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# Diapiric uplift of an MIS 3 marine deposit in SW Spain: Implications for Late Pleistocene sea level reconstruction and palaeogeography of the Strait of Gibraltar

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ABSTRACT

In the Bay of Cádiz (SW Spain) an Upper Pleistocene beach deposit (31.5 ka BP) has been recognised at about 1–3 m above m.s.l. The deposit is affected by a set of joints and fractures filled by calcretes and other subaerial sediments, dated at 19.9 ka BP. Deformation and uplift of this level is related to the moderate activity of a diapiric structure. The resulting uplift produced local emersion of the deposit and a transition from marine to continental conditions during the Late Quaternary. The deformational style and tectonic location of the deposit argue against strong vertical motion. Regional comparisons between this diapir and other similar and coeval structures near the zone suggest a vertical uplift of about 25 m. Therefore, between 30 and 20 ka BP the sea level can be supposed to have been placed near to its present-day position, probably less than 30 m below. These results confirm other regional data indicating that during MIS 3 several relative sea level rises took place, reaching heights of only several tens of metres below the present m.s.l. The palaeogeographical implications of these results include the existing controversy about the possible crossing of the Strait of Gibraltar by Neanderthals between ca 40 and 30 ka. The palaeogeographical reconstruction of the Strait for this period suggests that its width and depth were very similar to the present ones.



## 1. Introduction

It is generally accepted that during the Late Quaternary, climatic changes and sea level fluctuations were closely related: sea level rise and highstands were associated with warm periods, while sea level fall and lowstands were related to cold periods. Quaternary highstand phases are commonly represented by emerged marine terraces, relatively easy to study. Lowstands are usually recorded by marine sedimentary units included in the sedimentary cover of continental margins. Their study is much more difficult and needs the combined application of geophysical techniques (high-resolution seismic profiling) and ocean drilling. As a consequence, sea level reconstructions during glacial periods become very problematic (Dawson, 1992) and sea level curves are often based on theoretical models adjusted with regional data (Lambeck et al., 2002; Dumas et al., 2005). In addition, the combination of several factors like palaeoceanography, geophysical behaviour and, especially, coastal tectonics strongly influence the sea level evolution at a local/regional scale and introduce uncertainties (Mörner, 1996; Pirazzoli, 1996; Belluomini et al., 2002; Bailey and Flemming, 2008), sometimes resulting in contradictory trends between proximal sites (Hanebuth et al., 2006). Specific methodological problems arise when considering MIS 3 interstadials: $^{14}C$ dates older than 30,000 BP are affected by important standard errors, and these are even larger when ESR, TL and U-Th techniques are used, making it difficult to compare these determinations with $^{14}C$ dates (d'Errico and Sánchez Goñi, 2003).

In contrast with the abundant chronological data available for pre-Holocene marine terraces in the Mediterranean area, data for the southern European Atlantic coast are quite scarce and limited to certain favourable areas (Ménanteau et al., 1983; Chester and James, 1995; Cano et al., 1999; Moura et al., 2003). This unbalanced situation has led to the proliferation of simplistic correlations between the southern Atlantic coast and other distant coasts with more complete Quaternary records (Lowrie, 1986, in Hernández-Molina et al., 2002), often without taking into account all the factors and conditions named above. A certain tectonic stability has usually been assumed for the Quaternary evolution of the southern European Atlantic coast. However, recent publications show how this is not the case for the Atlantic Iberian coast (Granja, 1999), especially

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in its southern portion (Ribeiro et al., 1996; Maldonado et al., 1999). The coasts of the Gulf of Cádiz and Strait of Gibraltar have been subjected to active tectonic uplifting and subsidence throughout the Late Quaternary, with a considerable spatial and temporal variability (Zazo et al., 1996, 1999; Rodríguez-Vidal et al., 2004; Silva et al., 2005, 2006). Under these circumstances, Late Quaternary sea level reconstruction is very difficult and existing models (Hernández-Molina et al., 2000a) are based on seismic sequence stratigraphy and correlation with other global glacioeustatic sea level curves (Chappell and Shackleton, 1986; Dansgaard et al., 1993, among others). Unfortunately, no real interstadial palaeodepth has been determined in the Gulf of Cádiz-Strait of Gibraltar zone, and palaeogeographical reconstructions during lowstands with the presently published data would be merely speculative.

Within this uncertain framework, a growing controversy has arisen in recent years regarding the possibility that Neanderthals crossed the Strait of Gibraltar during the MIS 3 lowstand period (30 ka). A sea level supposedly much lower (about 140 m) than the present one would have reduced the Strait to a narrow water body with several islands, easily crossable by early humans (Smith et al., 1995; Fa et al., 2001; Caparrós, 2005). However, other researchers disagree with this possibility on both palaeontological and archaeological grounds (Straus, 2001; Finlayson, 2005; van der Made, 2005; O'Regan, 2008). Apart from isolated local bathymetric studies (Gutscher, 2005), up to now no general palaeogeographical reconstruction of the Strait of Gibraltar has been proposed.

In this tectonically active region, the Bay of Cádiz, located about 30 km to the NW of the Strait of Gibraltar, records the combined effects of sediment accumulation, glacioeustatic sea level changes and regional tectonics. However, the slight subsiding trend prevailing in the Bay during the Quaternary (Zazo et al., 1999) makes it difficult to find emerged records of former sea levels. Most of them lie below thick salt marsh sediments in the coastal plains (Dabrio et al., 2000) or under very recent marine sediments on the inner continental shelf (Gutiérrez-Mas et al., 2004). Very scarce remnants persist of former highstands and they are usually related to the mid-Holocene eustatic maximum (Gracia et al., in press).

The present work describes a case of interaction between sea level fluctuation and coastal tectonic/diapiric uplift in the Bay of Cádiz during the Late Quaternary, with important implications for regional palaeo sea level reconstructions. The tectonic uplift and emersion of a coastal deposit associated with the MIS 3 interstadial suggests that before the glacial maximum the sea level fluctuated around a depth not so low as supposed by simply applying classic global sea level curves. Data from other South European coastal areas confirm the need to reconsider the strict application of "global" curves, especially when they have been elaborated from data taken in the antipodes, under oceanographic and geophysical conditions completely different from the European ones and, obviously, with a different Quaternary evolution. Important implications for the palaeogeography of the Strait of Gibraltar during the development of Neanderthal settlements in South Iberia arise from the results obtained in the present study.

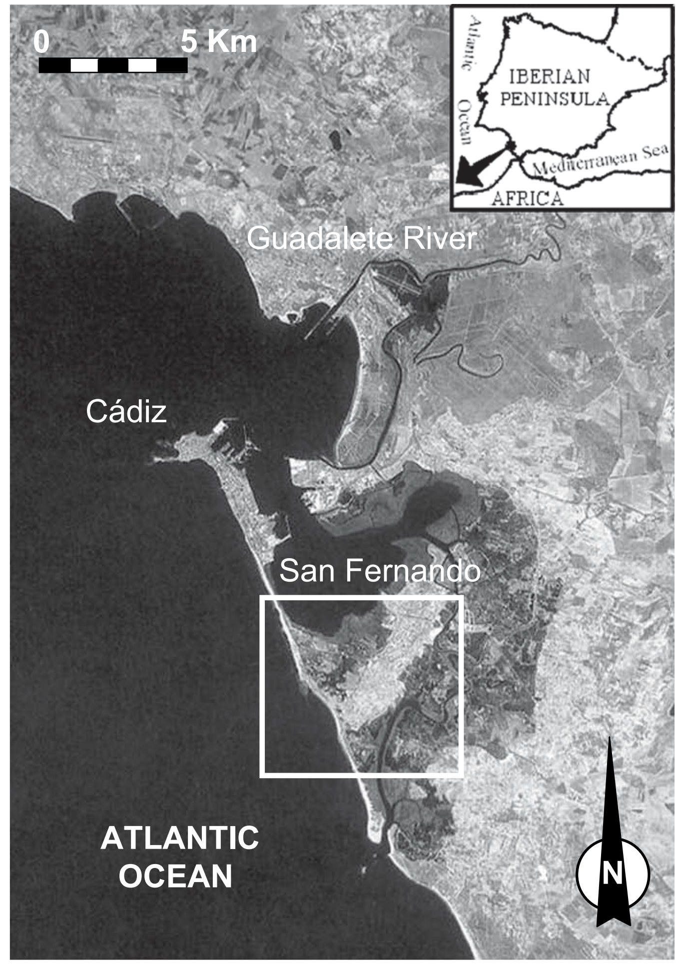


**Fig. 1.** Location of the study zone in the Bay of Cadiz.

## 2. Regional setting

### *2.1. Quaternary tectonics in the Bay of Cádiz*

The Bay of Cádiz is located at the southern Atlantic margin of the Iberian Peninsula, southwards of the Guadalquivir River mouth (Fig. 1). Geologically it is located within the Subbetic Zone of the Betic Ranges, which are formed by Mesozoic and Cenozoic sedimentary sequences faulted along preferred tectonic lineations (Sanz-de-Galdeano, 1990). The Bay of Cádiz is bordered by Tertiary units of clays and sandstones that form gentle eminences of less than 150 m in height. It is about 30 km long and 15 km wide, and is constituted by wide tidal flats isolated from the open coast by sandy beach ridges that form littoral spits growing southwards. The northern sector is mainly characterised by the mouth of the Guadalete River, one of the most important rivers in the region.

Originally the bay was formed as a tectonic depression during a distensive phase in the Upper Miocene – Pliocene (Benkhelil, 1976). The initial depression was occupied by a deltaic sedimentary system developed during the Upper Pliocene until the Lower Pleistocene, giving rise to a detritic stratigraphic unit ("Roca Ostionera") with mixed fluvial and littoral characteristics and typical deltaic facies (Benot et al., 1993). During the Middle and Upper Pleistocene, the spatial distribution of coastal environments was linked to eustatic fluctuations, with the development of alluvial plains during lowstands and flooding phases during highstands (Zazo et al., 1996).

Quaternary tectonics in the Bay is associated with the submeridian convergence between Africa and Eurasia, producing a maximum compressive horizontal stress direction approximately NNW–SSE (Ribeiro et al., 1996; Jiménez-Munt and Negredo, 2003). This tectonic regime is recorded in the Bay during the Late Pliocene and continued until present, generating several strike-slip faults (Benkhelil, 1976) that can be grouped in two main families, a sinistral NE–SW and a dextral NW–SE (Fig. 2). Accumulated horizontal displacements produced by these faults during the Quaternary often exceed 2 km, while the associated vertical motion hardly reaches some tens of metres (Gracia et al., 1999). This set of faults affects all the region and can be recognised in the mainland of the Gibraltar Strait region (Zazo et al., 1999), and also seawards

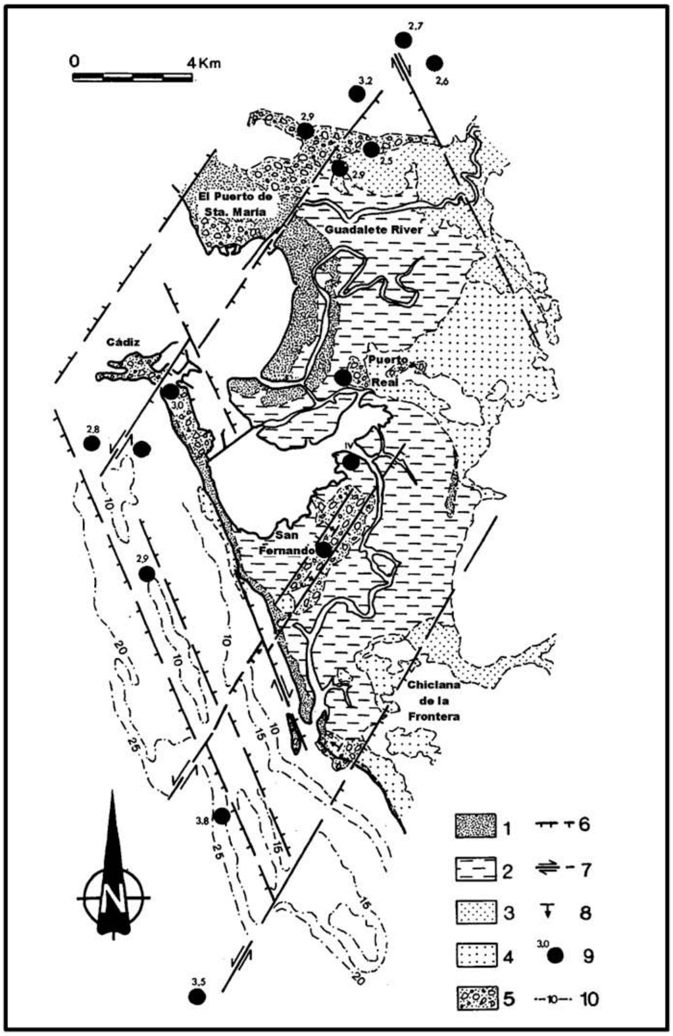


**Fig. 2.** Geological map of the Bay of Cádiz (modified from Gracia et al., 1999). 1: Holocene and present beach and dune deposits, 2: present salt marsh, 3: Holocene alluvial deposit, 4: Pleistocene deposit, 5: Pliocene to Lower Pleistocene deposits; 6: faults with vertical motion during the Quaternary, 7: strike-slip faults active during the Quaternary, 8: direction of dip in Plio-Quaternary deposits, 9: earthquake epicentre (number/letter refer to magnitude/intensity), 10: bathymetric contour in metre.

under the recent marine sedimentary cover, by seismic profiling and vibrocore drilling, especially on the inner shelf (Vázquez et al., 2000; Gutiérrez-Mas et al., 2004). On the outer shelf and continental slope, only the NE–SW tectonic direction prevails, associated with arcuate thrusts produced by the westward migration of allochthonous units during the Late Miocene (Medialdea et al., 2004).

As far as the vertical motion is concerned, Quaternary faulting activity in the Bay of Cádiz can be summarised in a block tectonics that has conditioned the distribution of emerged and submerged areas during Quaternary eustatic highstands. The tectonically elevated areas do not record any significant deposition during the Pleistocene (García de Domingo et al., 1987). Instead, subsiding zones between rising blocks record sedimentary aggradation, like the area between El Puerto de Santa María and Puerto Real, to the North of the Bay (Fig. 2). A similar case is the area between San Fernando and Chiclana de la Frontera, where a block elevated 15 m above m.s.l. progressively dips towards the NW and submerges below the present sea level, creating a wide depression presently occupied by marshland deposits (Fig. 2). Former coastal and marine deposits associated with Quaternary highstands may lie under recent sediments. Some high-resolution seismic reflection profiles made in the Bay have revealed the existence of buried palaeoforms consisting of flat surfaces stepping seawards that resemble marine terraces covered by other Holocene coastal and marine deposits (Gutiérrez-Mas et al., 2004). Regarding recent tectonics, the Bay of Cádiz and surrounding areas have recorded several historical earthquakes that have damaged buildings. This seismic activity dates back to the Classical era. Some authors describe tectonic disturbances of seismic origin in the old Roman villages of *Baelo Claudia* (Gibraltar Strait) and *Munigua* (Seville), respectively south and north of the studied zone (Goy et al., 1994; Alonso et al., 1997; Silva et al., 2005, 2006).

Diapiric structures are common in the region, and many of them affect Neogene and Quaternary units. They appear to be conditioned by NE–SW fractures, suggesting some recent rearrangements in basement structures, which in turn can induce this type of deformation (Rodríguez-Vidal et al., 1993). Many recent diapiric structures with a NE–SW strike have been also recognised on the continental shelf in the Gulf of Cádiz margin (Maldonado and Nelson, 1999; Lobo et al., 2003; Medialdea et al., 2004), some of them even affecting Holocene deposits (Fernández-Puga, 2004). It is difficult to evaluate the vertical extent and rate of uplift associated with these diapirs due to the general absence of altitudinal and chronological references. Rodríguez-Vidal et al. (1993) studied the Medina-Lake diapir, located about 20 km to the NE of the Bay of Cádiz, and estimated 20–25 m of uplift since the Middle–Upper Pleistocene, based on the archaeological dating and altitudinal deviation of a Middle Pleistocene fluvial terrace level belonging to the Guadalete River Valley, affected by the diapiric deformation.

In the surroundings of San Fernando, a rapid diapiric uplift during the Late Quaternary has produced the emersion of Pleistocene coastal deposits that elsewhere remain submerged and buried by Holocene marine sediments. The diapiric structure and the Pleistocene deposits are described in the next section.

### 2.2. The San Fernando diapir and the MIS 3 deposits

San Fernando village, at the very centre of Cádiz Bay, is located on an elongated hill up to 29 m above m.s.l., close to the coastline. Such a relief is formed by a diapiric anticline that affects the Plio-Pleistocene deltaic unit, "Roca Ostionera". The diapiric fold draws a general elliptical elongated shape, typical of diapirs controlled by tectonics (Jackson, 1995; Koyi, 1998), following a clear NE–SW trend (Fig. 3). It is exactly located in the prolongation of an important reverse NE–SW Quaternary fault identified by Maldonado et al. (1999) in the nearby continental margin. Less than 12 km from the San Fernando coastline seawards, Medialdea et al. (2004) identify through seismic reflection techniques a huge diapir following a NW–SE direction. It is obvious that the San Fernando diapiric fold represents the emerged expression of this diaper in the coastal zone. The intrusive mass is formed by Triassic evaporites and mudstones: primary marine sacaroid gypsum, secondary translucent gypsum, marl and clay with other components (dispersed fragments of sandstone and dolomite), forming chaotic assemblages (Baena et al., 1987). The Plio-Pleistocene deltaic unit dips up to 30° to the North in the northern anticline flank (Fig. 4), while on its SW border the structure draws a typical periclinal closure (Fig. 3).

Deformation locally affects Quaternary marine deposits at "El Estanquillo" zone (Fig. 5; see Fig. 3 for location). An abandoned quarry excavated in this zone has exposed the type of deformation produced in the contact between the intrusive mass and the sedimentary cover. The Triassic evaporites show a strong deformation showing subvertical layers and many small fractures of varying orientations. On a wall normal to the strike of the main fault two NE–SW reverse faults can be seen affecting a heterometric

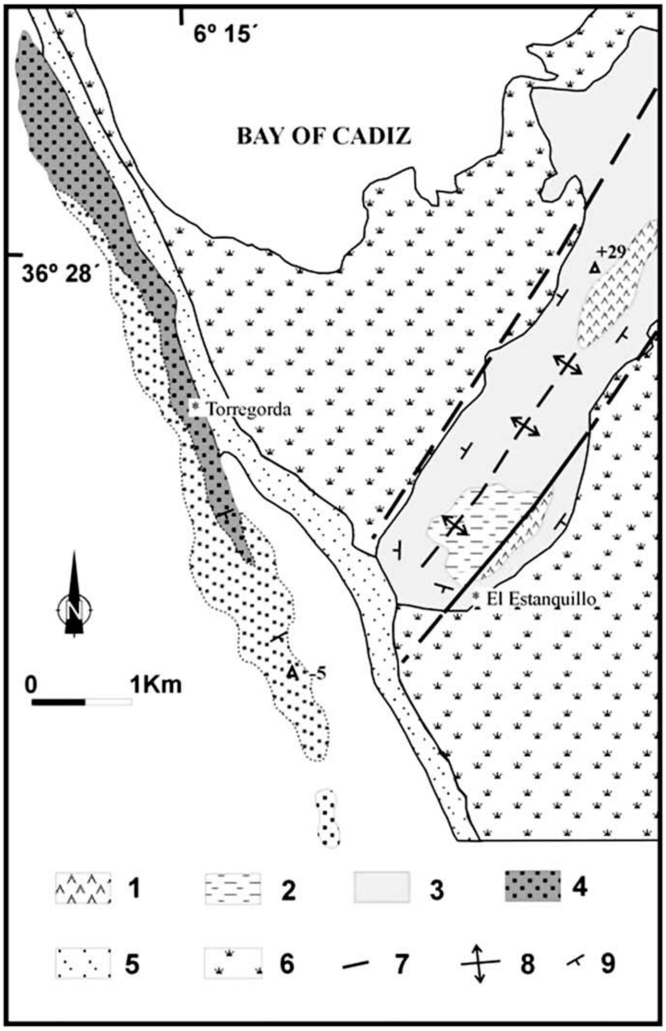


**Fig. 3.** Geological map of the study zone (modified from García-de-Domingo et al., 1987). 1: Triassic gypsum and clay, 2: Miocene marl, 3: Plio-Pleistocene sand and conglomerate, 4: Upper Pleistocene beach deposit (in grey: emerged; in white: submerged), 5: present beach and foredune, 6: present salt marsh, 7: main fault, 8: anticline axis, 9: direction of strata dip. Dashed line represent submerged outcrop.

terrigenous deposit of unknown age at about 6 m above the present sea level (Fig. 6). The deposit is capped by a calcareous crust 10–20 cm thick with clastic and laminated facies, including remains of microscopic marine organisms. Radiocarbon dating of the crust

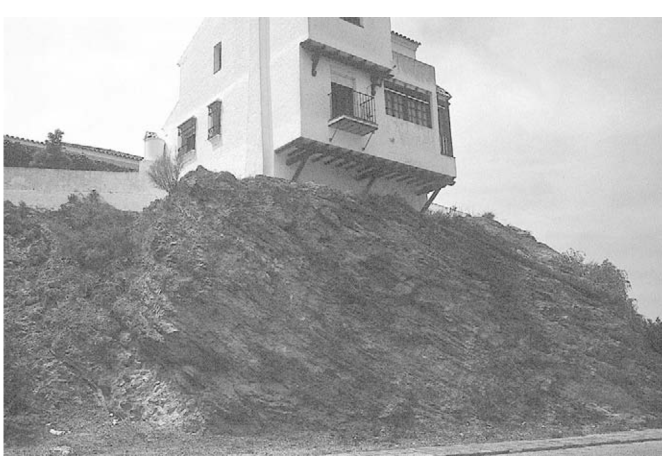

**Fig. 4.** The Plio-Pleistocene deltaic unit ("Roca Ostionera") is tilted to the NW in the northern flank of the San Fernando diapiric anticline.

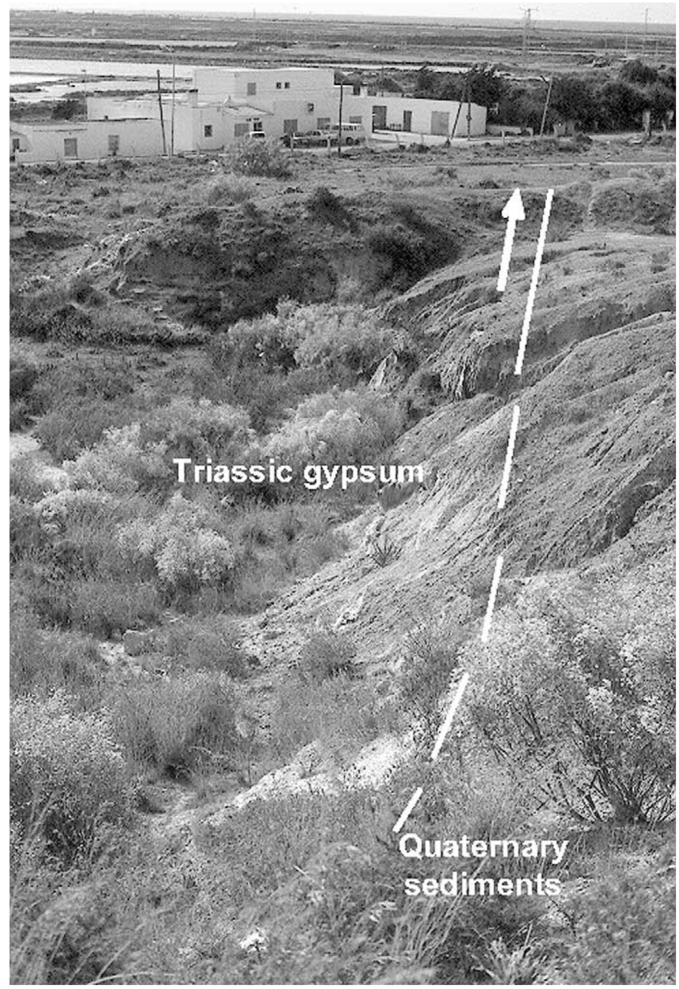


**Fig. 5.** Inverse fault in the SE flank of the San Fernando diapiric anticline, at El Estanquillo place.

gave an age ranging between 22,860 ± 310 and >44,500 BP (Table 1). A thin level of aeolian loose sand (Fig. 6c) and a slope deposit partly cover these units. The slope deposit contains many ceramics of an age at least younger than the 3rd century BC (Fig. 6d), although the remains do not strictly determine any chronology for this unit. Borja (1992) suggests an age ranging between the 2nd century BC and the 1st century AD for the slope deposit.

Very near "El Estanquillo", some archaeological evidence can be related to recent deformations. The floor level of a Roman salt fishery plant and Bronze Age and Roman settlements, partly built upon the Plio-Pleistocene deltaic unit overlying the Triassic evaporites, show strong undulations. This deformation should have taken place after the 2nd century AD, the date by which these settlements were abandoned.

## 3. Results

In the coastal area between Cádiz and San Fernando a conglomeratic unit outcrops forming a continuous rocky platform about 500 m wide that follows the coastline for nearly 2 km. It presents a rough and broadly undulating surface at 1–3 m above m.s.l., slightly inclined towards the SW. In its southernmost outcrops it dips to the SE and gently submerges under the present sea level (Fig. 3) until disappearing at about 10 m depth, in a zone locally very exposed to storm waves and hence subject to important coastal erosion (Gracia et al., 1997). The conglomeratic unit is

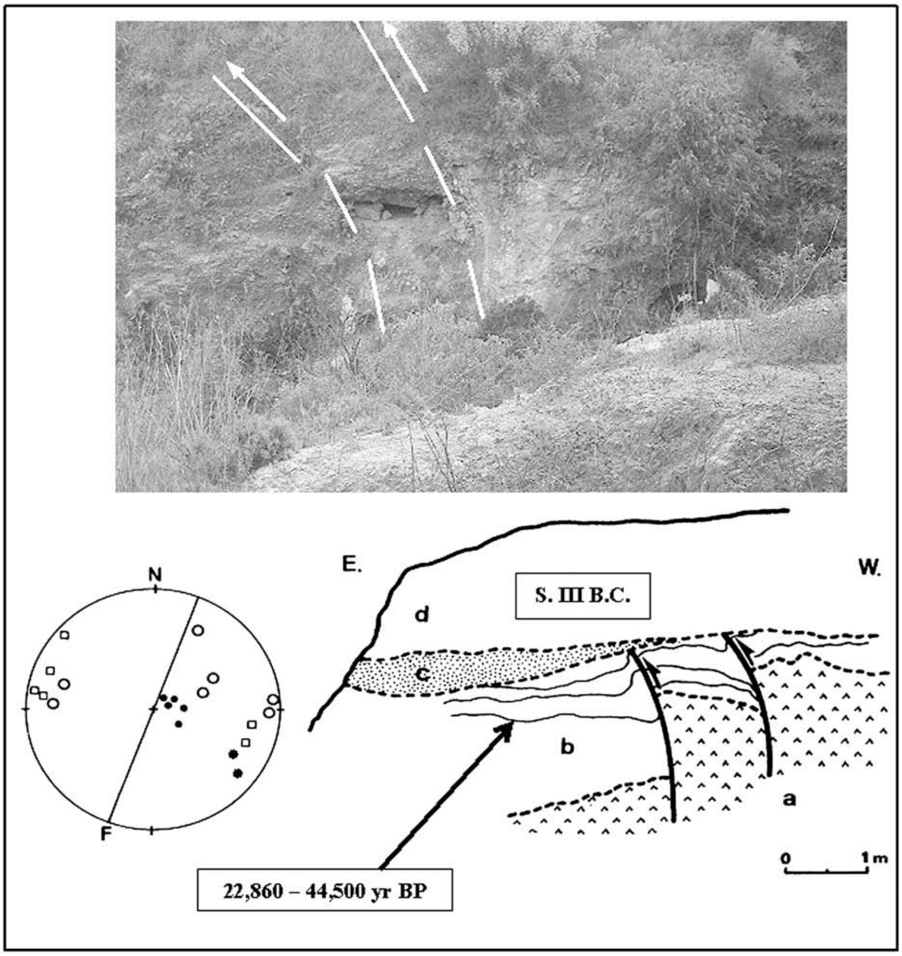


**Fig. 6.** Inverse faults affecting Pleistocene deposits at El Estanquillo place (see location in Fig. 3). a: Triassic evaporites; b: Pleistocene marine deposit with an upper calcareous crust; c: aeolian sand; d: historical slope deposit. Symbols in the stereogram: white square: stratification pole in Triassic gypsum; black dot: stratification pole in Quaternary deposits; white dot: fracture pole in Triassic gypsum; asterisk: fracture pole in Quaternary deposits; F: main fault (Fig. 5).

formed by more than 4 m of alternating laminated sandstones and quartzitic conglomerate levels. The basal outcropping levels are represented by about 0.5 m of planar imbricated clasts (centile of 18 cm) with bioclasts of *Ostraea*, *Glycimeris* and other bivalves. The intermediate levels are formed by very laminated cemented coarse sands and small pebbles, with plenty of bivalve shell fragments.

**Table 1**
$^{14}C$ radiometric age of samples from Upper Pleistocene beach and calcrete deposits taken at Torregorda

| Sample | Location | Sample material | $^{14}C$ conventional age (year BP) | $\partial\ ^{13}C‰$ | $^{14}C$ calibrated age (year BP) |
|---|---|---|---|---|---|
| R-2789 | Torregorda | Calcrete | 21,760 ± 250 | −8.47 | |
| R-2409 | Torregorda | Calcrete | 19,703 ± 144 | −7.87 | 19,982 ± 144 |
| R-2446 | Torregorda | Calcrete | 11,080 ± 80 | −2.10 | 13,083–12,902 |
| R-2450 | Torregorda | Calcrete | 27,980 ± 382 | −2.60 | |
| R-2451 | Torregorda | Calcrete | 12,398 ± 79 | −2.06 | 14,697–14,330 |
| R-2410 | Torregorda | Shell | 31,088 ± 773 | +1.27 | 31,515 ± 773 |
| R-2421 | Torregorda | Shell | 20,990 ± 270 | +1.17 | |
| R-2442 | Torregorda | Shell | >40,000 | −4.50 | |
| R-2437 | Torregorda | Shell | >42,000 | +2.22 | |
| R-2448 | Torregorda | Shell | 28,400 ± 600 | −4.52 | |
| R-2453 | Torregorda | Shell | >44,000 | −4.50 | |
| R-2454 | Torregorda | Shell | 26,510 ± 490 | −4.67 | |
| R-2432 | Torregorda | Shell | >40,000 | −4.18 | |
| R-2417 | Estanquillo | Calcrete | >44,500 | −7.08 | |
| R-2418 | Estanquillo | Calcrete | 22,860 ± 310 | −7.07 | |

Samples R-2417 and R-2418 were taken at El Estanquillo place.

Laminae show typical onlap structures with gentle dipping planes that suggest a progradational trend towards the WSW. Laterally some thin aeolianite levels can be recognised fossilising this laminated sequence. The upper levels are represented by a 0.5 m deposit of imbricated gravels with planar discoid clasts ending with a thin aeolianite layer of about 15 cm. These upper levels laterally pass into continental alluvial fan facies towards the East. The whole unit can be interpreted as a beach deposit formed by several prograding sequences, probably reflecting small sea level fluctuations (Mayoral et al., 1992). The radiocarbon dating of shell fragments from the intermediate levels gave an age of 31,515 ± 773 Cal BP, characteristic of the central-final moments of the MIS 3 interstadial. Other radiocarbon datings of shells gave ages ranging between the above age and 20,990 ± 270 BP, with five samples showing ages older than 40,000 BP (Table 1).

A very continuous laminated calcrete of subaerial origin, 10–20 cm thick, uncomformably overlies this deposit and extends into the intertidal zone (Fig. 7). The upper layers of the calcareous crust show a characteristic orange colour. Radiocarbon dating of the calcrete gave values between 27,980 ± 382 and 11,080 ± 80 BP (Table 1).

At Torregorda, south of this point (Fig. 3), the beach deposit is affected by several open joints. All of them present a very consistent NNW–SSE direction (Fig. 8), parallel to the coastline orientation of the zone, and to the regional NNW–SSE faulting family and the epicentre lineation of submarine earthquakes recorded near the

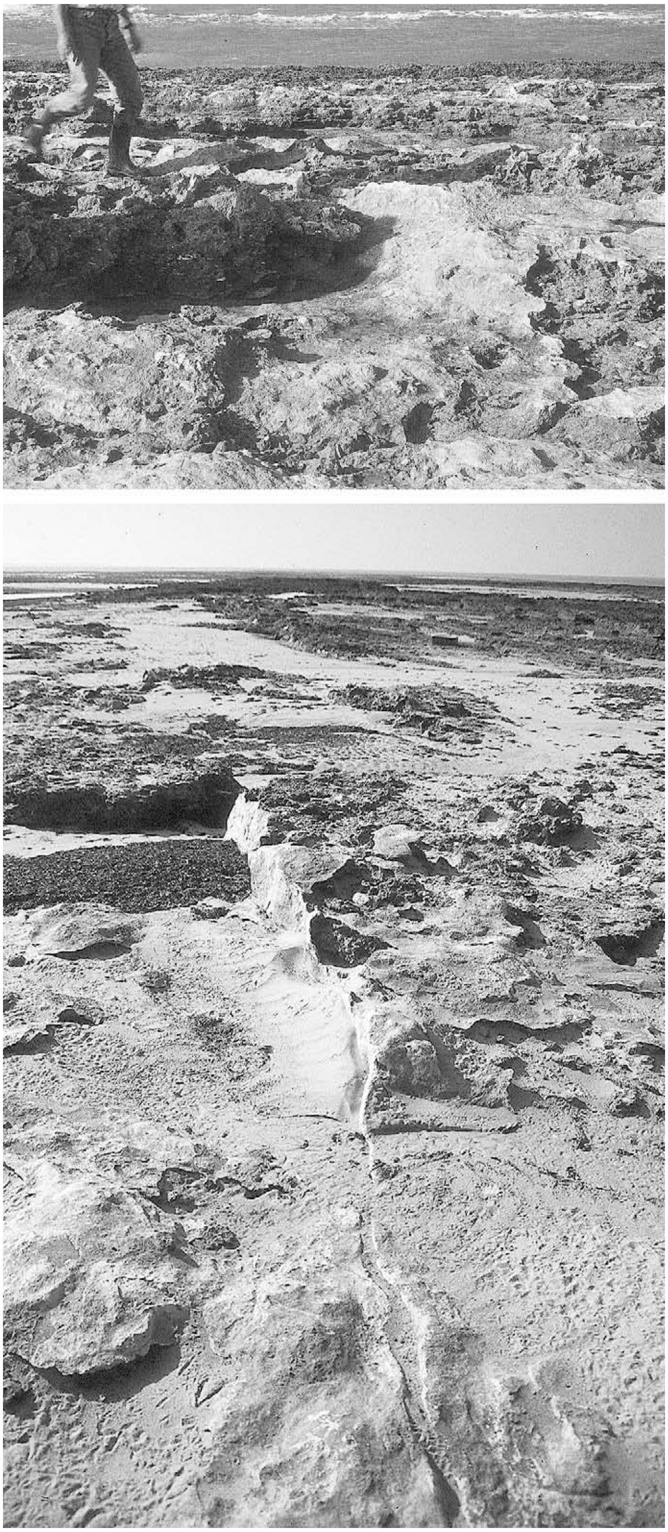

**Fig. 7.** Late Pleistocene (MIS 3) beach deposit forming a wide shore platform at Torregorda. A laminated calcareous crust can be seen covering most part of the beach deposit.

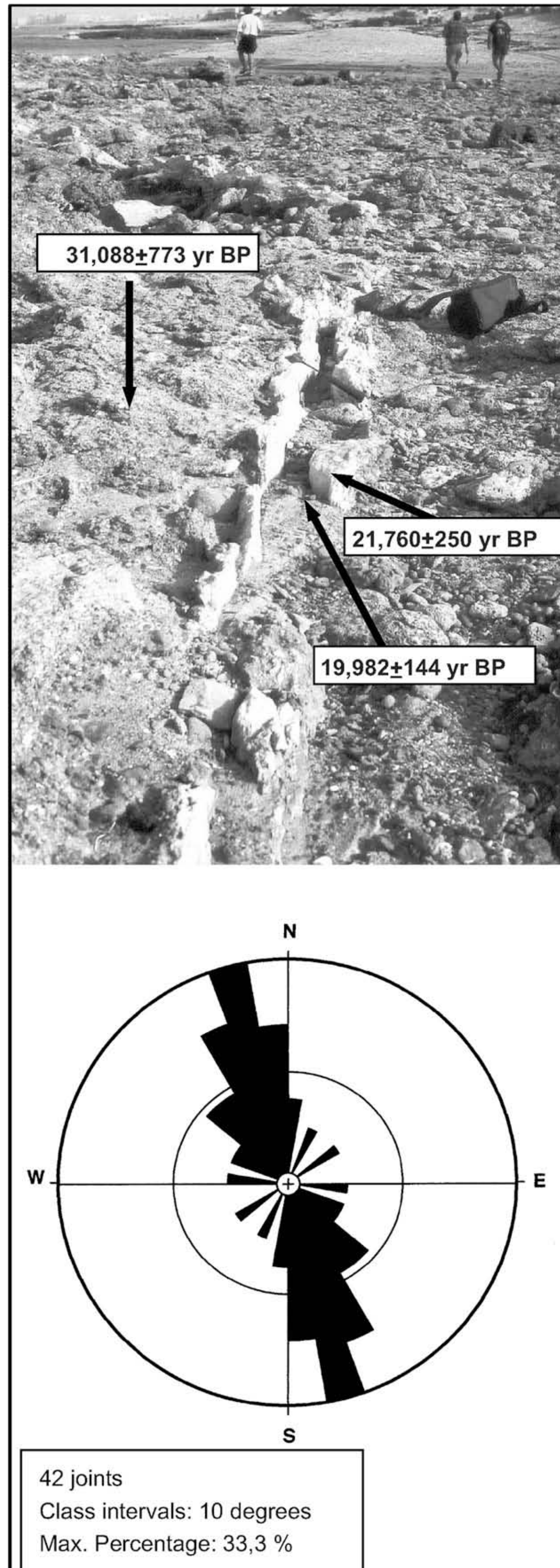


**Fig. 8.** Open fractures on Upper Pleistocene beach deposit at Torregorda (see Fig. 3 for location). A white calcrete can be seen filling the fracture, where two samples were taken for radiometric dating. Below: Rose of fractures and joints measured in the zone.

coast (Fig. 2). Fractures are mainly vertical, although some of them show a certain dip, both to the ENE and WSW. No slickenside indicator has been recognised in the zone. However, some fractures dislocate morphosedimentary surfaces at varying heights, commonly of about 0.5 m. The lithological and sedimentological characteristics of the deposits at these points rule out any differential erosion process and suggest that these fractures locally acted as faults, with submetric vertical motions. The fractures are partially filled by a white laminated calcrete deposit 30–40 cm wide. Radiocarbon dating of this crust filling gave an age of 21,760 $\pm$ 250 BP for a sample taken in contact with the host-rock, and 19,703 $\pm$ 144 BP for the central part of the crust (Fig. 8).

The crust filling is affected by a second fracturing episode, with fractures mostly parallel to the former, opened between 10 and 15 cm. These younger extensional episodes in many cases consisted of the reactivation and re-opening of previous fractures (Fig. 8). The newly opened joints are filled by a reddish clastic deposit of unknown age.

No other Quaternary unit has been recognised in this area and previous detailed geological studies and maps (García de Domingo et al., 1987) do not indicate any deposit apart from those described above. Hence, in the absence of other stratigraphic data, and due to their sedimentological similarities, we can consider as a working hypothesis that the cemented beach deposit at Torregorda (31 ka, Fig. 3) and the clastic deposit with marine fragments described at El Estanquillo (unit b in Fig. 6, aged between 22.8 and >44.5 ka) represent the same episode of coastal sedimentation generated during the Late Pleistocene.

## 4. Discussion

Reconstructions of Quaternary sea levels and coastal evolution are commonly based on radiocarbon dating of coastal deposits. However, dating and correlation between marine MIS deposits and emerged marine terraces is still problematic, mainly because of the limitations of geochronological methods (Zazo et al., 2003). When data come from calcretes they should be used with care due to the complex mineralogical evolution commonly experienced by such materials. Only calibrated radiocarbon data should be used and interpretations should be based on coherent dating series. Radiocarbon results shown in Table 1 indicate that, although there are many different ages around 30–40 ka, some of them have been calibrated and present a coherent succession of deposits and events (see Fig. 8) and thus can be regarded as "safe" $^{14}$C ages.

Different Pleistocene beach deposits have been identified along the Gulf of Cádiz coast, some of them located a few metres above the present sea level, and their dating by U-Th series commonly indicates an MIS 5 ascription (Zazo et al., 1999). However, they are typically covered by thick sequences of cemented dunes, suggesting a certain permanence of the coastal environment and sea level over some period of time. In contrast, the Torregorda beach deposit is the only one in the region directly covered by subaerial laminated calcretes, indicating a rapid sea level fall and the sudden onset of warm and dry continental conditions. Hence, apart from other minor sedimentological differences, this fact and the radiocarbon results make us consider the beach deposit at San Fernando as chronologically belonging to the late MIS 3. The following discussion is based on this premise.

### 4.1. *Tectonic vs. diapiric uplift*

The present location of the MIS 3 beach deposit at San Fernando, around the present sea level, is hardly compatible with a glacial palaeo sea level, supposed to have been located several tens of metres below the present one. It seems obvious that the deposit has been affected by uplift, of tectonic and/or diapiric origin. However, the subtle surface bending and the fracturing by joints mostly without relative movement are indicators of low deformation and presumably a limited amount of uplift.

The San Fernando anticline is strongly controlled by strike-slip faults that follow regional tectonic directions associated with the NNW–SSE compression prevailing in this zone of the Betic Ranges (Sanz de Galdeano, 1990; Jiménez-Munt and Negredo, 2003). This prevailing horizontal tectonic regime has been recognised through several morphological and sedimentary indicators in the Bay of Cádiz Bay, like the recent strike-slip faults that offset Pleistocene fluvial deposits in the northern Bay margins (Fig. 2; Gracia et al., 1999). Zazo et al. (1999) estimated recent rates of tectonic uplift in the Gibraltar Strait from the spatial distribution of MIS 5 marine terraces along the southern Iberian coast, resulting in values ranging between up to 0.15 mm/yr at Tarifa and 0.02 mm/yr near the Bay of Cádiz, while Rodríguez-Vidal et al. (2004) estimated an uplift rate of 0.05 mm/yr for the last 200 ka on the Gibraltar Rock. By considering both values, the accumulated uplift in the Strait of Gibraltar during the last 30 ka would have been of about 4.5 and 1.5 m, respectively. These values are quite slow if compared with the present convergence rates between Europe and Africa in southern Iberia (2–3 mm/yr; Jiménez-Munt and Negredo, 2003). This is due to the convergent-transpressive nature of this margin, where most of the recent deformation results in horizontal movements, rather than vertical. Compression is mainly released through the previously cited conjugate set of strike-slip faults, on both sides of the Strait of Gibraltar edge (Silva et al., 2006).

In this sense, a tectonic uplift rate of 0.02 mm/yr in the San Fernando anticline would have resulted in an accumulated rise of only 0.6 m for the last 30 ka, and hence the MIS 3 beach level would have been formed at a sea level very close to the present one, quite unlikely for a glacial period. It seems obvious that active diapirism may have played an important role in the uplift of this level over its former position.

Active diapirs are usually associated with previous fractures and anticline cores and are characterised by folding of the overburden surrounding the diapir and uplift above its regional topographic level, with typical reverse faults on the flanks and normal faults capping the diapiric structure. Mechanical contacts commonly follow the main regional tectonic directions and in plan their outlines are usually elliptical to elongated (Davidson et al., 1993; Jackson, 1995; Letouzey et al., 1995). Talbot et al. (2000), in their study of the active diapirism of the Zagros Mountains, concluded that diapirs that rise significantly higher than their surrounding country rocks, like the San Fernando case, are due to a combination of tectonic forces and gravity, topographically forming evaporite islands.

In many cases tectonic activity is determinant in triggering diapiric deformations. Fluid pressure reduces the minimum stress required for fracturing the sedimentary cover, and the diapiric material reduces the effective confining pressure. Distensive tectonic fracturing also diminishes the confining pressure and induces load differences and diapiric fluxes (De Ruig, 1995). Many tectonically-controlled diapiric folds have been described in the Betic Ranges, especially in its eastern foldbelt (Moseley et al., 1981), with Triassic evaporates at their core. However, density relationships between diapiric materials and overburden indicate that in most cases these folds were formed by buckling under lateral compression rather than by vertical diapiric motion (De Ruig et al., 1987).

In the San Fernando case study, the fold limbs are faulted by NNE–SSW structures, controlling the hill orientation, and the whole structure can be considered as a horst formed during Quaternary times (Fig. 9). Apart from locally important deformations of the MIS 3 deposit related to the mechanical contacts (Fig. 6), the different magnitude of deformation exhibited by the Plio-Pleistocene deltaic unit (Fig. 4) and the Late Pleistocene beach deposit (Fig. 8) indicates that most of the tectonic/diapiric uplift took place during the Lower and Middle Pleistocene. In fact, the only sedimentary unit that can be recognised in the nearby surrounding areas is the Plio-Pleistocene deltaic unit (Roca Ostionera) outcropping along the northern flank (Fig. 4). This unit

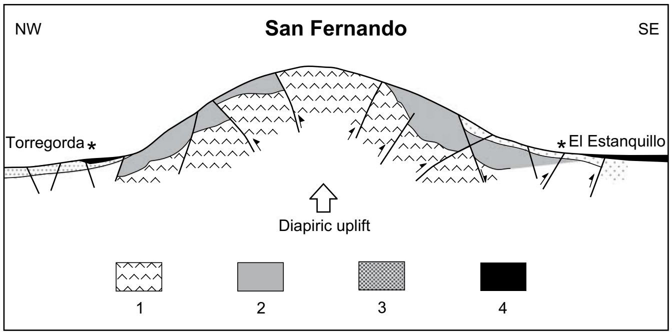


**Fig. 9.** Schematic geological cross section of San Fernando diapiric anticline (see location in Fig. 3). 1: Triassic evaporites and clay, 2: Plio-Pleistocene sand and conglomerate, 3: Upper Pleistocene beach deposit, 4: Holocene and present coastal sediments.

reaches a maximum altitude of 29 m in the centre of the diapiric island, although an unknown amount of the upper part was removed and transformed in the historical period by the urbanisation of San Fernando village (Figs. 3 and 9). North and south of San Fernando, this unit is affected by two gentle synclines that cause the surface to sink to about 15 m below m.s.l. (Fig. 2). Hence, an amount of at least 45 m could be estimated for the Quaternary uplift related to the San Fernando anticline, representing an average rate of uplift of 0.025 mm/yr. However, over a period of 30 ka this rate would have resulted only in an accumulated uplift of less than 1 m.

Several deformational episodes have been identified affecting the MIS 3 deposit, as in the Medina-Lake diapir case (Rodríguez-Vidal et al., 1993). Very probably, the deformational and uplift episodes in the San Fernando anticline are the result of a combination of regional tectonic compression and diapiric extrusion, favoured by an important NE–SW thrust fault identified on the continental shelf near this point (Medialdea et al., 2004). If we consider a tectonic diapiric uplift similar to the one recorded at the Medina-Lake diapir (20–25 m), a rate of about 0.6 mm/yr is obtained for the last 30 ka. This is a rather high value, although to some extent it is comparable to the uplift rates associated with other moderately-active salt extrusions and diapirs: 0.3 mm/yr for blind diapirs in Hormuz, Persian Gulf (Talbot et al., 2000); 0.15 mm/yr for the Gorleben salt diapir, Germany (Zirngast, 1996). Only very active "salt glaciers" and "salt fountains" exceed values of 3 mm/yr in the Zagros Mountains (Jackson and Talbot, 1986) and Persian Gulf (Bruthans et al., 2006).

Hence, tectonic evidence suggests that originally the MIS 3 deposit, and then the palaeo sea level 30 ka ago, was located at a depth of less than 25 m below the present sea level, and very probably at only a few metres below present m.s.l.

### *4.2. Late Pleistocene palaeoenvironmental and eustatic evolution*

The MIS 3 is generally regarded as a time of climatic amelioration and retreat of ice sheets, both in North America (Plum Point interstadial between 30 and 25 ka, Dredge and Thorleifson, 1987) and northern Europe (Alesund interstadial between 33 and 28 ka, Larsen and Sejrup, 1990). The seasonal patterns of Milankovitch insolation for this stage show that the overall pattern was similar to the present one (Dawson, 1992) during which rapid and short-term warm events occurred. These warm interstadials or "Dansgaar–Oeschger events" are attached to cool ones and the pair, lasting about 1500 years, is called a "Dansgaard–Oeschger cycle" (Bond et al., 1993). MIS 3 palaeoclimatic estimations from palaeontological and palynological data for southern Europe also indicate an alternation of climatic fluctuations, although it is still difficult to correlate them with particular Dansgaard–Oeschger cycles (d'Errico and Sánchez Goñi, 2003).

Radiocarbon age data from the Torregorda beach deposit range between 21 and >44.5 ka, but with a calibrated age at 31,515 ± 773 Cal BP. Global sea level curves indicate that during that time significant and rapid fluctuations of the order of ± 20 m took place (Shackleton, 1987) and at least 6 Dansgaard–Oeschger cycles have been recognised between 21 and 31 ka (interstadials nos. 2–7 from the division made by Dansgaard et al., 1993). Supposing a direct cause-effect relationship between minor temperature fluctuations and sea level oscillations, the wide extension and progradational evolution of the Torregorda beach deposit could have been generated or at least favoured by an oscillating sea level within a general falling trend.

Coastal environments during this epoch have been traditionally supposed to be located at about 140–150 m below present sea level, according to data obtained from marine terrace sequences in the Western Pacific (Aharon and Chappell, 1986). However, actually very few real data exist about MIS 3 sea levels in southern Europe. Indeed, data from several authors suggest that at some moments during that stage the sea level in the Gulf of Cádiz and Western Mediterranean probably reached depths of only several tens of metres below the present-day sea level.

Zazo et al. (1984) described a coastal deposit bearing *Strombus bubonius* at Almería (Western Mediterranean, SE Spain), 0–1 m above present sea level and dated at 34.7 ± 1.7 ka BP ($^{14}C$) and 39.0 ± 2 ka (Th/U). These authors considered this height occurrence as a consequence of probable strong vertical movements and uplift during the Last Glacial cycle in that area. In the southern Portuguese coast, Moura et al. (2003) dated *Balanus* and calcite deposits that covered platforms at elevations of 2–4 m, giving ages in the range 38–13 ka BP.

The age of beachrocks on La Palma Island (Canary Islands), developed on platform-forming lavas (Calvet et al., 2003), varies from ca 33 ka to recent. The position of the beachrocks at the present-day sea level would require a combination of eustatic and isostatic movements to keep the sea level stable at the present level during the past 33 ka.

On the sea bed of the Strait of Gibraltar, Izquierdo et al. (1996) found bioclastic accumulations (lithoherms) formed by cemented corals and briozoa fragments with a radiometric age ranging between 22 and 34 ka. At present they appear between 150 and 300 m depth. However, the species forming the mounds are represented by typical ahermatipic corals (*Madrepora oculata*, *Lophelia pertusa*, *Dendrophyllia cornigera*, etc.) that normally live and develop at great depths (150 m or more). Therefore, their bathymetric situation suggests that by that time the sea level was not far from its present-day location.

Constraints on the position of relative sea level from luminiscence data in southern Italy show that the sea level rose from −29 m during substage 5a to −15 and to +7 m during MIS 3 (Mauz, 1999; Mauz and Hassler, 2001). U-series dating and geochemical analyses performed on carbonate concretions associated with sea level marks on the coasts of Campania and Lucania (Italy) suggest an eustatic sea level position very close to the present one at the beginning of the MIS 3 (Iannace et al., 2003; Amato et al., 2003). Belluomini et al. (2002) recognised a transgressive cycle during the MIS 3 regression, represented by coastal deposits at 1–2 m a.s.l. in Taranto (southern Italy), dated at 44.2 ± 2.4 and 48.4 ± 2 ka ($^{230}Th$). These authors also reported the presence of MIS 3 above present-day sea level in a tectonically quiescent region (Sardinia Island). Mauz (1999) suggested that sea level lowering during MIS 3 in the Tyrrhenian Sea is not likely to have exceeded 20 m below present level.

Following Mauz and Hassler (2001), discrepancies in MIS 3 sea levels between southern Italy and the western Pacific highlight the lack of knowledge concerning Mediterranean thermohaline circulation and sea water exchanges between the Atlantic and Mediterranean seas during glacial cycles. Belluomini et al. (2002) indicated that this discrepancy can be explained if we consider that these curves do not lead to precise sea level determinations because ocean isotopic composition is not a linear function of ice volume and hence is not a linear function of sea level.

Hernández-Molina et al. (2000b) identified very recent submerged progradational sediment units at numerous points in the Gulf of Cádiz, including the Bay of Cádiz and other sites of the Spanish Mediterranean continental shelf. The units, several metres thick, present typical shoreface seismic facies and normally appear at 20–30 m depth. In their work these authors recognise the similarities between the wedges and submerged beach deposits and include a long list of references where other previous authors interpreted similar seismic facies as typical submerged beach deposits. However, Hernández-Molina et al. (2000b) consider them as generated by very recent to present downwelling storm currents and associated seaward transport of sediment, and call them "infralittoral prograding wedges". The average closure depth for the beaches of the Bay of Cádiz, a low energy zone, has been estimated at about 6 m by bedform analysis through sidescan sonar (Gutiérrez-Mas et al., 1998) and beach profile modelling (Muñoz-Perez et al., 1999). Typical storm waves in the Gulf of Cádiz hardly exceed 4 m in height (Benavente et al., 2000) and hence the location of a storm closure depth at 20–30 m depth is highly questionable. Beaches of the Mediterranean coast are expected to follow similar behaviour, due to equivalent or even lower average wave energy. As a consequence, it is very difficult to explain how rip and return currents associated with storms can generate sedimentary wedges so deep and so far from the shallow zone where they are produced. Moreover, their constant depth occurrence is very difficult to explain with such a hypothesis since storm energy dissipation varies greatly alongshore. Instead, these data could be used as an indicator in favour of submerged beach deposits associated with a palaeo sea level developed at 20–30 m below the present level.

Radiocarbon data from the Torregorda deposit indicate that the transition from a marine to a continental environment began after 28 ka (Table 1, Fig. 10). This change was due to sea level fall (beginning of the Last Glacial Maximum, at about 22 ka; Dawson, 1992) and tectonic/diapiric uplift (tectonic episode at 21.7 ka, Fig. 8). Carbonate subaerial deposits partially filled the joints and covered all the exposed beach deposit between 22 and 13 ka (Table 1, Fig. 10). A rapid change to warm and dry climatic conditions was recorded in southern Europe between 14 and 11 ka BP (Allen et al., 1999), parallel to a significant aridity increase and desert expansion in northern Africa (Gasse et al., 1990). As a consequence, the newly open fractures at Torregorda were infilled by a red terrigenous deposit, characteristic of dry conditions.

The postglacial sea level rise should have flooded all these deposits. However, a parallel uplift associated with the San Fernando tectonic/diapiric activity probably maintained this area always above (although near to) the sea level throughout the Holocene. The maximum postglacial sea level, about +4 m above the present sea level, was reached in this zone at 6400 BP (Gracia et al., in press). Very probably the dune deposit at El Estanquillo (unit c in Fig. 6) was generated during this highstand. The later slight sea level fall would have favoured the development of the historical colluvial deposit (unit d in Fig. 6).

### *4.3. Palaeogeographical implications*

The succession of events presented here consists of a prolonged period of sea level fluctuations around −20 m during the central and late MIS 3 (until about 30 ka) and a later and rapid sea level fall (starting at 21.7 ka or probably earlier) down to −130 to −140 m

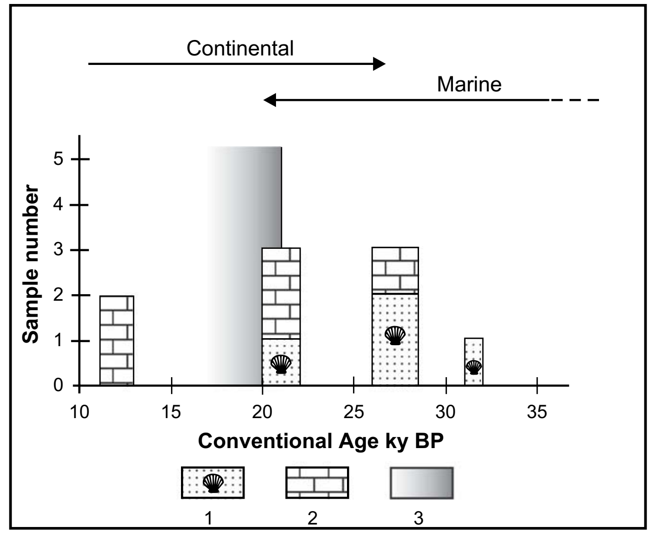


**Fig. 10.** Upper Pleistocene transition from marine to continental conditions in the study zone, based on radiometric datings (no. of samples vs. age). The progressive rising trend of this coastal zone was accelerated by the neotectonic event recorded at about 21.7 ka. 1: dated beach deposit, 2: dated calcrete deposit, 3: main neotectonic event.

(Hernández-Molina et al., 2000a). As a consequence, during the MIS 3 warm interstadials only the inner continental shelf would have been exposed to subaerial conditions and coastal environments would have occupied a zone not very far from the present coast. Only during the glacial maximum would the complete shelf have constituted an exposed continental low land.

Relict fluvial palaeochannels and alluvial deposits on the present continental shelves often give the key to palaeogeographical reconstructions during Pleistocene cold phases (Pirazzoli, 1996). Llave et al. (1999) applied a dense net of very high-resolution seismic profiles to the northern Bay of Cádiz. Under very recent marine sediments these authors recognised fluvial channel facies 8–13 m thick that develop a meandering outline starting from the present Guadalete River mouth and continuing several kilometres offshore along the present inner continental shelf. In the absence of any chronological data, these authors considered this "palaeoGuadalete" river channel as formed during the Late Pleistocene lowstand, between 110 and 20 ka. Despite the wider area covered by the geophysical survey, the isopach map drawn by the authors for this sedimentary unit shows that beyond 5 km from the present coast of Cádiz the "palaeoGuadalete" channel suddenly ends and disappears at 18–20 m depth. Such a point can be interpreted as the ancient river mouth and coincides with a continuous submerged slope break that divides different inner shelf domains at 16–21 m depth (Llave, 1998). The location of the palaeoriver mouth is perfectly compatible with the 30 ka sea level proposed in the present work, and very probably the Torregorda beach deposit and the ancient Guadalete River mouth were coeval. Other seismic surveys carried out on the inner continental shelf of the region reveal the existence of a discontinuous rock platform at a constant depth of 20 m, interpreted by Lobo et al. (2000) as submerged shore platforms.

Regionally, a sea level fall of 20 m would result in the exposure of the inner shelf, about 10 km wide between Cádiz and Conil. However, this width drastically decreases near Barbate, and virtually no shelf exists in the strict domain of the Strait of Gibraltar, where such a 20 m sea level fall would produce no significant change in the Strait width – nearly 14 km (Fig. 11A).

This possibility is especially important, given that between ca 40 and 28 ka, southern Iberia was the last refuge in Europe of

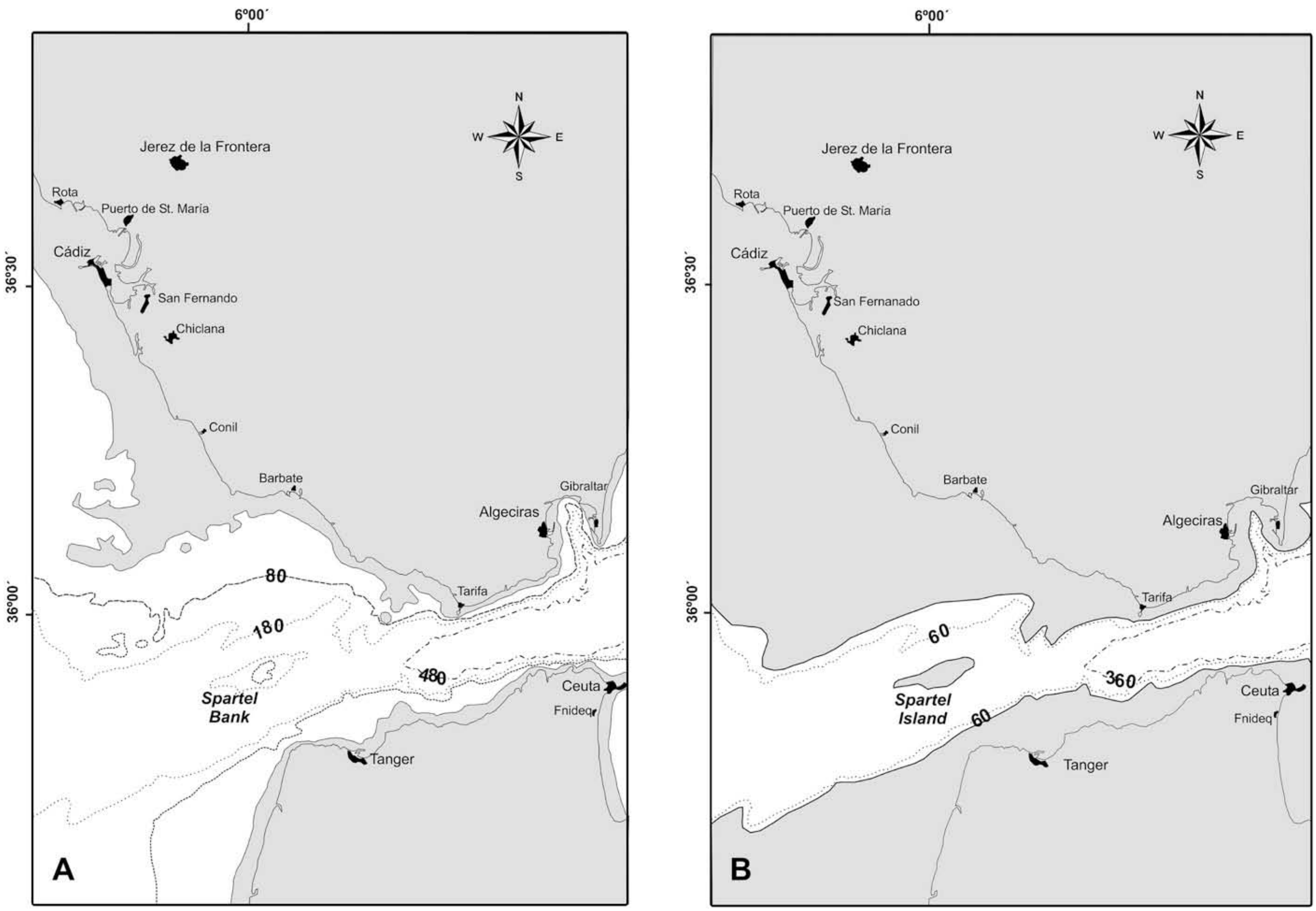


**Fig. 11.** Late Pleistocene palaeogeographical reconstructions of the Strait of Gibraltar. A: sea level at −20 m, during central-late MIS 3 (about 30 ka BP). B: sea level at −140 m, during Last Glacial Maximum (about 20 ka BP).

a Neanderthal population with Mousterian technology (Finlayson et al., 2006). The palaeogeographical reconstruction of the Strait during that period would help in the current dilemma about whether or not the Strait was a barrier to the contact and spread of Neanderthals between Africa and Europe (Straus, 2001).

Martinet and Searight, 1994 considered a sea level fall lower than 100 m, in which case several small islands would appear within the Strait in its western sector, facilitating shorter water crossings. These authors supposed that no important differences existed in the water currents between the lowstand situation and the present one. Other researchers in favour of an effective crossing are, among others, Smith et al. (1995) who used anatomical similarities between European and North African Pleistocene human groups, and Caparrós (2005) who elaborated archaeological arguments. Against the crossing hypothesis researchers like Hublin (1993), Currant (1994), Straus (2001), Finlayson and Giles (2000), Finlayson (2005) and van der Made, 2005 argue that, despite some possible isolated exchanges, multiple crossings were unlikely to have occurred. Similarities between industries on both sides of the Strait would then be the result of technological convergence or parallel development (Finlayson and Carrión, 2007; see also Ramos et al., 2008).

Present water interchange between the Atlantic and the Mediterranean through the Strait consists of a deep outflow of the warm and dense (highly saline) Mediterranean water and a shallow inflow of the cold and less dense Atlantic water into the Mediterranean Sea (Gascard and Richez, 1985). Total water flux through the Strait has been estimated at more than $100 \times 10^{12}$ $m^3$/yr (Bethoux, 1980), giving rise to strong currents and tides, and also energetic waves during easterly storms. At present such conditions inhibit easy crossing of the Strait and similar oceanographic dynamics can be assumed for a sea level 20 m below the present one (A. Izquierdo, pers. comm.).

A sea level fall of ca 140 m, supposedly reached during the Last Glacial Maximum (MIS 2), between 22 and 15 BP (Hernández-Molina et al., 2002) would present different conditions. The width of the Strait would decrease to less than 10 km and the Spartel Bank would emerge to form an island about 25 $km^2$ in extent (Fig. 11B). The detailed bathymetric study of this bank revealed wide zones with a significant flatness, interpreted by Gutscher (2005) as a paleoterrace at 120 m water depth that may record a long-lasting sea level lowstand. Although crossing of the Strait would have been probably much easier under such circumstances, many uncertainties still exist about how the currents operated through the Strait during those cold conditions and with a completely different geometry.

## 5. Conclusions

The San Fernando beach deposit in the Bay of Cádiz, dated as belonging to the central and late MIS 3, appears very close to the present sea level. The unit is affected by open joints partially filled by laminated calcretes. The dating of this later carbonate deposit indicates the existence of two main uplift episodes, the first one about 22 ka and the second one later than 19 ka. The nature of this MIS 3 sedimentary unit and the type of tectonic structure responsible for its deformation (diapiric anticline) introduces some uncertainties in exactly reconstructing the original coastline position during MIS 3. However, the deformational style and the tectonic location of the deposit, in the vicinity of the periclinal closure of the anticline, rule out any strong vertical motion of this level. Therefore, from indirect structural and regional considerations it can be inferred that around 30 ka the sea level was very probably located about 20 m below its present position.

Such a conclusion is confirmed by data taken by other authors in nearby areas (Strait of Gibraltar) and in the Mediterranean Sea and is even confirmed by different marine geophysical data obtained in the zone by other researchers. However, although this model follows the global sea level trends obtained for the Late Pleistocene in different ocean basins, it clearly contradicts the widely accepted assumption of a sea level more than 100 m lower than the present one. Our deductions are mainly based on several calibrated radiocarbon ages. However, as stated earlier, absolute dating of MIS 3 interstadials is often problematic, and different considerations apply, depending on whether the available MIS 3 dates are accepted or rejected:

(a) *If the MIS 3 radiocarbon ages are rejected*, the only remaining possibility is to consider the San Fernando beach deposit as belonging to MIS 5, associated with a palaeo sea level close to the present one. However, several palaeoenvironmental problems make this option rather unlikely. First, its sedimentological characteristics (thickness, marked progradational trend, absence of thick aeolian deposits, etc.) are very different from the typical MIS 5 beach deposits of the region. Second, the San Fernando deposit is directly fossilised by materials indicative of arid or semiarid continental conditions, suggesting a very rapid sea level fall and a sudden climatic transition to dry environments. No similar sequences have been identified for the MIS 5 deposits of the region. Moreover, this type of climatic evolution perfectly resembles the final stages of MIS 3, but hardly those of MIS 5.
(b) *If the MIS 3 radiocarbon ages are accepted*, data presented in this work indicate that at 30 ka the sea level was located about 20 m below the present one or even shallower, and very probably recorded frequent small fluctuations. This assertion does not contradict current palaeoclimatic models for that period (Finlayson et al., 2007; Jiménez-Espejo et al., 2007) and poses the problem of where to locate glacial sea levels in southern Europe. As far as the amount of sea level change is concerned, comparisons with Western Pacific Pleistocene sea levels may be inadequate. These almost antipodean locations belong to water masses where current circulation patterns, tectonic/isostatic trends and geoid behaviour have undergone a different evolution during the Late Quaternary. Although glacioeustatic sea level fluctuations can behave more or less in the same way in both locations, all these factors strongly affect their amplitude, so that the strict correlation of sea level heights between such different locations becomes unrealistic.

Direct consequences of the model presented in this paper include the reconsideration of traditional palaeogeographical premises and the Late Pleistocene evolution of coastal zones. In the case of the Strait of Gibraltar, the existence of a narrow and easy-to-cross water body at ca 30 ka would be questionable. Such a situation was surely attained 10 ka later, although by that time *Homo sapiens neanderthalensis* in southern Iberia had been completely replaced by *Homo sapiens sapiens*.

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