The record of the latter glacial and interglacial periods in the Guadalquivir marshlands (Mari López drilling, S.W. Spain)

El registro de los últimos periodos glaciares e interglaciares en las marismas del Guadalquivir (sondeo Mari López, S.O. de España).

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RESUMEN

El estudio de un sondeo de 65 m en las marismas del Guadalquivir permite reconocer siete intervalos que reflejan cambios climáticos y eustáticos e intensa neotectónica durante tres periodos interglaciares (IS 7?, 5 y 1) y dos glaciares (IS 6-Riss-, IS 4, 3 y 2-Würm). Se discute el valor de las 'vetas' como indicadores paleogeográficos.

Key words: *Glacial, Interglacial, radiocarbon, estuary, Pleistocene, Holocene, Doñana*

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Introduction

The geological history of the Plio-Quaternary sediments of Guadalquivir marshland (*marisma*) is poorly known partly duo to the monotonous lithology and the tectonic complexity of the basin. Salvany and Custodio (1995) correlated hydrological drillings and offered geological sections distinguishing four Units: Deltaic (Middle-Late Pliocene/Early Pleistocene), Alluvial (Late Pleistocene), Aeolian (Pleistocene/Holocene), and Marsh (Holocene).

The present Guadalquivir estuary (Fig. 1) is enclosed by the spits of Doñana and La Algaida (Lario, 1996, Rodríguez Ramírez *et al.*, 1996, Zazo *et al.*, 1996). After the maximum of the Flandrian transgression (ca. 6.500 ^{14}C yr BP), the estuaries in the Gulf of Cadiz experienced vertical aggradation until, ca. 2.500 ^{14}C yr BP, when coastal progradation and growth of spits prevailed (Zazo *et al.*, 1996). The estuarine barriers have been repeatedly studied (Goy *et al.*, 1996, Lario, 1996, Rodríguez Ramírez *et al.*, 1996) since Zazo *et al.* (1994) defined four spit units aged (reservoir effect corrected), H_1: 6.500-4.400 ^{14}C yr BP, H_2: 4.200-2.550 ^{14}C yr BP, H_3: 2.300-800 yr BP, and H_4: last 500 yr, and later cali-

Figure 1.- Geological map of the Guadalquivir marshland. Paleogene-Neogene includes olistostromes and allochthonous rocks. Key: (VC) Veta Carrizosa; (LN) Veta Las Nuevas-Tarajales; (LZ) Veta Los Zorros; (VQ) Veta Quemada; (VL) Vetalengua, (GM) Guadiamar-Matalascañas.

Figura 1.- Mapa geológico de la marismas del Guadalquivir. El Paleógeno-Neógeno incluye el olistostroma y otros materiales alóctonos. Siglas según pie en inglés.

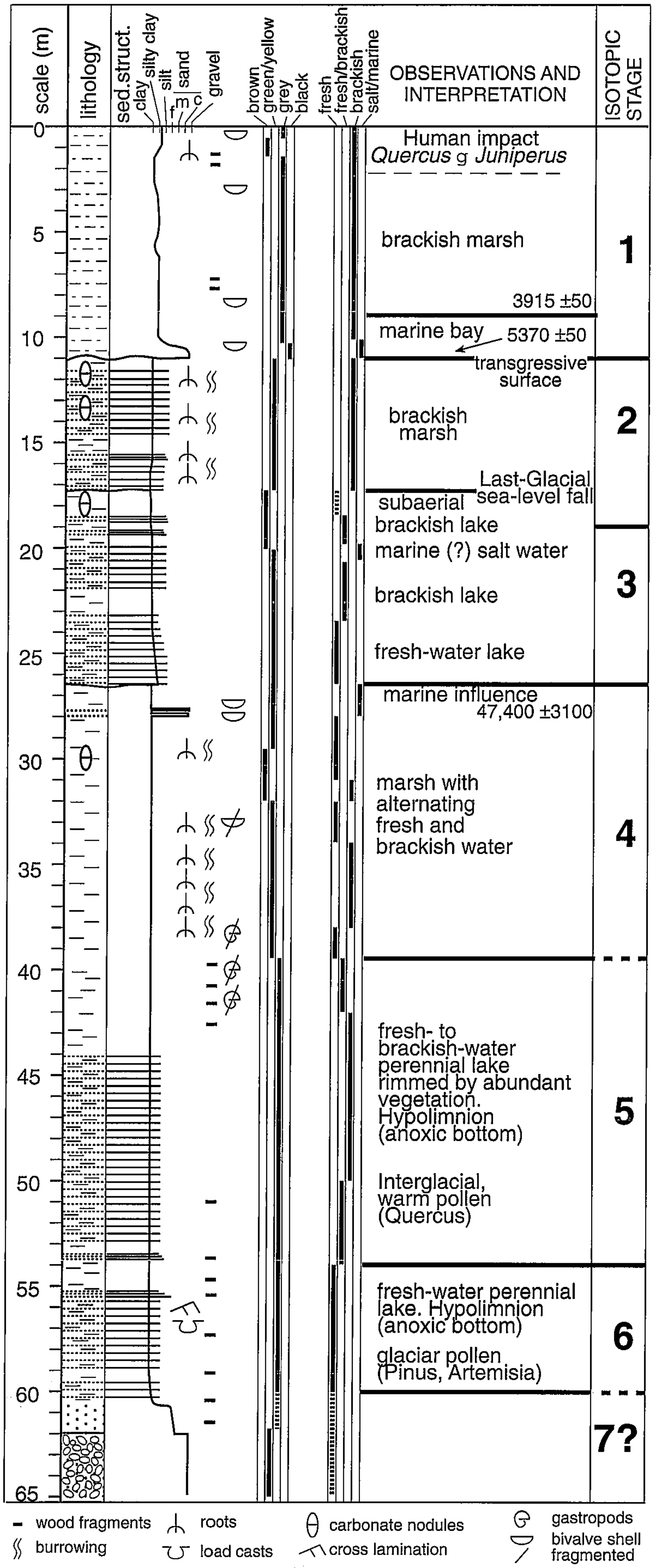

Figure 2.- Stratigraphic section of the Mari López drill core.

Figura 2.- Columna estratigráfica del sondeo Mari López.

brated by Borja *et al.* (1999). Dabrio *et al.* (in press) studied the post-glacial evolution of the Odiel-Tinto and Guadalete estuaries.

We offer the first palaeoenvironmental evolution of the Pleistocene–Holocene Guadalquivir estuary, based on the study of a 65 m-deep drilling, with additional information from other sources.

Geological setting

The semidiurnal mesotidal coast of the Gulf of Cadiz is of medium wave-energy, but prevailing south-westerly winds induce longshore drift and growth of spits to the south-east. The continental shelf extends 45 km, down to 130 m water depth, with average slopes of 0,28% (Rodríguez Ramírez, 1996).

The marshland covers 1.800 Km^2 with topographic elevations below +4 m (Fig. 1). Fluvial outflow in middle 19^{th} Century concentrated in the channels of Brazo del Este and Guadalquivir, whereas the flood tide entered the Brazo de la Torre to Isla Mayor (García Otero, 1847) and flooded the marshland, particularly in spring equinoctial tides. Silting up and public works have confined the tidal influence to the river channel.

Below the marshland, Plio-Quaternary deposits up to 300 m thick overlay unconformably the Late Miocene-Early Pliocene blue marls (Salvany and Custodio, 1995) and the olistostrome. Palaeozoic and Mesozoic rocks form the basement of the basin. Geomorphology and stratigraphic architecture of deposits evidence neotectonic activity at least until the Late Pleistocene along normal faults, promoting a domino tectonics that controls the drainage pattern of rivers and the present coastline. The most relevant faults are: (a) the E-W faults of Torre del Loro (Goy *et al.*, 1994, Zazo *et al.*, 1997, Zazo *et al.*, in press) and Hato Blanco [first deduced by Salvany and Custodio (1995), but named in this paper] located by geomorphological criteria; (b) the NNE-SSW faults of Guadiamar-Matalascañas (vertical offset ca. 150 m, Salvany and Custodio, 1995) and Bajo Guadalquivir (Viguier, 1977, Zazo *et al.*, 1985); and (c) the NW-SE system (Goy *et al.*, 1994, Flores and Rodríguez Vidal, 1994).

Estuary of Guadalquivir	Sample code	Locality	Laboratory code	^{14}C age yr (a)	Error yr ±	Cal BP age	$\delta^{13}C$ ‰ (PDB)	Material sampled	Depth (m)	Reference
Salt Marsh										
Drill core	**ML 97**	Mari López	GX–238339*	3915	50	3827	- 1.9	Shell	7.3	
Drill core	**ML 97**	Mari López	GX–23840-A*	5370	50	5680	+ 0.4	Shell	10.8	
Drill core	**ML 97**	Mari López	GX–23841*	47,400	3100		- 5.8	Shell	27.49	
Drill core	**LP13-1**	Lucio El Pescador	UtC–4028*	2490	60	2620		Twigs	7.3	(1)
Drill core	**LP13-2**	Lucio El Pescador	UtC–4031*	2490	105	2720	-2.9	Shell	7.3	(1)
Ridges *('vetas')*										
Trench	**MD-1****	Mari López	UtC–4024*	3240	100	3570	- 1.87	Shell	0.40	(2)
Trench	**MD-2****	Mari López	UtC–4177*	2720	100	2930	- 7.3	Shell	1.0	(2)
Trench	**VL-1**	Vetalengua	GX–21822	1625	115	1170	- 0.4	Shell	0.25	(2)
Surface	–	Vetalengua	R–2283	1730	90	-	-	Shell	0	(3)
Surface	–	Vetalengua	Beta–88016	1790	105	-	-	Shell	0	(3)
Surface	**LN-3**	Las Nuevas (Tarajales)	GX–21823	1960	120	1510	0.2	Shell	0	(2)
Trench	**LN-4**	Las Nuevas (Tarajales)	GX–21824	1955	80	1500	- 1.3	Shell	0.5	(2)
Surface	**LN-6**	Los Zorros	GX–21825	2895	75	2700	0.3	Shell	0	(2)
Surface	**LN-7**	Huerto del Caro	GX–21826	2010	110	1550	0.1	Shell	0	(2)
Surface	**VC4-1**	Veta Quemada	GX–21827	3160	130	2930	- 0.4	Shell	0	(2)
Trench	**VC4-4**	Veta Quemada	GX–21828	3180	85	2950	0.2	Shell	0.1	(2)
Surface	–	Veta Carrizosa	R–2273	4548	59	-	-	Shell	0	(3)

Table 1.- Data base of ^{14}C results, (1) Dabrio *et al.* (in press), (2) Dabrio *et al.* (1996), (3) Rodríguez Ramírez (1996). (m) Depth in meters below MSL (high-tide mark); (a) reservoir effect corrected (-440 ±85 yr BP); (*) AMS; (**) Reworked sample. Laboratories: (GX) Geochron Laboratories, Krueger Enterprises, Inc., Cambridge (USA); (UtC) Utrecht Van der Graff (The Netherlands); (R) Centro di Studio per la Geodinamica Applicata a la Stratigrafia Recente; (CNR) Dipartamento Fisica, Universita "La Sapienza", Roma (Italy); (Beta) Beta Analytic Inc. Miami, FL (USA).

Tabla 1.- Base de datos de muestras de ^{14}C según los trabajos y laboratorios indicados entre paréntesis. Profundidades en metros bajo el NMM (marea alta). (a) Efecto reservorio corregido (-440 ±85 yr BP). (*) AMS; (**) Muestra reciclada.

Methods

The borehole Mari López (ML–97, co-ordinates: 37° 01' 23" N; 6° 19' 56" W, elevation +2.5 m AMSL) was drilled using a rotation rig with core diameter 65 mm, to a depth of 65 m with continuous recovering. It is 400 m S.E. of the well 'Lucio de Mari López, Almonte' described by Menanteau (1979) and Salvany and Custodio (1995). We gathered information from cores of the neighbouring Lucio del Lobo, Lucio del Pescador (Lario, 1996), and Marismillas (Fig. 1), and trenches in Doñana (Zazo *et al.*, 1994, Borja *et al.*, 1999) and La Algaida (Rodríguez Ramírez, 1996) spits.

This study includes: (1) geological mapping of morpho-sedimentary units, (2) micropalaeontology (foraminifers and ostracods), macropalaeontology (including taphonomy), and palynology, (3) palaeomagnetism, particularly magnetic susceptibility, (4) mineralogical and textural analyses, (5) ^{14}C dating with accelerator mass spectrometry (AMS), (Table 1). Ages expressed in ^{14}C yr BP are normalised and corrected for marine reservoir effect (Table 1).

Palaeoenvironmental interpretation and chronostratigraphic results

According to our data from the neighbouring Lucio del Lobo drill core (Fig. 1), all the penetrated deposits are inside the Brunhes period of positive polarity. The magnetic susceptibility (MS) log shows a high anomaly (39.60 to 42.15 m) related to a notable increase in oxidative organic matter (Walkley and Black modified technique), but does not clearly depicts the peak at 11.90 m due to increased K and ^{232}Th.

We distinguish eight intervals, with limits at depths ca. 60, 54, 39, 27, 17, 11 and 9 m (Fig. 2).

Interval 65 (bottom) to 60 m is azoic. Predominance of quartz and fedspars upon scarce phyllosilicates and carbonates suggest deposition in clean, fluvial waters. This must represent the Isotopic Stage (IS) 7.

Interval 60 to 54 m. *Ammonia* sp., *Cyprideis* sp. and *Leptocythere* sp. characterise a fresh-water lake between 60 and 43 m. The pollen assemblage is typical of a glaciar period, with *Pinus* as a principal arboreal component and dominance of herbaceous steppe-like taxa such *Artemisia.* We interpret it as IS 6 (Riss).

Interval 54 to 39 m. Increase phyllosilicates and an oscillating decrease of quartz and feldspars (potassic and plagioclase) suggest more suspended load with frequent phases of settling of micas in a low-energy lake. *Hauffenia* sp. and *Cyprideis torosa* (43-39 m), dolomite and gypsum indicate brackish waters. The increase of *Quercus* pollen points to a more temperate climate and ample vegetal rims around the lakes. We interpret the warm event as Last Interglacial (IS 5), but its upper limit is uncertain.

Interval 39 to 27 m. Mineralogy evidences a quiet marsh environment dominated by settling, in fresh to brackish waters witnessed by ostracods (*Loxoconcha*, *Cyprideis* y *Leptocythere*), charofytes in two samples, reduced dolomite contents and absence of gypsum. Abundant macrofauna (*Ostrea*, *Cardium edule*) and microfauna (*Ammonia-Elphidium-Haynesina*) between 29 and 26.5 m suggest marine influence. We do not imply that the sea reached this elevation, but it should be close to it, and we interpret the alternations of fresh and brackish waters as eustatic oscillations with highstands below the present. As the age of sample ML 97, GX-23841 (47,400 ±3100, Table 1) is Last Glacial (Würm, probably IS 4), we correlate these oscillations with either one of the rapid glaciar retreats at 55–45 Ka (Duplessy *et al.*, 1998) or the highstand cited by Somoza *et al.* (1997) at ca. 60 Ka.

Interval 27 to 17 m. Detrital minerals (quartz, feldspar) increase at 27 m, followed upward by at least four 'pulses' or 'sequences' marked by small increments of detrital minerals, calcite and dolomite. Fauna and pollen are very scarce. We date this interval as IS 3 and correlate the event of marine influence at 19.75–20 m, indicated by miliolids and bryozoans with a glaciar retreat at ca. 33 Ka cited by Duplessy *et al.* (1998). We place the base of IS 2 (ca. 25 Ka) at 19m during subaerial exposure marked by fauna.

Interval 17 to 11 m. We interpret the change of colour and fauna, and the increase of sand at –17 m as the Last Glacial Period (ca. 18 Ka) when sea level dropped 125 m in this area (Somoza *et al.*, 1997) and the sea retreated 46.5 km.

Interval 11 to 9 m. An erosional surface at –11 m marks the Flandrian flooding surface overlain by a diversity of marine shells aged 5:370±50 ^{14}C yr BP (Tab. 1).

Interval 9 to 0 m (top). Halite, dolomite, some gypsum, macro and microfossils indicate restricted, brackish conditions in the muddy marsh where clay and mica prevail upon quartz and feldspar. The monotonous AP/NAP (Arboreal Pollen/ Non Arboreal Pollen) general index and specific taxa curves suggest a stable landscape physiognomy throughout this period until 2.15 m. In contrast, the increase in herbaceous taxa, the disappearance of Ericaceae (heather), and the progressive substitution of evergreen *Quercus* (Kermes oak) by *Juniperus* and *Pinus* (pine) in the topmost 2.15 m reflect unequivocally the impact of recent human populations. The prevalence of the fluvial input upon vertical accretion ca. 3.000-2.500 yr BP (H_2/H_3) caused restriction of marshes and a rapid growth of the estuarine barriers.

Linear ridges (*vetas*), shell accumulations and recent palaeogeographical evolution

Interpretations of the Late Holocene evolution of the estuary relay on geomorphology, palaeontology and radiocarbon dating of recent morpho-sedimentary units, particularly the narrow, linear, elongated sandy/silty ridges (the so-called *vetas*, Fig. 1) that barely rise 1.5 m above the muddy marsh ('marisma') and remain emergent during winter floods. Well preserved ridges follow former fluvial distributary channels. Geomorphological analysis demonstrates that the ridges generated as levees of channels, as suggested by Menanteau (1979). Accumulations, less than 25 cm thick, of shells pertaining to mixed biotopes (*Nassarius reticulatus, Murex brandaris, Truncularíopsis truncula, Bittium reticulatum, Ostrea sp., Cardium cf. glaucum, Glycymeris glycymeris, Dentalium*) cover the flanks of the ridges and the closest part of the adjacent marsh that face the prevailing winds from SW (Veta Quemada, Veta del Lucio de Mari López) and E/SE (Veta de los Zorros and Las Nuevas). The thanatocoenosis generated when wind-driven storm waves removed shells from the flat bottom of the marshes and accumulated them on the elevated levees, with gently inclined parallel lamination. This implies that, radiocarbon dating is inaccurate. Besides, the shallow-marine *Glycymeris* shells (that are usually collected for radiometric dating, Table 1) appear to have been carried by people to the inland *vetas* and used to pave the floor of huts, a cheap insulator still visible near Las Marismillas. Most huts have been demolished recently leaving behind the *Glycymeris* shells until run-off moved them to the thanatocoenosis at the toe of the ridge.

Conclusions

A multidisciplinary study of Mari López drill core permitted to recognise seven intervals, with limits at depths ca. 60, 54, 39, 27, 17, 11 and 9 m, that represent changing eustasy, climate, and neotectonics during two Glacial (Riss and Würm) and three Interglacial (7?, 5, and 1) Periods. Accordingly, the 'Marismas' unit (Salvany and Custodio, 1995) began to form at least in the Middle Pleistocene.

Neotectonic activity of NNE–SSW (Bajo Guadalquivir and Guadalquivir-Matalascañas, faults), E–W (Torre del Loro and Hato Blanco faults), and NW–SE fault systems in Middle-Late Pleistocene, together with eustatic oscillations explain the environmental pattern during IS 5 and IS 1 and the absence of Last Interglacial marine deposits.

Our interpretation the linear ridges (*vetas*) as fluvial levees, where storms and men mixed shells from diverse biotopes radically changes key assumptions concerning the genesis of the Holocene Guadalquivir estuary, namely: (a) The occurrence of *Glycymeris* does not necessarily indicate palaeoshorelines (as in Rodríguez Ramírez *et al.*, 1996); (b) The radiometric ages of *Glycymeris* shells collected from the ridges are unreliable palaeogeographical indicators.

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