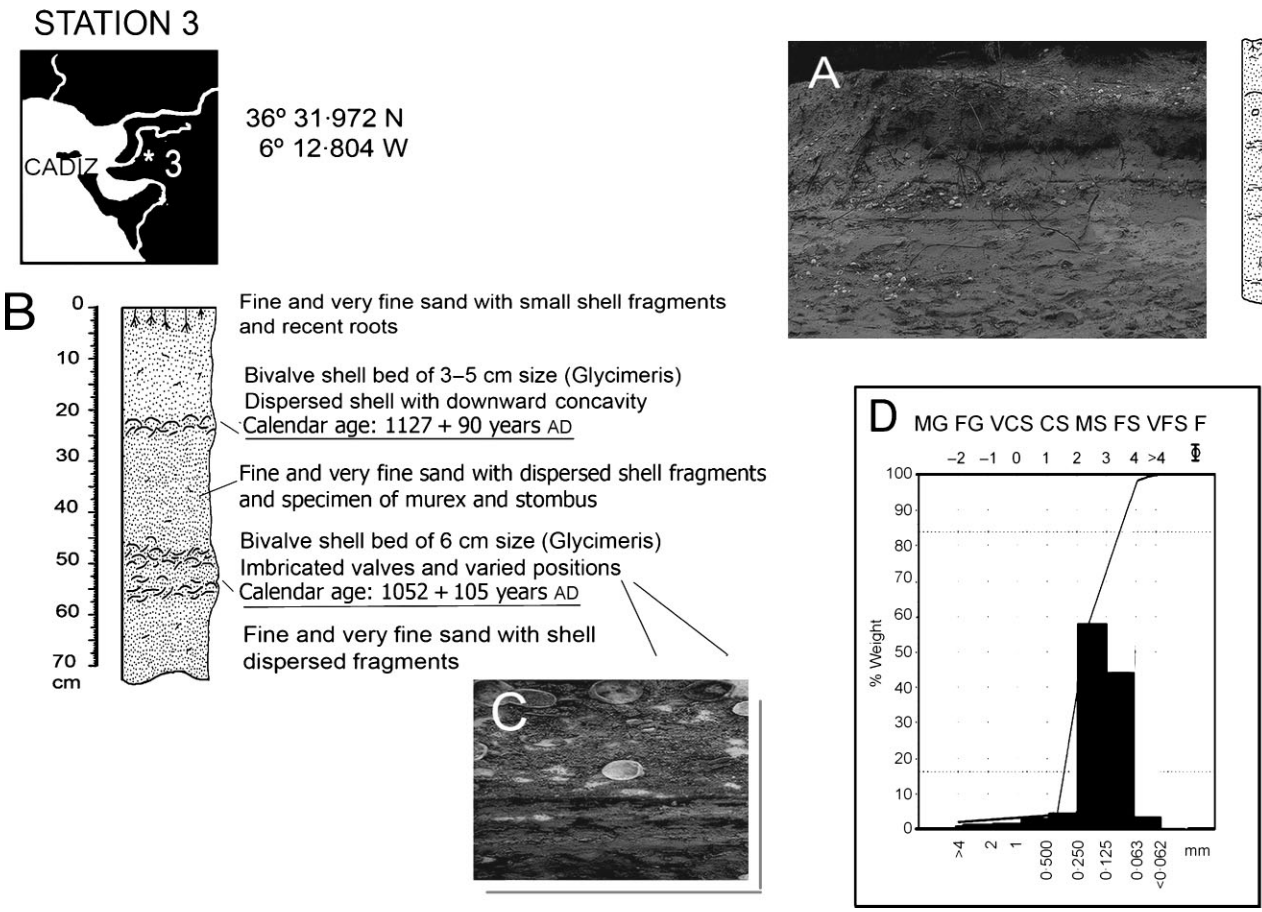

Figure 6. Sands and upper shelly layer, corresponding to Station 3. (A) Image of the outcrop. (B) Section at Station 3. (C) Close-up of the shelly level. (D) Grain-size distribution of the sandy sediments in this stretch.

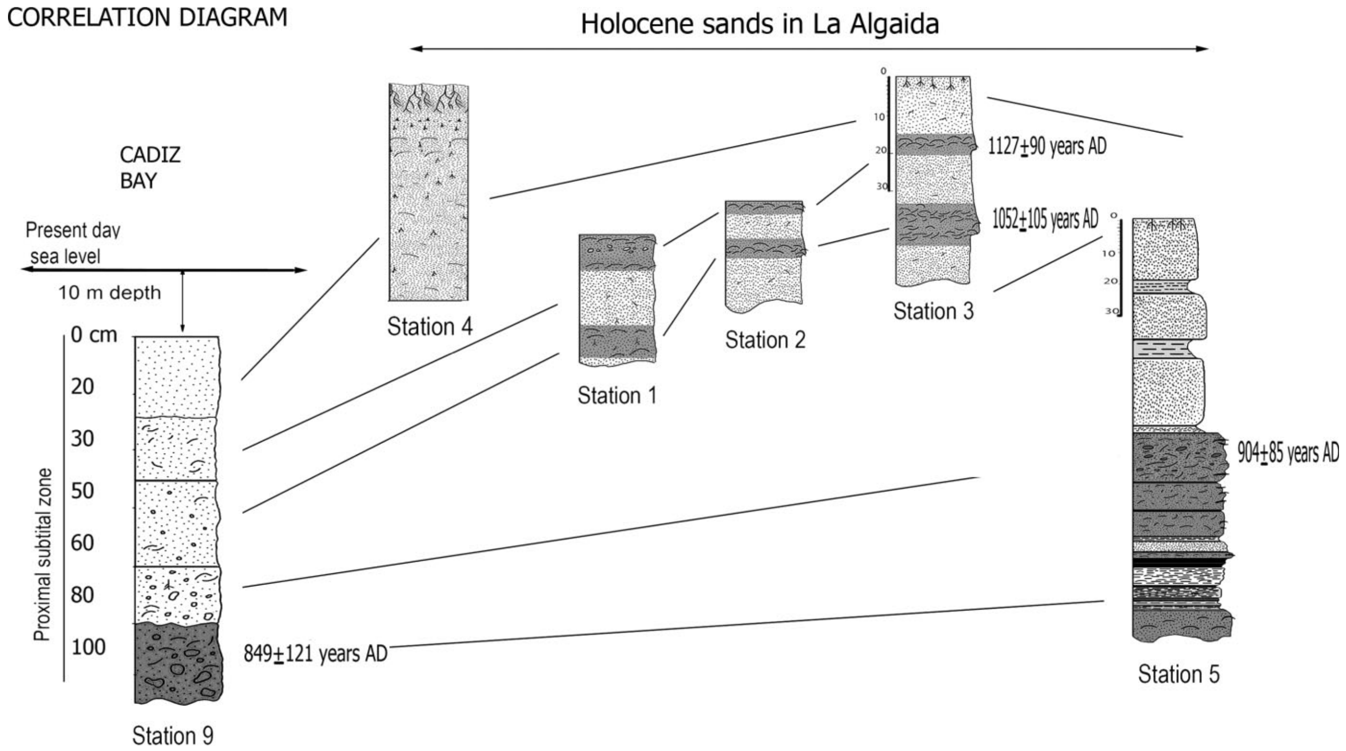

Figure 7. Correlation diagram of the stratigraphic sections in the study area.

Table III. Sample ages obtained using the carbon-14 method (sample location in Figure 2)

Sampling station	Geographic situation	Height (m)	Radiocarbon age (year BP)	Calibrated age (year BP)	Calendar age (year AD)
Station 9 (Subtidal zone)	36° 33·731′ N 6° 16·187′ W	–10	1960 ± 110	1101 ± 121	849 ± 121
Station 5 (*La Algaida*, lowest shelly bed)	36° 32·118′ N 6° 12·755′ W	2–3	1910 ± 60	1046 ± 85	904 ± 85
Station 3 (*La Algaida*, middle shelly bed)	36° 31·904′ N 6° 12·776′ W	4–5	1670 ± 60	898 ± 105	1052 ± 105
Station 3 (*La Algaida*, highest shelly bed)	36° 31·972′ N 6° 12·804′ W	3–4	1590 ± 60	823 ± 90	1127 ± 90

sediments have a lower sand content (78·7%) with respect to the littoral deposits, mode in medium and fine sand, and sorting at 1·06, corresponding to poorly-sorted sediments. In addition, they contain pebbles, imbricated *Glycimeris* valves, gastropods and continental wood and plant remains (Figure 9), while the foraminifer content is 4%, nearest to the values obtained in *La Algaida* sands.

Regarding the *Glycimeris* shells, despite the abundance of valves in the coastal area of Cadiz Bay, this mollusc has disappeared from the sea bottoms adjacent to Cadiz, as the sampling has clearly shown. The nearest spawning areas for this organism is in Mediterranean areas near the Strait of Gibraltar, such as *La Atunara* (San Roque), where commercial exploitations produce the variety *Glycimeris gaditanus*, a subspecies of *Glycimeris glycimeris* (Linné) (Consejería Agricultura y Pesca, 2002).

Age of the shelly layers

The dating of carbonated samples indicates a Late Holocene age (Table III). The oldest shelly bed is in the subtidal zone (Station 9) with a radiocarbon age of 1500 ± 70 BP, corresponding to a calibrated age of 1101 ± 121 BP and a calendar age of AD 849 ± 121 (Figure 7 and 9). The next oldest bed is located in the emerged zones (Station 5), with a radiocarbon age of 1910 ± 60 BP, corresponding to a calibrated age of 1046 ± 85 BP and a calendar age of AD 904 ± 85.

The most recent deposit is located in Station 3 (Figure 8), with a radiocarbon age of 1670 ± 60 BP, corresponding to a calibrated age of 898 ± 105 BP and a calendar age of AD 1052 ± 105 (Table III). In this same station, the most recent materials have been found (Figure 6), with a radiocarbon age of 1590 ± 60 BP, corresponding to a calibrated age of 823 ± 90 BP and a calendar age of AD 1127 ± 90.

Discussion

The results indicate that the *La Algaida* sands are similar to many present-day littoral deposits. They consist of quartzy and bioclastic sands with insignificant quantities of gravel and mud. The predominant sand grain size is fine and very fine. They present a massive inner ordination and an absence of any visibly sedimentary structures. Another resemblance is that miliolids are the most abundant foraminifers in large dunes, as in the higher levels of the *La Algaida* sands.

Similarities in the micropaleontological contents (Table II), both in the active dunes and in the *La Algaida* sands, could lead to the idea that the deposits share a common origin. It is possible that these dunes were originally constituted by the same sediments as those of the *La Algaida* sands, although they are now being reworked by wind, tide and surge action. In addition, intertidal sediments show a slight displacement towards a coarser grain size (Table I), while the foraminifer content is higher than the supra-tidal sediments. Sub-tidal

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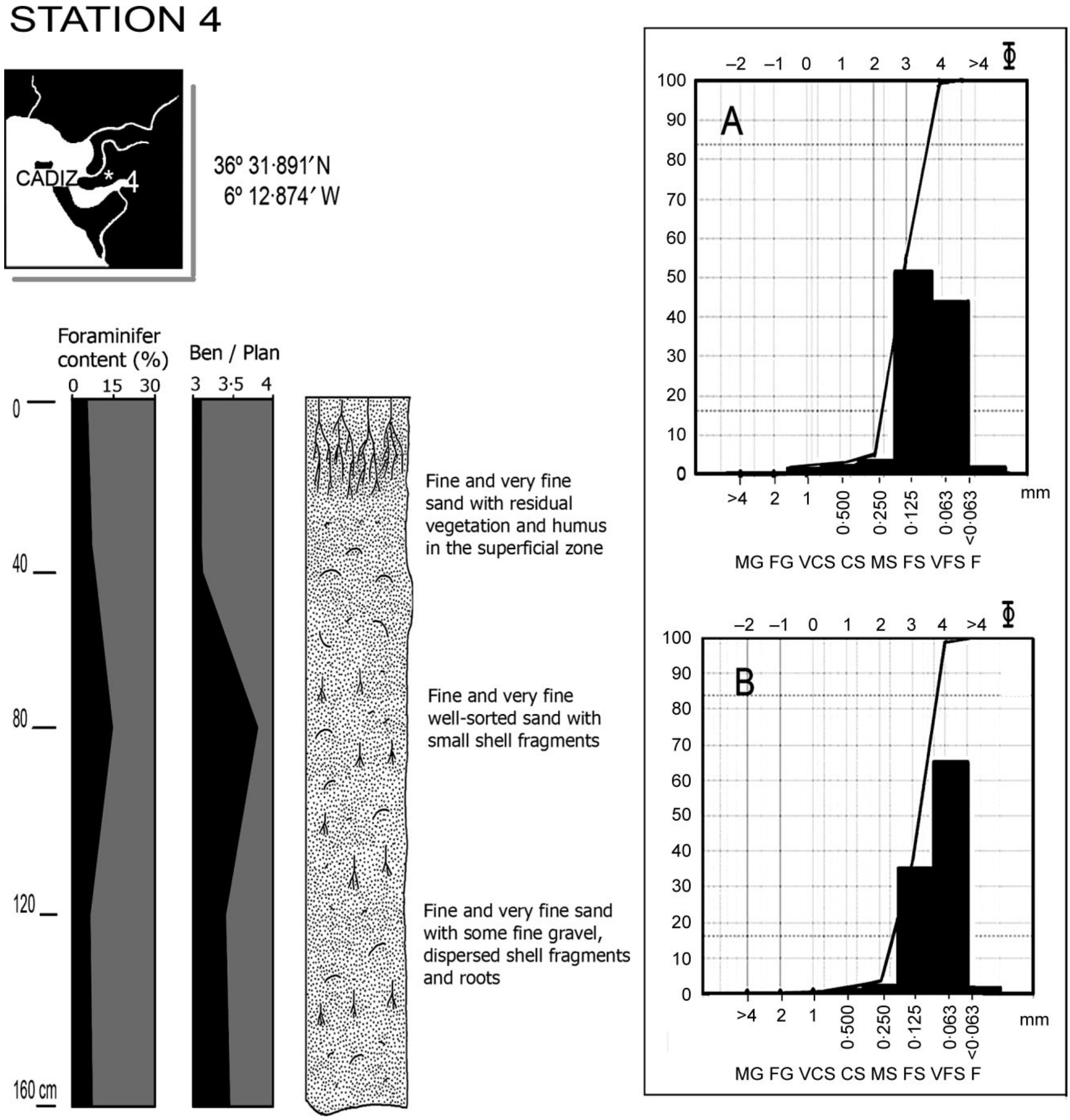

Figure 8. Section corresponding to the upper sandy layer (Station 4). (A) Grain-size distribution of the sandy sediments from the top of the section. (B) Grain-size distribution of sandy sediments from the base of the section.

sediments show remarkable differences with inter-tidal and supra-tidal sediments, from the lowest sand content, highest foraminifer content and the presence of imbricated *Glycimeris* valves, pebbles, and continental plant remains.

Origin of the *La Algaida* sands

From the facies and geographical position near the present-day sea shore (Tables I and II), the *La Algaida* sands appear to be coastal aeolian dunes or other littoral environments such as beaches, spit bars, etc. (Figures 10 and 11). Nevertheless, the absence of sedimentary structures, such as cross-bedding, erosional truncations, current marks, scours, etc., precludes the assignation of these deposits to a precise sedimentary environment. Furthermore, high foraminifer content is associated with deeper marine environments such as sub-tidal or nerithic zones and suggests these deposits have a marine origin. However, the abundance of well-sorted sands and shelly beds, make them a rather singular deposit, with mixed features pertaining to both littoral environments and deeper zones (Tables I and II).

These characteristics suggest a common origin, probably coming from the same source and transport agent. The predominance of fine and very fine sands and well-sorted sediments indicates that the source could be an old aeolian dune cordon. Furthermore, the presence of mollusc shells and benthic and planktonic foraminifers, suggests the incorporation of materials from adjacent sub-tidal and nerithic zones, which is only possible through the action of high-energy flows.

After the hydrodynamic processes that provoked their transportation, the sediments were deposited on different coastal environments and, subsequently, once the habitual dynamic agent was reactivated by surge and tidal action, provoked a new sedimentary redistribution, in accordance with the dominant agents in each environment. Nevertheless, despite the intense dynamic processes acting on the sediments, they still preserve

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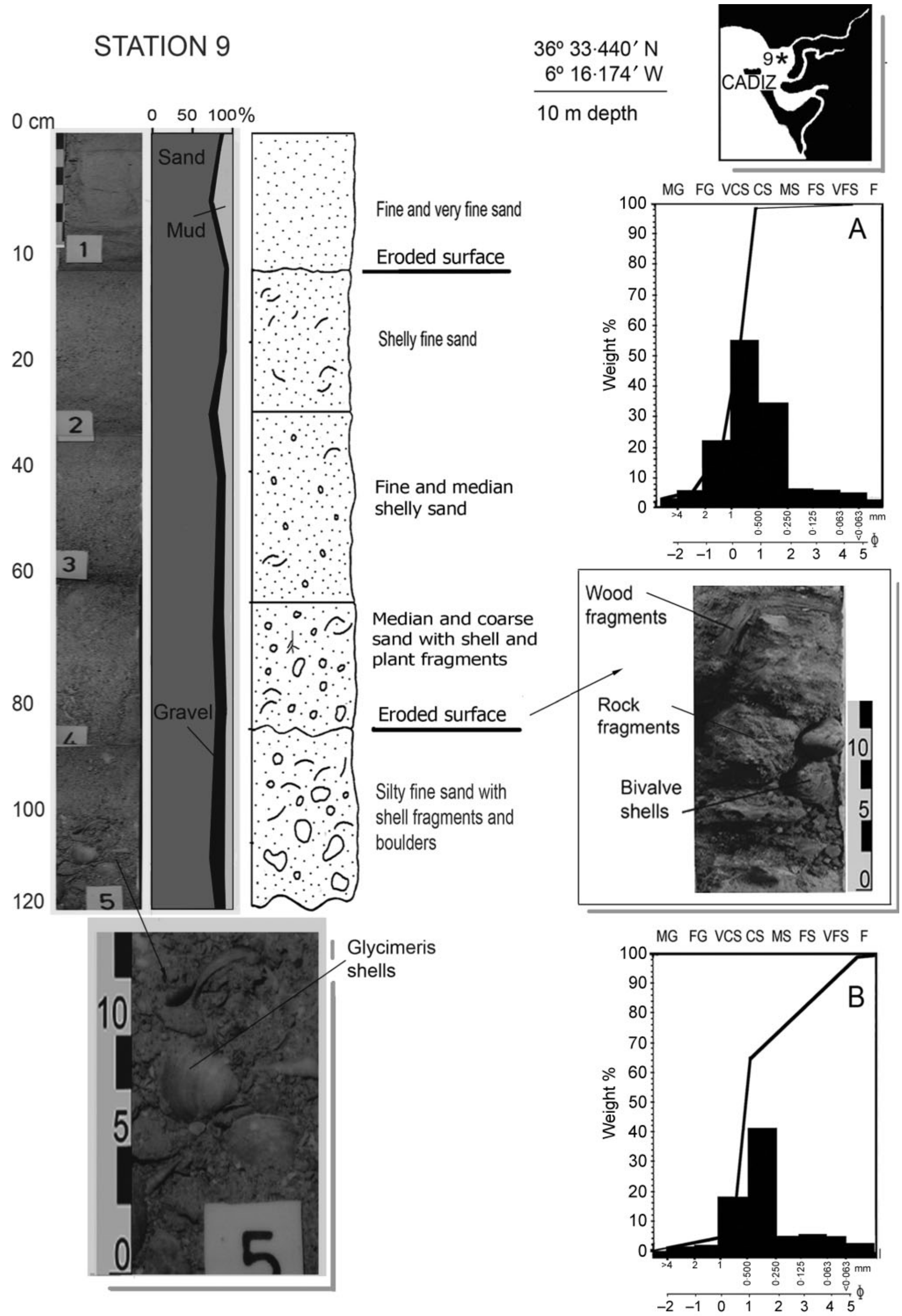

Figure 9. Section at Station 9, from the sub-tidal zone in Cadiz Bay. (A) Grain-size distribution of sediments from the top of the section. (B) Grain-size distribution of sediments at the base of the section.

a similar texture and grain-size distribution inherited from the pre-existent materials in the source areas.

Origin of the shelly layers

If the *La Algaida* sands were a product of processes that provoked the mobilization and re-sedimentation of pre-existent littoral deposits, the shelly layers could be a consequence of the most intense dynamic pulses, enabling the transportation of *Glycimeris* shells from their natural habitats of between 15 and 40 m depth. The *La Algaida* shelly layers clearly indicate the action of washover flows which exceeded the littoral zone. Flow directions are deduced from the orientation of the shelly outcrops. These are essentially orientated from WNW to ESE, pointing to a transversal flow with respect to the shoreline. The only aqueous flows of this type are those coming from the sea and generated by agents such as spring flood tides or high waves generated during powerful storms or tsunamis.

Moreover, the *Glycimeris* mollusc has disappeared as a living organism from the sub-tidal bottoms of Cadiz Bay and the adjacent continental shelf. Its disappearance could be related to environmental changes, depredation, over-exploitation or even the action of highly energetic events, which may have swept away part of the sandy substratum necessary for the support of their habitat.

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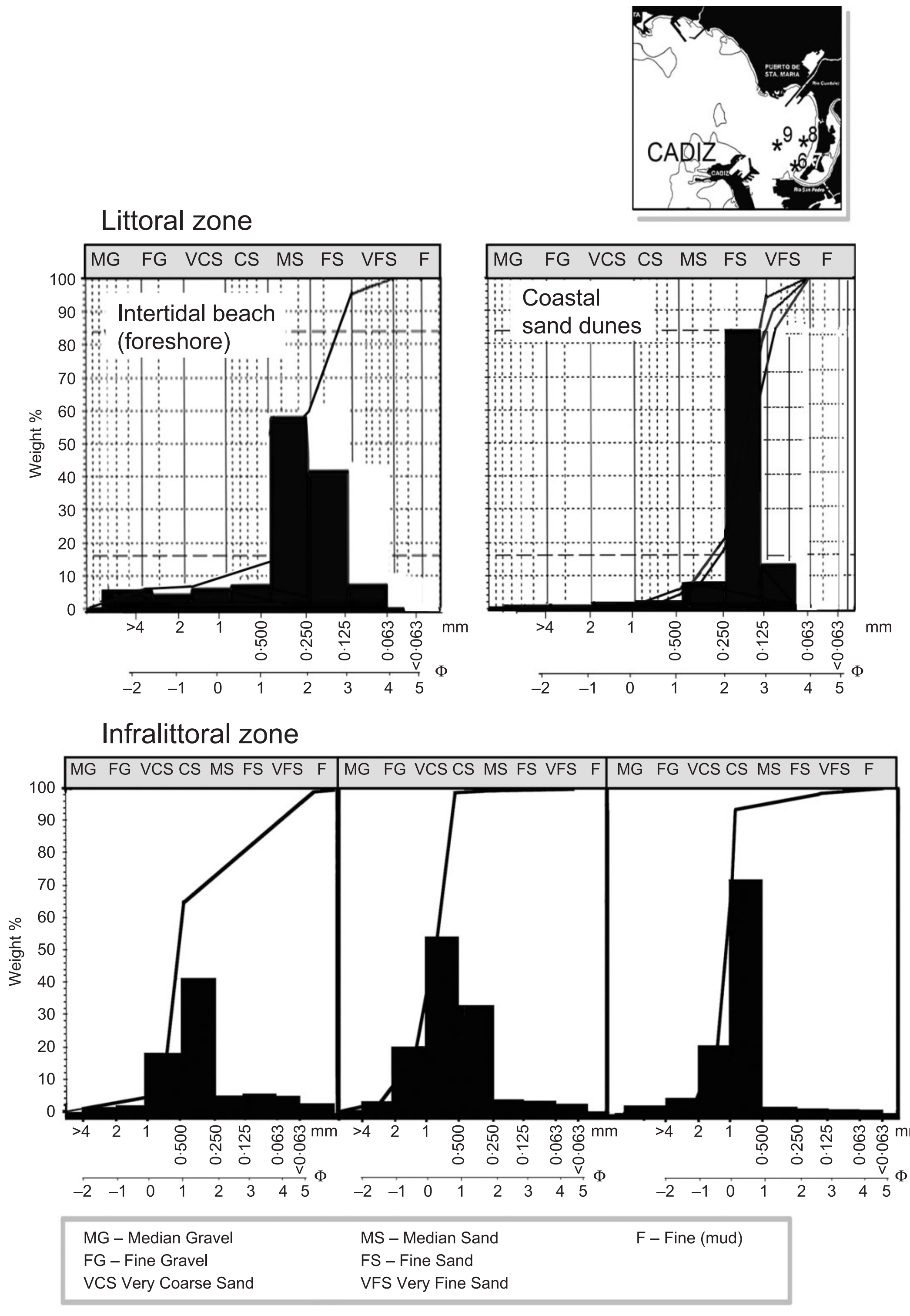

Figure 10. Grain-size distribution of the sedimentary deposits in littoral and sub-littoral environments in the study area.

Hydrodynamic processes

Tidal action is a plausible explanation for the origin of the *La Algaida* shelly layers. In fact, tidal washover is a very frequent present-day process in this littoral area, where flows reach far inland, through beach deposits and exceeding the present-day dune cordon. One main drawback to this hypothesis is the topographic height of some of the shelly beds which is above the maximum predicted sea level in the area. Given that in Cadiz Bay, tides have a maximum height of 4 m, this tidal flow would be insufficient to enable the mobilization of the sediments and *Glycimeris* shells present in sea bottoms, and furthermore, transport them a sizeable distance, a process for which a much more powerful flow would be required.

Combined action of tides and storms

Although tidal action alone can not explain the formation of the shelly layers, when specific meteorological conditions converge with flood tides, coastal sea level over-elevations can be provoked. Over-elevations can occur during intense storms, due to barometrical drops, direct action of wind and surge, or all these factors combined.

In the study zone, the dominant provenance of significant wave is from the west and south-west, with a maximum wave

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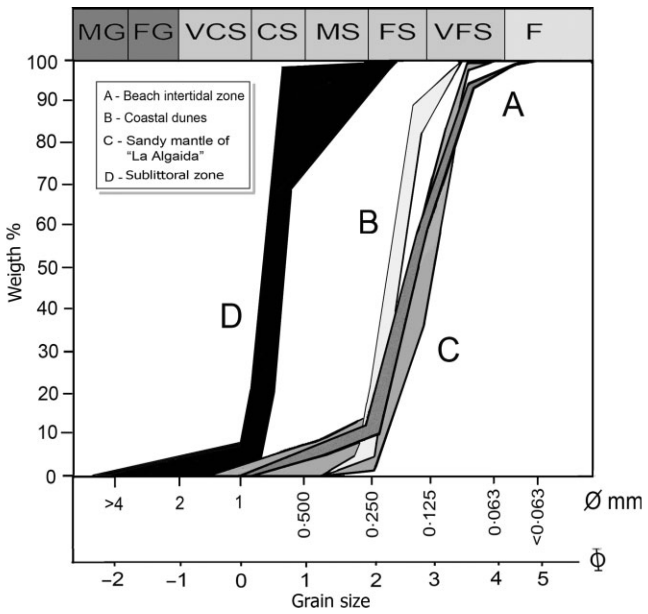

Figure 11. Comparison of grain-size distribution curves in sediments in littoral and sub-littoral deposit zones in the study area, and of the sandy mantle in *La Algaida*.

height of 4 m. Over-elevations caused by storm surge do not exceed 1 m in height and, even when they coincide with the spring flood tide, the maximum attainable height would be lower than 3 m over the mean sea level (Fraile Jurado, 1995). This can be sufficient to generate washovers which do reach the height of some shelly beds. Furthermore, major storm waves could remobilize sediments and shells present in shallow bottoms, whereas the combined action of upward tide and the incessant wave train could transport the materials towards the shore.

The main objection to this hypothesis is that sea level over-elevations, although possible, are statistically very unlikely, while the *La Algaida* shelly beds show a certain periodicity which indicates the action of recurrent washovers. Another difficulty is the fact that the *Valdelagrana* spit bar faces the surge, which could provoke a discharge of sediments before the flow could reach the opposite side of the San Pedro tidal channel, where the *La Algaida* shelly layers are located. Therefore, to overcome the *Valdelagrana* spit bar, higher sea level over-elevations and more energetic flows are needed. Another possibility is that the spit bar did not exist when the shelly deposits were formed. This circumstance would have permitted the direct action of the flow on the beach.

Regarding the origin of the shelly layers, these deposits remind one of the coquina beds that sometimes appear on the foreshore of the *Valdelagrana* beach. Live specimens with undivided valves, accumulate due to the autumn and winter surge (Figure 4D) and can form deposits of 0·2 to 1 m thick. The stranded coquina shells on the foreshore and backshore are promptly eroded by waves and tidal action, and consequently disperse along the shore and seaward.

Although the coquina deposits share some analogy with the *La Algaida* shelly beds (Figure 4D), the differences are notable. The *Glycimeris* valves are bigger and heavier than the coquinas. Whereas the coquina habitat is located in the shallowest bottoms and nearer to the sea shore, their remobilization and transport not requiring high waves or the convergence of meteorological and hydrodynamic conditions, the *Glycimeris* habitat is situated off-shore on deeper bottoms, requiring higher waves in order to be mobilized and transported. Another difference is that the coquina deposits lie on the foreshore or backshore sediments, whereas the *La Algaida* shelly beds lie over massive amounts of fine and very fine sands, with different sedimentary structures to the beach facies. Furthermore, *Glycimeris* layers are intercalated within the sands, consequence of a quick and immediate burying, whereas the coquinas remain exposed a short time, quickly being taken down and dispersed by sea agents.

Giant waves (rogue waves)

A third hypothesis to explain the origin of the shelly layers, could be the action of individual giant waves, known as rogue waves or freak waves, which appear suddenly and exceed the height of the surrounding waves (Didenkulova *et al*., 2006; Dysthe *et al*., 2008). These solitary great waves are much higher than would be expected in relation to the existing sea state, with a minimum height of 20 m, although they are in phase with the subsequent wave train. These waves are very dangerous on the open sea and can cause the sinking of ships. Their existence was confirmed through Project MaxWave (Rosenthal, 2002). Satellites of the European Space Agency (ESA), equipped with Synthetic Aperture Radar (SAR), registered images of the sea surface corresponding to a period of three weeks before and after the incidents of the cruise ships Bremen and Caledonian Star. Once the spectral analysis was made, and despite the brief time period registered, 10 individual giant waves of more than 25 m in height were detected. This data triggered a turnabout regarding the existence of giant waves and a higher frequency period than that previously thought.

The formation mechanism of rogue waves is not yet well known. They often appear to form when ordinary storm waves, due to the strong winds generated, run into oceanic currents, producing an energy concentration and increment in wave height. They can also be generated by major strong and persistent winds amplify the waves, or when wave trains, by different storms generated, were coupled, increasing their energy and height. The rogue waves are different to earthquake-induced tsunami waves, which have longer periods and are almost invisible in open sea, since they only obtain dangerous heights near the shore.

Regarding the hydrodynamic behaviour of rogue waves in shoal waters and their implications on the sedimentary dynamics of littoral zones, when the waves reach the continental shelf, they quickly break and dissipate their energy before reaching the shore, affecting only the bottoms of continental shelves deeper than storm wave base level in the area, where sediment and organism remains are mobilized and transported. However, in narrow continental margins, these waves can also provoke damage on the coast and generate sea level over-elevations and washovers on the littoral zones (Didenkulova *et al*., 2006). In the Cadiz area, there are no references to solitary giant waves, but there is enough historical documentation on earthquakes and tsunamis.

Tsunami wave action induced by earthquakes

In an active seismic area such as Cadiz Gulf, the hypothesis of a tsunamigenic origin of the shelly layers ought to be considered. Evidence of these types of processes has been found in nearby areas such as the earthquake and tsunami that destroyed the old roman settlement of *Baelo Claudia* during the fourth century AD (Silva, 2002; Silva *et al*., 2005). Moreover, in the *Huelva* estuary, *Doñana* and *Valdelagrana* spit bars, some deposits have been attributed to tsunamis, such as the one which occurred between AD 216 and AD 218 (Galbis, 1932, 1940; Borja and Díaz del Olmo, 1995; Luque *et al*., 2002a, 2002b; Morales *et al*., 2008). However, the best known tsunami is the one which followed the Lisbon earthquake in 1755, which had catastrophic results on the south-west Iberian

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Peninsula coast, generating waves of up to 15 m in height in Cadiz. Several washover fans in the *Valdelagrana* spit bar (Cádiz Bay) have been attributed to this tsunami (Dabrio *et al.*, 1998). Andrade and co-workers (Andrade, 1991; Andrade *et al.*, 1994, 1997, 2004), described their effects on the *Formosa* spit bar, in Algarve (Portugal), which generated large washover fans and the appearance of abundant shells.

Tsunamis are energetic events able to produce coastal modifications, mobilize sediments and generate deposits that can sometimes be mistaken with storm layers (Dawson *et al.*, 1988, 1996; Dawson, 2005; Nanayama *et al.*, 2000; Shi, *et al.*, 1995; Goff *et al.*, 2004). Cisternas *et al.* (2000) recognized a deposit generated by a tsunami in 1960, in the estuary of the Maullin river (Chile). He deduced that the sands came from a dune cordon situated at the river mouth.

The study deposits in Cadiz Bay present some clear evidence of a tsunamigenic origin, since they contain imbricated glycimeric valves, which indicate the action of directional flows from the west. The stratigraphic section (Figure 5), shows a succession of alternating layers of imbricated valve beds, mud, sand and thin humus beds. With respect to sub-tidal deposits, the sections present similar characteristics to the gravel fraction, consisting of imbricated *Glycimeris* shells, pebbles and continental plant remains (Figures 7 and 9).

Moreover, if the age dates of the deposits are considered, AD 849 ± 121 for sub-tidal sediments, and AD 904 ± 85 for the lower *La Algaida* shelly bed, these are coincident with two historically documented tsunamis, which affected the Cadiz coast in AD 881 and AD 949, respectively (Galbis, 1932, 1940) (Table III and Figure 7). This chronological correspondence shows a closer coincidence between the sub-tidal deposits and the AD 881 tsunami. Nevertheless, the brief time lapse between both events, only 61 years, suggests that these deposits could have been successively affected by both tsunamis.

With respect to the higher shelly layers, the oldest has provided a calendar age of AD 1052 ± 105 (Table III and Figure 7), near to the age of AD 949 and AD 1033 tsunamis, both historically documented (Galbis, 1932, 1940; Martins and Mendes, 2001). This deposit was probably generated by the AD 1033 tsunami, but could also have been provoked by a giant earthquake occurring in northern Algeria in AD 1040 (Lorito *et al.*, 2007), the effects of which could have re-mobilized pre-existent sediments.

The higher and youngest shelly layer has provided a calendar age of AD 1127 ± 90 (Table III and Figure 7). Although there are no references of nearby seismic and tsunami events on the Cadiz coast during that time, documentation does exist on giant earthquakes and tsunamis occurring in the Mediterranean during the same period, such as Venice (AD 1117), Syria and Egypt (AD 1138), southern Italy (AD 1169) and northern Egypt (AD 1201), the latter being one of the most lethal in history (Tinti *et al.*, 2005; Lorito *et al.*, 2007).

Nevertheless, the seismic history may be incomplete, and there are certain difficulties in the correlation of the deposits to historically documented events due to the error rank given by the dating method, since recurrent short-period events can be difficult to discriminate. However, the data and results obtained through this work indicate that the period between AD 850 and AD 1200 was a period of intense seismic and tsunamigenic activity. So results from recent paleogeographic studies, indicate substantial changes in the Cadiz Bay which modified the physiography of this zone, such as collapses, rises and buildings buried below sediments, caused by several natural catastrophes. On this point, the twelfth-century Andalusian writer al-Zuhrí, remarked the fear the inhabitants of Cadiz had, of going into the sea, where there were waves as big as mountains, and of the progressive ruin and abandonment of the old town, part of which remained submerged underwater (Sanchez-Saus, 2005).

Tsunamigenic area

The Cadiz coast is exposed to tsunami action generated in the Atlantic Ocean and the Mediterranean Sea (Figure 12). The south-west margin of the Iberian Peninsula is characterized by high seismic activity, a consequence of its geographical position near to the limit of the Euroasiatic and African plates (Grimison and Chen, 1986). It is a broad and diffuse area where tectonic activity has provoked intense earthquakes and tsunamis, such as the 1775 Lisbon earthquake (Dawson *et al.*, 1996). The location of the seismic focus of this particular earthquake has been questioned for a long time (Udias *et al.*, 1976; Campos, 1991, 1992; Ribeiro, 1995), although it is currently thought to be located at 100 km from the San Vicente Cape, associated with the *Gorringe Bank* subduction zone near the *Marques de Pombal Fault* (Campos, 1991, 1992; Ribeiro, 1995; Gutster, 2005).

Another potential earthquake and tsunami source is the Mediterranean basin, specifically the *Tell-Atlas* thrust belt. Due to the relatively small size of the Mediterranean Sea, any tsunamigenic focus could potentially reach the Spanish coast, including Cadiz Gulf (Figure 12). The last great earthquake occurring in this area (21 May 2003), had an intensity of between 6·8 and 6·9, and a focus located at 40 km from Algiers. This earthquake generated a tsunami wave that was recorded by the tide gauge on the Spanish coast (Lorito *et al.*, 2007). After 45 minutes, waves reached the south-eastern coast of Spain and finally entered the Alboran Sea, reaching the Cadiz Gulf. Earthquakes of 6·8 in intensity and focus in northern Algeria can generate tsunami waves of 2 m in height on the North African coast, and some smaller waves on the Atlantic Spanish coast. Therefore, the most intense historical earthquakes such as the one occurring in AD 1202, could have provoked greater tsunami waves, able to provoke over-elevations which, converging with other hydrodynamic or meteorological factors, would be sufficient to justify the washovers that generated the shelly layers studied in the *La Algaida* sands.

Events and depositional regime in Cadiz Bay

In Cadiz Bay, the role of earthquakes and tsunamis has been an important control factor over the depositional regime. This control was essentially carried out by the dynamic action of the tsunami waves, sometimes combining with other agents such as storm surge or heavy tides. The most efficient processes were the remobilization of pre-existent sediments and their transportation and re-sedimentation in the littoral zones. The most intense pulses of these events are characterized by the presence of coarse grains, mollusc shells, pebbles and rock fragments. In addition, the continued dynamic action on sea bottoms, could have provoked the sweeping of the sandy substrate and the subsequent loss of the natural habitat of some organisms, such as *Glycimeris*.

Conclusions

In the coastal zone of Cadiz Bay (south-west Spain), several Holocene shelly layers have been studied. These beds are interbedded in the relict sand mantle of *La Algaida*, and they are fundamentally composed of *Glycimeris* valves, some gastropods, rolled pebbles and rock fragments. The habitat of these molluscs is situated between 15 and 40 m depth,

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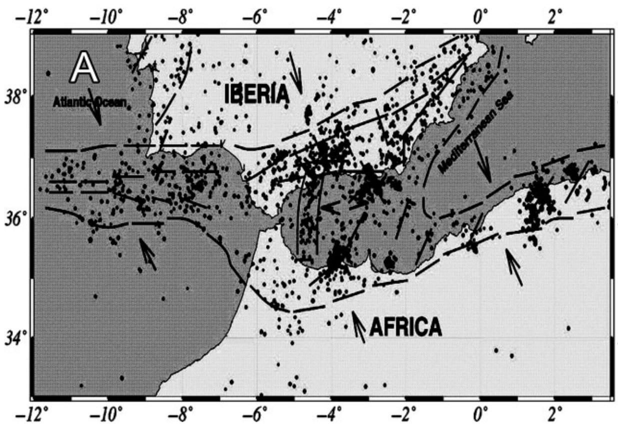

Figure 12. Seismic tectonic scheme of the region Azores-Gibraltar (modified from Udías *et al.*, 1976 and Campos, 1992).

and, despite the great profusion of *Glycimeris* valves present in the coastal areas of Cadiz, sampling did not provide live specimens, and there is no evidence of them from recent biological studies carried out in the area. The evidence indicates that this organism is not present in the current sea bed zone, because of climatic changes, over-exploitation, or by the accumulated effects of successive high-energy events, which swept the fine sands of the substratum where their habitat was situated.

The origin of these shelly layers is probably related to sea washovers exceeding several metres in height above the predicted maximum sea level, circumstances which are only possible when particular hydrodynamic conditions converge with high-energy events such as storms or tsunamis. The oldest shell samples correspond to sub-tidal deposits from Cadiz Bay, and they show a calendar age of AD 849 ± 21, which coincides with a documented tsunami which affected the Cadiz coast in AD 881. The next oldest deposit corresponds to a low shelly bed in *La Algaida* sands, with a calendar age of AD 904 ± 85, coinciding with another documented tsunami in AD 949. Given the brief time elapsed between these documented tsunamis, it is possible to conclude that the deposits were affected by both events.

Above the previous deposits, a higher shelly bed, dated at AD 1052 ± 105, coincides with a documented tsunami in AD 1033. However, due to the error rank resulting from the analysis method, the possibility that this deposit was provoked by a tsunami in AD 904 ± 85, and subsequently modified by the AD 1033 tsunami cannot be discarded. Finally, the youngest shelly bed gave an age of AD 1127 ± 90. The nearest event is the previously quoted AD 1033 tsunami, as no other references of other nearby events have been found. It is possible that this deposit corresponds to an earlier event. If the error rank resulting from the analysis method is considered.

Sandy sediments in *La Algaida* have textural and granulometric features which are similar to many littoral deposits in the study zone, such as dunes, backshore and washover. They are characterized by the predominance of sand fraction, approaching 100%, absence of gravel and mud, and mode in fine sand size. The differences were found in the foraminifer content, which in the case of the *La Algaida* sands, is higher than in some current littoral deposits, but similar to that found in sub-tidal and nerithic sediments.

Textural and granulometric data indicate pre-existent aeolian deposits as the source area, which were mobilized by successive sea events, giving way to a restructuring of the inner ordination and dispersal along the littoral zone. Subsequently, the sediments were affected by the ordinary hydrodynamic agents, which gave way to slight textural variations, although they conserve the dominant characteristic granulometric features obtained from materials in the source area.

Control of the depositional regime has been carried out mainly through the action of great tsunami waves, and sometimes combined with other marine agents such as spring flood tides and storm surge. The most efficient sedimentological action was the re-mobilization of pre-existent sediments and their transportation and dispersion along the coast. The most intense pulsations of these events are characterized by thicker levels of granulometry and the presence of shells. In addition, this persistent dynamic action could have led to the sweeping of the sandy substrate of some areas on the sea bottom and the loss of various habitats, such as that of the *Glycimeris*, which have disappeared as a live species from the bottoms of Cadiz Bay.

The recognition of tsunamigenic deposits constitutes valuable information on the frequency of these events. In the *La Algaida* deposit, at least four recorded and successive tsunamis are represented. Recent geological and archaeological data indicates a clustering of seismic and tsunamigenic activity which affected the Cadiz Gulf coast. These Late Holocene tsunamis occurring between the eleventh and thirteenth centuries, and their sedimentary records denote a recurrence period of barely 100 years during this time cycle.

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