Revista de la Sociedad Geológica de España 25 (3-4)

PLIOCENE LITHOFACIES WITHIN THE MARINE GEOLOGIC RECORD FROM THE CADIZ BAY (SW SPAIN): ENVIRONMENTS AND PROCESSES

Litofacies del Plioceno en el registro geológico marino de la Bahía de Cádiz (SW de España): ambientes y procesos

José Manuel Gutiérrez-Mas[1] and Ramón Mas[2]

[1] Departamento de Ciencias de la Tierra, Universidad de Cádiz. Polígono Río San Pedro s/n. 11510 Puerto Real, Cádiz, Spain. josemanuel.gutierrez@uca.es
[2] Departamento de Estratigrafía, Universidad Complutense de Madrid - IGEO, CSIC. c/Jose Antonio Novais, 2. 28040, Madrid, Spain. ramonmas@geo.ucm.es

***Abstract**: Depositional trend that characterized the post-orogenic sedimentary fill in the southern sector of the Guadalquivir Basin has been established by means of sedimentological analysis of Pliocene marine deposits from the Cadiz coast (SW Spain). Lithofacies indicate important variations of depositional regime, alternating calms and storm periods with occasional oceanographic events, which are characterized by the deposition of bioclastic and boulder deposits. According to the features and fossil content, several lithofacies types have been identified, from muddy sands to sandstones, calcarenites, bioclastic accumulations, and large boulder accumulations. Sands, sandstones and calcarenites show features which indicate a seasonal depositional regime, while bioclastic and large boulder beds show different features respect to the over and underlying beds, having been classified as event deposits. The origin of the event deposits and the involved depositional processes is also discussed. Both, lithofacies and tectonic setting are coherent with historical data, and indicate that these deposits were generated by very-high energy oceanographic events, such as major storms or tsunamis.*

***Key words:** Pliocene, high-energy deposits, boulders, tempestites, tsunamites, Cadiz Gulf.*

***Resumen:** Mediante el estudio sedimentológico de los afloramientos Pliocenos de la costa de Cádiz (SO de España), se ha establecido la tendencia deposicional que caracteriza el relleno sedimentario post-orogénico en el sector sur de la cuenca del Guadalquivir. Las facies indican variaciones importantes del régimen deposicional, alternando períodos estacionales de calma y tormenta con eventos ocasionales de muy alta energía, caracterizados por el depósito de materiales clásticos y bioclásticos de mayor tamaño. De acuerdo con las características sedimentarias y el contenido fósil, varios tipos de litofacies han sido identificadas. Las arenas, areniscas y calcarenitas muestran características que indican un régimen estacional, mientras que las capas bioclásticas y los depósitos de bloques muestran características completamente distintas a los depósitos infra y suprayacentes, habiendo sido clasificados como depósitos de eventos. También se ha discutido el origen de estos depósitos y los mecanismos deposicionales involucrados en su formación. Tanto las litofacies como el marco tectónico y el registro histórico, indican que estos depósitos fueron generados por eventos oceanográficos de muy alta energía, tales como grandes olas generadas por importantes temporales o tsunamis.*

***Palabras clave**: Plioceno, depósitos de alta energía, Golfo de Cádiz.*

Gutiérrez-Mas, J.M. and Mas, R. (2012): Pliocene lithofacies within the marine geologic record from the Cadiz Bay (SW Spain): Environments and processes. *Revista de la Sociedad Geológica de España*, 25 (3-4): 119-132.

The Pliocene shallow marine records from Cadiz coast (SW Spain) were studied with the aim of establishing the depositional conditions that characterized the sedimentary evolution in the south-western sector of the Guadalquivir Basin (Figs. 1 and 2). This basin is result of the flexural subsidence of the Iberian Foreland during the formation of the Betic Mountain Range (García-Castellanos *et al*., 2002; González-Delgado *et al*., 2004). Several high-energy deposits were identified, whose analysis provided information on the effects of sedimentary processes. There has been controversy regarding the interpretation of these accumulations, specifically with respect to the provenance of the boulders and the involved processes.

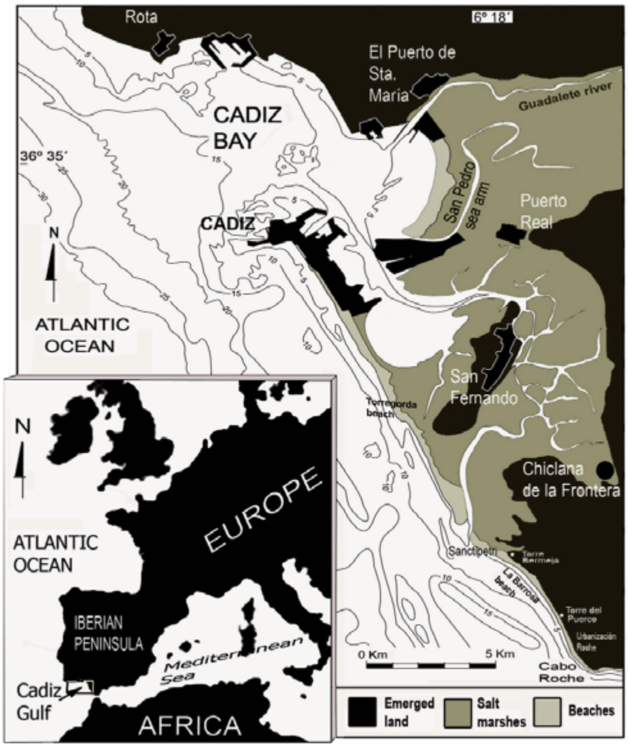


Fig. 1.- Geographic location of the studied area.

Geological setting

Tectonic setting

The study zone is located in the Atlantic coast of Andalusia (SW Spain) between the Guadalquivir River mouth and Trafalgar Cape (Fig. 3). It is located in the border between two adjacent domains, Betic Mountain Range and Guadalquivir Basin. This basin was formed by the tectonic burden of the Betic Orogene on the Iberian Foreland during the Alpine Orogeny (García-Castellanos *et al*., 2002; González-Delgado *et al*., 2004; Martínez del Olmo *et al.,* 2005). Two stages are distinguished, both separated by an intra-Burdigalian unconformity. During the first stage (Permian to Early Miocene), the sedimentation took place along a passive margin Atlantic type (South-Iberian Margin). During the second stage, the Alpine Orogeny began with the E-W motion and collision of the Alboran plate during the Burdigalian (González-Delgado *et al*., 2004; Martinez del Olmo *et al*., 2005). After the Burdigalian accretion of the new terrain of the Alboran Plate (internal zones from Betic Mountains), a Langhian-Serravallian extensional stage opened the Alboran Sea. This phase was followed by a N-S to NNW-SSE contraction, due to the rotation of the African and European plates that began in the late Miocene (Martinez del Olmo *et al*., 2005).

During the late Miocene, a new rising of the Betic-Rif Mountain Range caused a marine regression and the interruption of the communication between the Atlantic Ocean and Mediterranean Sea (Messinian Crisis). Later, extensional stress causing the subsidence of a sector of the Gibraltar Arc, and the re-establishment of the communication between the two seas. After the Miocene regression and a rapid sea-level rise, the Pliocene sedimentation began (Aguirre, 1995) (Fig. 2). From the early Pliocene to middle Pliocene, silty sands were deposited in shoreface and neritic environments, while during the late Pliocene, the littoral facies were dominant (Viguier, 1974). From late Pliocene to early Pleistocene, a renewed uplift of the Mountain Ranges tilted the Pliocene deposits, causing an angular and erosional unconformity between the Pliocene and Pleistocene units (Estevez and Sanz de Galdeano, 1980; Rehault *et al*., 1985; Sanz de Galdeano and Lopez Garrido, 1991).

The Pliocene outcrops (Fig. 3) show evidence of a relatively intense neo-tectonic activity, being affected the Pliocene deposits by tilting and faulting (Viguier, 1974; Benkhelil, 1976; Mezcua Rodriguez and Martínez Solares, 1983; Sanz de Galdeano and Lopez Garrido, 1991; Aguirre, 1995). Two neo-tectonic stages are distinguished: a) a Mio-Pliocene extensional stage, evidenced by normal faults orientated N 110º E and E-W, and an angular unconformity between the late Miocene and Pliocene, and b) a compressive stage from Late Pliocene to Holocene, which reactivated older fractures, and gave way to dextral tear faults oriented NE-SW and E-W.

Stratigraphy

The study of the post-orogenic deposits from Cadiz coast early starts by the geologist MacPherson (1873) in the late of 19th century, and somewhat later, in the first half of the 20th century by Gavala and Laborde (1959 y 1992, who focus their studies from a stratigraphic and cartographic point of view (Gutierrez Mas *et al*., 1991). During the second half of 20th century, Viguier (1974) carried out detailed studies about the Neogene from lower Guadalquivir basin, including the Cadiz province. Almost simultaneously, Benkhelil (1976) studied of post-orogenic tectonic deformation in this area, coming to identify two major neo-tectonics stages.

Zazo (1979, 1980), studied the Pliocene-Quaternary boundary on the Cadiz, considering that the Pliocene to Quaternary step is represented by an erosive unconformity and a karstic surface that separates the Pliocene materials of the "red sands", which represent the first Quaternary deposit. Aguirre (1990, 1995), studies the Pliocene stratigraphy between Cadiz and Conil, distinguishing three stratigraphic units separated by unconformities. Unit I consisting of homogeneous and bioturbated yellow fine sands;

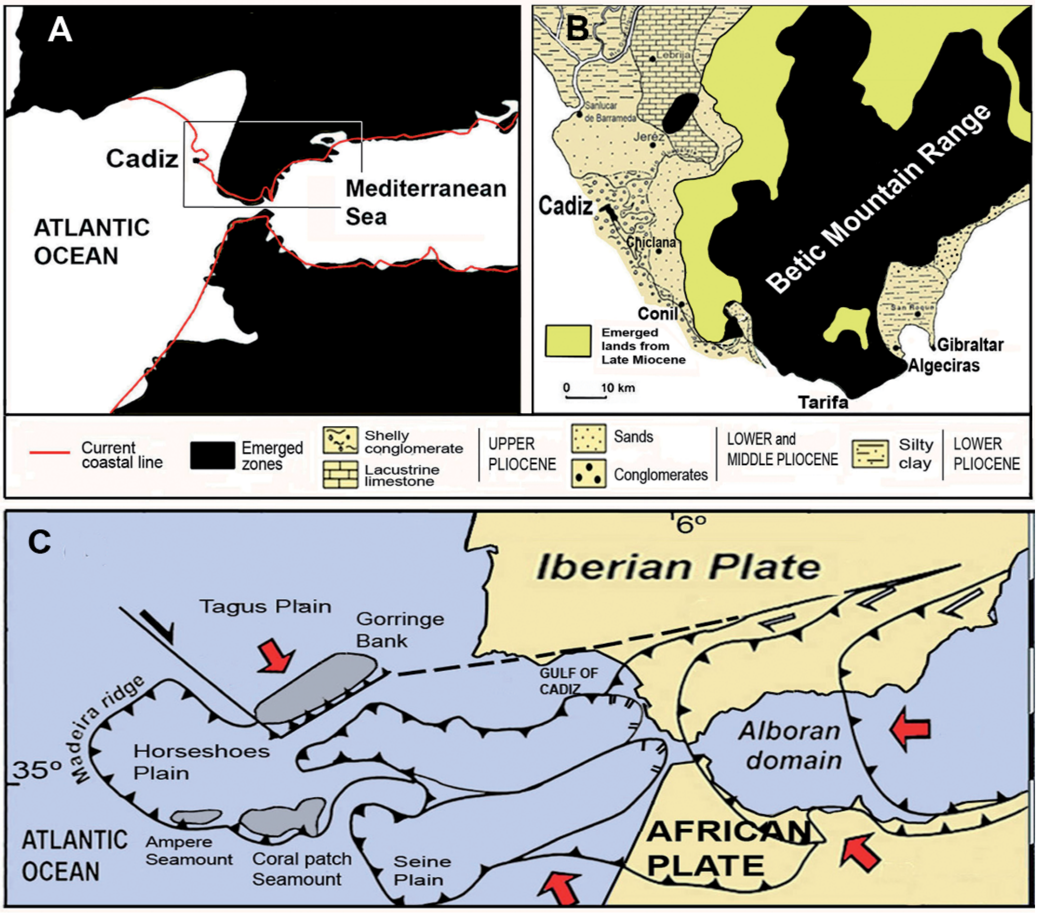


Fig. 2.- A) Paleogeographic map of the Cadiz Gulf and Gibraltar Strait during the early Pliocene (modified from Martín *et al*., 2009 and Toscano-Grande *et al*., 2010); B) Geographical distribution of the Pliocene deposits from Cadiz province (modified from Viguier, 1974 and Gutierrez-Mas *et al*., 1991); C) Tectonic setting of the study zone (modified from Maldonado *et al*. 1999). Red arrows: main stress directions.

unit II is conformably on the previous one and consists of cemented calcarenite with abundant remains of *Ostrea edulis* and *Pecten sp*. Finally, the unit III consists of a conglomeratic set, on which appears a well marked erosive surface fossilized by Quaternary "red sands". More recently, Rico-García *et al*. (2008), studies the Pliocene pectinids from Vejer de la Frontera outcrops, and Rico-Garcia and Aguirre (2008), study the taphonomic features of the fossil associations from Pliocene deposits of this basin. These define three taphofacies types: a) taphofacies from inner shelf, b) taphofacies from shallow lagoon, and c) taphofacies from storm deposits.

Methods

Field work consisted of outcrop studies, sedimentological and stratigraphic analyses and sampling (rocks and fossils) of eleven stratigraphic sections along the Cadiz coast (Figs. 3, 4, 5 and 6). The sedimentological study included the analysis of the lithofacies and petrographic samples. The textural, petrographic and mineralogical analyses were carried out in order to characterize the deposits, whereas the microscopic analyses of different types of boulders and clasts aimed at determining their petrographic features and similarities, provenance, transport distance and sedimentary evolution.

The $^{87}Sr/^{86}Sr$ Isotopic Relation Analysis Method was used to determine the absolute age of 12 calcareous samples (Table 1). Strontium isotope analysis is based on the variation of the average $^{87/86}Sr$ ratio in seawater (McArthur *et al*., 2001). The samples were analysed in the Geochronology and Isotope Geochemistry Laboratory of the Universidad Complutense de Madrid. The Sr measurements were corrected for possible ^{87}RB interferences, and normalized to $^{87}Sr/^{86}Sr = 0.1194$, due to possible mass fractionation during the analysis. Age was determined using the relation $^{87}Sr/^{86}Sr$ and the marine Sr-Isotope Curve for 509 Ma (millions of years) (Table 1). The standard seawater marine curve given by McArthur *et al*. (2001) was used. The chronostratigraphic position of the units was based on Scale of the International Stratigraphic Commission (Gradstein *et al*., 2004) (Table 1).

Results

The oldest deposits are Miocene marls from Guadalquivir Olistostrome Complex, located at base from section 6 (Fig. 5). These are composed of white marls with olistoliths with a variable lithology, such as, blocks of sandstones, limestones, gypsums, etc., belonging to different units from the Betic Mountain Range. Blue marls from Upper Miocene are also present at the section 6 (Fig. 5), while Upper Miocene calcarenites are present to the south of the study zone, near the town of Conil (Figs. 3 and 6).

Pliocene deposits are mostly represented by silty sands, bioclastic sands, and calcarenites (Figs. 3 to 7). An exceptional case is the presence of a group of spherical blocks of quartzarenite, which are interbedded in Pliocene sands and

Samples			$^{87}Sr/^{86}Sr$	Error	Age (Ma BP)	Deposit age
Fuente del Gallo (section 10)	**12**	Unit 2a Oyster ** ●	0.709092	5	1.9	Pleistocene
	11	Unit 2 Pecten **●	0.709070	4	2.6	
	10	Unit 2 Cardiun **●	0.709043	6	4.8	Upper Pliocene
	9	Unit 2 Oyster **▲	0.709153	5	0.65	Pleistocene
La Barrosa (section 4)	**7**	Unit 4 shell from boulder *▲	0.709139	5	1	
	6	Unit 5 Pecten (upper conglomerate) **●	0.709094	5	1.7	
	8	Unit 5 Oyster (upper conglomerate) **●	0.709083	5	2.1	
	5	Calcarenites *▲	0.709049	6	4.4	Lower Pliocene
	4	Unit 2 Pecten ** ●	0.709019	5	5.1	Lower Pliocene
	3	Pecten (lower conglomerate) *▲	0.709025	5	5.3	Lower Pliocene-Late Miocene
	2	Oyster (lower conglomerate) *▲	0.709025	6	5.3	
	4	Unit 2 Pecten ** ●	0.708964	5	5.7	Late Miocene
Roman oven (section 3)	**1**	Unit 6 Shell in sands **▲	0.709053	5	4.5	Lower Pliocene
		▲ Trusted samples; ● Unreliable samples; ** Allochthonous fossils; * In situ samples				

Table 1.- Samples Age from $^{87}Sr/^{86}Sr$ Isotopic Analysis

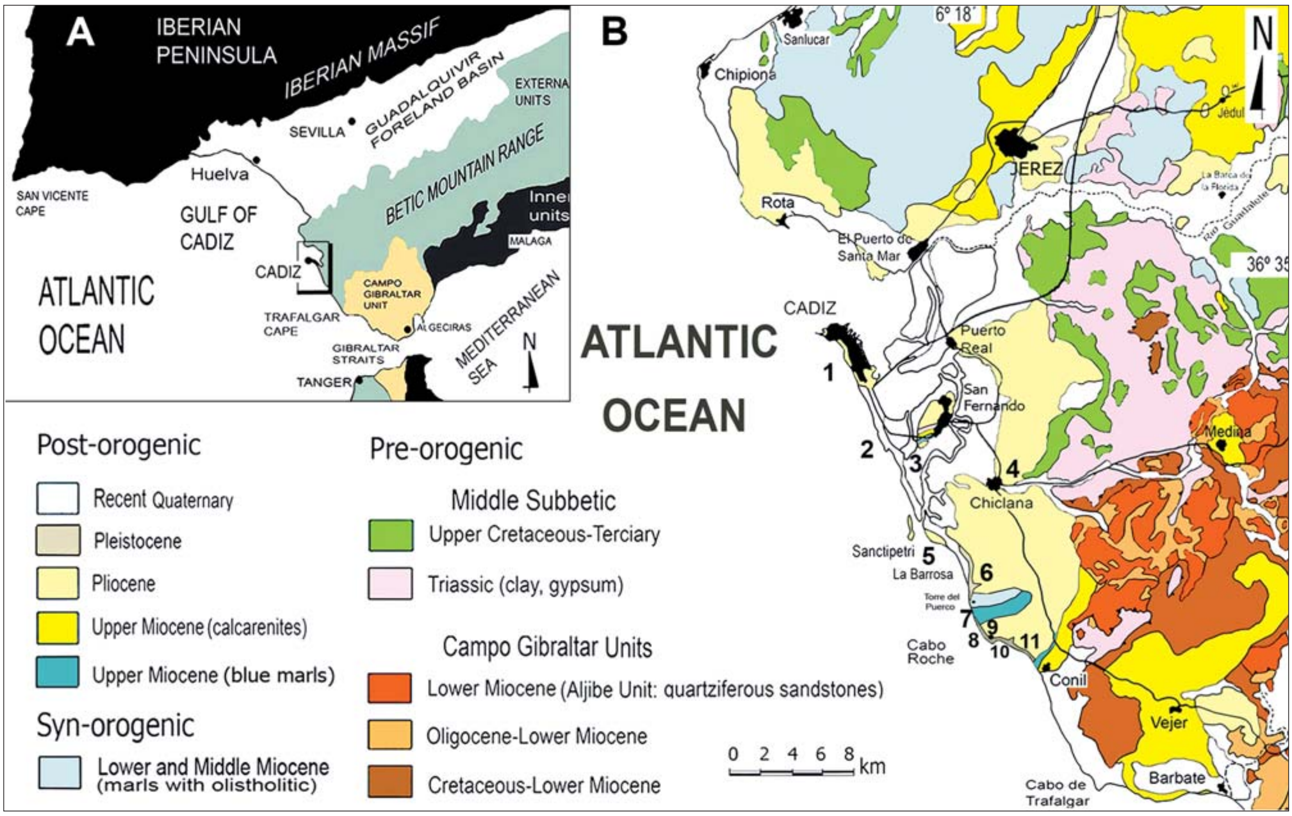


Fig. 3.- A) Geological map of the study zone; B) Geological map of the study zone, and stratigraphic section location (modified from Gutierrez-Mas *et al*., 1991).

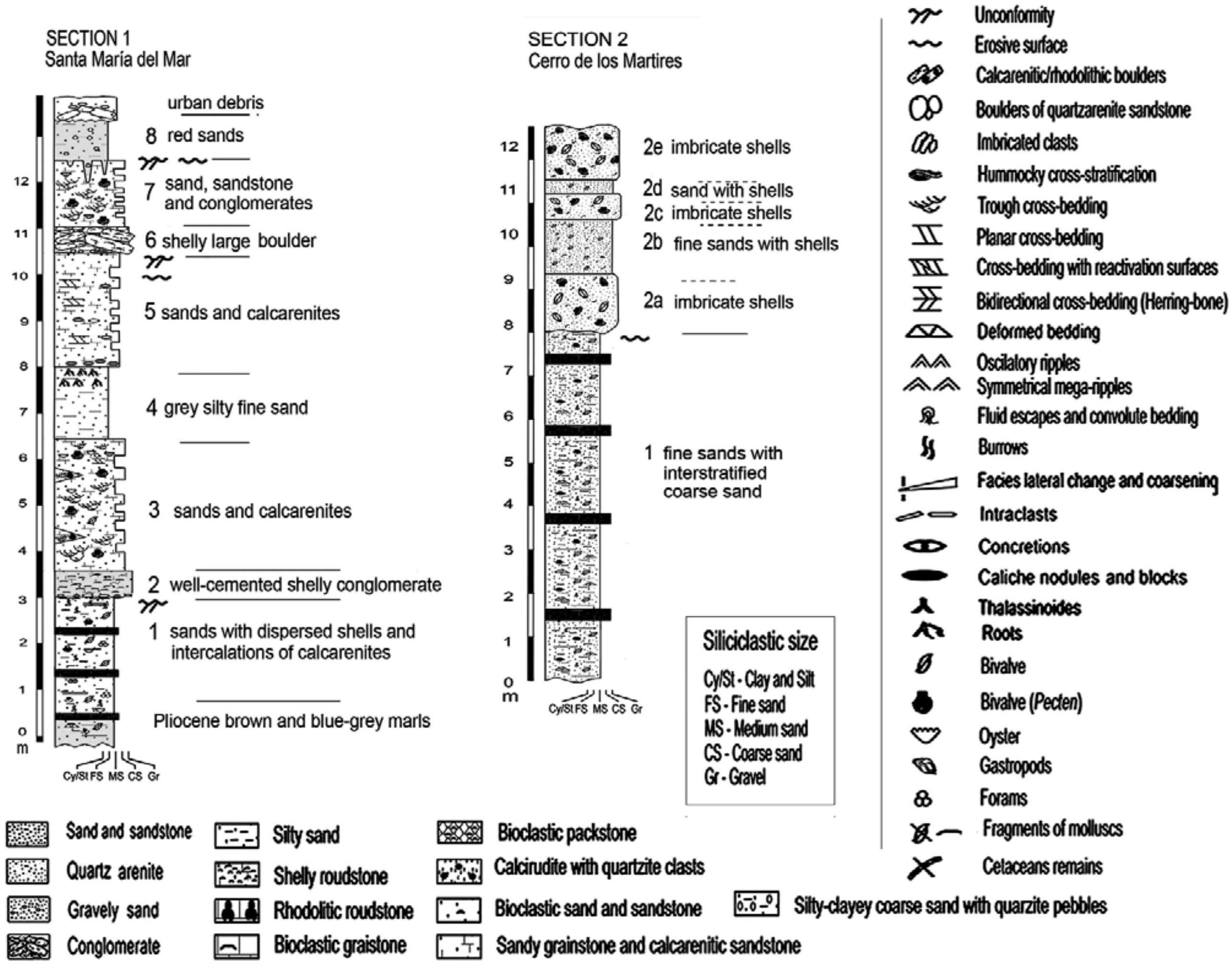


Fig. 4.- Stratigraphic sections from 1 to 2 (Location in Figure 3), and general legend.

calcarenites, which are present in the section 10 (Figs. 6 and 7). The macrofauna is mainly represented by bivalve mollusks, primarily oysters and pectinid shells. In general, the shells are disarticulated, with biofouling, bioerosion, fragmentation and abrasion signs. Also gastropods, brachiopods, rhodoliths, corals and scaphopods are present.

Pectinids are the most represented family. Genus *Aequipecten* is represented by three species: *Aequipecten escabrellus*, *Aequipecten opercularis* and *Aequipecten radians*. Genus *Pecten* is represented by the species: *Pecten jacobaeus*, *Pecten maximus* and *Pecten benedictus*. Genus *Chlamys* is represented by: *Chlamys multistriata* and *Chlamys varies*. Other identified fossils are: *Hinnites crispus*, *Ostrea edulis*, *Flexopecten flesuoxus*, *Balanus and Mytilus sp*. Some fossils are in mold state, as *Glycymeris sp* and *Panopea sp*. Bryozoans are present in several bioclastic levels, while Brachiopods, although not abundant, are also present.

Regarding the age of the bioclastic deposits and sands, isotopic analysis results (^{87}Sr/86^{Sr} ratio) of 12 shelly samples, indicate ages between 5.7 Ma and 1.5 Ma, that is, from the Upper Miocene (late Messinian) to the Pleistocene (Table 1). In the section 5 (Fig. 5), an *Amusium cristatum* shell provided an age of 4.25 Ma (early Pliocene) (Table 1), while in section 4 (Fig. 5), fossils from bioclastic sands have yielded an age of 4.4 Ma (Zanclean, early Pliocene).

Lithofacies types

In the Pliocene deposits have been distinguished five lithofacies types (Figs. 7 and 8, Table 2).

I. Muddy sands with pectinids: Yellowish silty sands containing pectinid shells, graded bedding, cross-bedding and burrows (Fig. 8A). Hydroplastic structures (fluid escapes and convolute-bedding) are also present. Sandstone and calcarenite with hummocky cross-stratification (HCS) are interbedded in the sands.

II. Calcarenites: Sandy bioclastic grainstone with HCS, which are interbedded in the bioclastic sands (Fig. 8B), with erosive base and intense burrowing.

III. Bioturbated fine sands with pectinids: Sandy-bioclastic-grainstones with pectinid and oysters, interbedded with calcarenites (Figs. 8C).

IV. Shelly conglomerates: Well-cemented or no-cementated layers of sandy-gravelly-bioclastic-rudstone, with shells of oysters, pectinids, gastropods, bryozoans, echinoderms and benthic foraminifera (Fig. 8D).

V. Aljibe sandstone blocks: Discrete group of sub-spherical and rounded boulders of quartzarenite from the Aljibe For-

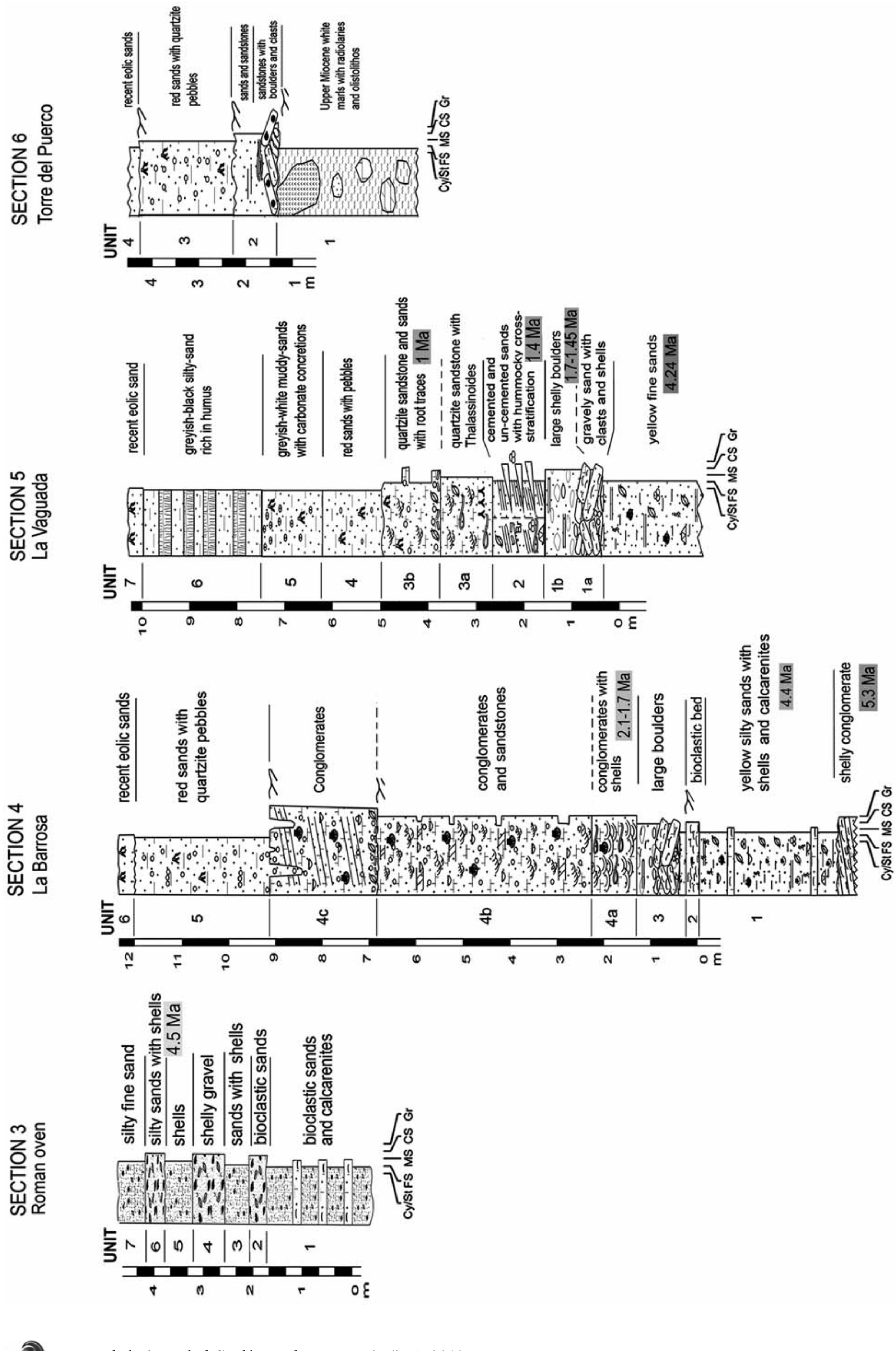


Fig. 5- Stratigraphic sections from 3 to 6 (Legend in Fig. 4, Location in Fig. 3).

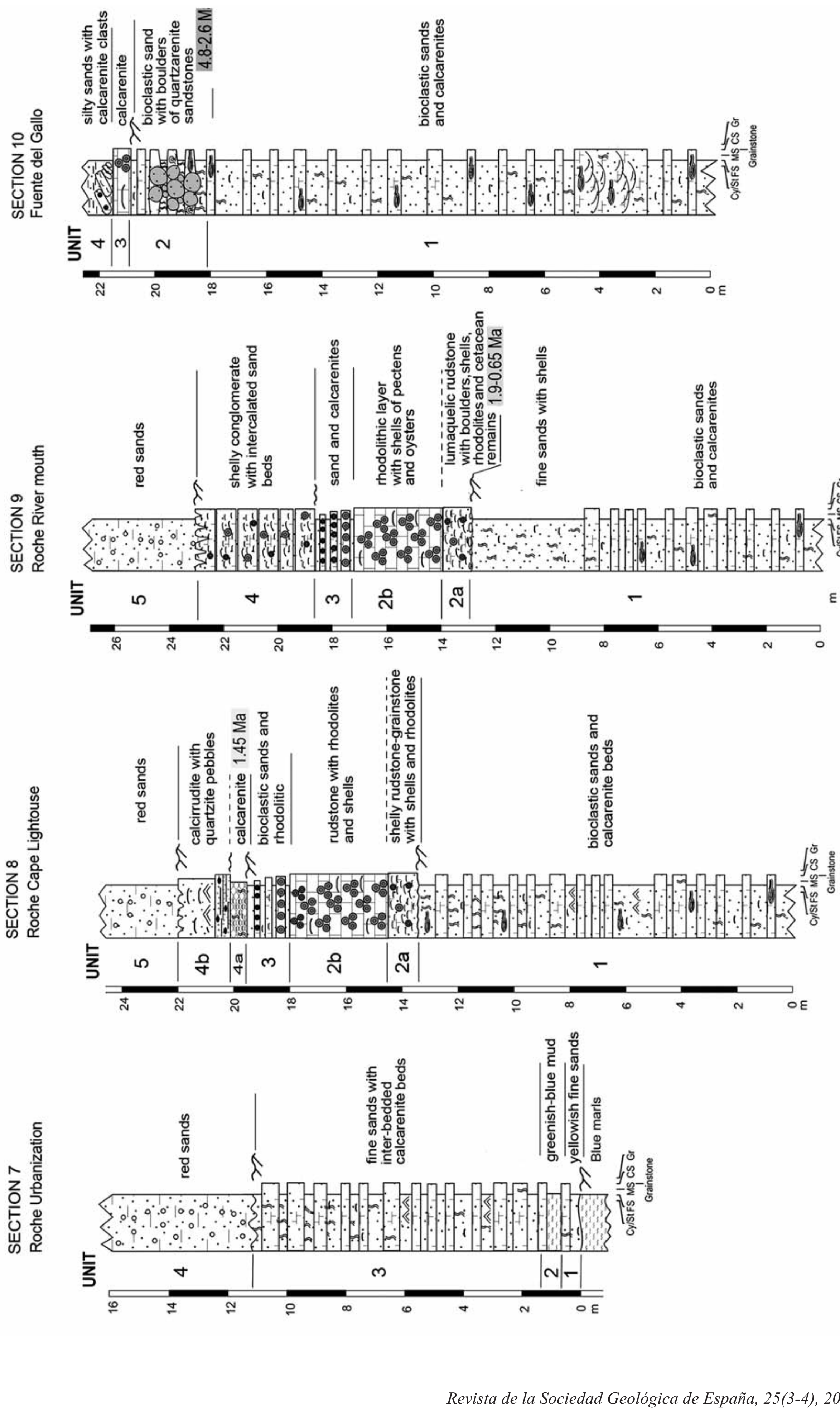


Fig. 6.- Stratigraphic sections from 7 to 10 (Legend in Fig. 4, Location in Fig. 3).

Fig. 7.- Imagen of a Plio-Pleistocene outcrop from the sea clift of the La Barrosa beach: a) Miocene-Pliocene calcarenites; b) Pliocene bioclastic sands (pectinid sands); c) Shelly layer with erosive base; d) Bioturbated muddy fine sands; e) Bioclastic sands; f) Pleistocene upper conglomerates; g) Pleistocene continental "red sands".

mation (Unit of Campo de Gibraltar, from Betic Mountain Range) (Fig. 8E), which are interstratified with sands and calcarenites.

Petrography of boulders and clasts

From their petrographic characteristics, different types of clasts have been distinguished:

Quartzarenite boulders: These are sub-spherical and rounded blocks of 0.3 to 0.7 m in size, which are present in the upper part of section 10 (Figs. 6, 8 and 9). Those are bioclastic to feldspathic litharenite. The microfacies show a 60-65% content of quartz, 10-15% of feldspars and 30-35% of calcareous fragments and cement (Fig. 9D). The calcareous fragments include fragments of bryozoans, echinoderms, bivalves, foraminifers, calcispheres, ferruginous cemented fine-grained sandstone and muscovite. Their petrographic features are similar to the *Aljibe sandstones* (Campo de Gibraltar Units), which must be the source rock). The outcrops have local character, since they depend on the proximity of *Aljibe sandstone* outcrops (Figs. 2, 6 and 8).

Pliocene calcarenitic clasts: They are pebbles of 10 to 20 cm in size, with greyish white to blue colours, ellipsoidal shape, well-rounded surfaces, and bioturbation marks (Fig. 9). Two types are distinguished: 1) clasts with microfacies of intraclastic grainstone-packstone, quartz grains, ferruginous sandstone, glauconite grains, foraminifers and calcispheres (Figs. 9A and 9B); 2) clasts with microfacies of sandy bioclastic-intraclastic rudstone-grainstone, recrystallized bivalve fragments, bryozoans, foraminifers, ostracodes, quartz and glauconite (Fig. 9E). Both types of clasts have microfacies similar to the calcarenitic layers interbedded in Pliocene sands.

Discussion

Depositional processes

The results suggest that the entire Pliocene deposits were deposited in shallow marine and coastal environments. The fossil content and the variety of species present in the deposits, indicate a conditions of waters warmer than the Present day and Pleistocene (Monegatti and Raffi, 2007). According to the energy and the involved hydrodynamic processes, the lithofacies are grouped into three types (Table 2):

Low-energy facies: The deposits show lithofacies of sandy mud, muddy sand and fine sand. Structures such as graded bedding, parallel lamination, planar cross-bedding and bioturbation marks are also present. The lithofacies type I is representative, being present in the lower part of the sections (Figs. 4, 5 and 6). The facies indicate low-energy environments (Table 2), where the prevalent calm conditions favour the settling of silt and clay. In spite of the dominance of fine sediments, the sedimentary structures indicate that a part of the sediment was also transported as bed load (fine and medium sand). Later the sediments were deposited and bioturbated by vertical burrows in subtidal environments.

High-energy facies: These deposits have siliciclastic or bioclastic nature, coarse grain size, erosional base, and wealth of sedimentary structures, such as, upper flow-regime, parallel lamination, imbricated clasts, graded bedding, cross-stratification, trough cross-stratification, HCS, and reactivation surfaces (Fig. 8B and Table 2). The most representative lithofacies are the types II and III (calcarenites).

Very high-energy deposits: These are represented by siliciclastic or bioclastic gravel accumulations. They have erosional base, with irregular top, graded bedding, cross-bedding, minor inner erosional surfaces, and imbricated clasts and shells (Fig. 6). Most of the mollusc shells are fragmented, while others are intact, and occasionally with articulated valves. The most representative lithofacies is the type IV (Pliocene shelly conglomerate) (Fig. 8E and Table 2).

A special deposit are the *Aljibe sandstone* boulders (lithofacies V), which are inter-stratified in the Pliocene fine sands (Figs. 8E and Table 2). They are allocthonous boulders originating from the Betic Mountains, whose shape and size is controlled by the thickness of the original beds and fracture directions. The high sphericity and round-

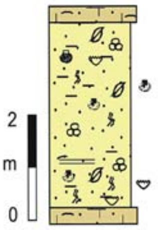
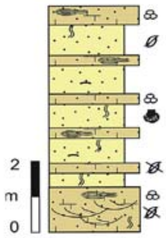
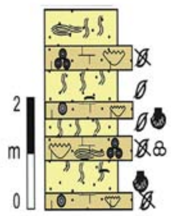
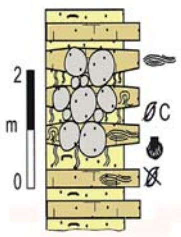
Lithofacies			Energy	Processes	Environments
	I	***Yellow muddy fine sands***	L	Fair-weather and tidal currents	Off-shore (nerithic) and distal estuarine
	II	***Calcarenites***	H	Storm-weather and rip-currents	Subtidal-shoreface (litoral)
	III	***Bioturbated fine sands***	H	Storm-weather and rip-currents	Off-shore (nerithic) or shoreface (litoral)
	IV	***Shelly conglomerate***	VH	Major storm or tsunami	Shoreface (litoral)
	V	***Aljibe sandstone boulders***	VH	Major storms or tsunami	Shoreface (litoral)
L.- Low-energy **H**.- High-energy; **VH**.- Very high-energy					

Table 2.- Pliocene lithofacies.

ness of the boulders indicate that they were alternately erosioned by successive fluvial, littoral and marine processes. The boulders were re-mobilized and transported seaward by return currents generated by very high-energy oceanographic or meteorologic processes, and deposited in shallow marine environments, such as the inner continental shelf (Fig. 10).

Environments and hydrodynamic agents

The fossil content and the lithofacies suggest that the Pliocene materials were deposited between the inner continental shelf and the foreshore, under warm climatic conditions, such as indicates the presence of abundant fauna (Monegatti and Raffi, 2007). The highest biodiversity in the study area was reached between the upper Messinian and the early Pliocene, between 5.6 and 5.3 Ma (Monegatti and Raffi, 2007), which is the time interval in which a greater number of genera and species appears. These data are largely consistent with the models of climatic distribution and diversity from Monegatti and Raffi (2007) and Marques da Silva *et al*. (2010). According to this information, in the latitude areas such as the present Gulf of Cadiz, the biodiversity gradient was increased at the end of the Miocene, when the boundary between the subtropical and tropical zones was located at higher latitudes than at present, with more penetration of warm water northward, and a greater extension of the subtropical faunas along the North Atlantic coasts (Monegatti and Raffi; 2007; Williams, 2012). 3 Ma ago, an Earth cooling caused significant climatic and oceanographic changes that led to the migration to the South of the boundary between subtropical and tropical areas, reaching latitudes of the southern Portugal, with the subsequent decrease in biodiversity in these areas. This situation remained until 2.7 Ma ago, i.e. until the beginning of the Pleistocene (Monegatti and Raffi, 2007; Marques da Silva *et al*., 2010).

Under a depositional view point, the facies features show important flow regime fluctuations, from low-energy environments, represented by very bioturbed muddy sands, to medium and high-energy environments, represented by

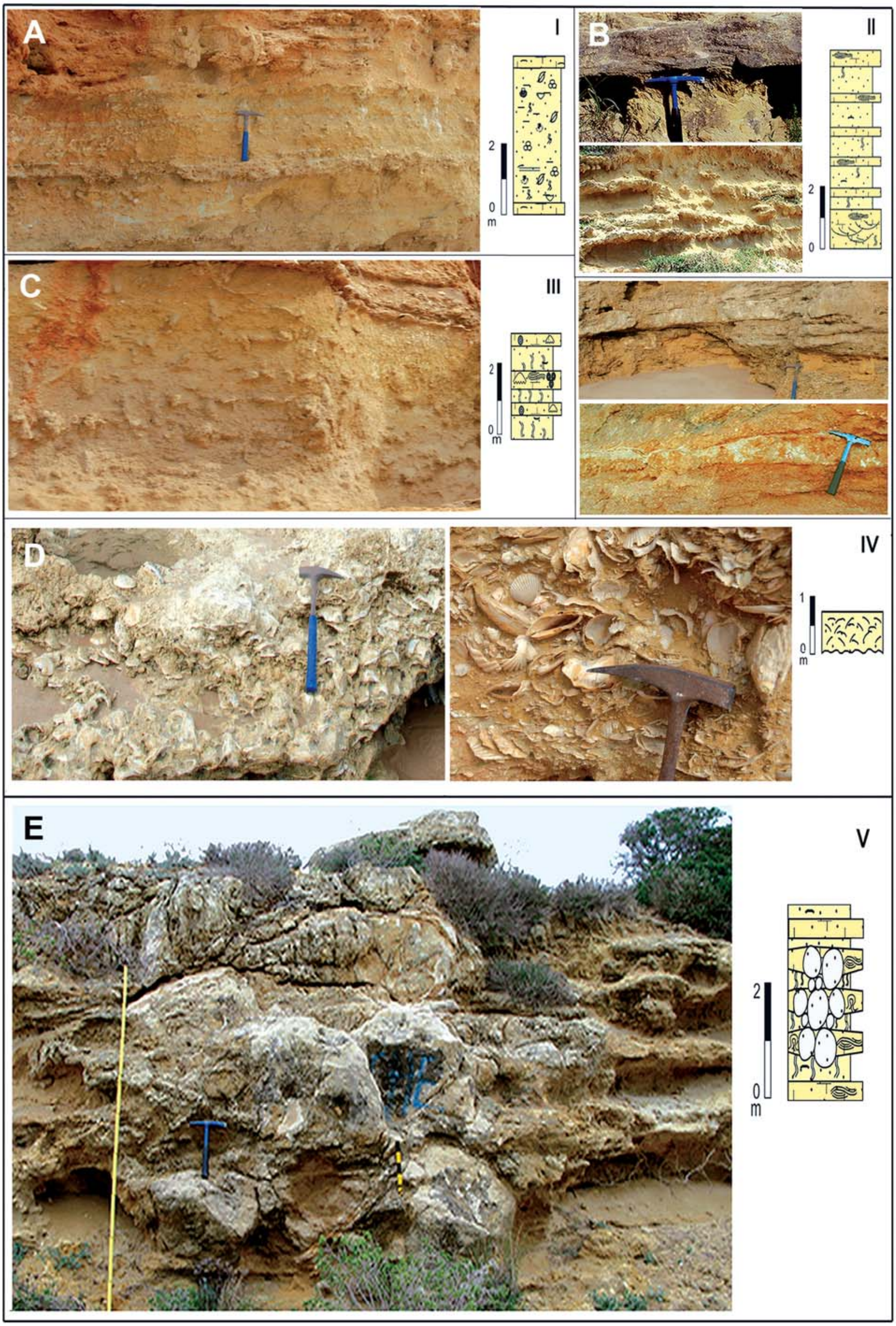


Fig. 8.- Pliocene lithofacies: A) Yellow muddy sands with pectinid shells and bioturbated silty fine sands; B) Calcarenites; Alternation of bioturbated silty sands and calcarenite beds with *HCS* C) Bioturbated yellow muddy sands; D) Shelly conglomerates; E) *Aljibe sandstone* boulders interestratified in Pliocene sands and calcarenites.

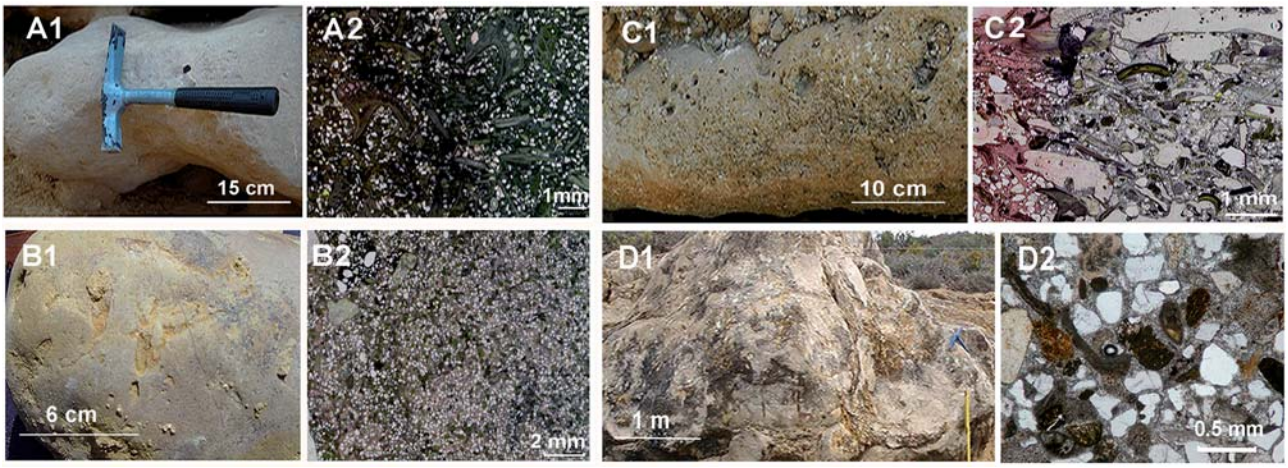


Fig. 9.- Microfacies. A1) Pliocene calcarenite, A2) Thin section: sandy bioclastic-intraclastic rudstone-grainstone with bryozoans, bivalves, foraminifers, echinoids, quartz and glauconite; B1) Pliocene calcarenite*,* B2) Thin section: sandy intraclastic grainstone with benthic and planktonic foraminifers, calcispheres, quartz and glauconite; C1) Aljibe sandstones boulders, C2) Thin section: fragmented shelf bivalves, foraminifers, quartz, feldspar and rock fragments; D1) Shelly calcirruditic bed, and D2) Thin section: sandy rudstone with oysters, bryozoans, echinoderms, foraminifers, quartz and glauconitic crusts.

bioclastic sands and calcarenites. Three types of environments and depositional processes are differentiated: a) Protected shallow environments, b) Inner continental shelf, c) Storm layers (tempestites), and d) Event layers.

a) Protected shallow environments: Low and moderate-energy sediments, mostly represented by bioclastic silty-fine sands. The calm conditions favored the deposition processes from the suspension. The calm stages were interrupted by storm episodes, represented by thin calcarenite layers. During the calm periods, both sands and tempestites were subjected to an intense bioturbation by action of subtidal marine organisms.

b) Inner continental shelf: These are bioclastic and siliciclastic sands with cross-lamination, and interbedded sandstone and calcarenite with HCS. The materials were deposited in open coastal environments, from the foreshore to the shoreface, and they are constituted of massive accumulations of bivalve mollusk shell fragments.

c) Storm layers (*tempestites*): These are high-energy deposits, being represented by calcarenites interbeded in the

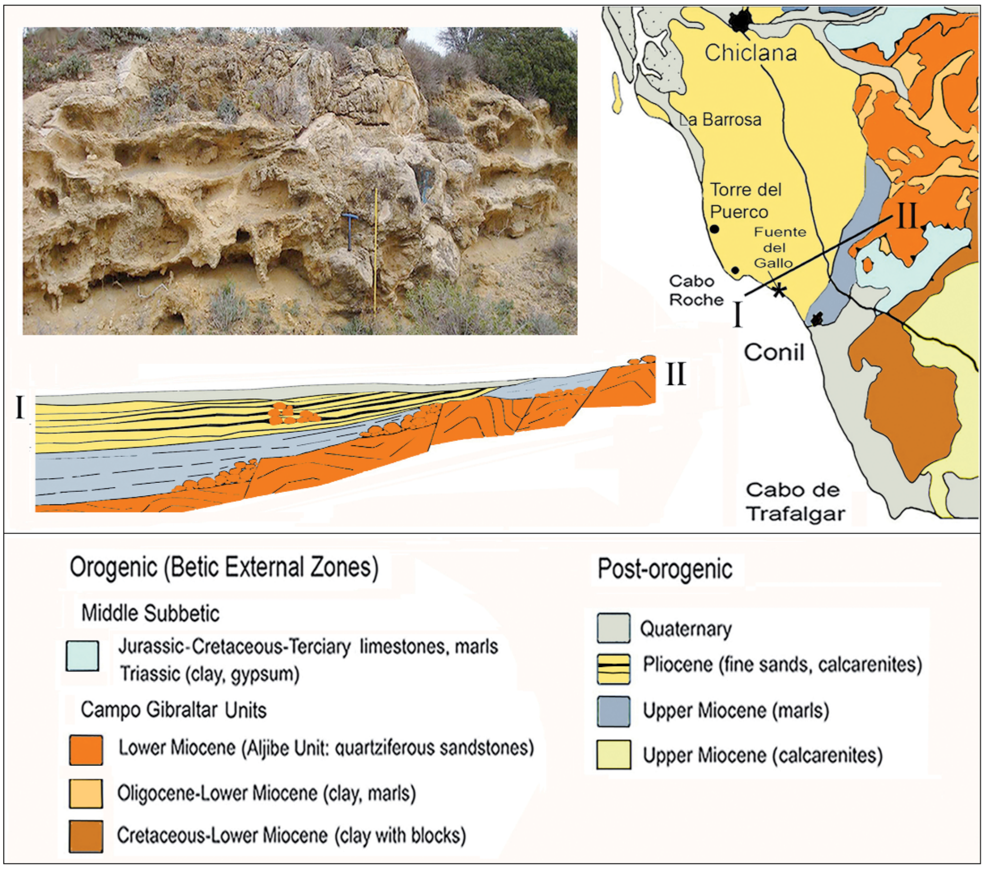


Fig. 10.- Image of the *Aljibe sandstone* boulder outcrop sandwiched in Pliocene sands and calcarenites (section 10). Local geological map and profile.

Pliocene sands. These layers show progradational character, being more frequent and thicker towards the top of the sections, consequence of their deposition in a full time shallower environment. This shallowing process was probably caused by an elevation of the Betic Mountain Range, which resulted in marine regression during the late Pliocene (Benkhelil, 1976; Estevez and Sanz de Galdeano, 1980).

d) Event deposits: These represent an important part of the Pliocene record. They are deposits of very high-energy, which show important differences with the seasonal deposits. The interbedding of these deposits into the bioclastic sands and calcarenites, suggests that they are event deposits, very different from the characteristic storm-layers (Shanmugam, 2006, 2008; Gutierrez-Mas *et al*., 2009a y b; Gutierrez-Mas and Mas, 2010). They are a consequence of the action of very energetic oceanographic processes, which developed their maximum effectiveness in shallow marine environments (Aigner, 1985).

But, which agent was able of producing such deposits? The depositional features indicate the action of strong flows and a high conservation potential of the deposits, due to its deposition in depths greater than the wave base level (Fujino *et al*., 2006; Massari *et al*., 2009). They are represented by massive accumulations of bivalve mollusk shells and large boulders, which can only be generated by greater waves of major storms and tsunamis. Both processes are able to generate deposits similar, sometimes difficult to differentiate, especially in wave dominated shallow environments (Shanmugam, 2006, 2008; Gutierrez-Mas *et al*., 2009a and b; Kortekaas and Dawson, 2007; Kennedy *et al*., 2007; Morton *et al*., 2007). This problem is especially pronounced when we study older deposits, which have lost some depositional features, while the historical records and meteorological data are not available. If the lithofacies are not enough to differenciate them, other additional criteria should also be taken into consideration (Dawson, 2004; Dawson and Stewart, 2007; Dott, 1996; Nanayama *et al.,* 2000; Goff *et al.,* 2001; Bryant and Nott, 2001; Nott, 1997, 2003). In this sense, the study area is located near the Eurasian and African plates boundary, where most recent historical earthquakes and tsunamis are documented (Udias *et al*., 1976; Campos, 1991; Ribeiro, 1995, Luque *et al*., 2001, 2002, Gutscher *et al*., 2006, Silva *et al*., 2005, Gracia *et al*., 2006, Morales *et al*. 2008), while meteorologic data points to the possibility that these depositional events may have been generated both by the action of tsunamis as major storms, such that either can totally be discarded (Gutierrez-Mas *et al*., 2009a and b).

Conclusions

The Pliocene marine records from Cadiz Bay (SW Spain) have been studied with the aim of establishing the depositional trends that characterized the sedimentary filling in this sector of the Guadalquivir basin. During the Pliocene the zone was occupied by a sea whose shoreline would be similar to the present, but shifted to the NE, so that the depth of the Pliocene Sea would increase toward SW.

During the Pliocene there was great faunistic diversity, represented by abundant fossil remains of marine organisms typical of tropical and subtropical waters, mainly bivalve molluscs. The maximum Pliocene biodiversity was acquired in the Gulf of Cadiz 5.5 Ma ago, time when the boundary between tropical and subtropical zones was farther north than the present-day. The decline in biodiversity, evidenced by the disappearance of many species and the migration to southern boundary of the limit of the tropical and subtropical areas, happened 3 Ma ago, indicating the onset of a cold period that points out the beginning of the Pleistocene.

The Pliocene lithofacies indicate shallow marine environments, mainly neritic and littoral. According to the sedimentary features, several lithofacies types are differentiated, which indicate important variations in the depositional regime, a consequence of the alternation of seasonal deposits, calms and normal storms, and very high-energy events. The sedimentary features reflect the action of very high-energy flows. The event deposits show anomalous depositional features with respect to the over- and underlying sedimentary beds, with abrupt facies changes, erosional bases, internal erosion surfaces, and allocthonous fossils.

The repetition in the stratigraphic sections of massive bioclastic accumulations and large boulder deposits, which interrupt the seasonal deposits, suggests the action of very-high energy processes, such as major storms or tsunamis. The proximity of the area to the Eurasian plate boundary and Africa, and the historical record of earthquakes and tsunamis that occurred in the Gulf of Cadiz, to suggest that the option tsunamigenic to explain these bioclastic accumulations should not be discarded.

Acknowledgements

This paper has been financed by the Project GL2010-16878 from the Ministerio de Ciencia e Innovación (Spain) /FEDER. Our acknowledgement to the reviewers and to the Dr. Morales González from Huelva University by his suggestions and revisions.

References

Aguirre, J. (1995): Implicaciones paleoambientales y paleogeográficas de dos discontinuidades paleogeográficas en dos depósitos pliocénicos de Cádiz (SW de España). *Revista de la Sociedad. Geológica de España*, 8: 161-174.

Aguirre J. (1995): Implicaciones paleoambientales y paleogeográficas de dos discontinuidades estatigráficas en los depósitos pliocénicos de Cádiz (SW de España). *Revista de la Sociedad. Geológica de España*, 8: 161-174.

Aigner, T. (1985): *Storm Depositional Systems*. Lecture Notes in Earth Sciences 3, Springer-Verlag, Berlin, 122 p.

Berastegui, X., Banks, C., Puig, C., Taberner, C., Waltham, D. and Fernández, M. (1998): Lateral diapiric emplacement of Triassic evaporites at the southern margin of the Guadalquivir Basin, Spain. In: *Cenozoic Foreland Basins of Western Europe* (A. Mascle, C. Puigdefábregas, H.P. Luterbacher and M. Fernández, Eds.). Geological Society, Special Publication 134, 49-68.

Benkhelil J. (1976): *Étude Néotectonique de la Terminaison occidentale du Cordilléres Bétiques*. Thése 3eme cycle. Université de Nice. 180 p.

Bourrouilh-Le Jan, F.G., Beck C. and Gorsline D.S. (2007): Catastrophic events (hurricanes, tsunami and others) and their sedimentary records: Introductory notes and new concepts for shallow water deposits. *Sedimentary Geology*, 199: 1-11.

Bryant E.A. and Nott J. (2001): Geological indicators of large tsunami in Australia. *Natural Hazards*, 24: 231-249.

Campos, M.L. (1991): Tsunami hazard on the Spanish coasts of the Iberian Peninsula. *Science of Tsunami Hazard*, 9: 83-90.

Dawson, A.G. (2004): Tsunami hazards in Europe. *Environment Internacional*, 30: 577-585.

Dawson, A.G. and Stewart, I., (2007): Tsunami deposits in the geological record. *Sedimentary Geology*, 200: 166-183.

Dott, Jr. R.H. (1996): Episodic event deposits versus stratigraphic sequences shall the twain never meet? *Sedimentary Geology*, 199: 1-11

Fujino S., Masuda F., Tagomori S. and Matsumoto, D. (2006): Structure and depositional processes of a gravelly tsunami deposit in a shallow marine setting: Lower Cretaceous Miyako Group, Japan. *Sedimentary Geology*, 187: 127-138.

García-Castellanos, D., Fernández, M. and Torné, M. (2002): Modeling the evolution of the Guadalquivir foreland basin (southern Spain). *Tectonics*, 21: 1018-1029.

Gavala y Laborde J. (1959 y 1992 Red.): *La Geología de la Costa y Bahía de Cádiz y el poema "Ora marítima", de Avieno*. Serv. Publ. Diputación de Cádiz, 315 p.

Goff J.R, Chague-Goff C. and Nichol S. (2001): Palaeotsunami deposits: a New Zealand perspective. *Sedimentary Geology* 143: 1-6.

González-Delgado, J.A., Civis, J., Dabrio, C.J., Goy, J.L., Ledesma, S., Pais, J., Sierro, F.J. and Zazo, C. (2004): Cuenca del Guadalquivir. In: *Geología de España* (J.A. Vera, Ed.). SGE-IGME, 543-550.

Gracia, F.J, Alonso C., Benavente J., Anfuso G. and Del Rio L. (2006): The different coastal records of the 1755 tsunami waves along the South Atlantic Spanish coast. *Zeitschrift für Geomorphologie, Supplementbände,* 146: 195-220.

Gradstein, F.M., Ogg, J.G., and Smith, A.G. et al., (2004): *A geologic time scale 2004.* Cambridge University Press, 589 p.

Gutierrez-Mas J.M, Martín Algarra A, Domínguez Bella S and Moral Cardona JP. (1991): *Introducción a la Geología de Cádiz*. Servicio de Publicaciones de la Universidad de Cádiz, 315 p.

Gutierrez Mas, J.M., Juan, C. and Morales, J.A. (2009a): Evidence of high-energy events in shelly layers interbedded in coastal Holocene sands in Cadiz Bay (south-west Spain). *Earth Surface Processes and Landforms*, 34: 810-823.

Gutierrez-Mas, J.M, López-Arroyo, J. and Morales, J.A. (2009b): Recent marine lithofacies in the Cadiz Bay (SW Spain). Sequences, Processes and control factors. *Sedimentary Geology*, 218: 31-47.

Gutierrez-Mas, J.M. (2011): Glycymeris shell accumulations as indicators of recent sea-level changes and high-energy events in Cadiz Bay (SW Spain). *Estuarine, Coastal and Shelf Science*, 92: 546-554.

Gutscher, M.A., Baptista, M.A. and Miranda, J.M. (2006): The Gibraltar Arc seismogenic zone (part 2): Constraints on a shallow east dipping fault plane source for the 1755 Lisbon earthquake provided by tsunami modeling and seismic intensity. *Tectonophysics,* 426: 153-166.

Kennedy, D.M., Tannock, K.L., Crozier, M.J. and Rieser U. (2007): Boulders of MIS 5 age deposited by a tsunami on the coast of Otago, New Zealand. *Sedimentary Geology,* 200: 222-231.

Kortekaas, S, and Dawson, A.G. (2007): Distinguishing tsunami and storm deposits: an example from Martinhal, SW Portugal. *Sedimentary Geology*, 200: 208-221.

Luque, L., Lario, J., Zazo, C., Goy, J.L., Dabrio, C.J. and Silva P.G. (2001): Tsunami deposits as paleoseismic indicators: examples from the Spanish coast. *Acta Geologica Hispanica*, 36: 197-211.

Luque, L., Lario J., Civis, P.G., Zazo, C., Goy, J.L. and Dabrio, J.C. (2002): Sedimentary record of a tsunami during Roman times, Bay of Cadiz, Spain. *Journal of Quaternary Science*, 17: 623-631.

Mac-Pherson, J. (1873): *Bosquejo Geológico de la Provincia de Cádiz*. Imprenta Revista Médica, 156 p.

Maldonado, A., Somoza, L. and Pallares, L. (1999): The Betic orogen and the Iberian–African boundary in the Gulf of Cadiz: geological evolution (central North Atlantic). *Marine Geology*, 155: 9–43.

Marques da Silva, C., Landau, B., Domènech, R. and Martinell, J. (2010): Pliocene Atlantic molluscan assemblages from the Mondego Basin (Portugal): Age and palaeoceanographic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 285: 248–254.

Martínez del Olmo, W., García Mojonero, C. and Torrescusa, S. (2005): The Guadalquivir and Gulf of Cádiz Gas Basins (SW Spain). In: *AGGEP XXV Aniversario*.(W. Martínez del Olmo, Ed.), 105-121.

McArthur, J.M., Howarth, R.J. and Baley, T.R. (2001): Strontium isotope stratigraphy: LOWESS Versión 3. Best-fit line to the marine Sr-isotope curve for = to 509 Ma and accompanying look-up table for deriving numerical age. *Journal of Geology*, 109: 155-169.

Massari, F., D'Alessandro, A. and Davaud, E. (2009): A coquinoid tsunamite from the Pliocene of Salento (SE Italy). *Sedimentary Geology*, 221: 7-18.

Mezcua Rodriguez, J. and Martínez Solares, J.M. (1983): *Sismicidad del área Ibero- Magrebí*. Publicación, 203, Instituto Geográfico Nacional, Madrid, 301 p.

Monegatti, P. and Raffi, S. (2007): Mediterranean-Middle Eastern Atlantic Façade: molluscan biogeography & ecobiostratigraphy throughout the Late Neogene. *Açoreana Supplement*, 5: 126-139.

Morales, J.A., Borrego, J., San Miguel, E.G., Lopez-Gonzalez, N. and Carro, B.M. (2008): Sedimentary record of recent tsunamis in the Huelva Estuary (Southwest Spain). *Quaternary Science Reviews*, 27: 734-746.

Morton, R.A., Gelfenbaum, G. and Jaffe, B.E., (2007): Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples. *Sedimentary Geology*, 200: 184-207.

Nanayama, F., Shigeno, K., Satake, K., Shimokawa, K., Koitabashi, S. and Ishii, M. (2000): Sedimentary differences between the 1993 Hokkaido-nansei-oki tsunami and the 1959 Miyakojima typhoon at Taseu, southwestern Hokkaido, northern Japan. *Sedimentary Geology*, 135: 255-264.

Nott, J. (1997): Extremely high-energy wave deposits inside the Great Barrier Reef, Australia: determining the cause-tsunami or tropical cyclone. *Marine Geology*, 141: 193-207

Nott, J. (2003): Waves, coastal boulder deposits and the importance of the pre-transport setting. *Earth and Planetary Science Letters*, 210: 269– 276.

Rehault, J.P., Boillot, G.Y. and Mauffret, A. (1985): The western Mediterranean basin. In: *Geological Evolution of the Mediter-*

ranean Basin (D.J. Stanley and F.Z. Wezel, Eds.). Springer-Verlag, 101-129.

Ribeiro, A. (1995): Deformable plate tectonics of the Azorez-Gibraltar boundary-where the next 1755 earthquake Hill strike again? In: *Actas del 1er Simpósio sobre a margen continental Ibérica Atlântica*, Lisboa, 46-47.

Rico-García, A. (2008): Pectínidos Pliocenos de la Cuenca de Vejer (Cádiz, SO de España). Pliocene pectinids from the Vejer Basin (Cádiz, SW Spain). *Studia Geologica Salmanticensia*, 44: 91-140.

Rico-García, A. and Aguirre, J. (2008): Taphonomy and taphofacies models of the Pliocene deposits of Vejer de la Frontera (Cádiz, SW Spain). *Geobios*, 41: 543–558.

Sanz de Galdeano, C. and López Garrido, A. C. (1991): Tectonic evolution of the Malaga basin (Betic Cordillera). Regional implications. *Geodinamica Acta*, 5: 209-250.

Shanmugam, G. (2006): The tsunamite problem. *Journal of Sedimentary Research,* 76: 718-730.

Shanmugam, G. (2008): The constructive functions of tropical cyclones and tsunamis on deep-water sand deposition during sea level highstand: implications for petroleum exploration. *AAPG Bulletin*, 92: 443-471.

Silva, P.G., Borja, F., Zazo, C., Bardají, T., Luque, L., Lario, J. and Dabrio, C.J. (2005): Archaeoseismic record at the ancient Roman City of Baelo Claudia (Cadiz, South Spain). *Tectonophysics*, 408: 129-146.

Udías, A., López Arroyo, A. and Mezcua, J. (1976): Sismotectonics of the Azores-Gibraltar Region. *Tectonophysics*, 31: 259-289.

Viguier, C. (1974): *Le Néogéne de l'Andalousie Nord-occidentale (Espagne). Histoire géologique du bassin du bas Guadalquivir*. Thése Univ. Bordeaux, 449 p.

Williams, M., Haywood, A.M., Harper, E.M., Johnson, A.L., Knowles, T., Leng, M.J., Lunt, D.J., Okamura, B., Taylor, P.D. and Zalasiewicz J. (2012): Pliocene climate and seasonality in North Atlantic shelf seas. *Phil. Trans R. Soc*., 357: 85-108.

Zazo, C. (1979): El problema del límite Plio-Pleistoceno en el litoral S y SE de España. *Trabajos N/Q,* 9: 65-72.

Zazo, C. (1980): *El Cuaternario marino-continental y límite Plio-Pleistoceno en el litoral de Cádiz*. Tesis Doctoral, Univ. Computense de Madrid. 320 p.

Manuscrito recibido el 10 de Enero de 2012.
Aceptado el manuscrito revisado el 19 de julio de 2012.