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Research article

Sedimentary evidences of historical seawater temperature and sea level changes in the Cadiz Bay (SW Spain). Relation with regional high-energy oceanic events

Evidencias sedimentarias de cambios históricos de temperatura del agua y de nivel del mar en la Bahía de Cádiz (SO de España). Relación con eventos oceánicos regionales de alta energía

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ABSTRACT

The study attempts to establish the depositional history of recent coastal bioclastic sediments from the Cadiz Bay (SW Spain). These deposits are carbonated shelly intercalations interbedded in coastal sands. They are lying to different heights above the present-day sea level. Their ^{14}C ages represent a time interval from 200 years (yr) BC to 850 yr AD, which includes the Roman Warm Period and the start of the Medieval Warm Period. Sedimentary, mineralogical, chemical, and isotopic ($\delta^{18}O$) analyses were used to determine responses of the coastal depositional environments to the environmental changes and to the action of high-energy oceanic events. Sedimentologic analysis of these shelly beds shows depositional features typical of high-energy directional flows caused by great waves from storms or tsunamis, which would also explain the origin and the topographic position of these shelly accumulations. The $\delta^{18}O$ values obtained suggest that in this North Atlantic area, the seawater temperature fluctuations were relatively small, with an amplitude similar to the present-day seasonal temperature fluctuations of the Mediterranean Sea. This fact may be attributable both to a middle-low latitude of the study zone and mix of water masses from the Atlantic and Mediterranean currents, which could moderate the effects caused by the climate changes observable in Atlantic areas of higher latitude.
Keywords: focal mechanism, inversion, stress tensor, permutation, stress orders

RESUMEN

El estudio trata de establecer la historia deposicional de sedimentos bioclásticos recientes en la Bahía de Cádiz (SO de España). Estos depósitos contienen acumulaciones conchíferas interestratificadas en la arena costera localizadas a diferentes alturas sobre el nivel del mar actual. Sus edades ^{14}C cubren un intervalo de tiempo entre 200 años aC y 850 años dC que incluye el periodo Cálido Romano y el inicio del Periodo Cálido Medieval. Se realizaron análisis sedimentológicos, mineralógicos, químicos e isotópicos ($\delta^{18}O$) para determinar la naturaleza de los depósitos y la respuesta deposicional de los medios costeros a los cambios medio ambientales y a la acción de eventos oceánicos de alta energía. El análisis sedimentológico indica que las acumulaciones conchíferas estudiadas muestran rasgos deposicionales similares a los causados por flujos direccionales de alta energía, generados por grandes olas de temporales o tsunamis, lo que explicaría también el origen de los depósitos y la posición topográfica en la que se encuentran. Los valores de $\delta^{18}O$ obtenidos sugieren que, en esta región del Atlántico Norte, las fluctuaciones de temperatura del agua del mar fueron relativamente pequeñas para el intervalo de tiempo estudiado, siendo su rango de amplitud similar al de los cambios de temperatura estacionales actuales en el mar Mediterráneo. Este hecho puede ser atribuible tanto a la latitud media-baja de la zona de estudio como a la mezcla de masas de agua de las corrientes atlántica y mediterránea, que pudo moderar el efecto de los cambios climáticos observables en áreas atlánticas de mayor latitud.
Palabras clave: cambios climáticos recientes; movimientos eustáticos; isótopos de oxígeno; *Glycymeris nummaria*; Golfo de Cádiz; España.

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1. INTRODUCTION

Shallow marine coastal environments from Cadiz Bay (SW Spain) are vulnerable to sea level changes and other oceanic processes such as, very high energy oceanic processes (storms and tsunamis), which caused sedimentary and physiographic changes, as well as a particular distribution of the coastal sedimentary facies (Dabrio et al., 1998; Luque et al., 2001; Lario et al., 2008; Gutierrez-Mas et al., 2009a; Gutierrez-Mas, 2011; Gutierrez-Mas y García-López, 2015; Gutierrez-Mas et al., 2015; Gutierrez Mas et al., 2016).

Modern studies on marine and coastal deposits have improved the understanding of environmental changes by reconstructing of seawater temperature fluctuations through measurement of the Oxygen-18 Rate ($\delta^{18}O$) from marine biogenic carbonates (Lisiecki y Raymo, 2005). To establish the responses of the coastal environments and determine the depositional history of the deposits affected, mineralogical, chemical, isotopic, sedimentary and stratigraphic analysis were made.

The $\delta^{18}O$ values recorded in marine carbon-based shells depend from the temperature and isotopic composition of the seawater (Kennett y Voorhies, 1996). In marine sediments where foraminifer samples are recrystallized and/or cemented, the calcium carbonate mollusc shells are a useful tool to study the water temperature fluctuations from ancient marine environments (McCrea, 1950; Seidenkrantz et al., 2008; Royer et al., 2013). Analysis of carbonated fossils of mollusc shells provide valuable information about seawater temperature fluctuations occurred in historical times in the study zone. These samples set are representative of a time interval from 200 years (yr.) BC to 850 yr. AD, which includes the Roman Warm Period and the start of the Medieval Warm Period.

The $\delta^{18}O$ values were determined from calcium carbonate constitutive of *Glycymeris nummaria (G. nummaria*) shells, a bivalve mollusc that lives in sandy and muddy bottoms, between 10 and 30m depth. The species *G. nummaria* has a broad biogeographic distribution in both Mediterranean and Atlantic areas and it quickly responds to seawater temperate changes (Dettman et al., 2004; Sivan et al., 2006; Crnčević et al., 2013; Martins et al., 2014; Featherstone, 2017). In the Cadiz zone, fossil specimen of this species appears in Pliocene, Pleistocene and Holocene and Late Holocene outcrops, and even in most recent deposits. Their shells can be observed on the surface of current beaches, but live specimens are rare or non-existent (Sivan et al., 2006; Gutierrez-Mas et al., 2009a; Gutierrez-Mas et al., 2009b; Gutierrez-Mas 2011).

2. GEOLOGICAL SETTING AND HYDRODYNAMIC REGIME

The Cadiz Bay is located at the Andalusian Atlantic coast (SW Iberian Peninsula) in SE sector from Gulf of Cadiz. Under a geological point of view, this region is belonging to three main geological realms: Betic Mountain Range, Guadalquivir Basin and Gulf of Cádiz (Fig. 1). Its location, close to the Eurasian-African plate boundary, results in a relatively high neo-tectonic activity (Grimison y Chen, 1986; Gutscher et al., 2002), which affects both, bottom and coast morphology and distribution of the coastal sedimentary environments.

The present-day coastal sedimentary environments from Cadiz Bay are controlled by a complex barrier-island system (Fig. 1A and B), with two main littoral sandy spits, one located at central sector (Valdelagrana spit) with NNW-SSE orientation, other one at West and SW sectors (Camposoto-Sanctipetri spit) with NW-SE orientation (Fig. 1A). Both spits limit lagoon areas where extensive tidal flats are developed, which are cross by numerous tidal creeks and tidal channels, as well as by several bay-deltas located on both sides of the sandy spits (Fig. 1).

The continental margin from Gulf of Cadiz is affected by two main oceanic currents. One is the North Atlantic Surface Water (NASW), relatively cold and slightly saline, which sweeps the continental margin southestard, carrying sediments from the Guadiana and Guadalquivir River mouths toward the Mediterranean Sea (Lacombe y Tchernia 1972; Zenk 1975; Thorpe 1976; Ambar and Howe 1979; Gutierrez-Mas et al. 2009a). The second is the Mediterranean Outflow Water (MOW), that flow deeper carrying denser and more saline waters from Mediterranean Sea toward the Atlantic Ocean following the continental margin physiography.

Tidal regime is semidiurnal and mesotidal range. Mean tidal height is 2.39m and average spring tidal height is 3.71m. Wind and surge have seasonal character, prevailing westerly winds. Wind waves have period below 7s and amplitude of ~0.5m (summer) and ~1m (winter). Swell waves have periods of 12-15s. Significant wave height is 0.6-1m (Alvarez et al., 1999). Maximum wave height during stormy weather is 4m. Main littoral-drift spreads towards the southeast, but easterly winds generate littoral-drifts northward and northwestward.

Dabrio et al. (1995) studied the estuarine deposits from Guadalete river mouth accumulated during the Last Eustatic Cycle. They recognised four estuarine barriers corresponding to four progradation stages. The estuary fill occurred during the Flandrian Transgression caused by the Holocene warm, which caused the coastline retreat and retrogradation of coastal deposits.

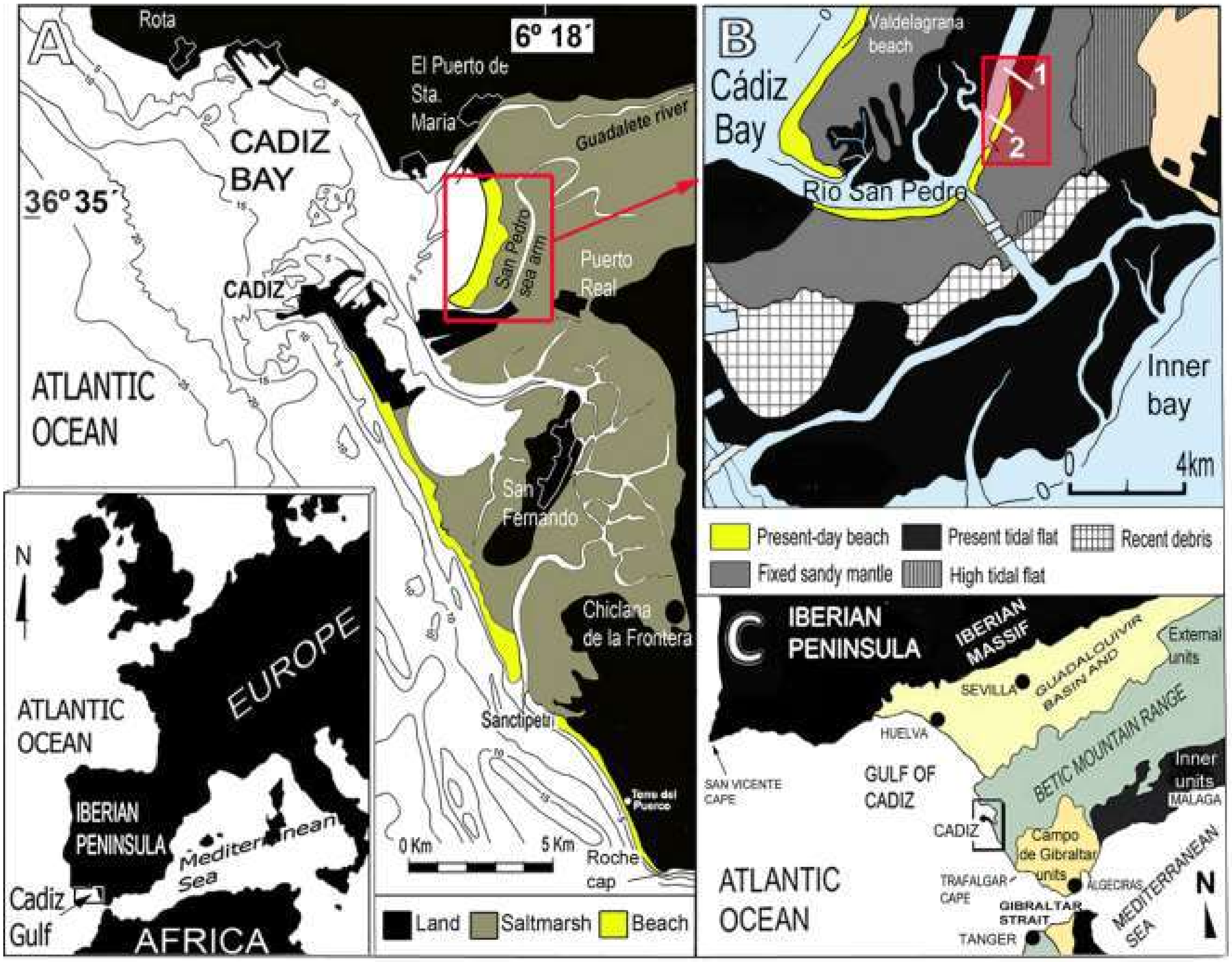

Figure 1. A) General geographic location. B) Detailed geography and locations of studied outcrops, stratigraphic and environmental profiles (1 and 2), and stratigraphic sequence shown in Figs. 2 and 3. C) Regional geologic setting.

The Eustatic Maximum was reached 6500-6000 yr. ago, and subsequently, both terrestrial and marine erosion destroyed almost all the coeval estuarine barriers (Gagan, 1998; Davis et al., 2003; Kaufman et al., 2004).

After Holocene Maximum, a cooling stage caused a sea level fall and the progradation of coastal sedimentary environments. Later, the zone experienced an alternation of cool and warm stages (Gutierrez-Mas, 2011). From 4200–2550 yr BP to 2300–800 yr BP, the sedimentation occurred mainly in the estuarine barriers and flood plains. The coastal morphology and the predominance of littoral currents from W to SE favoured the progradation of the sand spits and bay-deltas toward SE.

From 900 Yr AD to 1300 yr AD, a temperature rise caused a warm period (Medieval Warm Period) (Gagan, 1998; Davis et al., 2003; Kaufman et al., 2004; Gutierrez-Mas, 2011) that was followed of a cooler period historically called Little Ice Age, but deposits of this last stage have not recognized in the study zone.

In addition, the sedimentation was also controlled by the neo-tectonic activity in the zone due to readjustments of the close Betic Mountain Range. Furthermore, nearby submarine tectonic accidents caused a relatively high seismic activity, even some tsunami events. Data about the Gulf of Cadiz show the evidence of historical tsunamis, such as that occurred after the Lisbon earthquake (5/Nov/1775) (Gutscher et al., 2002; Dabrio et al., 1998 and 2000).

3. METHODS

Systematic fieldworks consisted in the collection of sediments and fossil samples, data acquisition on the geologic outcrops and elaboration of stratigraphic sections. Shell samples come from different stratigraphic levels. Main difficulty for sampling was the existence of a discontinuous geological record, with outcrop lack in some places due to erosive processes that affect coastal areas.

Laboratory work consisted of textural, mineralogical and chemical analysis. The sediments were analysed for grain-size distribution by dry and wet sieving for sand and fine fractions respectively. Optical analysis was utilised to observe the main constituent of the sand fraction. Samples were analysed in the in the laboratories of the Earth Sciences Department of Cadiz University.

Mineralogical composition was analysed by X-Ray Diffraction (XRD) with a Brucker D8Advance diffractometer, employing Cu-Ka radiation and graphite detector. Qualitative and semi-quantitative mineralogical composition was identified by EVA software. Chemical composition of shell samples was carried out to check the presence or absence of silica in the shells, necessary step before the ^{18}O isotopic analysis. Chemical composition was established by X-Ray Fluorescence (XRF) with a Brucker S4 Pioneer, being the results expressed in wt.% of oxide concentration. Both analyses were carried out at the Central Scientific and Technological Research Services (SCICYT) of the University of Cadiz.

Shell radiocarbon age was determined in the National Accelerator Centre of the Seville University. ^{14}C method was applied to carbonated shell samples. Ages were established using the Washington University CALIB Programme (5.01) and marine Curve 04 (Blackwell et al., 2009). Prior to calibration, the measured ^{14}C ages were corrected applying the local reservoir effect: ($\Delta R = -135 \pm 20$ years) established by Monge Soares y Matos Martins (2009) for Atlantic waters from the Gulf of Cadiz (SW Spain).

Isotopic analysis of stable Oxygen isotopes (^{18}O) was determined in the Stable Isotope Laboratory of the Biologic Station of Doñana (LIE-EBD, Seville, Spain; www.ebd.csic.es/lie/index.html). The HTP (High-Temperature Pyrolysis) method was used to determinate the $\delta^{18}O$ values from the shell samples.

For determination of ^{18}O ratio ($\delta^{18}O$), eighteen samples of powdered shell material were weighed (0.30mg) into silver capsules. Approximately 0.30mg of catalytic compound AgCl was then placed into the silver capsule to help the conversion of carbonate to carbon monoxide (Gehre y Strauch 2003, Crowley et al., 2008). Oxygen isotopic measurements were determined on CO derived from high-temperature (1,400°C) flash pyrolysis using Flash HTP elemental analyser (EA), which was coupled to a Delta-V Advantage isotope ratio mass spectrometer (IR-MS) via a CONFLO IV interface (Thermo Fisher Scientific, Bremen, Germany).

To check the fidelity and accuracy of the method, oxygen isotopic data were then reported using the standard delta (δ) per mil (‰) notation relative to Vienna Pee Dee Belemnite (V-PDB), calculated by the following equation: $\delta = 1000 \cdot (Rx/Rstd)-1$ where Rx and Rstd are the isotopic ratios of the samples and standard, respectively.

Because the pyrolysis efficiency for oxygen yield depends on the material type, three reference materials (CaCO3) were used: a) C1 (Calcite, internal standard), b) C10 (Calcite, internal standard), and c) NBS 18 (Calcite, international standard), which are distributed by the International Atomic Energy Agency (IAEA) (Kornexl et al., 1999). Typical analytical reproducibility used of reference was ± 0.3‰. The linearity between observed and expected values for the three used standards (Fig. 5B) showed that they have a similar behaviour in the pyrolysis process.

4. RESULTS

4.1. Types of sediments, stratigraphy and deposit ages

The whole of studied deposits consists in an extensive sandy mantle fixed by Mediterranean scrub (Gutiérrez-Mas, 2011). The deposits are composed of well-sorted coastal sands with cross-lamination and marine shells. The grain size distribution is: fine sand (97.7%), gravel (0.7%), mud (1.2%). Interbedded in the sands there are shelly layers of sandy-muddy matrix, erosive base and imbricate shells and clasts.

The carbonate fraction has biogenic origin and it is constituted by accumulations of bivalve mollusc shells, essentially G. *nummaria*, it is also known as *G. gaditanus, G. insubrica and G. violacescens*) (Fig. 4). The shells have size from 4 to 6cm, with sub-quadrangular morphology, fine radial grooves and serrated ventral margin (Peharda et al., 2012, Crnčević et al., 2013) (Fig. 4). Their habitat is the continental shelf, on fine sands or muddy-sands (Legac y Hrs-Brenko, 1999; Crnčević et al., 2013). Geographical distribution is essentially Mediterranean but also Atlantic, even from higher latitudes (Crnčević et al., 2013; Martins et al., 2014). Gastropods are also present in minor quantities and without continuity in the stratigraphic sections, such as, *Murex, Ocenebra, Strombus, Turritella, Crossostre, Solen a*nd *Chamelea*.

In northern sector an unconformity between muddy deposits from current intertidal zone and underlying older sands it is observed (Fig. 2, A1 and C). A narrow muddy tidal flat whose surface is bioturbated by crustacean burrows and halophyte vegetation constitutes the intertidal zone. Landward ends in a remarkable scarp dug in the fixed sands, which are covered by pinewood and other Mediterranean vegetation (Fig. 2A and Fig. 3). In southern sector, sand from erosion of these fixed sand has formed a sandy beach (Fig. 2 A2) with scattered shells and pebbles also coming from erosion of those fixed sands (Figs.2 and 3).

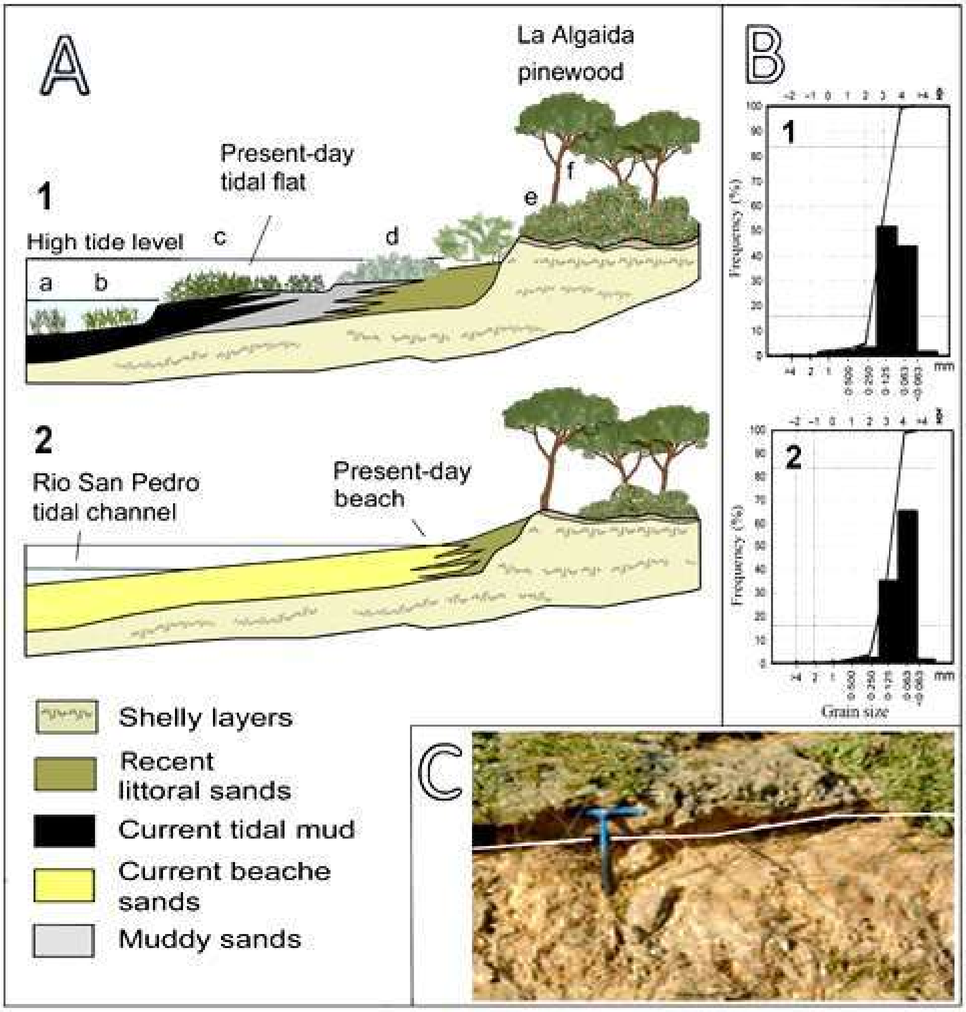

Figure 2. A) Representative scheme of the littoral environmental located on bank from San Pedro tidal channel (Cadiz Bay): 1) North sector. Halophytes and terrestrial plants: a) *Zoostera nolti*; b) *Spartina maritima*; c) *Sarcoconia permnis*; d) *Limoniastrum monopetalum*; e) *Retama monosperma*, *Tamarix canariensis*, f) *Pinus pinea*, *Pistacha lentiscus*, *Juniperus Phoenicia*, *Olea europea*. 2) South sector. B) Frequency and grain size distributions curves from fixed sands (profiles 1 and 2). C) Unconformity between the fixed sands and sandy-mud from present-day tidal flat. (Modified from Gutierrez-Mas y Garcia-Lopez, 2015).

From base to top, the stratigraphic section shows the next succession (Fig. 3):

Unit 1. 1-2m of fine sands with tangential cross-stratification and interspersed *G. nummaria* shells. ^{14}C Age: 167 ± 34 yr BC.

Unit 2. 0.4m of a shelly layer with *G. nummaria* shells. ^{14}C Age: 89 ± 110 yr BC.

Unit 3. 2-3m of well-sorted fine sand with cross-stratification and benthic and planktonic foraminifers.

Unit 4. 0.5m of a shelly accumulation with erosive base and articulated valves of *G. nummaria*. Other macrofossils present are Murex, Ocenebra and Strombus, echinoderms, bryozoans, ostracods, corals, fish bones and sponge spicules. ^{14}C Age: 322 ± 106 AD.

Unit 5. 5-7m of fine sands with cross-stratification and interspersed *G. nummaria* shells. ^{14}C Age: 350 ± 99 yr AD.

Unit 6. Unconformably on the previous units, there are 2-3m of fine sands with cross-stratification.

Unit 7. 0.4m of sandy-gravel with *G. nummaria* shells. ^{14}C Age: 631 ± 72 yr AD.

Unit 8. 1-2m of fine sands with scattered shells.

Unit 9. Shelly sands with *G. nummaria* shells. Some terrestrial seeds found inside articulate valves. ^{14}C Age: 849 ± 121 yr AD.

Unit 10. 1-1.5m of fine sands with cross-stratification.

Unit 11. Current humus layer covered by Mediterranean scrub.

Unit 12. Unconformably on the previous units, lie two youngest layers: 12a) 0.5-0.8m of mud with crustacean burrows and halophyte plants from the current intertidal zone, and 12b) well-sorted sands from current beaches located on the bank of San Pedro tidal channel (Figs. 2, 3 and 4).

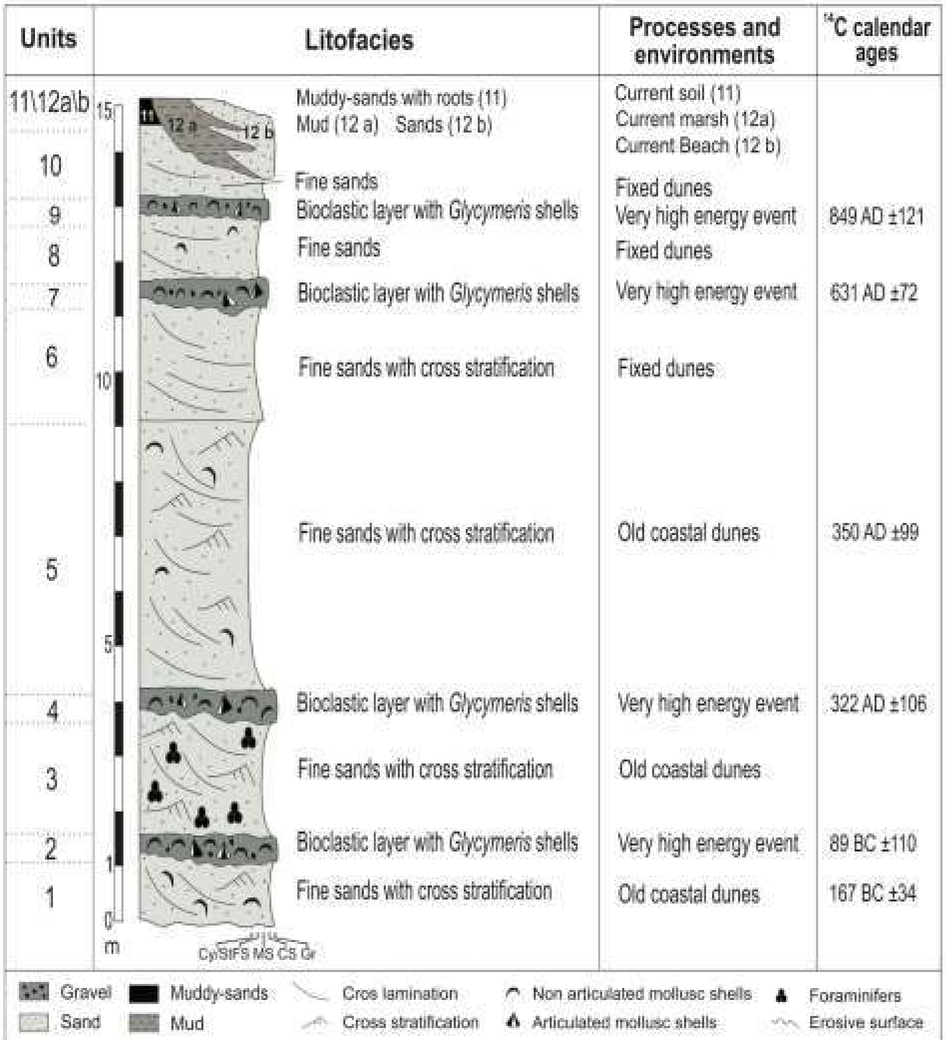

Figure 3. Stratigraphic section representative of sedimentary deposits in the bank of the San Pedro River tidal channel (Cadiz Bay).

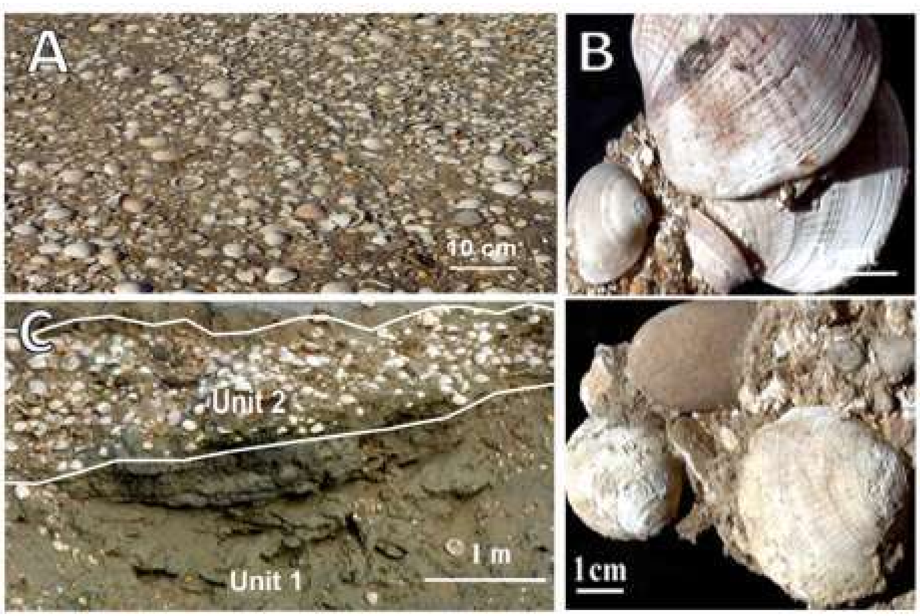

Figure 4. A) Shell pavement of *G. nummaria shells* on fixed sands from the Rio San Pedro tidal channel (Cadiz Bay). B) Details of shell accumulations. C) Deposit of *G. nummaria shells* interbedded in fixed sands.

4.2. Mineralogical and chemical composition

The XRD results indicate that *G. nummaria* valves are carbonate in nature (CaCO3), predominantly consisting of aragonite (97 to 100%) (Fig. 5A and Table 1). Calcite is present in very low concentration (1 to 2.3%) in some sample and may be encrusted remains of other organisms.

Chemical composition from X-Ray Fluorescence analysis (XRF) indicates that *G. nummaria* shells present dominance of carbonate of up to 93% CaO (Table 1). Silica is almost completely absent, except some samples that show silica content of less than 3%, which may be due to presence of small fine sand grains encrusted in the valves. The chemical results are consistent with mineralogical data, which confirm the carbonated nature of the shell samples, which is a required condition before samples can be analysed for oxygen stable isotopic ratio by mean of the HTP method.

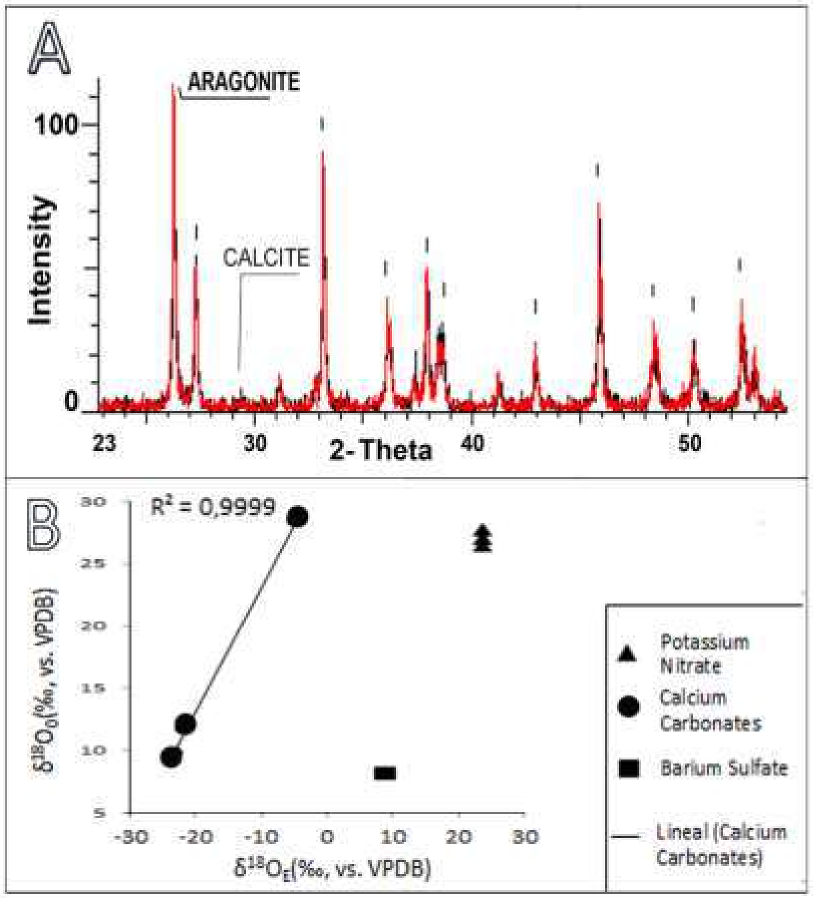

Figure 5. A) X-R Diffractogram showing mineralogical composition of *G. nummaria* valves. B) Observed $\delta^{18}O_O$ values vs. Expected $\delta^{18}O_E$ values. Calcite standards: NBS-18 (IAEA standard), C1 and C10 (Internal standards), interspersed between samples used to normalize results.

4.3. Stable oxygen isotopic ratio ($\delta^{18}O$)

The $\delta^{18}O$ values are variable according to the abundance of ^{18}O and 16O present in carbonates (Calcite or Aragonite) constitutive of *G. nummaria* valves. According to Grossman y Ku (1986) the variations of $\delta^{18}O$ values indicate seawater temperature fluctuations during a time interval from oldest to youngest samples. In studied case, the interval is from 167 ±34 yr BC to 849 ±121 yr AD, that is to say, from II Century BC to IX Century AD.

The oldest shells are from Unit 1 with ^{14}C age of 167 ±34 yr BC, which yielded an average $\delta^{18}O$ value of 1.15‰ (Fig.3, Table 2). Younger samples from Unit 2 (^{14}C age 89 ±110 yr BC) yielded an average $\delta^{18}O$ value of 1.90‰. Shells from Units 4 and 5, with ^{14}C ages of 322 ±106 yr AD and 350 ±99 yr AD, yielded average $\delta^{18}O$ values of 0.72‰ and 0.83‰ respectively. Youngest samples (Units 7 and 9) with ^{14}C ages of 631 AD ±72 yr and 849 AD ±121 yr, yielded average $\delta^{18}O$ values of 1.2‰ and 1.18‰ respectively.

Respect to $\delta^{18}O$ values from samples belonging to a same deposit (Table 2), these are representatives of shorter temperature

Table 1. Mineralogical and chemical composition of samples from *G. nummaria* valves from different sedimentary units from Río San Pedro (Cadiz Bay).

Sample	Mineralogical composition (%)			Chemical composition (%)			
	Calcite	Aragonite	Quartz	CaO	SiO_2	SrO	Al_2O_3
Unit 9	1.4	9.6	0	93.04	0.16	2.85	0.02
Unit 7	1.2	98.8	0	87.96	3.08	2.27	0.16
Unit 5	0	100	0	91.95	0.12	2.53	0.01
Unit 4	2.1	97.9	0	88.53	0.30	1.08	0.02
Unit 2	0	100	0	91.50	0.09	1.87	_
Unit 1	2.3	97.7	0	93.59	0.18	2.63	0.02

Table 2. Calendar ages and measured $\delta^{18}O$ values of carbonated samples from *Glycymeris nummaria* shell (Río San Pedro, Cadiz Bay)

Shelly accumulations	^{14}C Ages	Samples	$\delta^{18}O$ ‰ Variability	$\delta^{18}O$ ‰ Average
Unit 9	849 AD ± 121	**9.3**	2.11	
		9.2	0.37	1.18
		9.1	1.08	
Unit 7	631 AD ±72	**7.3**	1.83	
		7.2	1.65	1.2
		7.1	0.38	
Unit 5	350 AD ±99	**5.3**	1.01	
		5.2	0.86	0.83
		5.1	0.01	
Unit 4	322 AD ±106	**4.3**	-0.52	
		4.2	1.47	0.72
		4.1	0.19	
Unit 2	89 BC ±110	**2.3**	1.67	
		2.2	1.71	1.90
		2.1	2.34	
Unit 1	167 BC ±34	**1.3**	1.65	
		1.2	0.92	1.15
		1.1	0.88	

fluctuations occurred during the lifetime of a determined population of *G. nummaria*. These are indicative of minor changes. Oldest shelly deposit (Table 2, Unit 1) with ^{14}C age of 167 ±34 yr BC, yielded $\delta^{18}O$ values of: 0.88‰, 0.92‰ and 1.65‰. Unit 2, with ^{14}C age of 89 ±110 yr BC, yielded $\delta^{18}O$ values of: 2.34‰, 1.71‰ and 1.67‰.

Unit 4, with ^{14}C age of 322 ±106 yr AD, yielded $\delta^{18}O$ values of: 0.19‰, 1.47‰ and -0.52‰ (Table 2). Other shelly layer of close age (^{14}C age of 350 ±99 yr AD) (Table 2, Unit 5) yielded $\delta^{18}O$ values of: 0.01‰, 0.86‰ and 1.01‰.

Younger samples (^{14}C age of 631 ±72 yr AD) yielded $\delta^{18}O$ values of: 0.38‰, 1.65‰ and 183‰, while the youngest of the studied shelly units (^{14}C age of 849 ±121 yr AD) yielded $\delta^{18}O$ values of: 1.8‰, 0.37‰ and 2.11‰.

5. DISCUSSION

5.1. Origen of the fixed sands and shelly accumulations

The littoral shelly accumulations from Cadiz Bay are located at different heights above the present-day sea level and they are currently out of reach of marine agents, tides and waves (Figs. 2, 3 and 4). Shelly deposits are interstratified in older fixed littoral sands (Figs. 2 and 3). The sands (Fig 4, Unit 1) have grain-size, texture and structure similar to the present-day coastal dunes, characterised by predominance of fine sands, absence of gravel, silt and clay, high sorting and a marked trough cross-stratification (Fig. 4).

According to the depositional features, the sands from Unit 1 correspond to old coastal dunes, currently stabilised by terrestrial vegetation and topographically out of reach of marine agents (Gutiérrez-Mas, 2011). Interbedded in the fixed sands appear shelly beds to several meters above the present-day sea level. Since the natural habitat of *G. nummaria* is the continental shelf, from 10 to 30m depth, the origin and topographical height above the current sea level of the shelly deposits has been alterated. Two main causes of this alteration could be responsible: i) Recent relative sea level variations (Fig. 6) which produced displacements of the *G. nummaria* habitat on sea bottom. ii) Great waves caused by strong storms o tsunamis (Sivan et al., 2006; Gutiérrez-Mas et al., 2009a and 2009b).

Respect to sea level variations, according to the shell samples ages, these changes must occur in historical times. During high-stand sea level stages, *G. nummaria* habitats were displaced towards shallower waters even previously emerged (Gutierrez-Mas 2011). During the low-stand stages, the sea level fell, causing the shallowing of the previous sea bottom, displacement off shore of *G. nummaria* habitats and emersion of a recently flooded area, while remains of ancient *G. nummaria* habitats remained emerged (Fig. 6C). The Fig. 6B shows physiographical and environmental changes caused in Cadiz Bay by historical sea level changes.

In accordance with the mentioned above, sea level changes can explain the presence of the shelly deposits to different topographic heights. Respect to their ages, recent sea level variation curves for North-Atlantic areas close to the study zone, show a high frequency of small rises and falls of sea level, with successive stages of high stand and low stand (Fig. 6A) (Fairbridge, 1962; Bard et al., 1990; Compton, 2001; Martin et al., 2003; Mörner 2007).

Nevertheless, although sea level changes could explain the origin of the shelly accumulations, some depositional features observed in the deposits as, very imbricate shells and clasts, articulated and unarticulated valves, inner erosion surfaces and other sedimentary structures (Fig. 4B), suggest the action of fast directional flows, great sedimentary discharges and a fast burial of the shells (Gutierrez-Mas et al., 2009b). Therefore, beyond the proposed factors, other depositional processes are necessary to explain the formation of these carbonated deposits.

The fact that the original *G. nummaria* habitat is the continental shelf, while studied shelly remains are located several meters over the present-day sea level, suggests that the shells could be remobilized from the neritic zone and transported towards shallower waters and landward, where they were deposited over previous coastal sands.

Historical very-high oceanic events are documented in the Gulf of Cadiz (Campos, 1991; Ribeiro, 1995; Luque et al., 2002 and 2004; Lario et al., 2008; Gutierrez Mas et al. 2016). In close Valdelagrana sandy spit, on left margin from Rio San Pedro, tsunami deposits have been described by Dabrio et al. (1998) and Luque et al. (2004), to whose deposits assign ages from 2000 yr BP to 1500 yr BP, dates that are partly coincident with the ages of some shelly deposits here studied (Figs. 6B, D and Fig. 7). However, the mentioned high-energy depositional features cannot be definitively assigned to a single agent, since these deposits could have been also caused by large waves of storms. We can only associate them to very high-energy events.

In this way, it is more than likely that the studied shelly deposits were result of the combined action of tectonic processes and different depositional agents. During high stand stages the original habitat of *G. nummaria* would be displaced towards landward, while the shells remain were leave on shallower bottoms or directly on land. During low stand stages abundant shells remains emerged. Rises and falls of sea level in addition to recurrent action of great waves can explain the heights reached by shelly layers as well as the sedimentary structure of the deposits.

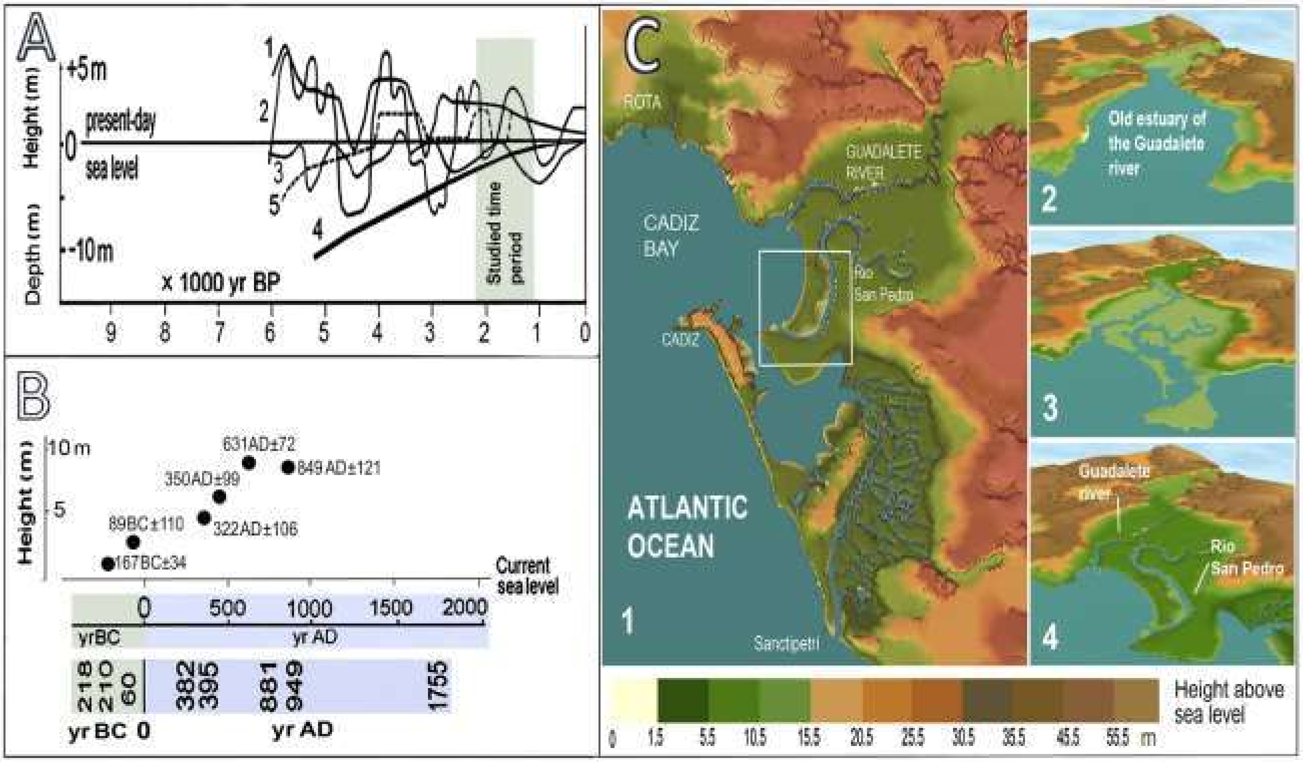

Figure 6. A) Recent sea level change curves proposal for North-Atlantic close to Cadiz Bay (1: Compton, 2001, 2: Martin et al., 2003, 3: Fairbridge, 1962, 4: Bard et al., 1990, 5: Mörner 2007. B) Ages and topographic heights of G. nummaria deposits from Cadiz Bay, and historical tsunamis recorded in the Gulf of Cadiz (Ribeiro, 1995). C) Evolution of the Cadiz Bay caused by historical sea-level changes: 1. Present-day, 2. Guadalete estuary during a recent high stand stage, 3. Guadalete estuary during recent low stand stage, 4. Current Rio San Pedro (Modified from Gutierrez-Mas, 2011).

5.2. Sea-water temperature variability

Mineralogical and chemical composition of shelly samples make them very suitable to the application of the HTP method to determinate the $\delta^{18}O$ values, because they have a totally carbonated composition. In addition, shells are well preserved with few marks of dissolution and recrystallization. Regarding the analysis method used to measure the stable isotope ratios (HTP), both instrumentation and experimental procedure are simple and cost effective. The isotopic composition results are shown for international reference materials and selected laboratory for reference materials, which demonstrate the precision and accuracy of this method (Gehre y Strauch, 2003).

The $\delta^{18}O$ values from carbonated G. nummaria valves depend of the seawater temperature when the carbonate was precipitated, which allows them to be associated with the seawater temperature fluctuations (Grossman y Ku, 1986). The 16O isotope tends to diffuse rapidly, in a way that the first water vapor formed during the evaporation is enriched in 16O from water, while the residual water is enriched in ^{18}O (Miller et al., 2006). On the other hand, it is accepted that during the Cenozoic an increase of 1 ºC in seawater temperature results in a decrease in $\delta^{18}O$ value of 0.3‰ (Grossman y Ku, 1986; Grossman 2012).

Regardless, some authors think that oxygen isotopic analysis from mollusc shells should not be used to make conclusions on seawater palaeotemperatures, because the temperature effect can be modified by fluvial discharges (Keith y Parker, 1965). In this regard, we must consider that although the studied accumulations of G. nummaria shells currently appears on coastal sands, the true natural habitat of this organism is the neritic zone, where these organisms are less affected by fluvial discharges during their growing, and their shells not suffer chemical or mineralogical alterations.

The $\delta^{18}O$ values obtained from shelly deposits from Cadiz Bay represent a time interval from 200 BC to 850 AD, time during which significant climate changes occurred, such as Roman Warm Period and Medieval Warm Period (Fig. 7). The maximum and minimum $\delta^{18}O$ values during the entire period studied (Table 2), in accordance with Grossman y Ku (1986), indicate that the maximum temperature fluctuation was of about 6°C. This change occurred between 89 yr BC and 322 yr AD, a time interval which correspond to the end of the Warm Roman Period (Fig. 7B), when the highest temperatures of this period were reaches. This was an epoch of general warmth in Europe and North Atlantic region. Paleoclimatic records from tree rings, alpine glaciers, lake sediments and $\delta^{18}O$ ice cores in Greenland, indicate warming and temperatures higher than today (Ljungqvist et al., 2012).

On the other hand, if average $\delta^{18}O$ values are considered (Table 2), the average temperature fluctuations for the entire time interval studied would have been of about 3.9ºC. The oldest shelly deposits (167± 34 yr BC) show minor temperate fluctuations, while younger shell layers (89 ±110 yr BC) show a transition to a short colder period, which was followed of a warming stage (322 ±106 AD). This temperate fluctuation is similar to the current seasonal temperature fluctuation in the Mediterranean Sea (Bakun y Agostini 2001), that indicates a low response of the seawater in the study zone to climatic changes recorded in the North of Europe and other Atlantic areas.

Other shorter changes are also deduced from $\delta^{18}O$ values from carbonated shells within a same shelly layer. The $\delta^{18}O$ values yielded show temperature fluctuations similar to the deduced for entire studied period (Table 2 and Fig. 7). A cooling of about 2ºC is observed between 167 ±34 yr BC and 89 BC ±110 (units 1 and 2), which was followed of a light warm-up of 1ºC, which continued until 322 yr AD ±106 (Unit 4) and still reached the 350 AD yr ±99 (Unit 5).

A water-cooling is observed for 350 yr AD, which is coincident with a prevailing cooler and wetter conditions recorded in Europe, known as the Dark Age. However, this cooler interval is not well recorded in the studied zone. Regarding short changes, the analysis data show $\delta^{18}O$ values of 0.01‰, 0.86‰ and 1.01‰ (Table 2), suggesting a light tendency to the cooling. From 631 ±72 yr AD to 849 ±121 yr AD, the $\delta^{18}O$ values yielded are 0.38‰, 1.65‰ and 1.83‰ (Unit 6) and 1.08‰, 0.37‰ and 2.11‰ (Table 2, Fig. 7), which suggests a progressive cooling of the water interrupted by some short warm interval.

From a temporal point of view, the end of this interval coincides with the start of Medieval Warm Period (MWP) (Fig.7), during which the climate conditions were slightly warmer than today in Europe and North America (Lamb, 1986). However, the $\delta^{18}O$ values suggest a slight cooling. It is possible that an activation of the thermohaline oceanic current can explain these data, in addition to the moderating effect of the Atlantic and Mediterranean water masses on the Gulf of Cadiz. Both currents could act in a similar way to the present-day, cooling during the warm seasons and warming during colder seasons.

The results suggest that the water temperature during the studied time interval was relatively stable in the zone of the Cadiz Bay, and that the seawater was not dramatically affected by the climate changes occurred in the northern Europe and other northern Atlantic regions.

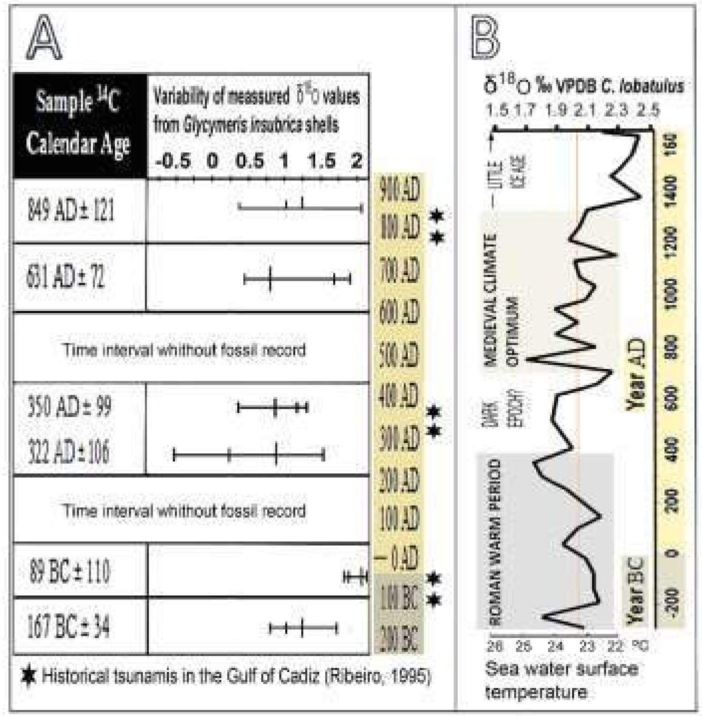

Figure 7. A) ^{14}C ages and $\delta^{18}O$ values from *G. nummaria* for 200 yr BC - 800 yr AD interval in Bay of Cadiz. B) Historical climatic periods and seawater temperature fluctuations for 200 yr BC - 1000 yr AD interval from $\delta^{18}O$ values of benthic foraminifers (*Cibicides lobatulus*) (Modified from Patterson et al., 2010).

The results of this study, carried out on the historical fossil record, should not be related to current climate change, since this work has obtained data on seawater palaeotemperatures, controlled especially by the presence of important marine currents from different water masses, and not direct conclusions on climatic variations.

6. CONCLUSIONS

The study of mollusc shell layers preserved in recent fixed coastal sands has provided information about historical changes and water temperature fluctuations from the Bay of Cadiz (SW Spain), a North Atlantic zone of medium-low latitude. The sets of analysed shell beds cover a time interval from the II Century BC to IX Century AD. These shelly layers are interstratified in fixed recent aeolian-sands.

The combination of sedimentary, mineralogical, chemical and isotopic analyses, allowed to know the deposit ages and to establish the effects of recent climate changes on the sea level and water temperature, as well as to compare the results with climate periods recognized in North of Europe and other North Atlantic areas. Very high-energy depositional processes also occurred in the zone during the studied time interval.

XRF chemical analysis indicates that G. nummaria shells present a dominance of carbonate (CaCO3) of up to 93% CaO (Table 1), while silica is absent. XRD mineralogical analysis indicates that G. nummaria valves are predominantly of aragonite (97-100%). Both chemical and mineralogical data are consistent and confirm the carbonated nature of the studied shells, a required condition before samples can be analysed for oxygen isotopic ratio by mean of the HTP method. HTP method used to determine $\delta^{18}O$ values and to establish the seawater temperature variations provides a fast and precise analysis, as well as high similarity between expected and obtained values from the measured standards.

Different depositional processes explain the origin and topographic height respect to present-day sea level where these shelly accumulations are actually located. The origin of these shell deposits is related to recent climate and sea level changes, as well as to depositional very high-energy processes. Some of these events are recognized in historical record of the coast from Cadiz Gulf, and were caused by great waves caused by strong storms or tsunamis.

Significant climate changes are well recognized in both Europe and North America, such as the Roman Warm Period and the start of the Medieval Warm Period, which are not so well recorded in the zone during the studied time interval. Here, $\delta^{18}O$ values indicate that the seawater temperature fluctuations were relatively minors, with similar amplitude to current seasonal fluctuations in the Mediterranean Sea, which suggests a climate relatively stable during this time interval. The action of marine currents in addition to the medium-low latitude could had a moderating effect on the climate and seawater temperature.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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