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Estimating RSL changes in the Northern Bay of Cádiz (Spain) during the late Holocene

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***Abstract* – The Bay of Cádiz (SW Spain) is an example of long historical human occupation of a typical estuarine saltmarsh environment affected by notable historical changes that have conditioned the sedimentary evolution of emerged and submerged zones. This study aims to present new data regarding the RSL position during the late Holocene within the Northern bay of Cádiz. Bibliographic data coming from boreholes carried out in the study area were combined with the analysis of a new core. RSL positions, extracted from depositional sea-level index points, were calculated from saltmarshes and tidal deposits dated between 3.0-2.0 ky BP. Comparing these data with the new eustatic sea-level curve of the Bay of Cádiz carried out in this research, we observed that, during the last 3.0 ky BP, the sector has been affected by prevailing subsidence ranging between 0.9 m and 4.3 m.**

I. INTRODUCTION

The Bay of Cádiz, located within the Guadalquivir Tertiary Depression (SW Spain), is made of low-lying coasts that during the Holocene were affected by erosional and progradational episodes, with the development of subsequent beach ridge systems [1, 2, 3, 4].

The Bay, characterized by a mesotidal range of 2.1 m, has an average length and width of 30 km and 15 km respectively and it is mainly made of marshes, extending several kilometers inland and separated from the sea by sand barrier systems.

During the Quaternary, as a result of the N-S convergence between Africa and Eurasia, two main families of strike-slip faults (NE-SW and NW-SE oriented) formed along the southern Iberian coast. [5]

In the Bay of Cádiz such fault system controlled the distribution of emerged and submerged areas and led to the formation of two semi-circular embayments [6, 7].

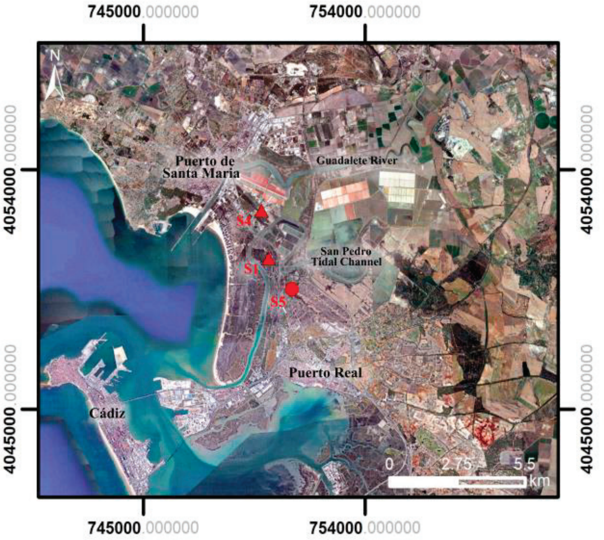

Fig. 1. Location of the study area, the boreholes S1, S4 (Alonso et al.[8]) and the new core S5.

Our study area, located in the northern sector of the Bay of Cádiz, is associated with the estuary of Guadalete River.

During the Pleistocene, the Northern Bay of Cádiz (between Puerto Real and Puerto de Santa Maria, Fig. 1) was affected by significant sedimentary aggradation through the deposition of 30 m of marsh and fluvial sediments. About 6.5 ky BP, the postglacial sea level reached its maximum height in this sector, flooding the former Pleistocene alluvial plains and converting them into a marine bay subject to a still active sedimentary infilling, with sediments mainly supplied by the Guadalete River [2, 3, 9, 10].

II. METHODS

A. Boreholes, stratigraphic analysis and dating

Stratigraphic data from two boreholes (S1 and S4), performed in the study area and published in Alonso et al., 2015, have been revised and combined with those from a new core (S5) carried out in June 2008 and still unpublished. The boreholes are related to a research project elaborated by Gracia and Martín [11]. The obtained continuous cores were stored in appropriate coring-boxes and kept at the laboratories of the University of Cádiz. The description of the cores was carried out in three stages, an initial visual description of the sediments (type, colour, presence of organic remains and organisms), a detailed analysis of the sand fraction using a stereomicroscope, and analysis of the clay fraction on a petrographic microscope. All the detected features were used to define different lithofacies and sedimentary units on which all the boreholes were associated.

Macrofossils such as fragments of shells and roots, as well as bulk sediments where macrofossils were not found, were used for radiocarbon dating at the Centro de Nacional de Aceleradores (CSIC-Spain). Four samples were taken at different depths in boreholes S1, S4 and S5 in levels including rests of skeletons or valves and near the main facies transitions for ^{14}C age determination. Samples were pre-treated with organic solvents and cleaning with AAA. Calibration was made according to curve Marine13 (probability of 95%) [12] by using Calib Rev. 7.0.4 software [13]. A correction had to be made due to the reservoir effect of marine radiocarbon (ΔR), very important in the coasts of the Gulf of Cádiz [14]. In the present work, a weighted value of the reservoir effect of $\Delta R = -108 \pm 31$ ^{14}C years was applied [15].

B. Depositional sea-level proxies

The stratigraphic analysis carried out in this research led to the identification of 4 depositional units, related to specific environments. The recovery of shells fragments inside these layers enabled the dating of different samples characteristic of the Units 3 and 4 and respectively related to saltmarsh and intertidal environments.

According to Vacchi et al. [16], saltmarshes are generally located close to large deltas and coastal lagoon and their samples can be used as sea level index points (SLIPs) by calculating their Indicative Meaning (IM, senu Shennan [17]). We assume for this kind of samples an Indicative Range (IR) ranging from the HAT (sensu Shennan, [17]) to the MSL [16] and a RWL equal to the half of the IR.

The samples collected from intertidal deposits have been used as SLIPs considering an IM with an IR ranging between the MHW and the MLW and a RWL equal to the half of this IR.

Knowing the above-mentioned values, the RSL positions were estimated using the formula proposed by Shennan [17]:

$$RSL = E - RWL \tag{1}$$

Where E is the elevation of the sample (m above MSL).

C. Reconstruction of the RSL curves

The local RSL changes are primarily affected by glacial- and hydro-isostatic adjustment (GIA), which regulates the response of the solid Earth and of the geoid to the melting or accretion of continental ice masses. The GIA-driven RSL changes are described by the gravitationally self-consistent sea level equation (SLE). Solving the SLE for a prescribed ice-sheets chronology and solid earth rheological model [18], yields the regionally varying RSL change over time. The latter strongly depends on the rheological parameters that define the solid Earth model which is assumed to be spherically symmetric, self-gravitating, rotating, radially stratified and characterized by linear Maxwell viscoelastic layers. A suite of RSL curves were produced by using ANICE-SELEN coupled ice-sheet - sea-level model [19]. The sea-level equation (SLE) has been solved for a total of 18 models (6 mantle viscosity profiles x 3 lithosphere thickness). We assumed three values of lithosphere thickness, respectively of 60 km, 90 km and 120 km, and we considered values for the lower, intermediate and mantle viscosity ranging between 2-10, 0.5-1 and 0.2-0.5 Pas, respectively.

III. RESULTS

A. Analysis from the cores

The sedimentological analysis of the cores included in this study reflects the main geomorphological and sedimentary elements presently recognizable in the Bay of Cádiz. In particular:

- S1: This core, with a maximum depth of 6.5 m, was performed in a tidal plain area, inside a palaeomeander of the ancient Guadalete River. The succession is composed of three different sedimentary units (Table 1). The lower unit (U4) is characterized by sandy facies interpreted as the remains of an estuary channel of the Guadalete River. This hypothesis is in accordance with the interpretation of borehole PSM109 performed in the same location by Dabrio et al. [2]. The upper sedimentary units (U1, U3), made of muddy sands and clays, testify the transition from an estuarine environment to a salt marsh system. Unit 4, interpreted as saltmarsh deposit, was used as a SLIP due to the radiocarbon dating of a shell founded in living position, with an age of 2.8 ky BP.
- S4: This core, located in the inner sand bar of the

old H2 beach ridge [2, 4], has a sedimentary sequence 5 m long and the observation of the stratigraphy led to the identification of 2 sedimentary units (Table 1). The first one (U2, upper 2.4 m), represents a washover deposit, characterized by coarse sands with mollusc fragments. The second unit (U3) is mostly constituted by clays, with a major content of organic matter and remains of macrofauna, and interpreted by Alonso et al. [8] as a typical saltmarsh deposit, here used as SLIP. The ^{14}C calibrated dating carried out from shells, founded in living position and located both at the top and the base of U3, established the formation of the salt marsh between 1.88 and 2.8 ky BP.

- S5: The core is located in the tidal plain developed to the south of San Pedro tidal channel and reaches a maximum depth of 6 m. Three different sedimentary units were identified (Table 1). In this case, the deposition of sediments is characterized by a cyclic sequence with the alternation of muddy and sandy facies. The stratigraphic succession is similar to the one of S1, but in S5 a stable establishment of salt marshes has been recorded for a shorter time span. The ^{14}C calibrated dating performed on a shell in living position established the age of 3.1 ky BP for the base of unit U4.

Table 1. Stratigraphical description of the boreholes and environmental interpretation of the deposits

Cores	Unit	Lithofacies	Env. Int.
S1	U1	Dark brown clays with remains of thin roots and amorphous aquatic material. Coarsening upward.	Dried-up saltmarsh
		Yellow sands with remains of roots similar to the upper level. Finning upward.	
		Grey sandy muds with shells remains. Finning upward.	
	U3	Brown muddy sands with no remains of organic matter. Coarsening upward in the first 30 cm and subsequent homogeneity	Active saltmarsh
	U4	Yellow sands similar to the previous level but with a different colour that may represent a transitional period.	Transitional environment
		Coarse-grained sands with visible quartz grains. Abundant shell macro-fragments. Rounded grains of small size at the base, finning upward.	Tidal environment
S4	U2	Brown sands with remains of roots. Low content of water. Present soil.	Washover fan (high energy)
		Yellow fine sands with abundant remains of marine bivalves, gastropods and other organisms.	
	U3	Grey clays with remains of herbal organic matter and foraminifer shells.	Active saltmarsh
	U4	Silty clays with organic remains of amorphous aquatic material and coal.	Tidal plain with fluvial influence
S5	U1	Brown clays with macro-fauna remains (shells). Coarser grains at the base.	Dried-up saltmarsh
		Dark yellow fine sands with shell remains.	Energetic event
	U3	Greyish clays.	Active saltmarsh
		Dark brown muddy sands.	
	U4		Tidal channel

B. *RSLs evaluation*

On the basis of the methodology described in section II of Methods, the related RSLs associated with samples coming from saltmarsh deposits were calculated taking into account that in the Gulf of Cádiz the value of the highest astronomical tide (HAT) is 1.89 m MSL, considering the closest tide gauge to the studied sector [20] (Table 2).

Instead, the RSLs related to samples collected from intertidal deposits were deducted taking into account that in the Gulf of Cádiz the mean high water (MHW) and the mean low water (MLW) are respectively equal to 1.05 m MSL and -0.93 m MSL, considering the closest tide gauge to the study area [20] (Table 2).

Table 2. RSLs from sea-level index points (SLIPs).

Sample	Unit	yr BP	IR	RWL	RSL (m MSL)
S1_a2	U3	2863±134	HAT to MSL	(HAT to MSL)/2	-4.14 ± 0.94
S4_a1	U3	2886±138	HAT to MSL	(HAT to MSL)/2	-2.64 ± 0.94
S4_a2	U3	2005±132	HAT to MSL	(HAT to MSL)/2	-1.14 ± 0.94
S5_a1	U4	3114±212	MHW to MLW	(MHW to MLW)/2	-4.79 ± 0.99

IV. DISCUSSION AND CONCLUSIONS

The RSL positions obtained from the depositional SLIPs (with their specific vertical and horizontal uncertainties) were compared to the eustatic values of the sea-level curve proposed for the area (Fig. 2).

Such a comparison suggests that a prevailing subsiding trend affected the Norther Bay of Cádiz during the last 3.1 ky BP.

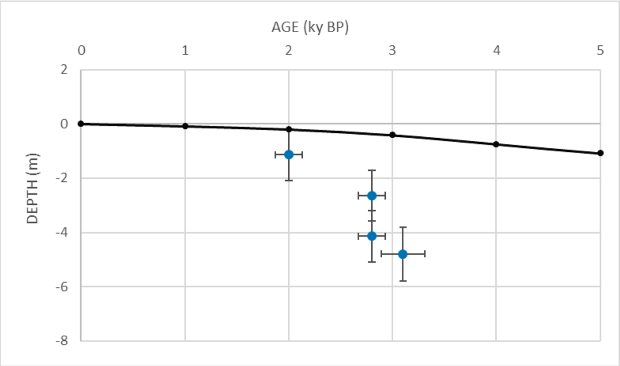

Fig. 2. Graph of the relative sea-level measurements carried out from the depositional SLIPs compared to the GIA model (ANICE-SELEN ice-sheet - sea-level model) proposed for the Gulf of Cádiz.

Such phenomenon progressively reduced its effect as testified by the values of the local vertical displacement (VD) decreasing with time.

In particular, the value of the subsiding rate is 1.4 mm/yr for the SLIP dated at 3.1 ky BP, with a VD of -4.34 m, and 0.47 mm/yr for the younger sea-level marker dated at 2.0 ky BP, with a VD of -0.94 m. In accordance with this trend, the subsiding rate for the SLIPs dated 2.8 ky BP is equal to 1.07 mm/yr, with a mean VD of -3.0 m.

The detected subsiding trend can be interpreted as the main effect of the sediment compaction affecting the youngest deposits of the coastal plain [21, 22, 23, 24].

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