

# Late Holocene evolution of the southwestern Doñana National Park (Guadalquivir Estuary, SW Spain): a multivariate approach

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## Abstract

Four phases are distinguished in the Late Holocene evolution of the southwestern Doñana National Park (SW Spain), based on a multidisciplinary analysis of the sediments present in drill cores. In the oldest phase ( $\approx 2400\text{--}2500$  cal. yr BP), a coastal lagoon (the Roman Lacus Ligustinus) was recognized in the central part of this area, partly closed by the Doñana spit and limited by fluvial levees. The following phase ( $\approx 2400\text{--}2200$  cal. yr BP) is characterized by high-energy events, which caused the breakthrough of the Doñana spit and the creation of new littoral strands in the inner areas. In the third phase ( $\approx 2200\text{--}2050$  cal. yr BP), this new outlet was closed, coinciding with the progradation of the Doñana spit. The last phase ( $\approx 2050$  cal. yr BP<sup>Recent</sup>) comprises three periods: (a) an unstable period ( $\approx 2050\text{--}1950$  cal. yr BP), with the deposit of cheniers over the previous levees; (b) an infilling period, with a diminution of the marine influence; and (c) the appearance of temporary ponds between the emerged levees and cheniers.

Keywords: geomorphology; mineralogy; paleontology; estuarine evolution; Late Holocene; SW Spain

## 1. Introduction

The evolution of coastal environments (estuaries, deltas, fjords) is the result of the interaction

between the original geomorphology, waves, tides and fluvial supplies, with modifications derived from relative sea-level changes, climatic setting or human activities (Davies, 1964; Chiverrell, 2001). This interaction may cause changes in the local sedimentation rates, the creation of new geomorphological formations (spits, cheniers, levees), sudden biological crises or an alteration of the

natural hydrodynamics (Gerdes et al., 2003; Le-duc et al., 2002; Ybert et al., 2003). For a detailed definition of these changes, it is necessary to combine the analyses of geomorphological, sedimentological, faunal and mineralogical features in order to determine past environmental evolutions in these littoral areas (Chamley, 1989; Dalrymple et al., 1992; De la Vega et al., 2000; Edwards, 2001; Umitsu et al., 2001).

These geological investigations can be completed with datings which might lead to a revision of the historical record. Knowledge of the geological evolution is very useful to obtain information about old marine connections (Kristensen et al., 1995), beginning, end or impact of man's interventions (Favero and Serandrei, 1981; Albani et al., 1995; Favero et al., 1995), changes in paleo-environmental conditions (Albertotanza et al., 1977; Angliano et al., 2000) or the refining of radiocarbon ages (Borja et al., 1999).

Along the southwestern Spanish coast, there are four estuaries (Fig. 1: Guadiana, Piedras, Tinto-Odiel, Guadalquivir) partly enclosed by spits. A number of studies have concentrated on the Holocene evolution of this littoral area, suggesting a chronology of events of progradation and erosion based on the radiocarbon dating of shells collected from these spits (Zazo et al., 1994; Lario et al., 1995; Goy et al., 1996; Rodríguez-Ramírez, 1996; Rodríguez-Ramírez et al., 1996; Dabrio et al., 1999). Two major Holocene phases of coastal progradation have been recognized after the transgressive maximum (6500 cal. yr BP; Zazo et al., 1994), including four spit systems. The limits for progradation of the spit units, with a reservoir correction (3440 ± 85 yr; Dabrio et al., 1999), are 6500–4400 cal. yr BP, 4200–2550 cal. yr BP, 2300–800 cal. yr BP and 500 cal. yr BP to the present. These phases are divided by erosional events at 4500–4200 cal. yr BP, 2600–2300 cal. yr BP and 1100–1000 cal. yr BP. Other studies have investigated the Holocene estuarine facies (Borrego, 1992; Morales, 1993) and the reconstruction of the Holocene sedimentary evolution based on drill cores (Borrego et al., 1999; Dabrio et al., 2000).

The Guadalquivir River is the most important fluvial stream of this zone. The first historical de-

scription of its estuary was made by the Roman chronicler Strabo in his work *Geographica*, written between 29 and 7 BC. He referred to the southern part of this estuary as an inland lagoon (Lacus Ligustinus), a paleogeography confirmed 40 years later by Mela, a Spanish chronicler, in his work *De Chorographia* (García Bellido, 1987). Most recently (19th–20th centuries), studies of this area have been centered on its exceptional biological assemblages whereas little information is found about the geological evolution (e.g., Carretero et al., 2002), a fundamental basis to understand the recent ecological expansion.

In this paper, we perform an integrated, geological analysis of the southwestern part of this estuary, using geomorphological techniques, radiometrically dated cores, lithostratigraphic and biotic analyses (macrofossils, ostracodes) and mineralogical data. The main aim is to specify the environmental changes occurring in this historical lagoon in the last millennia, which may explain the recent geomorphological features of the Doñana National Park, a privileged biological site in southwestern Spain. Other investigations carried out in the remaining estuaries of this coast were conducted in order to compare the chronology of the main events which happened during the Late Holocene in this area.

## 2. The Guadalquivir estuary

The Guadalquivir River (560 km long) drains a catchment of 57 000 km<sup>2</sup>, comprising mainly Tertiary sedimentary rocks. This river is partly blocked in the lower reach by sandy barriers, resulting in a large estuary (1800 km<sup>2</sup>). In the southwestern sector (Fig. 1), this estuary includes the Doñana National Park, a UNESCO-MAB Biosphere Reserve. This site is one of the largest wetlands (50 720 ha) in Europe and represents the last tract of relatively undisturbed marsh in this system.

Fluvial regime, tidal flux, wave action and drift currents control the hydrodynamic processes. This river is the main sediment source of the southwestern Spanish coast, with a mean annual discharge of 164 m<sup>3</sup>/s. The highest runoff ( $\leq 1000$

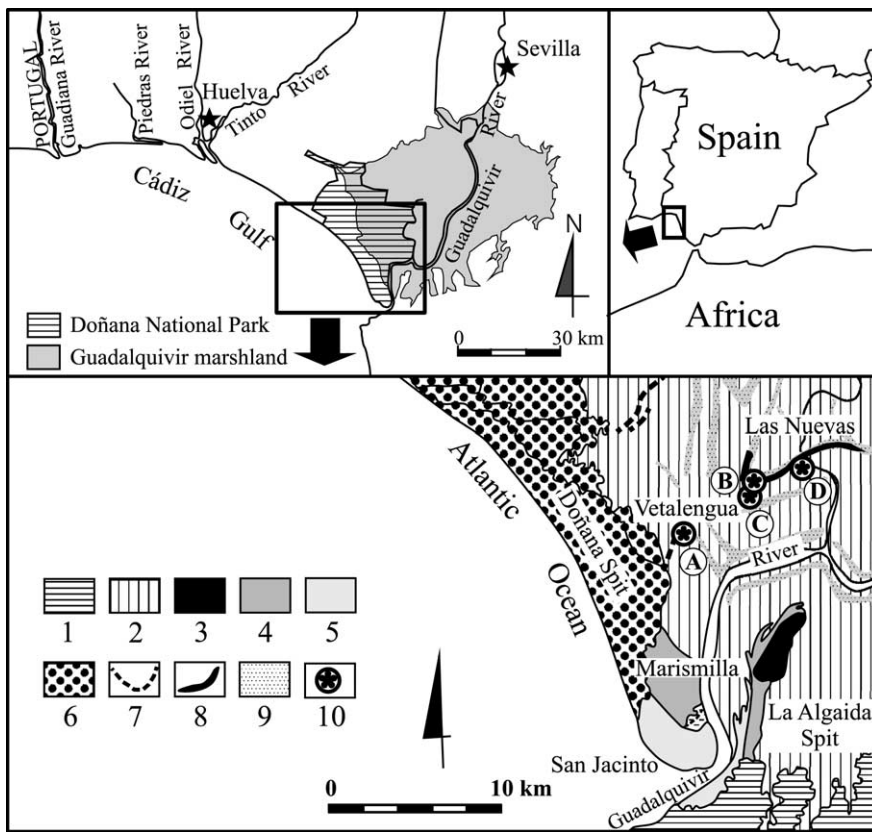


Fig. 1. Geographical setting and geomorphology of the Guadalquivir River mouth. Key: 1: Plio-Quaternary substrate; 2: marshes; 3-5: progradational phases of the littoral spits; 6: Quaternary dune systems; 7: littoral ridges; 8: estuarine ridges; 9: clayey levees; 10: location of the drillings studied (A-D).

$\text{m}^3/\text{s}$ ) occurs from January to February, when the propagation velocity of the discharge peaks rises up to  $1 \text{ m/s}$  (Vanne, 1970; Menanteau, 1979)

The tidal regime is mesotidal and semidiurnal, with an average tidal range of approximately  $3.6 \text{ m}$  (Borrego et al., 1993). Dominant waves associated with the Atlantic circulation come from the southwest, with a medium wave energy because 75% of the waves do not exceed  $0.5 \text{ m}$  in height. These conditions favor the development of broad lowlands, usually sheltered by spits, where tidal flats and freshwater marshes extend several kilometers inland. Littoral drift currents transport sand-size sediments from the Portuguese coast to the Spanish nearshore zone, determining the form of each coastal stretch (C.E.E.P.Y.C., 1979; Cuenca, 1991).

### 3. Material and methods

#### 3.1. Geomorphology

In a prior step, the geomorphology of the Doñana National Park was mapped from  $1:33\,000$  aerial photographs, taken in 1956. The initial cartography of the fluvial elements (i.e., levees, fluvial channels) and marine forms (i.e., spits) was partly modified with direct observation in the field, owing to a modest topographic gradient of about  $1 \text{ m}$  difference in height. Finally, a more restricted area (Fig. 1: Vetalegua-Las Nuevas) was selected for coring, containing the main geomorphological features of the estuary. Four cores (A-D) were collected with a  $20 \text{ mm}$  diameter vibrocore reaching up to  $1 \text{ m}$  depth. The lithology

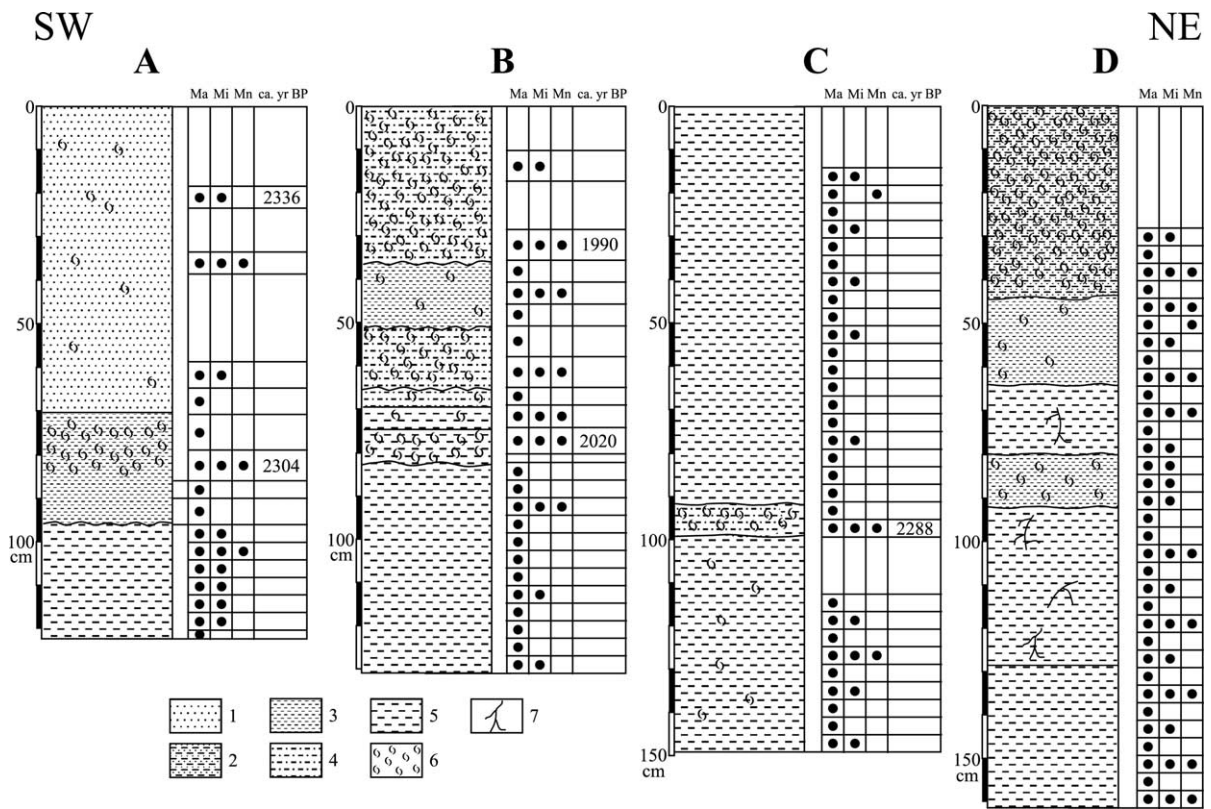


Fig. 2. Lithological features of the cores, including the situation of the samples taken and the type of studies realized in each sample. Age: highest probability age in cal. yr BP. Lithological key: 1: sands; 2: silty sands; 3: silts; 4: silty clays; 5: clays; 6: accumulations of invertebrate shells; 7: roots. Ma : macrofauna; Mi : microfauna; Mn : mineralogy.

of each core was described during field sampling (Fig. 2).

### 3.2. Mineralogy

The mineralogy of 22 samples was studied by X-ray diffraction applied to the whole sample (Fig. 3). The equipment used was a Philips PW 1130/90, with an automatic slit, using KK radiation of Cu and a Ni filter at 20 mA and 40 kV. The <math>62 \mu\text{m}</math> fraction was separated by a standard sedimentation method (Barahona, 1974). Before the separation, carbonates were eliminated using 0.6 N acetic acid.

Three groups of minerals may be differentiated in the final results, according to the origin: (a) detritic minerals (quartz, calcite, feldspars, dolomite, aragonite); (b) decantation minerals (phyl-

losilicates); and (c) evaporative, syngenetic minerals (halite).

### 3.3. Paleontology

One hundred samples were obtained for macrofossil analysis (Fig. 4). Samples were collected and prepared by washing the bulk sediment (12 cm<sup>3</sup>) through a 1-mm sieve. Bivalves and gastropods were identified to the species level and counted to study the semi-quantitative distribution in each core. In relation to the reduced amount of sediment studied, the abundance of a species in each sample was described as follows: fragments, rare (one specimen), frequent (2-5 specimens) and abundant ( $\geq 5$  specimens).

Forty-seven samples of approximately 15 g were taken for microfossil analysis, which are se-

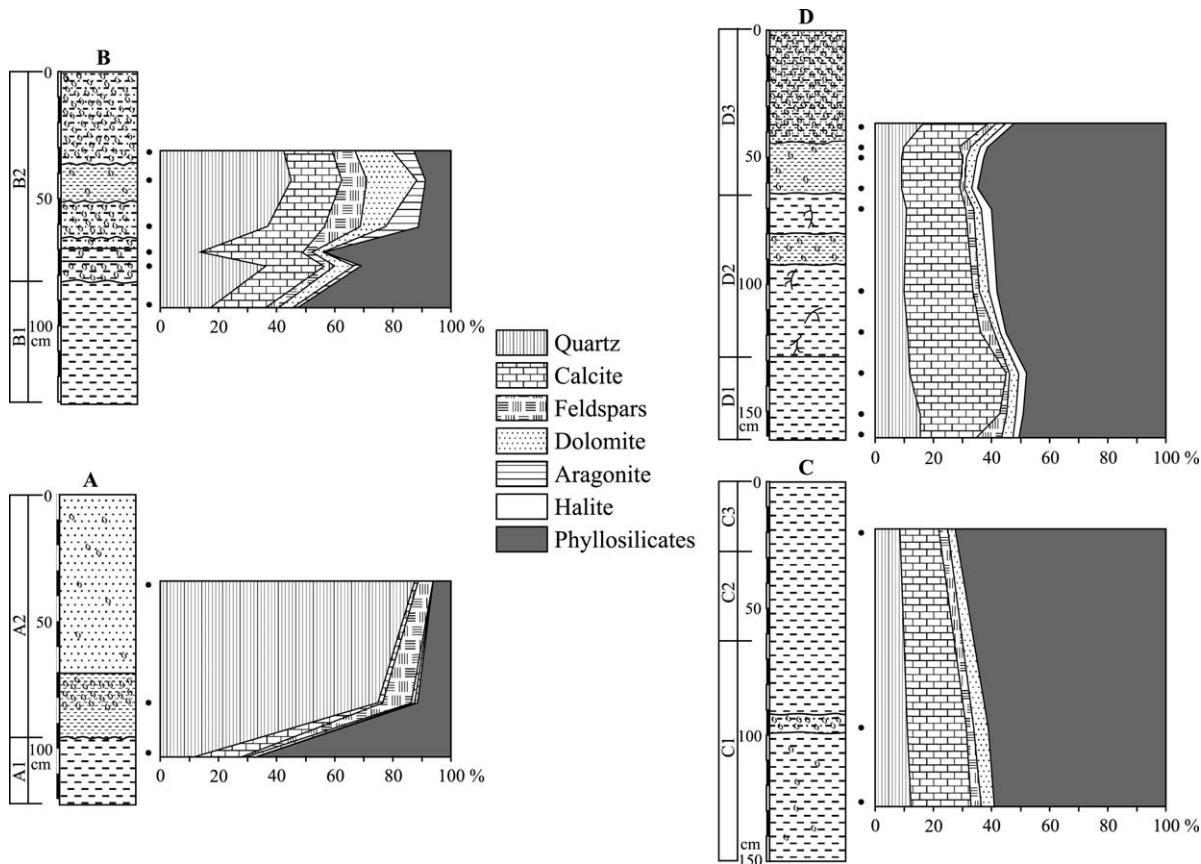


Fig. 3. Mineralogical record of the cores.

lected according to the main sedimentary changes observed in the cores (Fig. 5). These samples were washed through a 63- $\mu$ m sieve to remove the mud fraction and then dried. If possible, more than 300 ostracode valves and carapaces from each sample were picked onto faunal microscope slides. Both the abundance of each species and the number of individuals per gram in each sample were calculated (Fig. 5). A total list of recorded macro- and microfossils in the cores is given in the Appendix.

### 3.4. Dating

Five datings were carried out at the Beta Analytic Laboratory (Miami, FL, USA) and the Centro di Studio per il Quaternario e l'Evolutione Ambientale del CNR (Rome, Italy) by radiocar-

bon methods applied to mollusc shells (Table 1). Data were calibrated using CALIB version 4.3 (Stuiver and Reimer, 1993) and the Stuiver et al. (1998) calibration dataset. The final results correspond to calibrated ages (cal.) using 2 $\sigma$  intervals, with a reservoir correction (3440  $\pm$  85 yr) as suggested in Lario (1996) and Dabrio et al. (1999, 2000) for this area. Ages discussed below will be expressed as the highest probable age of the 2 $\sigma$  calibrated range (e.g., Van der Kaars et al., 2001)

## 4. Results

### 4.1. Geomorphology of the Doñana National Park

The geomorphological analysis makes it possi-



Table 1  
Data base of <sup>14</sup>C results

Core	Depth (cm)	Lab. number	Material dated	Uncorrected age (yr BP)	Error (Qyr)	Max. age (cal. yr BP)	Highest probability age (cal. yr BP)	Min. age (cal. yr BP)
A	82	R-2283	Mollusc	2171	36	2511	2304	2056
A	20	B-88016	Mollusc	2230	60	2696	2336	2108
B	90	B-154079	Mollusc	1960	40	2293	2020	1813
B	31	B-154082	Mollusc	1940	60	2294	1990	1766
C	95	B-145203	Mollusc	2140	70	2593	2288	1975

Laboratory: B: Beta Analytic (Miami, FL, USA); R: Centro di Studio per il Quaternario e l'Evoluzione Ambientale del CNR, Dipartimento Scienze della Terra, Universita La Sapienza (Rome, Italy).

ble to delimit the fluvial levees flanking the river and its former courses, with two main directions (north<sup>^</sup>south and west<sup>^</sup>east). These levees have a variable width (300<sup>^</sup>1500 m) and length (upto 3<sup>^</sup>5 km), reaching heights of 0.8<sup>^</sup>1 m above the adjacent marshes. Soils are aquic xerochrepts (Clemente et al., 1998), with vegetation composed of *Arthrocnemum macrostachyum*.

The 'hills' (2<sup>^</sup>2.5 m about the marsh level) are occupied by some levees overlain by characteristic accumulations of bivalves, with a beach ridge morphology (Figs. 1 and 7, F: Las Nuevas). They are elongated (3<sup>^</sup>6 km), with a narrow width (20<sup>^</sup>30 m) and thickness (0.5<sup>^</sup>0.7 m) and can be classified as cheniers (Otvos and Price, 1979; Augustinus, 1989; Rodriguez-Ramirez et al., 2001). Cores B and D were collected over one of these 'hills' (Las Nuevas).

Depressions (core C) are formed by the active<sup>^</sup>inactive fluvial channels and other areas conged by channels or former levees. These areas remain wet during the summer months, containing permanent waters or delimiting temporary ponds from November to June. Vegetation is characterized by the presence of *Scirpus lacustris* and *Scirpus maritimus*, living over typic salorthid or aquollic salorthic soils (Clemente et al., 1998).

Finally, the estuary is partly enclosed by two main sandy spits (Fig. 1): Domana (western bank) and La Algaida (eastern bank). These beds are composed of active dunes disposed in narrow (6<sup>^</sup>100 m) and elongated (1<sup>^</sup>2 km) alignments, with a limited thickness (6<sup>^</sup>1.5 m) in most cases.

## 4.2. Lithostratigraphic, mineralogical and macrofaunal analysis

### 4.2.1. Core A

The lower 28 cm of this core are represented by massive, green to grayish clays with scattered fragments of bivalves. The total mineralogy is composed of phyllosilicates (68%), calcite (16%) and quartz (12%). These clays are overlain by a silty bed (25 cm thickness) with numerous fragments of bivalves (*Cardium edule*) and gastropods. The upper 80 cm are composed of yellow, fine to medium sands very rich in quartz (Fig. 3: 75<sup>^</sup>88%), with phyllosilicates (6<sup>^</sup>11%) and feldspars (5<sup>^</sup>10%) as accessories.

### 4.2.2. Core B

This core can be divided into two lithological intervals. Between 132 and 68 cm below surface, this core is characterized by a continuous sequence of green-gray silty clays with scarce traces of burrowing organisms. Phyllosilicates (31<sup>^</sup>52%) are dominant over quartz (14<sup>^</sup>36%) and calcite (19<sup>^</sup>35%), with feldspars and dolomite as minor constituents. The limited paleontological record is composed of the pulmonate gastropod *Melanopsis* and numerous fragments of roots.

The upper zone (68 cm thickness) is formed by two levels of silty clays (5Y 4/2) enclosing lumachelle accumulations of invertebrate shells. These sediments are rich in quartz (37<sup>^</sup>42%), calcite (17<sup>^</sup>19%), phyllosilicates (12<sup>^</sup>13%), feldspars (8<sup>^</sup>13%), dolomite (8<sup>^</sup>13%) and aragonite (8<sup>^</sup>12%). Macrofauna is strongly dominated by disarticulated

valves of the bivalve *Cardium edule* with multiple growth stages (0.25^2 cm length) and frequent specimens of *Melanopsis* (Fig. 4). These species are accompanied by numerous juvenile valves of *Venerupis decussatus* and, to a lesser extent, by other marine bivalves (i.e., *Crassostrea angulata*, *Donax vittatus*, *Corbula gibba*, *Glycymeris glycymeris*) and gastropods (*Calyptraea chinensis*). In addition, the uppermost samples contain both freshwater and pulmonate gastropods (*Helix* sp., *Gyraulus laevis*).

A more silty bed (52^38 cm below surface) is interbedded between these fossiliferous units, containing frequent shells of bivalves (*Cardium edule*, *Venerupis decussatus*). Quartz (45%) and dolomite (17%) are more abundant, whereas aragonite (3%) and phyllosilicates (10%) decrease.

#### 4.2.3. Core C

This core is composed of clays with very limited sand contents (6.2%). Color makes it possible to distinguish between a lower layer (color 10YR 5/3) and an upper zone (6.44 cm depth; color 5Y 4/2). In the former layer, the phyllosilicate content (58^62%) increases toward the top, whereas calcite (6.21%) and quartz (11^13%) decrease in the same direction. Sediments from this bed contain a macrofauna composed of bivalves (*Venerupis decussatus*, *Cardium edule*, *Crassostrea angulata*), with a frequent occurrence of echinoderm spines. A silty layer with numerous mollusc shells was observed at 102^94 cm below surface, with similar mineralogy. *Crassostrea angulata* and fragments of *Venerupis decussatus* are very abundant (≈ 20% dry weight) in this layer.

In the upper part of this core, there is a clear enrichment in phyllosilicates (72%), with lesser quantities of quartz (8%) and calcite (14%). Macrofauna is absent or very scarce in most samples.

#### 4.2.4. Core D

This core presents a lower interval (162^129 cm below surface) characterized by massive, blue clays with very sparse macrofauna. These fine sediments are composed of quartz (13^16%), calcite (19^32%) and phyllosilicates (47^51%). Over this zone, very similar sediments (129^63 cm below surface) present abundant fragments of pha-

nerogams, numerous roots and an increasing phyllosilicate contents (55^61%). This homogeneous lithology is only interrupted at a core depth of 91^79 cm by a silty level with scattered fragments of bivalves (*Cardium edule*).

The third interval (63^43 cm below surface) is represented by silts with frequent shells of *Cardium edule*, *Spisula solida* and *Rissoa* sp. Phyllosilicates are very abundant (60^65%), with the quartz (9^10%) and calcite (19^21%) contents nearly constant. The upper 43 cm present a yellow, sandy body (18% quartz) with abundant and well-preserved molluscs (mainly *Cardium edule*). This macrofauna was disposed in massive beds or in plane-parallel strata.

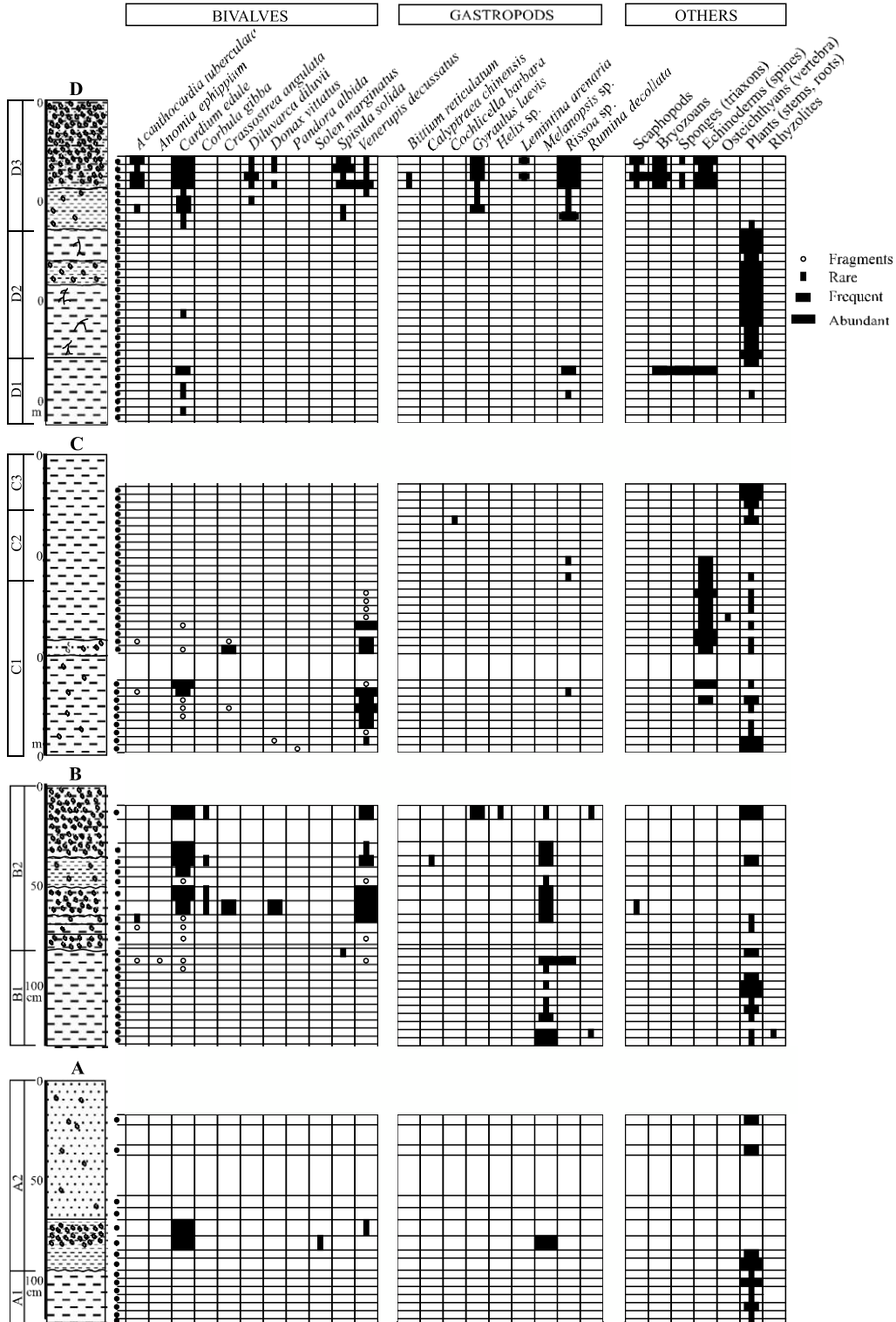
### 4.3. Microfossil analysis

#### 4.3.1. Autoecological groups of ostracodes

Three main groups of ostracodes may be distinguished (Fig. 5), each one constituted by species with analogous ecology (Carbonel, 1980; Clavé et al., 2001): (a) fresh to low brackish water assemblage: *Cyclocypris laevis*, *Cypridopsis vidua*, *Cypris bispinosa*, *Herpetocypris chevreuxi*, *Ilyocypris gibba* and *Cyprinotus salinus*; (b) high brackish water assemblage: *Cyprideis torosa* (smooth ornamentation), *Leptocythere castanea* and *Loxoconcha elliptica*; and (c) coastal, marine assemblage: *Carinocythereis whitei*, *Neocytherideis subulata*, *Palmoconcha guttata*, *Palmoconcha laevata*, *Pontocythere elongata*, *Semicytherura* sp. and *Urocythereis oblonga*.

#### 4.3.2. Zonation of the cores

4.3.2.1. Core A. The ostracode record makes it possible to delimit two zones in this core. In the lower 28 cm (Zone A1), the very scarce ostracode valves observed (*Cyprideis torosa*, *Leptocythere castanea*, *Loxoconcha elliptica*) are found together with numerous estuarine foraminifers (*Ammonia tepida*, *Astrononion stelligerum*) and some marine specimens, both benthic (*Uvigerina peregrina*, *Globulimina auriculata*) and planktonic (*Orbulina universa*, *Globigerina bulloides*). Towards the top, this assemblage coincides with the presence of numerous plant fragments. Zone A2 (upper 96 cm)





is characterized by the absence of both foraminifers and ostracodes.

4.3.2.2. Core B. Two zones may be distinguished in this core. In the lowermost samples (Zone B1: 132–110 cm below surface), ostracodes are poorly represented by some juvenile instars of *Leptocythere castanea* and *Urocythereis oblonga* (synonym of *Urocythereis britannica*). In the upper samples (Zone B2), the number of individuals per gram is very low (6–13), *Cyprideis torosa* being the most representative species (89% of the valves). *Loxoconcha elliptica* and *Pontocythere elongata* are well represented through these samples.

4.3.2.3. Core C. The ostracode content and composition delimit three zones in core C. Zone C1 (148–72 cm below surface) is characterized by a very high density (500 individuals/g) with a maximum at 3124 cm depth. The ostracode assemblage is composed of *Cyprideis torosa*, *Leptocythere castanea* and *Loxoconcha elliptica* (Fig. 5), *Cythereis gschleri* being the main secondary species. Other species (*Palmoconcha laevata*, *Semicytherura* spp., *Neocytherideis subulata*, *Pontocythere elongata*) are only represented by juvenile instars in some isolated samples. In the upper part of this zone (100–90 cm below surface), the ostracode density decreases (200–250 individuals/g), coinciding with the presence of frequent bivalve shells.

Zone C2 (72–32 cm below surface) presents a marked drop in the ostracode density (6–35 individuals/g), with a progressive disappearance of the latter assemblage and the appearance of new species (*Cyprinotus salinus*, *Cypridopsis vidua*). This zone is also evidenced by the appearance and increasing abundance of calcareous gyrogonites belonging to the genus *Chara*, a charophyte alga (Class Charophyceae).

Zone C3 (0–32 cm depth) is dominated by *Cyprinotus salinus*, with minor contributions of *Ilyocypris gibba*, *Herpetocypris chevreuxi*, *Cypridopsis*

*vidua*, *Cypris bispinosa* and scarce, poorly mineralized specimens of *Cyprideis torosa* (instars A-3 to A-1). Density is difficult to estimate, with abundant fragmented valves of these weakly calcified species. Charophytes and fragments of stems and roots are very numerous.

4.3.2.4. Core D. Ostracode analysis enables three zones to be established in this core. Zone D1 (162–129 cm below surface) presents a rich ostracode assemblage dominated by *Cyprideis torosa* and *Loxoconcha elliptica*, with *Leptocythere castanea* and *Leptocythere tenera* as additional species. In this zone, the number of ostracodes decreases towards the top. A second zone (D2: 129–63 cm below surface) is defined by the absence of ostracodes or the presence of sparse specimens (6–2 individuals/g) belonging to very juvenile individuals (instars A-4 to A-6) of *Cyprideis torosa* and/or *Loxoconcha elliptica*. This zone includes a diversified assemblage (16 species) at a core depth of 91–79 cm, with abundant valves of *Cyprideis torosa*, *Palmoconcha laevata* and *Loxoconcha elliptica*. In Zone D3 (upper 63 cm), both the ostracode diversity and density increase towards the top. *Cyprideis torosa*, *Palmoconcha laevata* and *Pontocythere elongata* are the main species in this zone.

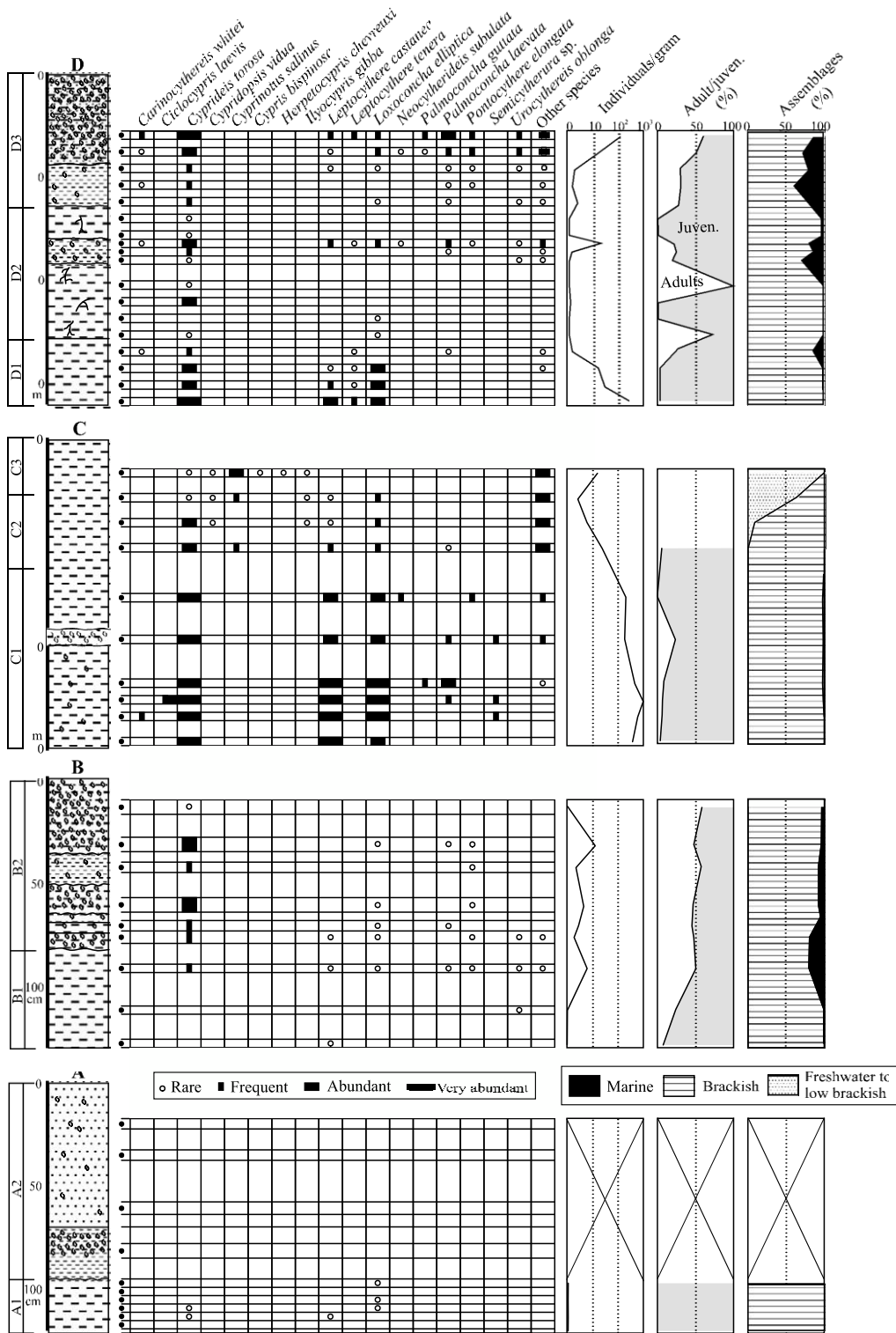
#### 4.4. Radiometric dating

In core A, two dates were obtained on the estuarine bivalve *Cardium edule*, indicating the calibrated age of Vetalegua: 2511–2304–2056 yr BP (82 cm depth) and 2696–2336–2108 yr BP (20 cm depth). Another two samples were dated in core B, collected in the chenier of Las Nuevas: 2293–2020–1813 yr BP (90 cm depth) and 2294–1990–1766 yr BP (31 cm depth). These data may indicate some reworking of the upper shells collected in either cores or, more probably, the deposit of the whole cheniers in the same events.

An additional, lateral sampling makes it possible to correlate the chenier of Las Nuevas with

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Fig. 4. Distribution of macrofossils in the cores. Abundance: rare (one specimen); frequent (2–5 specimens); abundant (5 specimens).



the upper 43 cm of core D. Finally, an additional sample was dated in core C (2593<sup>±</sup>2288<sup>±</sup>1975 yr BP; 95 cm depth), very close to the radiocarbon age of Vetalegua.

## 5. Paleoenvironmental reconstruction of the cores

Four phases may be separated in the environmental sequence of the cores collected.

### 5.1. Phase 1 (c. 2400<sup>±</sup>2500 cal. yr BP)

The lower limit of this phase is not observed in the cores studied, whereas the upper limit coincides with the first level of bivalve accumulation, which presents similar ages in cores A and C (highest probability between 2288 and 2336 yr BP) and may be laterally correlated with core D. In core A, the ostracode and foraminiferal assemblages (mainly *Ammonia tepida*, *Haynesina germanica*, *Trochammina inflata*, *Quinqueloculina seminulum*) of Zone A1 evidence a mudflat deposit (Cearreta, 1998), with introduction of marine, planktonic species (*Orbulina*, *Globigerina*) during the tidal flux. Near the top (105<sup>±</sup>96 cm below surface), the presence of frequent phanerogam fragments and the reduced microfauna indicate the transition towards a vegetated, supratidal salt marsh (Fig. 6). In this environment, ostracodes are usually absent (Penney, 1985).

During this phase, the rich ostracode assemblage (*Cyprideis torosa*, *Loxoconcha elliptica*, *Lepetocythere castanea*) collected in Zones C1 (lower part) and D1 indicates the presence of a brackish lagoon (salinity 6.25<sup>±</sup>30‰) in the southwestern sector of the Doñana National Park. These species characterize the inner, shallow areas (6.1 m depth) of recent lagoons with marine connection, located near the lagoon shore and close to a river mouth (Athersuch et al., 1989; Marocco et al., 1996; Montenegro and Pugliese, 1996; Ruiz et al., 2000a).

The fine to very fine sediments observed indi-

cate a calm environment dominated by suspension processes, with NaCl-rich waters as evidenced by the smooth-shelled Cyprideis (Anadón et al., 1986). The marine influence was strong, with transport of marine bivalves (mainly *Venerupis decussatus*) and instars of ostracodes (*Palmoconcha laevata*, *Palmoconcha guttata* or *Semicytherura* spp.) towards the inner lagoon during the tidal flux or by storms. These species are frequent in the recent marine assemblages (6.20 m depth) of the southwestern Spanish Atlantic coasts (Pérez Quintero, 1989; Ruiz et al., 1997).

### 5.2. Phase 2 (c. 2400<sup>±</sup>2200 cal. yr BP)

In the lower part of Zone A2, the occurrence of a fine level of bivalves, including estuarine (*Cardium edule*) and marine (*Venerupis decussatus*, *Solen marginatus*) species, may be indicative of a storm deposit (Regnauld, 1999). This level lies unconformably over the marsh deposits and is followed vertically by eolian, fine to medium sands with very high quartz contents (c. 75%). This bed is perpendicular to the Doñana spit and may represent a breakthrough of this spit owing to a high-energy event (strong storm?, tsunami?). This area will remain emerged in the successive phases.

This rupture permits the introduction of both marine macrofauna (*Crassostrea angulata*, *Venerupis decussatus*, fragments of scaphopods, bryozoans and sponges) and microfauna (*Basslerites berchoni*, *Carinocythereis whitei*, *Semicytherura* sp.) towards the inner lagoon. These reworked faunas are accumulated in core C (middle part of Zone C1) and, to a lesser extent, in core D (boundary between Zones D1 and D2).

### 5.3. Phase 3 (c. 2200<sup>±</sup>2050 cal. yr BP)

The intertidal<sup>±</sup>supratidal areas of this lagoon are represented in Zone B1, with scarce ostracods, presence of pulmonate gastropods, rhizolites and the absence of marine shells. Similar features were

Fig. 5. Ostracode distribution in the cores collected. Abundance: rare (c. 10 specimens); frequent (11<sup>±</sup>100 specimens); abundant (101<sup>±</sup>1000 specimens); very abundant (c. 1001 specimens).

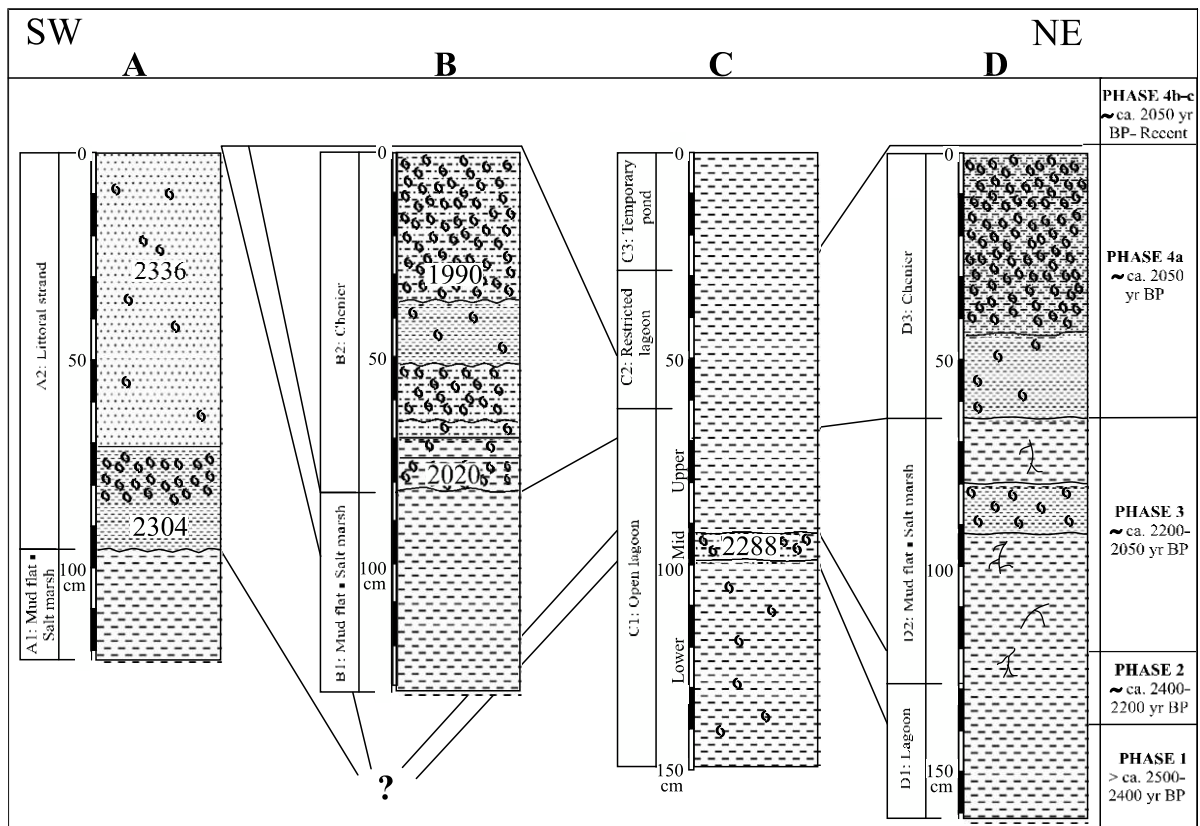


Fig. 6. Paleoenvironmental reconstruction and correlation of the cores, including the mean calibrated ages obtained.

found in Zone D2, indicating the emersion of the eastern sector during this phase. In this zone, the total mineralogy of the bottom lagoon and the intertidal areas is very similar (phyllosilicates, calcite and quartz).

The immersed area (upper part of Zone C1) presents a marked reduction of the ostracode density ( $\approx 500$  to  $200$ – $250$  individuals/g), disappearance or diminution of species adapted to quiet hydrodynamic conditions (i.e., *Cytherois øscheri*; Ruiz et al., 2000b) and the introduction of small marine ostracodes (*Neocytherideis subulata*, *Semicytherura incongruens*) and molluscs.

#### 5.4. Phase 4 ( $\approx 2050$ cal. yr BP–Recent)

This phase may be divided into three episodes. Cheniers (Zones B2 and D3;  $\approx 2000$  cal.  $^{14}\text{C}$  yr BP) are the most characteristic feature of the first

period (Fig. 6). These deposits are produced due to storms, sea-level changes, tidal fluxes, drift currents or biological crises (Augustinus, 1989), but the final result is the accumulation of massive beds (0.4–1.5 m thickness) of estuarine macrofossils over the intertidal–supratidal areas of the lagoon (boundary between Zones C1 and C2), with some additional marine specimens. The estuarine association is composed of the bivalve *Cardium edule* and numerous ostracode valves (*Cyprideis torosa*, *Loxoconcha elliptica*). In addition, some larger marine species ( $\approx 1$  cm length) of bivalves (*Venerupis decussatus*, *Corbula gibba*, *Donax vittatus*, *Crassostrea angulata*) and gastropods (*Rissoa* sp., *Calyptrea chinensis*) were transported, probably in saltation, from the coastal areas during these events (storms?, tsunami?, exceptionally high tides?), together with the suspension transport of juvenile instars of some ostracode species

(*Palmoconcha laevata*, *Pontocythere elongata*, *Urcythereis oblonga*), very frequent in these shallow zones (Ruiz et al., 1997).

The second episode (Zone C2) has been differentiated according to the diminution in the marine macrofauna (Fig. 4: *Venerupis decussatus*, *Rissoa* sp., spines of echinoderms) and the ostracode density. In this group, *Cyprideis torosa* is replaced by freshwater species, such as *Cyprinotus salinus* or *Cypridopsis vidua* (Bodergat, 1983; Bronshtein, 1988). In addition, the charophytes increase progressively towards the top of the core. These changes are interpreted as a more restricted tidal flux in this area, decreasing the marine inputs. In the area studied, the consequence is the partial isolation of a local depression between the chenier of Las Nuevas and the new, youngest levees, growing towards the south. Both the diminution of the marine influence and the domain of the fluvial component cause an environmental crisis in the estuarine assemblages.

The final episode (Zone C3) marks the definitive establishment of freshwater conditions. *Cyprinotus salinus* becomes the main ostracode species, with *Ilyocypris gibba*, *Cypridopsis vidua* and *Herpetocypris chevreuxi* as additional forms. The charophyte gyrogonites (mainly the genus *Chara*) are very abundant in these upper sediments. Today, this ostracode^charophyte assemblage is found in the temporary/permanent ponds (locally known as 'lucios') of the Doñana National Park (Ruiz et al., 1996). These ponds are small, shallow (61 m depth) waters with alkaline pH (7^10.6) and large water temperature variations (8^10°C in December^January and 25^30°C during the summer) (Serrano and Toja, 1995).

## 6. Late Holocene evolution of the Roman Lacus Ligustinus

In the last 2500 years, the paleoenvironmental changes of the southwestern Guadalquivir estuary have been registered both in the different geomorphological elements and in the succession of biological assemblages observed in the cores studied. Before 2400^2500 cal. yr BP, the inner estuary was formed by a wide, relatively quiet lagoon

(Fig. 7A: phase 1 in this work), with a clayey bottom colonized by numerous populations of the bivalve *Cardium edule* and an ostracode assemblage composed of *Cyprideis torosa*, *Loxoconcha elliptica* and *Leptocythere castanea*. The marine influence was strong, with introduction of shallow, coastal bivalves (*Venerupis decussatus*) and ostracodes (*Palmoconcha guttata*, *Palmoconcha laevata*) during the tidal fluxes. The Doñana spit was shorter and narrower than at present, with a good development of dunes (Rodríguez-Ramírez et al., 1996). Further north, this coastal lagoon was limited by emerged salt marshes, with an extensive development of fluvial levees, similar to digitate deltas (Rodríguez-Ramírez et al., 1997). This lagoon may be assimilated to the Lacus Ligustinus described by the chroniclers Strabo and Mela.

Between 2400 and 2200 cal. yr BP, an erosive phase (Fig. 7B: phase 2) occurred in this area. A high-energy event (storm?, tsunami?) broke the Doñana spit and opened a new communication with the sea, with generation of washover fan deposits represented in Zone A2 (Vetalengua). This event is also recorded by an erosive step in the different beach ridges of the Doñana spit (Rodríguez-Ramírez, 1996, 1998). In the inner lagoon, this opening caused the introduction of reworked, marine assemblages (middle part of Zone C1). This phase coincides with the final stage of an erosive phase defined by Zazo et al. (1994) and the presence of tsunami-induced deposits in the southwestern Spanish littoral (Luque et al., 2001; Lario et al., 2001, 2002).

In a third phase (Fig. 7C: 2200^2050 cal. yr BP), the estuarine infilling was the main feature and the new, western marine connection tends to disappear, in relation with the progradation of the Doñana spit (Rodríguez-Ramírez, 1996). The limited supply of marine waters entered the area in the eastern outlet, with a decreasing salinity in the inner lagoon. In this area, the development of fluvial levees originated the emersion of new areas, with an additional reduction of the marine influence. These new conditions caused a biological crisis in the estuarine assemblages, with a prominent reduction of the ostracode density.

This crisis increased during a later, unstable



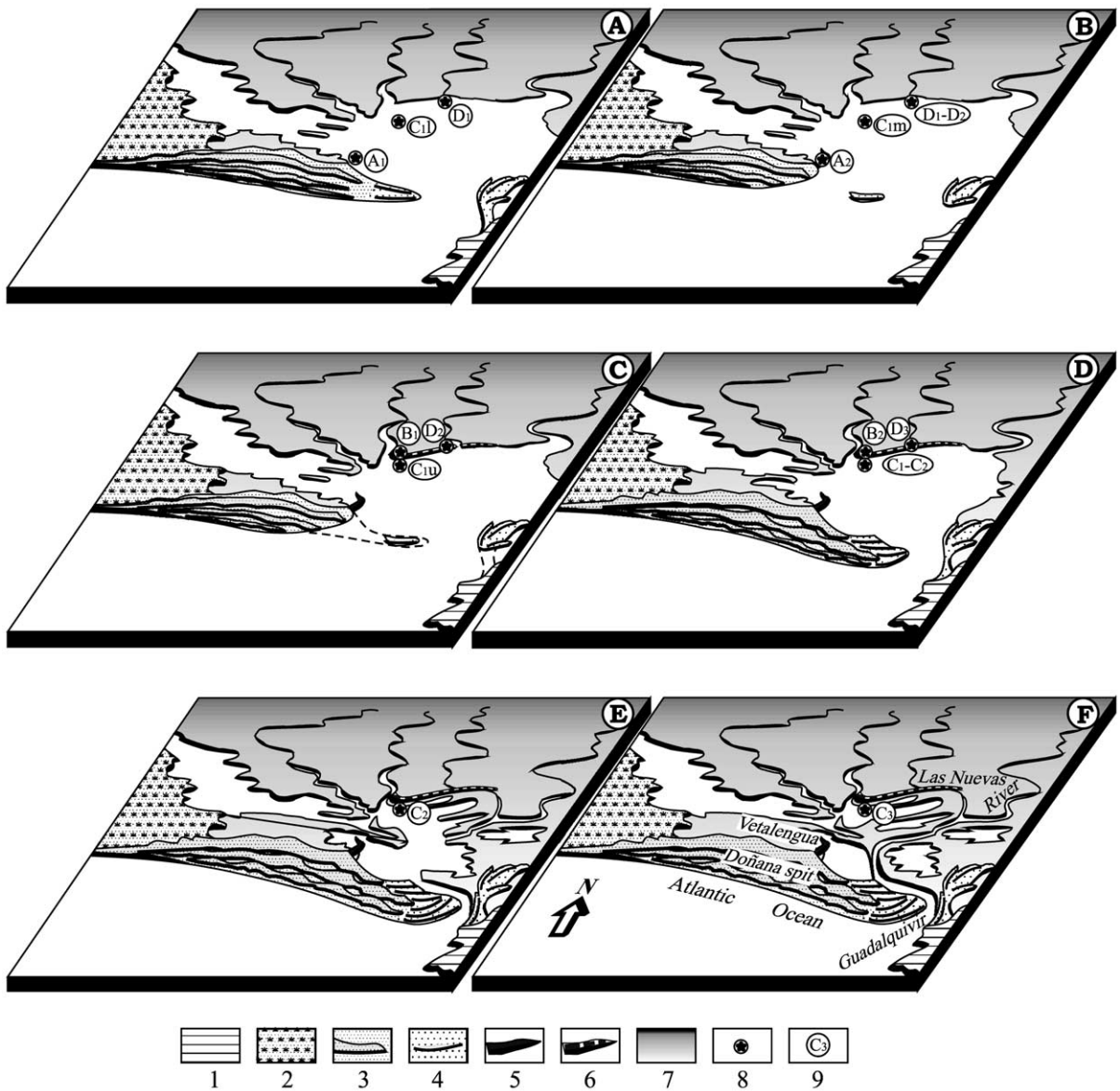


Fig. 7. Late Holocene evolution of the southwestern Doñana National Park. A: Phase 1; B: Phase 2; C: Phase 3; D: Phase 4a; E: Phase 4b; F: Phase 4c<sup>Recent</sup>. Key: 1: Plio-Pleistocene substratum; 2: stabilized eolian sands; 3: active eolian sands with dunes (gray); 4: littoral spits (ridges in gray); 5: littoral ridge of Vetalengua; 6: chenier of Las Nuevas; 7: marshes (and levees); 8: location of the cores; 9: microfossil zones (u: upper; m: middle; l: lower).

period (Fig. 7D:  $\nabla$ 2050 cal. yr BP). The clayey bottom of the Lacus Ligustinus was eroded by storms or other high-energy events, with accumulation of different bodies of mollusc shells (cheniers) over the previous emerged levees (phase 4a). Moreover, some marine species were introduced

into the lagoon via a single mouth, being deposited in the eastern part of these cheniers (upper part of the core D).

In the last two periods of this phase (Fig. 7E,F), the growth of fluvial levees and the estuarine infilling caused the final disappearance of the

Lacus Ligustinus. Some depressions are isolated between the new levees and cheniers, being periodically flooded by freshwater and/or tidal inputs. The clayey bottom of these 'lucios' is colonized by charophytes, one of the main foods for the numerous ostracode assemblages present, with characteristic, weakly calcified carapaces (upper part of core C). Today, these isolated areas are very common in this sector of the Doñana National Park (Serrano and Toja, 1995).

## 7. Conclusions

A Late Holocene evolution of the southwestern Doñana National park is proposed, based on the multidisciplinary analysis (texture, color, geomorphology, paleontology, mineralogy, dating) of the sediments present in four drill cores collected. This study makes it possible to delimit the geological features of the different paleoenvironments deduced: (a) open lagoon, with numerous bivalves (*Cardium edule*) and ostracodes (*Cyprideis torosa*, *Loxoconcha elliptica*, *Leptocythere castanea*) living in silty/clayey bottom sediments; (b) restricted lagoon, with a lower number of individuals of the same associations and the appearance of new, low brackish species; (c) temporary pond, with freshwater to low brackish ostracodes (*Cypriinotus salinus*, *Cyclocypris laevis*, *Ilyocypris gibba*) and charophytes; (d) salt marsh/mudflat, with numerous stems and roots and scarce microfau- na; and (e) littoral strand, with sandy sediments originated by the erosion of littoral spits during high-energy events.

In the last 2500 years, four phases have been distinguished, with a progressive estuarine incelling conditioned by the growth of fluvial levees and the progradation of the Doñana spit towards the east. This incelling was periodically interrupted by high-energy events, causing the breakthrough of the Doñana spit and the biological crisis of the estuarine faunas. This crisis induced a strong reduction of the estuarine assemblages (ostracodes and bivalves), with introduction of reworked marine faunas towards the inner estuary. Finally, the studied area is isolated as a temporary pond.

This study may present several practical appli-

cations. The correlation of this evolution with historical data makes it possible to delimit the evolutionary history of the Lacus Ligustinus, an old lagoon cited by several Roman and Spanish chroniclers. In addition, this integrated study presents an adequate geological explanation for the recent geomorphological features observed in this UNESCO-MAB Reserve, known worldwide for its biological diversity.

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## Appendix. Macrofossils and microfossils collected in the Doñana cores

Bivalvia  
*Acanthocardia tuberculata*  
*Anomia ephippium*  
*Cardium edule*  
*Corbula gibba*  
*Crassostrea angulata*  
*Donax vittatus*  
*Pandora albida*  
*Spisula solida*  
*Venerupis decussatus*  
Gastropoda  
*Calyptrea chinensis*  
*Cochlicella barbara*  
*Gyraulus laevis*  
*Helix* sp.  
*Melanopsis* sp.  
*Rissoa* sp.  
*Rumina decollata*  
Other macrofossils  
Scaphopoda  
Echinodermata (spines)

Ostracoda  
 Acanthocythereis sp.  
 Basslerites berchoni  
 Carinocythereis whitei  
 Cielocypris laevis  
 Cyprideis torosa  
 Cypridopsis vidua  
 Cyprinotus salinus  
 Cypris bispinosa  
 Cytherois øscheri  
 Herpetocypris chevreuxi  
 Ilyocypris gibba  
 Leptocythere castanea  
 Leptocythere fabaeformis  
 Leptocythere porcellanea  
 Loxoconcha elliptica  
 Loxoconcha rhomboidea  
 Neocytherides subulata  
 Palmoconcha guttata  
 Palmoconcha laevata  
 Pontocythere elongata  
 Semicytherura incongruens  
 Semicytherura sp.  
 Triebelina raripila  
 Urocythereis oblonga (= U. britannica)  
 Xestoleberis communis  
 Foraminifera (main species)  
 Benthic  
 Ammonia beccarii  
 Ammonia tepida  
 Astronionion stelligerum  
 Elphidium crispum  
 Globobulimina auriculata  
 Haynesina germanica  
 Quinqueloculina seminulum  
 Uvigerina peregrina  
 Planktonic  
 Globigerina bulloides  
 Orbulina universa  
 Other microfossils  
 Gyrogonites of Charophyta (mainly Chara spp.)

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