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The western lagoon marshes of the Ria Formosa (Southern Portugal): Sediment-vegetation dynamics, long-term to short-term changes and perspective

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Abstract

The study concerns the lagoon marshes of the "cul-de-sac" of Ancão (CDSA), situated in the western part of the Ria Formosa. The aim of this article is to propose a quantification of the sedimentary volume in lagoon marshes on the long-, medium- and short-term, to precise the respective part of the natural and human factors driving the sedimentary changes, and to put in perspective the results with the predictions on the rise of sea level. The environmental analysis is based on a set of botanical, morpho-sedimentary and chronological (^{14}C, ^{137}Cs, ^{210}Pb, ^{226}Ra) indicators, on the use of surface marks to measure the vertical growth of saltmarshes, and on the photo-interpretation. Results show that the present available volume of fine-grained sediments represents ~1,549,215 m^3. The muddy deposits are concentrated both in the upstream (30%) and downstream (63%) part of the CDSA. The pluri-secular accretion rates (0.4 mm/a between 1681 BC and AD 2001) obtained in the Holocene Ludo ria are relatively low, compared with the pluri-10-year accretion rates (8–9 mm/a between AD 1941 and AD 2000) calculated from the excess ^{210}Pb and ^{137}Cs activity concentrations. On the short-term (AD 2000–2002), the measures of accretion rates confirm field observations, namely a critical situation where saltmarshes are in dominant erosion. Changes in sedimentary secular trend, spatial heterogeneity of present accretionary deficit and preservation potential of the CDSA marshes are discussed.

Keywords: Ria Formosa; Lagoon marsh; Vegetation map; Marsh levels; Radiometric dating; Sedimentation rate; Marsh erosion; Sedimentary volume

1. Introduction

Lagoon marshes, as transitional coastal environments located at the land–sea interface, constitute an original category of tidal marshes. On the marine side, they are bounded both by mobile barrier-islands and peninsular spits whereas on the terrestrial side

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their intertidal surfaces are limited by several inherited relief features. This double physical constraint is particularly strong in the lagoon marshes of the Ria Formosa (Fig. 1), in the context of high mesotidal regime and absence of coastal plain (Pilkey et al., 1989).

Since lagoon marshes occupy the transitional zone between terrestrial and marine environments, they are strongly vulnerable to erosion and submergence by rising sea level and negative accretionary balance (e.g., accretion rate minus relative sea-level rise—RSLR). Sustainability of lagoon marshes threatened by rising sea level and negative accretionary balance will depend on landward migration and accretion rates (French and Spencer, 1993). In the Ria Formosa, the terrestrial-side boundaries of lagoon marshes strictly depend on inherited landforms and human actions, that considerably limit the adjustments of the landward marshes. Furthermore, accretion rates depend on sedimentation processes and accumulation of organic matter derived from net primary production of marsh vegetation (Reed et al., 1999). In the Ria Formosa, the sedimentary balance of lagoon marshes was altered by human activities and many marshes do not receive sufficient sedimentary inputs to support their growth. In the mean time, the marsh vegetation was affected by water pollution (Newton et al., 2003).

In the year 2000, the program APN-Ria Formosa supported by the French Centre for Scientific Research (CNRS) was developed with the aim of defining the medium- to short-term evolution and conditions of conservation of lagoon marshes which was recently (1987) given National Park status. The present study focuses on the lagoon marshes of the "cul-de-sac" of Ancão (abbreviated CDSA in the text). In this western part of the Ria Formosa lagoon, the interference of human activities with natural processes are particularly marked and threatening for conservation of marshes. The environmental analysis is based on a set of botanical and morpho-sedimentary indicators, and on the use of the photo-interpretation. The goal of this paper is

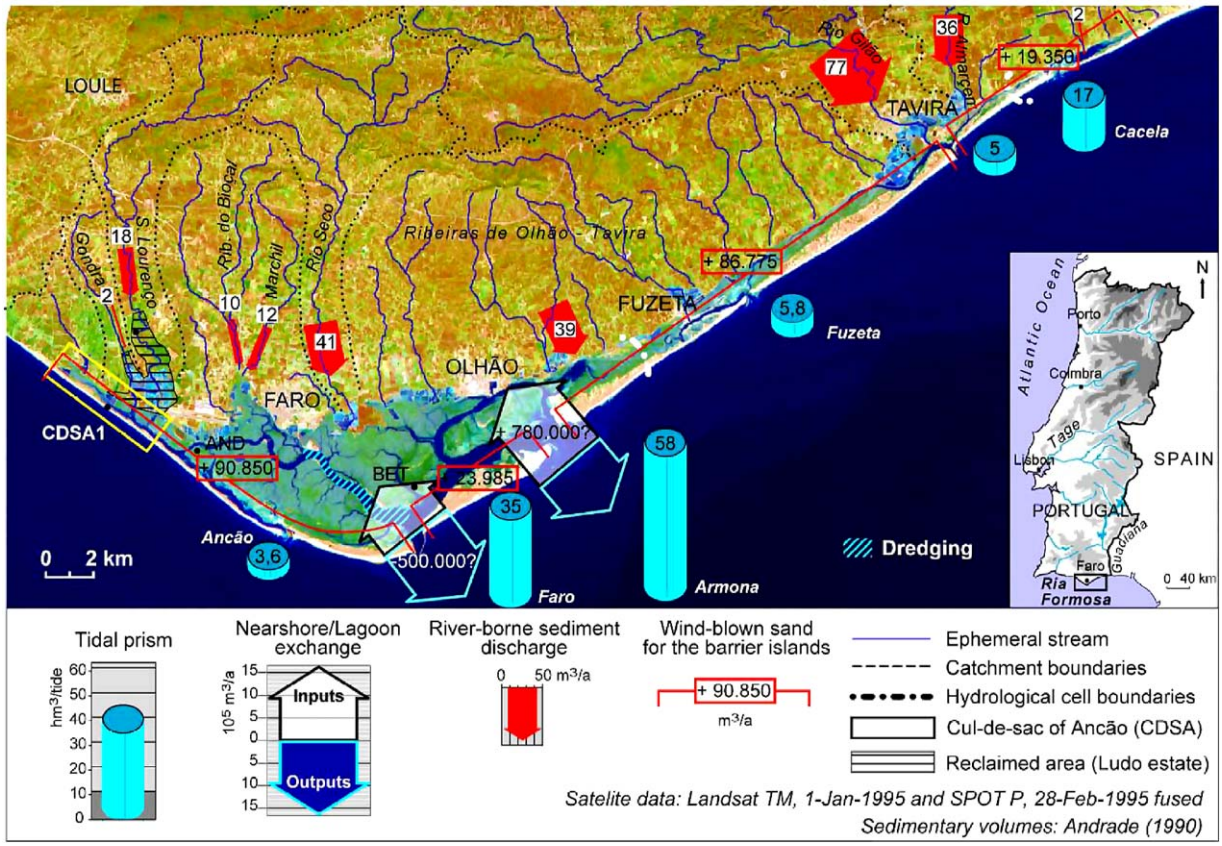


Fig. 1. Location of study area in the lagoon marshes of the Ria Formosa, Southern Portugal.

Table 1
Classification of vegetation communities in the "cul-de-sac" of Ancão, Ria Formosa, Southern Portugal (see also Fig. 1)

Mapping unit	Classification of European habitats (code)
Low marsh	
1. Continuous saltgrass meadows	Annual glasswort swards (15.1111)
2. Discontinuous saltgrass meadows	Flat-leaved [*Spartina*] swards (15.21)
Lower middle marsh	
3. Creeping glasswort mats	Creeping glasswort mats (15.611)
4. Creeping glasswort and salt-grass mosaic	Flat-leaved [*Spartina*] swards (15.21)
Upper middle marsh	
5. Continuous sea-purslane thicket	Mediterranean sea-purslane thicket (15.616)
6. Discontinuous sea-purslane thicket	
7. Woody glasswort shrub	Woody glasswort scrubs (15.612)
8. Sea-purslane and red glasswort mosaic	Upper-shore glasswort swards (15.1133)
High marsh	
9. Mediterranean thermo-Atlantic scrubs	Mediterranean saltmarsh driftlines (15.56)
	Glaucous glasswort thickets (15.613)
	Shrubby seablite thickets (15.614)
	Mediterranean *Limoniastrum* scrubs (15.63)
Brackish water vegetation	
10. Previous reclaimed marshes (salgados)	*Halophile scirpus* beds (53.11)
	Mediterranean fine-leaved rush beds (15.58)
	Seablite-samphire communities (15.1112)
Dune vegetation	
11. Shifting coastal dunes occupied by open grasslands	Halo-nitrophilous pioneer communities (15.12)
	Embryonic shifting dunes (16.211)
	Shifting dunes along the shoreline with [*Ammophila arenaria*] white dunes (16.212)
12. Fixed (grey) dunes occupied by perennial grasslands	Mediterranean–Atlantic grey-dune (16.233)
	Malcolmietalia dune grasslands (16.228)
Other vegetation	
13. Plantations	*Acacia* plantations (83.3)

(1) to propose a quantification of sedimentary volume in the lagoon marshes, on the long-term (1700 BC–AD 2000), the medium-term (20th century) and the short-term (AD 2000–2002), (2) to discuss the respective part of the natural and human factors leading this evolution, and (3) to put in perspective the results with the predictions on future RSLR (Table 1, Fig. 2).

1.1. Physical and human context of lagoon marshes

Situated in the northwest part of the Bay of Cadiz, the Ria Formosa is a large (111 km^2) coastal lagoon extending along the eastern part of the south coast of Algarve, between Olhós de Agua and the mouth of the Guadiana River (Fig. 1). The Algarve region is characterised by a Mediterranean climate (Csb or Csa according to Köppen's classification), with hot, dry summers and warm, wet winters.

According to the geomorphological concept of barrier-system (Oertel and Woo, 1994) and the stratigraphical model of the Ria Formosa proposed by Bettencourt (1994), the CDSA corresponds to an environmental system characterised by several fitted morpho-sedimentary units due to the contraction of the lagoonal basin. The backdrop of the marsh landscapes is represented by the metasediments of the Serra massif and by the late-Pleistocene fluviatile unconsolidated sands ["formation of Quarteira" (Chester and James, 1995)] of the piedmont slope. The geological basement of the lagoon marshes is constituted by sands of barrier platform, reshaped in a prism that degraded during the slowing down of the RSLR from 6000 BP

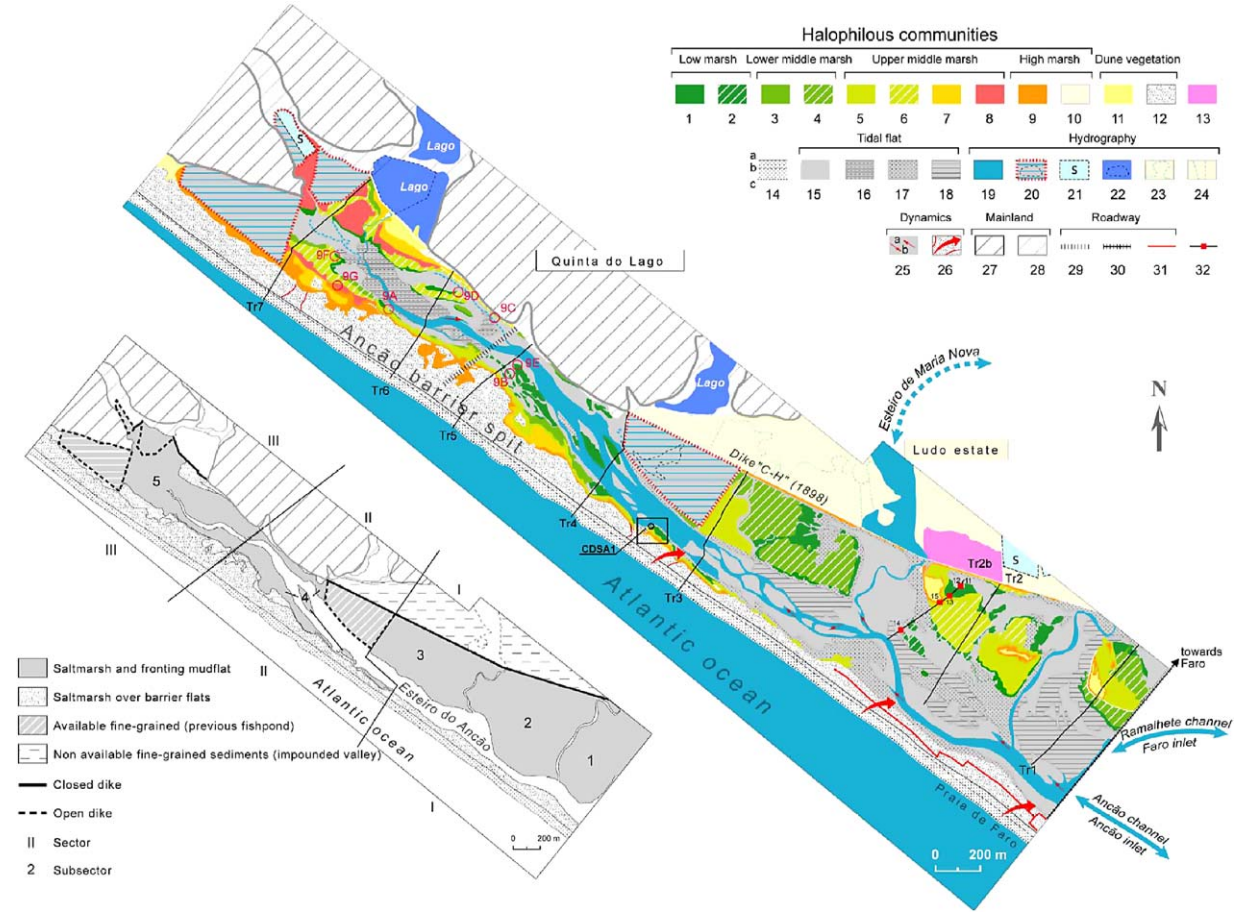


Fig. 2. (A). Ecological map of the Ancão lagoon marsh, Ria Formosa, Southern Portugal. 1–13: see Table 1; 14: ocean beach and related significant lines (a: backshore line; b: high water line; c: swash line); 15: bare mudflat; 16: mudflat with erosional spurs and grooves; 17: sandflat; 18: mudflat exploited for clam gathering; 19: tidal channel at mean low water; 20: former reclaimed marsh (fish pond); 21: salt pond; 22: artificial lake; 23: palaeochannel; 24: former drain; 25: flood (a) and ebb (b) rills; 26: washover fan; 27: plateau (glacis); 28: embanked small valley; 29: footbridge; 30: road bridge; 31: constructions; 32: transversal transect and measuring site. (B) Morpho-sedimentary subdivision of the CDSA, Ria Formosa, Southern Portugal.

(Bettencourt, 1994). Stratigraphical studies (O'Connor et al., 1998) show that tidal channel, ebb-delta and saltmarsh constitute the main depositional sub-environments of the barrier platform. The saltmarshes are separated from the sea by peninsular sand spits and barrier islands. In particular, the Ancão spit was connected to the continent during the tsunami of 1 November 1755. Then, the migration of the spit towards the continent was linked to rollover mechanism. The recent overwash events were responsible for the partial burial of marshes connected to the spit. This latter evolves longitudinally under the control of (1) a powerful littoral drift oriented W–E (130,000 m^3/a), fed from the erosion of the cliffs of Barlavanto coast (Granja et al., 1984; Andrade, 1990; Bettencourt, 1994), and (2) the cyclic migration of the tidal inlet of Ancão (Balouin, 2001; Andrade et al., 2004).

With a tidal range varying from 1.1 m (neap tide) to 3.8 m (spring tide), the tide is the dominant energy input. The CDSA is included in the western hydrodynamic cell of the Ria Formosa (Sallès, 2000) in which the inlets of Ancão, Faro and Armona represent, respectively, 9%, 60% and 31% of the exchanges of water (97 hm^3) between the ocean and the lagoon (Andrade, 1990). However, the main part of sediments transferred to the lagoon by the ebb is confined to the immediate neighbourhood of the inlets. So the CDSA is away from the domain of redistribution of marine sediments by

tide. The sedimentary exchanges between the CDSA and the ocean by overwash processes seem much more significant. The whole peninsula can be submerged during a 5-year storm, with a positive storm-surge of ~0.5 m (Andrade, 1990). This phenomenon puts the problem of the maintenance of the lagoon marshes in the CDSA, in the context of RSLR estimated for the period AD 1910–1990 at Lagos to 1.5 ± 0.2 mm/a, including the probable crustal uplift (0.3 ± 0.2 mm/a) proper to the Lagos station (Dias and Taborda, 1992). Furthermore, the wind is an important dynamic agent that it is necessary to consider in the sedimentary balance of the CDSA. A quantification of both longitudinal and transversal aeolian fluxes shows that dunes of the CDSA supply annually 90,850 m^3 of sands towards the continent (Andrade, 1990). This volume is almost the same that the resulting from the tidal accumulation (76,500 m^3/a) observed on the internal side of the Barra Nova inlet (Vila-Concejo et al., 2002). It exceeds even the sediment discharge yielded by the main rivers of the CDSA, the São Lourenço (18,700 m^3/a) and the Gondra (2400 m^3/a), which supply practically no more sediment in the lagoon, since their alluvial plain was impounded at the end of the 19th century.

Although they widely declined today, the agricultural activities developed from the end of the 19th century both in Gondra and São Lourenço rias altered durably the configuration and the hydrosedimentary functioning of the CDSA (Arnaud-Fassetta et al., 2002; Goeldner-Giannella et al., 2003). The impoudments of these two estuaries reduced the surface of the intertidal basin of ~5.6 km^2. These engineering works were responsible for the eastward migration and for the chronic instability of the tidal mouth of the CDSA (Bettencourt, 1994; Balouin, 2001). These anthropogenic alterations also modified the geometry both of the tidal channels and marshes. During the 20th century (1923–1976), the Ancão Channel recorded a considerable widening (up to several hundreds of metres), as a consequence of the distance of the mouth and erosion of the marshes. From the end of 1970s, the intensification of the irrigated agriculture, tourism and urbanisation of the continental margins of CDSA profoundly modified the functioning of lagoon marsh. The punctual discharges of urban effluents as well as the diffuse pollution of the subterranean waters lead to the eutrophication of marshes (Newton et al., 2003). Today, the lagoon marsh is a complex network of tidal channels, some of which are navigable to join the main ports like Faro, via natural or artificial inlets. The new inlet (Barra Nova) of Ancão, opened artificially more on the west in June 1997 during the INDIA project (Williams et al., 2003; Andrade et al., 2004), constituted a pole of important sandy supplies derived from the erosion of the external platform (Bertrand et al., 2003). Since the end of the 18th century its position varied between the present road bridge, situated at 5.5 km from the spit root, and a limit point reached in 1997, 5.5 km farther in the east (Vila-Concejo et al., 2004). In addition, the navigable channels have been extensively dredged since the last years. The average depth of the navigable channels is ~6 m, but most sections are less than 2 m deep.

2. Analytical methods of vegetation and sediment dynamics

2.1. Sampling areas and delimitation of plant communities

The CDSA was surveyed using vegetational profiles running in a grid of shore-normal transects. Line transects (height in all) focused on selected areas where the plant communities were representative of phytosociological associations that had already been recognised using the classic hierarchical phytosociology approach (Costa et al., 1996). Sampling was led in order to obtain an equivalent number of samples for each type of vegetation. Transects were defined so as to cross the various vegetation communities while taking into account topographical and substrate modifications. Relations between the distribution of the vegetation and topography could be specified thanks to planimetric and altimetric surveys obtained using a system of Differential Global Positioning System (D-GPS) that delivers measurements with centimetric precision.

Saltmarsh communities were defined according to the methods of integrated synusial phytosociology approach (Gillet, 1998) as followed. In a first stage, the work concerned the recording plant composition and dominance in quadrats, considering the dominance of an adaptive strategy (Raunkiaerian life form, morphological type). In a second stage, the transects served to identify particular spatial sequences which were also used for grouping units communities (synusiae) organised spatially and functionally within the same bionomic level (low/middle/high marsh). The reference work for this study is the hierarchical classification of habitats produced through the Palaearctic Habitat programme built on the former

CORINE classification (Devillers and Devillers-Terschuren, 1996).

At a higher level, the comparison of various sequences ensured that plant distribution was not only a reflection of altitude but could also be related to physiographic features such as environmental settings and sediment type or anthropogenic factors (impoundments), modifying the occurrence of distinctive communities (zonation).

2.2. Mapping and description of saltmarsh vegetation

Land cover map of CDSA was generated by remote sensed images acquired from aircraft platform. The information was extracted by an image interpretation supported by surface level signature verification and species identification. Mapping of habitats was performed from several overlapping vertical photographs registered with ER Mapper© software to the same geographic *datum* and to the same map projection before being displayed into a RGB unbalanced image mosaic to create a continuous representation of the area. The image of January 1999 (mission Uaga-F, no. 13160) was chosen since its true colour emulsion gives more information than black and white or infrared films. Furthermore, its 1:16,000 scale seemed to be a good compromise among resolution of signatures, coverage of coastal habitats and inclusion of land features for control. In addition, tide around 10:00 AM at the acquisition date approaches mean low tide as predicted in Portos de Sotavento tide tables (Agenda dos Portos de Sotavento do Algarve, 1999), allowing an optimal visualisation of both emergent communities (saltmarsh) and submerged communities (seagrass communities) located above water line. The spatial resolution (1.35-m pixel size) of the 300 dpi scanned paper prints and the spatial extent of the area (6.21 km^2) were the two key issues in the definition of a 1:20,000 scale mapping. Although some land cover categories such as *Spartina* grasslands may have a very low minimum measurement unit due to the distinctiveness of their signature, the minimum mapping unit of 400 m^2 imposed a determined polygon size for all land cover categories.

2.3. Strategy of sampling to estimate the thickness of sediment and accretion rates

The measure of thickness of sediments and chronological data allowed us to obtain accretion rates in the marshes at three scales of time.

Long-term (1000–100 years) accretion rates: a campaign of boring with a manual auger (∅ 50 mm) was realised in March 2001 in the sector of Ludo, at once near the CDSA. Two boreholes (LU6 and LU10), among the 10 realised, revealed sedimentary units containing enough organic debris to be dated by ^{14}C. Two AMS ^{14}C dates [Lyon-1811 (GrA-20833) and Lyon-1812 (GrA-20834)] were obtained by dating the organic matter (ligneous macroremains) accumulated syndepositionally in fine-grained sediments. The analyses were supervised by the Centre de Datation par le Radiocarbone, université Claude-Bernard (Lyon 1). The ^{14}C ages were converted to calendar years using the curve of Stuiver et al. (1998).

Medium-term (100–10 years) accretion rates: a natural (e.g., erosional scarp) stratigraphic section (CDSA1) was exploited on the marsh shoreline of the CDSA with the aim of characterising/dating the sedimentary units of the marsh. Sampling of the marsh sediments was obtained in November 2000 by collecting 5-cm intervals from a stratigraphic section 0.8 m in height. The site was selected to be representative of marsh storage in the CDSA and thus to provide information on variations of accretion rates. Sixteen sub-samples were analysed by gamma spectrometry for ^{210}Pb, ^{226}Ra and ^{137}Cs at the Laboratoire de la CRII-RAD/Valence, using an EGG Ortec N-type germanium hyperpur detector (Chareyron, 2001). Counting errors were generally about 10%. Besides, on every sample subjected to the radiometric measurement was realised a grain size analysis. Grain size distributions were measured with a Coulter LS230 laser diffraction granulometre. In addition, 133 short boreholes (length: 0.1–3.5 m) were made with a small auger (∅ 12 mm) in November 2000 along 7 transects perpendicular to the Ancão tidal channel, to determine the thickness of fine-grained sediments (marsh deposits) in the whole CDSA. On each transect, the topography was surveyed using a D-GPS, with a precision of ± 5 mm. Finally, we exploited these thickness measurements to complete the data obtained on the stratigraphic section of the CDSA. A correlation between stratigraphic units and the use of the chronology obtained by radionucleids analysis allowed us to date the beginning of the edification of the marshes that constitute the present landscape of the CDSA.

Short-term (10–1 years) accretion rates: they were studied over a 2-year period (July 2000–March 2002) by measuring (45 values) the thickness of the

top sediment layer relative to a 0.3×0.3 m plastic patch buried at 0.1–0.2 m under the marsh surface in July 2000. Five plots (with 9 measurements by plot) were situated in transect 2b perpendicular to the Ancão tidal channel. The measurements were made on four dates (October 2000, March 2001, October 2001, March 2002), with a periodicity from 3 to 7 months. In addition, altimetric measurements (63 values) were led in July 2000 and March 2002 on the marsh surface situated under the bridge of Quinta do Lago (upstream of the CDSA). The distance between the bridge and the marsh surface was measured every 5 m with a decametre (precision of ± 5 mm).

3. Results

3.1. Hierarchical framework of habitats dynamics

3.1.1. General features of vegetational pattern

Regarding the saltmarsh as part of the intertidal profile, visible distinctive vegetational units may quite easily be defined on both sides of altitudinal boundaries and sometimes on erosional features. These boundaries design a hierarchical framework permitting comparisons between sites. On the basis of the integrating value of the vegetation, four levels of intertidal platforms are distinguished (Table 2):

- The lower level, between 1.80 and 2.30 m, rise gently from the adjacent tidal flats. Higher points are colonised by pioneer communities of glasswort (*Sarcocornia perennis*) and cord grass (*Spartina maritima*) showing clonal extension. Small hummocks found around isolated patches of *Spartina* suggest that vascular plants assist the deposition of material by reducing current energy in that so-called pioneer zone or low marsh (Units 1–2).
- As the surface rises gradually above 2.10 m or suddenly upward a saltmarsh cliff, the surface becomes fully vegetated defining the saltmarsh flat proper. The lowest third of it, between 2.10 and 2.55 m, support either flat-leaved *Spartina* swards or creeping glasswort (*Sarcocornia perennis*) thickets often in a closed mosaic appearance. This lower middle marsh (Units 3–4), which is not distinguished in former marsh types classifications, is recognised on the basis of its remarkably flat appearance rather than on floristic homogeneity.
- In the middle levels of the well-established marsh, between 2.45 and 2.75 m, the surface is covered by extensive pure stands of the shrub sea-purslane (*Halimione portulcaoides*) and woody glasswort (*Sarcocornia fruticosa*) which form communities of generally high vegetation cover. The ramifying hydrographic network sometimes modified into channel-pans colonised by upper-shore glasswort swards, is the most distinctive feature of this mature upper-middle marsh (Units 5–8).
- The high marsh starts above 2.75 up to 3.40 m and is dominated by typically Mediterranean saltmarsh scrubs (Unit 9). This zone is characterised by a strong environmental gradient and considerable ecological heterogeneity, due to the elevation gradient as well as the influence of drift litter and human impacts (impoundments, paths) on vegetation communities (Unit 10).

In conclusion, detailed elevation data show considerable variations between sites in the present pattern of communities' distribution across the marsh. Only the middle marsh and the high marsh exhibit a well-established boundary around 2.75 m. Zones boundaries in the more seaward part of the

Table 2
Lower and higher limits (in metres above hydrographic *datum*) of marsh levels of the Ria Formosa (Southern Portugal) according to various authors

Marsh levels	Vegetation units	cul-de-sac Bertrand et al. (2004)	Ria Formosa		
			Costa et al. (1996)	Bettencourt (1994)	Andrade (1990)
Low marsh	1–2	1.69–2.31	—	—	<2.00
Lower-middle marsh	3–4	2.12–2.56	2.50–3.00	2.50–3.00	2.00–4.00
Upper-middle marsh	5–8	2.43–2.74	3.00–3.30	3.00–3.50	
High marsh	9–10	2.75–3.84	3.30–3.40	>3.50	≈4.00

marsh show an approximate contiguity due to broader ecological tolerance of many species, for instance *Halimione portulacoides*, reaching dominance at low or middle elevations.

This altitudinal pattern can be compared with the whole Ria Formosa lagoon. Our measurement (2 March 2002) of the high tide mark elevation (3.61 m) along the inner side of the lagoon indicates that the maximal tidal amplitude throughout the lagoon is quite similar to high tide heights predicted nearby Ancão and Faro inlets (3.65 and 3.71 m). The elevation range of the Ancão saltmarsh surface is 0.7 m higher than that suggested by previous works (Table 2). These differences are all the more remarkable as the average elevations of different marsh levels are 0.30 m (lower-middle marsh), 0.45 m (upper-middle marsh) and 0.80 m (high marsh) lower to those retained by Bettencourt (1994) and Costa et al. (1996) as well as those measured in the marshes of Mar Santo (Bertrand, 2003). Only Andrade (1990) considered that the lower limit of the marsh (*sapal*) corresponds to the mean sea level (2.00 m), which our measurements seem to confirm if one takes account of an average difference of +0.11 m between the levels observed inside and those predicted outside the lagoon (Sebra de Melo, 1989).

These various observations tend to show that the marshes in the downstream part of the CDSA are subjected to duration of submergence longer than in other parts of the lagoon, in relation with lower altitude. Thus, the elevation of marsh zones boundaries do not agree as a whole with "critical tidal levels" recognised elsewhere. Indeed, the average elevation of the upper-middle marsh (2.58 m) corresponds to the tide height of the mean high water neap tide (2.61 m) where in sheltered shore, the transition between the low and middle marsh is usually found (Beefink, 1977). The low marsh starts between 1.70 and 1.80 m, slightly below the mid-tide level (1.93 m) and this appears in better conformity with common observations and suggests that lower zones are defined better by tidal levels than the upper ones. Thus, the present zonation pattern seems to be adjusted to substantial hydrological changes involving changing in water levels.

3.1.2. Hydrological factors of vegetational variation between sites

Marsh level average elevation shows little variation for the height of transversal transects (Fig. 3). The mean surface elevation of the high marsh ranges from 0.1 m higher on transect t4—probably in relationship with an elevated water table—to 0.2 m lower on transect t2 since the impoundments of São Lourenço marshes.

The vertical variation of the lower limit of the marsh (0.75 m) is ultimately much more remarkable being understood that this limit corresponds either to the edge of pioneer or secondary low marsh (transect t3), or to the edge of a well-consolidated marsh (transect t6) in erosion. Variation of low marsh elevation between the studied sites depends on variation in tidal energy that can be related to position along the estuarine gradient and across the marsh surface. The height of the lower limit of the marsh decreases according to the distance to the Ancão Channel, involving more determining variations in energy gradient across the intertidal (mudflat and saltmarsh) profile than along the main channel. This assumption is suggested by the distinct physiographic features on the north side of Ancão Channel as shown by the transect t6. The outer part of the bank is characterised by a highly dissected mudflat consisting of a series of rills cut deeply into the intertidal profile. Further inland, a second morphological zone consists of two parallel-sided creeks surrounding an elongate upper marsh island. These creeks are fringed by pioneer marshes dominated by *Spartina* that may start 0.4 m lower than the height of the dissected front zone. A greater magnitude of the flood velocity pulse near the seaward end of the mudflat–saltmarsh system and decreasing hydrodynamics towards the landward margins probably explain these transversal contrasts.

In conclusion, for equal supply of suspended sediment, the degree of protection and the topography that determine the extent and the rate of saltmarsh growth cannot be simply correlated in CDSA with position along the estuarine (longitudinal) gradient.

3.1.3. Geomorphological factors of vegetational variation between sites

Reclamation of peripheral wetlands, especially along the mainland side of the lagoon, created a tidally segmented lagoon in relation to the morphological partitioning of the CDSA. Since numerous dikes were constructed across the valleys that drained into the barrier lagoon (Goeldner-Giannella et al., 2003), the shape of the fringe saltmarshes along the mainland is no more controlled by the

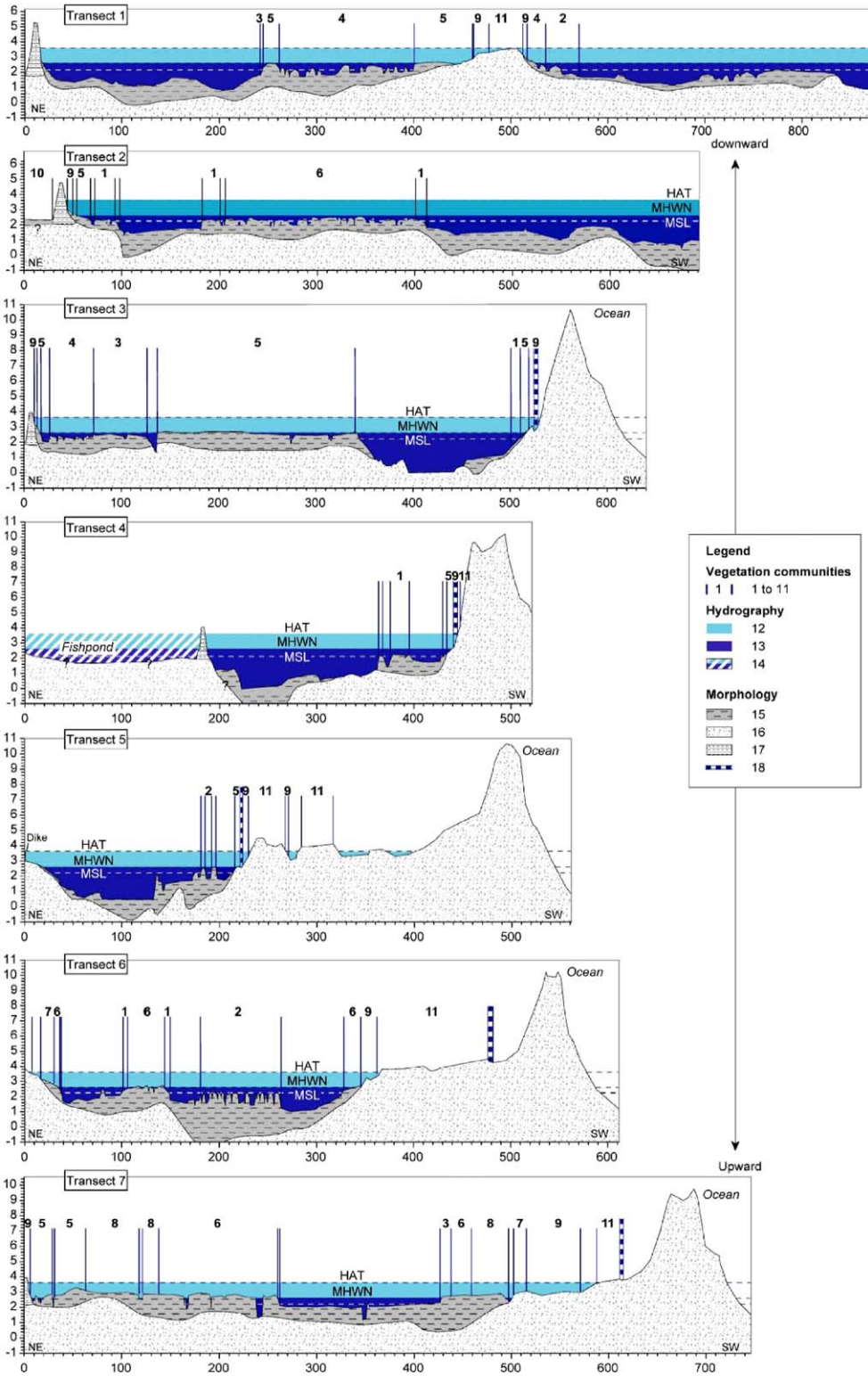


Fig. 3. Longitudinal variations of the average altitude [in metres above chart *datum* (−2 m MSL)] of marsh levels of, Ria Formosa, Southern Portugal. 1: continuous cordgrass swards; 2: discontinuous cordgrass swards; 3: creeping glasswort mats; 4: creeping glasswort and sea-purslane mosaic; 5: continuous sea-purslane thicket; 6: discontinuous sea-purslane thicket; 7: woody glasswort shrub; 8: sea-purslane and red glasswort mosaic, 9: Mediterranean thermo-Atlantic scrub; 10: previous reclaimed marsh (*salgados*); 11: open grasslands over shifting coastal dunes; 12: maximal cross-section area at highest astronomical tide (HAT); 13: minimal cross-section area at mean high water neap (MHWN); 14: idem under human control; 15: mudflat; 16: barrier platform and barrier spit; 17: dike; 18: footpath.

configurations of the previous mainland shoreline. Instead, marshes form a contiguous and rather continuous border—except where the lagoon has been infilled for golf course—along the mainland fringe. However, the zonation of saltmarsh vegetation is less marked than on the lagoon side of the peninsular spit, in relation to recurrent microscale environmental patterns, such as the change from channel-bank to inter-creek basins across the mouths of watersheds (transect t7) or the transition from saline to non-saline habitats in front of more or less watertight banks (transect t6). The mosaic appearance is in deep contrast with the arrangement of species and communities in belts parallel to the shore that occurs in various sites along the lagoon side of the barrier spit (transects t3 and t4), although in some upper parts of fully mature marsh covered by aeolian and water-borne sediments the shrubby vegetation may be fairly open (transect t5).

To conclude, the two major factors (hydrology and geomorphology) of vegetational variation can be combined to produce a tripartite division of CDSA in which diversity of saltmarsh biota varies from the mouth to the head of the enclosed estuary. Three sectors can be distinguished as follows:

- The seaward sector (I) consists of a wide asymmetric mudflat-system decreasing in width from the road bridge to the eastern bank of the central fishpond. The marshes are primarily a reflection of an antecedent extensive system of hammock marshes that has formed across the mouths of the former São Lourenço estuary. Elongate basins between relict beach ridges are at some good distance from the main channel and are, therefore, excellent sites for marsh colonisation.
- In the central sector (II), reclamation for fish production created strong funnelling so that the tidal prism cannot discharge over the headland marshes formerly drained by the sheet flow. Since tidal energy cannot dissipate within the adjacent narrow fringe marshes, the creek system here develops a series of straight channels. Tidal currents reactivate the antecedent channels by providing energy for tidal-scour and fill process which lead to the formation of natural levee at the margin of the channels. These are suitable habitats for tidal channel fringe-marshes.
- The landward sector (III) exhibits the resonant characteristics of a closed estuarine channel with high flow velocities. The hydrographic network adapts to these high-energy conditions developing a typical spur and groove topography. Further inland, the tidal energy forces further into the low/mid marshes, developing a small number of highly sinuous creeks and widening the tributary creeks at their landward end into near-circular pans. The consequence is (1) the appearance of tidal flat facies within the low/middle tidal-channel marshes fringing both sides of the Ancão Channel and (2) the occurrence of a distinctive upward edge as the creek system ends abruptly against sandy facies of hammock (on the mainland side) and storm-surge platform (on the back-barrier side) upper marshes.

This broadest-scale pattern in saltmarsh vegetation reflects the currently acting effects of geomorphic process as well as the legacy of long-range directional trend and—disrupting natural or human—events. In the following discussion, the physiographic state of the CDSA will be evaluated considering the thickness and the geometry of marsh facies.

3.2. Quantification of sedimentary volume in lagoon marshes

The sub-superficial sandy units (Fig. 3) reached by coring within 4 m of depth can be attributed to the tidal channel and tidal delta deposits (Bettencourt, 1994; O'Connor et al., 1998; Barnhardt et al., 2002). The muddy deposits which cover them correspond to a regressive vertical sequence deposited in a lagoonal-estuarine environment, indicating an abrupt transition between high-energy subtidal environment and low-energy intertidal (semi-enclosed) environment (Faugères et al., 1986). The

Table 3
Quantification of the present intertidal fine-grained sediments in the Ancão lagoon marsh, Ria Formosa, Southern Portugal (the impounded marshes are excluded)

Sector	Subsector	Depth (m)	Area (m^2)	Volume (m^3)
I	1	0.75	327,400	245,500
	2	0.95	484,150	459,950
	3	0.76	332,535	252,730
	Total I		1,144,100	958,220
II	4	1.30	364,230	473,500
III	5	0.67	175,425	117,535
	Total I + II + III		1,683,740	1,549,215

most evident features of the fine-grained sediment infilling of CDSA are, on the one hand, little thick deposits (mean thickness: 0.49–1.07 m; Table 3) and, on the other hand, the relative complexity of the stratigraphy (Fig. 3), with frequent, discontinuous sedimentary units. Variations of thickness and the geometry of sedimentary infilling constitute the base of the subdivision in three well-differentiated morpho-sedimentary sectors.

The seaward sector (sector I; transects t1–t3; Fig. 2) singularises by little thick deposits (mean thickness: 0.52–0.90 m, with variations from 0 to 2 m), but the values are higher than those of sector II and lower than those of sector III. Here the abundant sediment supply yielded by the São Lourenço River until the end of the 19th century allowed the edification of a vast platform marsh arising from the coalescence of marshes, either, around the distal parts of flood deltas (flood-delta marshes), or, in border of the tidal channels (tidal-channel fringe marshes). The distinctive shield or beach ridge morphology that can observed in the middle of the discontinuous platform marsh indicates that (1) the lagoonal infilling is unfinished and/or (2) the present lagoon marshes are in situation of sedimentary deficit, linked to the reduction of the detritic supply due to human actions on the environment.

In the narrowed middle part of CDSA (sector II; transects t5 and especially t4; Fig. 2), the lagoonal deposits (muds and underlying sands) were reworked by tidal channels. In this sector, the little thick (mean thickness: 0.49–0.63 m, with variations from 0 to 1.45 m) fine sediments of the marshes cover sandy accumulations, deposited as washover fans or storm-surge platforms. These two types of accumulations determine the general shape of the marshes, which is scalloped in the case of washover-fan marshes, and massive for storm-surge platform marshes.

The landward sector (sector III; transects t6 and t7; Fig. 2), the most distal from the Ancão inlet, presents continuous and thick deposits (mean thickness: 1.00–1.07 m, with variations from 0 to 3.50 m) typical of a low-energy lagoonal infilling (sheltered situation). These conditions were favourable to the development of fringe marshes, but the soil-surface elevation in the axis of CDSA (transect t6), at a level compatible with the installation of the colonising plant species, did not lead to the development of a mid-lagoon marsh, as it is the case in the other parts of the lagoon (Bertrand et al., 2002).

In conclusion, the quantification of the present sedimentary volume in the lagoon marshes allowed us to estimate the available volume of fine-grained sediments as being equal to 1,549,215 m^3. This sedimentary volume, distributed by sector in Table 3, puts in evidence a concentration of the muddy stock both in the downstream (seaward sector I; 958,220 m^3 ~63%) and upstream (landward sector III; 473,500 m^3 ~30%) parts of the CDSA. Except in the fish-breeding basin, the muddy stock is little important (117,535 m^3 ~7%) in the central sector II, which corresponds to an interruption of the downstream morpho-sedimentary continuum of the CDSA. The decrease of the fined-grained sediment volume in sector II is explained by the important specific stream power of the Ancão tidal channel, which increased as a result of (1) the extension of the washover fans (right bank) and (2) the artificial channel narrowing (eastern bank) in the year 1970 that restricted the amount of fine-grained sediment available to the suspended load. These high-energy hydraulic conditions favour a strong channel transport capacity of the channel, which, in return, limits the deposition of fine-grained sediments in the adjacent fringe marshes.

3.3. Pluri-secular to pluri-annual accretion rates

3.3.1. Pluri-secular accretion rates

The stratigraphic log deduced from the borehole LU6 (Fig. 4) shows the succession of five sedimentary units, interpreted here in terms of distinct depositional environments and described from the bottom to the top:

- Unit 1 (between 4.00 and 2.00 m in depth): interstratified sandy silt/clayed-sandy silt and sandy silt/clayed sand with abundant lagoonal-marine fauna correspond to a middle estuarine environment;
- Unit 2 (between 2.00 and 1.65 m): medium sand with lagoonal-marine shell debris corresponds to a tidal channel bar (São Lourenço River);
- Unit 3 (between 1.65 and 0.95 m): an upward fining sequence of clayed-sandy silt and sandy silt with occasional ligneous debris shows the presence of a lagoon marsh;
- Unit 4 (between 0.95 and 0.20 m): azoic clayed sand and silty sand with scattered gravels are interpreted as being a part of an adventive cone which progrades towards the axis of the ria;

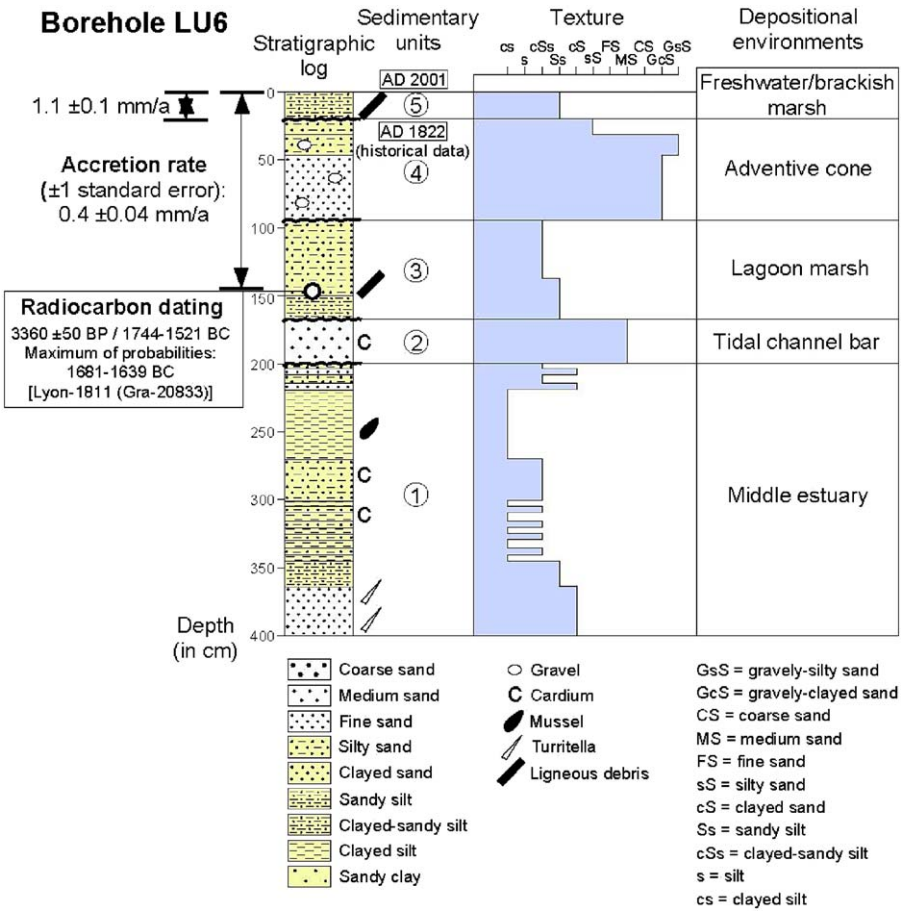


Fig. 4. Sedimentological analysis, depositional environments, radiometric dating and long-term accretion rates derived from borehole LU6, Ria Formosa, Southern Portugal.

- Unit 5 (between 0.20 and 0 m): sandy silt with abundant organic debris correspond to a freshwater/brackish marsh set up since the construction of the Ludo dike in AD 1822.

In sum, this palaeoenvironmental succession can serve as a model to illustrate a high-level prograding prism, where the marine influence gives up gradually the place to an environment dominated by essentially continental conditions. At the top of the sequence, a ^{14}C dating placed at 1.5 m under the present surface indicates a calibrated age of 1744–1521 BC, with a maximum of probabilities between 1681 BC and 1639 BC. If we retain this last chronological interval, the accretion rates, from 1681–1639 BC to AD 1822 and from 1681–1639 BC to AD 2001, are equal to 0.4 mm/a. The accretion rates would be globally higher (1.1 mm/a) in the Unit 5 corresponding to the freshwater/brackish marsh.

To conclude, the pluri-secular accretion rates obtained in the lagoonal zone are very close to those obtained by Andrade et al. (2004) in Ancao's sector. Indeed, the authors put in evidence, from the sedimentological study of two boreholes (SB3 and SC4) a lagoon marsh dated 3635–400 BC (Unit B) and 4595–780 BC (Unit B), in which accretion rates are equal in 1.13 ± 0.04 and 0.66 ± 0.02 mm/a, respectively. However, one should admit that they are relatively low compared (1) to long-term accretion rates observed in other parts of the Ria Formosa (Fig. 5), and (2) to medium-term evolution in the CDSA (see below). That can be explained by (1) a smoothing of the information, due to the fact that the studied sedimentary sequence was able to integrate phases of erosion and sedimentation, and/or (2) a possible auto-compaction of the organic, fine-grained sediments, and/or (3) the probable difference between the apparent age of the sediment

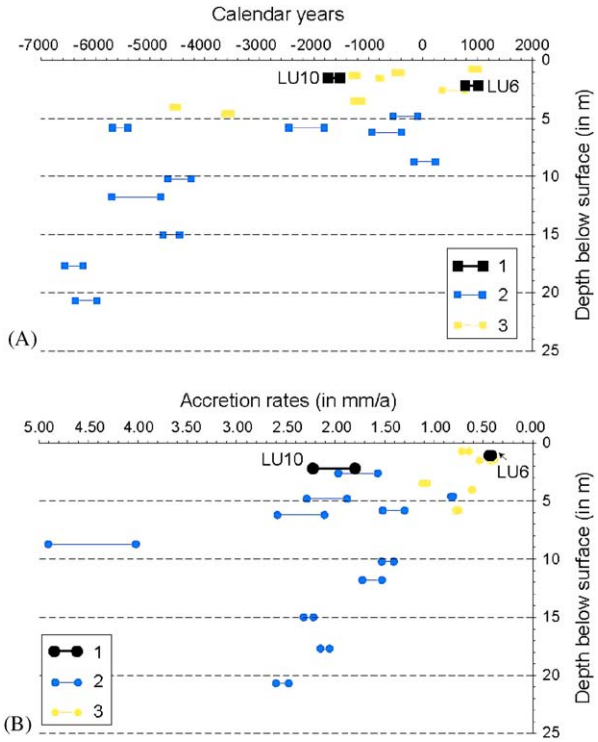


Fig. 5. Long-term accretion rates in lagoon marshes derived from several boreholes, Ria Formosa, Southern Portugal. (A) Radiocarbon dates (cal. BC/AD) vs. depth below surface. (B) Accretion rates vs. depth below surface. 1: data from Arnaud-Fassetta (unpublished); 2; data from Bettencourt (1994); 3: data from Andrade et al. (2004).

deposit, determined by the radiocarbon, and the true age of this one the radiocarbon dates were obtained on macro-ligneous fragments. Therefore, one cannot exclude that these fragments are older than the sediment deposit in which they are. In that case, it would explain why the sedimentation rate obtained on the studied site is lower than those generally observed on the long term in the Ria Formosa (Bettencourt, 1994; Andrade et al., 2004). Finally, terrestrial, sandy sediment supplies efficiently participate to the accretion process on the margin of the lagoon marsh. The stratigraphic log deduced from the borehole LU68 shows that alluvial sand (adventive cone) represents 41% of the marsh infilling.

3.3.2. Pluri-10-year accretion rates

The stratigraphic section CDSA1 (Fig. 6) represents the sedimentary sequence of a washover-fan marsh. It shows the succession of two sedimentary units divided in four sub-units, from the base upward:

- Unit 1 (between 0.95 and 0.80 m in depth): medium to coarse well-sorted sand corresponds to a tidal channel bar. This unit constitutes the basement of the recent marshes in the CDSA.
- Unit 2 (between 0.80 m and 0): it can be subdivided into three sub-units, namely a coarse-grained sediment unit arranged in sandwich between two fine-grained sediment units; sub-unit 2a (between 0.80 and 0.55–0.50 m): very fine sand corresponds to a first lagoon marsh; sub-unit 2b (between 0.55–0.50 and 0.45–0.40 m): medium sand represents a washover fan covering the lagoon marsh; sub-unit 2c (between 0.45–0.40 m and 0): silty sand and fine sand correspond to a second lagoon marsh. The high values of median grain size (D_{50}), even in marsh sediments nevertheless usually characterised by lower values (Baraut, 2003), certainly indicate the mixing of muds with sandy aeolian or marine supplies. Furthermore, sand peaks (A15, A12, A6, A2) in sub-units 2a and 2c are interpreted as minor washover fans or aeolian deposits. Considering the median grain-size ($0.3\,\text{mm} < D_{50} < 0.5\,\text{mm}$) of marine-beach sand of Praia de Faro (Andrade, 1990), a large part of the sand fraction observed in Unit 2 is likely to be blown up into dunes along the margin of the washover zones. Therefore this sand should be considered as relatively coarse, most likely deflation sands, representing washover sands more or less reworked by aeolian actions. Nevertheless, most of sand packages such as sub-unit 2b must have been delivered by overwashes related to particular storms. Several of them are well known. Thus, a major storm occurred in the region in January 1941 (Weinholtz, 1964; Esaguy, 1985; Andrade, 1990) and determined large washover fans on the adjacent island of Culatra (Garcia et al., 2002). Then, during the February 20/21, 1966 storm event, the Ancão dune line was overwashed forming eleven breaches (Guillemot, 1979; Pilkey et al., 1989). Besides, three other marine storms occurred in March 1961 (Weinholtz, 1964; Esaguy, 1986), January 1973 (Pita and Carvalho, 1987) and 1997 (Andrade et al., 2004).

Concerning unit 2, the activity of total ^{210}Pb, strongly correlated in that of ^{226}Ra, indicates an

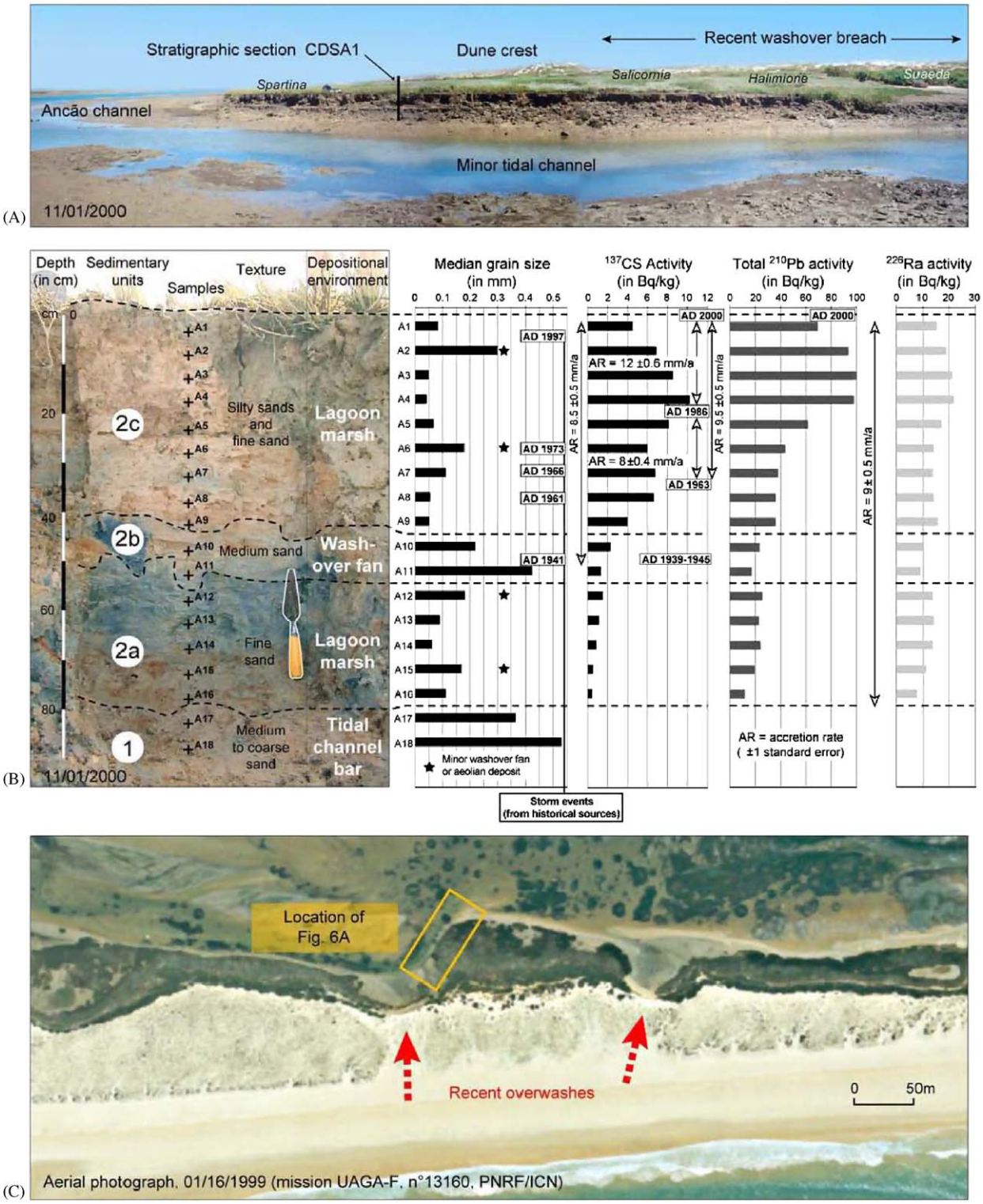


Fig. 6. Sedimentological analysis, depositional environments, radiometric dating and medium-term accretion rates derived from stratigraphic section CDSA1, Ria Formosa, Southern Portugal. (A) Frontal view of the washover fan (photograph: F. Bertrand). (B) Stratigraphic section CDSA1 (photograph: G. Arnaud-Fassetta). (C) Aerial photograph of the washover fan.

accretion rate of 9 mm/a. Furthermore, concerning more specifically sub-unit 2c, the activity of the ^{137}Cs shows two peaks, the first one between A8 and A7 and the second in A4. These two peaks correspond, respectively, to the atmospheric nuclear tests (AD 1963) and to the accident of Tchernobyl's nuclear power station (AD 1986). We deduct from this chronology that (1) the accretion rate from 1963 to 2000 is equal to 9.5 mm/a, with lower values from 1963 to 1986 (8 mm/a) than from 1986 to 2000 (12 mm/a). By considering the historical record of storm events (Vila-Concejo et al., 2002), we would be incited of associate sub-unit 2b (washover fan) to the major storm event of January 1941. It is interesting to note that the dating of sub-unit 2c by radionucleids, by considering an accretion rate of 8–9.5 mm/a, gives a chronological amplitude (AD 1939–1945) which includes the year 1941 deduced from the historical source.

To conclude, sedimentation rates calculated from the excess ^{210}Pb and ^{226}Ra activity concentrations are in good agreement with sedimentation rates calculated from the ^{137}Cs data. This correspondence between the results obtained by two independent methods gives credit to the suitability of both techniques. The pluri-10-year accretion rates observed in a washover-fan marsh of the CDSA are relatively high, compared to pluri-secular accretion rates. The sudden sand supplies (washover fans or aeolian deposits) represent 37.5% of the marsh infilling.

3.3.3. Pluri-annual accretion/erosion rates

The pluri-annual accretion/erosion rates were derived from measures realised between July 2000 and March 2002 on two sites, the first one being situated upstream and the second downstream to the CDSA. Fig. 7 and 8 suggest that the sedimentary balance is negative both in low marsh and lower-middle marsh, with average erosion rates varying from −9 mm/a (upstream) to −3.7 mm/a (downstream).

In the upstream part of CDSA (Fig. 7C), the most important sectors in erosion are situated in the Ancão tidal channel (average erosion rate: −71.8 mm/a). Low marsh, high marsh and lower-middle marsh are sectors of lesser erosion, with average erosion rates of, respectively, −14.9, −2.1 and −1.2 mm/a. Only the watt and upper-middle marsh show a positive sedimentary balance, with average accretion rates of, respectively, 196.4 and 1.6 mm/a. These results are confirmed by the evolution of the occupation coefficient of each depositional sub-environment. From July 2000 to March 2002, the extension of watt and high marsh increased to +67% and +31%, respectively. In the mean time, low marsh, lower-middle marsh and upper-middle marsh surfaces, respectively, decreased to −63%, −33% and −33%. Strong reduction of low-marsh surface is confirmed by numbers of denuded sites, which is maximum, and several forms of erosion (Figs. 9B, C and E–G). In the downstream part of CDSA (Fig. 8), measures were made only in lower-middle marsh and low marsh. These two sectors present a contrasted sedimentary balance, with average values varying respectively from −10.2 to −1.8 mm/a.

To conclude, the measures of the accretion/erosion rates on the short-term confirm our field observations in CDSA, namely a critical situation where marshes are in dominant erosion (Fig. 9). This accretionary deficit can be shown by the erosion of the marsh edge, forming either a steep cliff (Fig. 9B) or a series of rills cut deeply into the intertidal profile ramp (Figs. 9A and D). It can also be observed within the middle marsh through the enlargement of pans despite protective biological activity near the bottom (Fig. 9F). In a general way, vegetal denudation of sites gives an appreciation of erosion intensity. In the upstream part of CDSA, near Quinta do Lago footbridge, the denuded sites represented 52% of the total studied sites in July 2000, 63% in March 2002, indicating an annual increase of denudation of 13%.

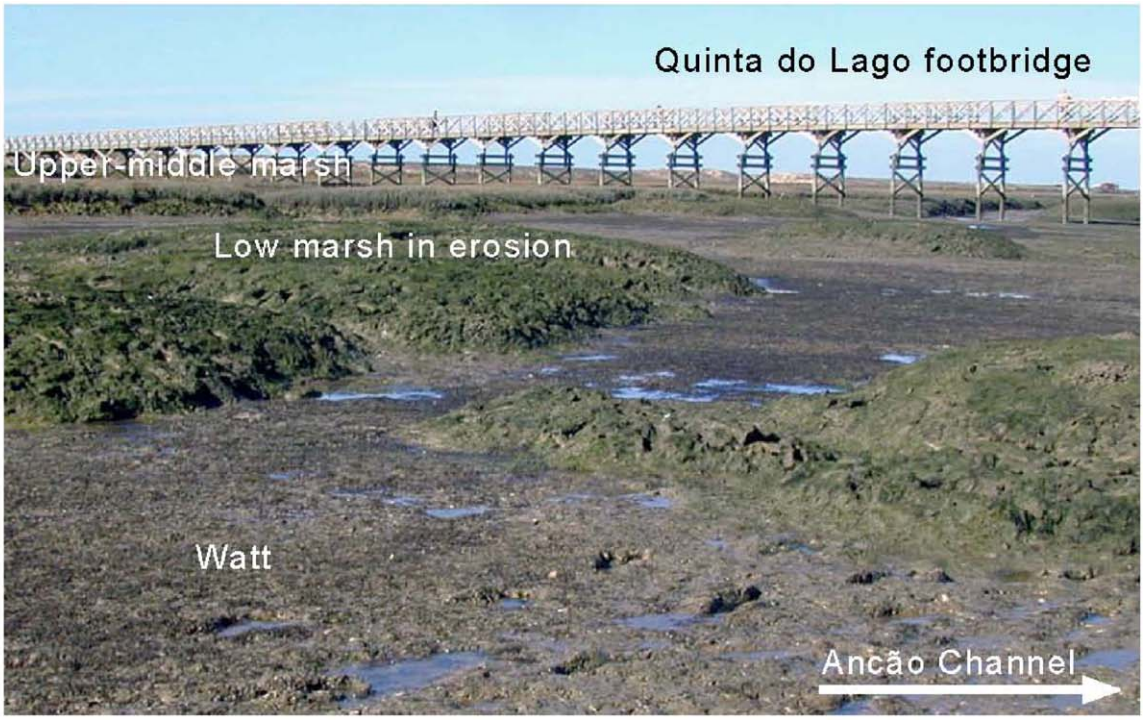
In conclusion, the estimations concerning the evolution of accretion/erosion rates both on the long (the last 3500 years) and medium (20th century) terms suggest that accretion processes are predominant in the lagoon marshes of the CDSA. These results are opposed to those obtained on the 2000–2002 period, which indicate predominant erosion.

4. Discussion and conclusions

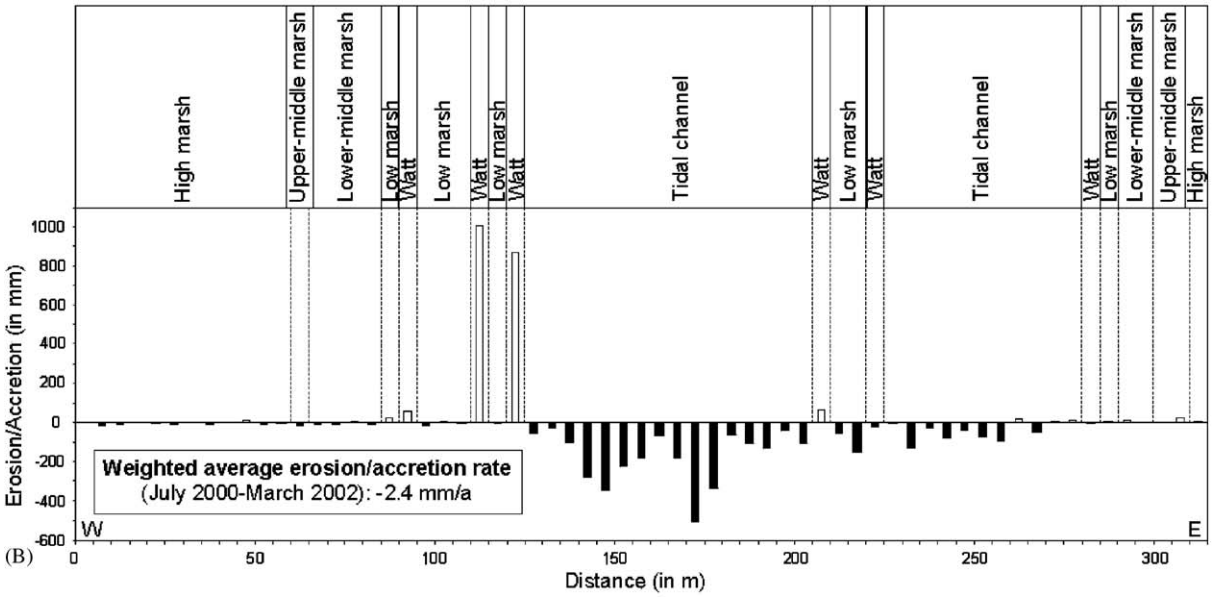
4.1. Changes in sedimentary secular trend

In the lagoon marshes of the CDSA, changes in directional trends appear enough pronounced to lead to substantial changes in dominating geomorphic process and habitats dynamics. Significant accretion/erosion rates were measured and these latter have been compared to estimates concerning RSLR:

- On the long term, average accretion rate was 0.4 mm/a between 1681–1639 BC and AD 2001,



(A)



(B)

Depositional subenvironments	Occupation coefficient			Erosion/Accretion rates (in mm/a)				Number of sites denuded between July 2000 and March 2002
	July 2000	March 2002	Variations (in %)	Mean value	Minimum value	Maximum value	Standard deviation	
High marsh	0.21	0.27	+31	-2.1	-9.0	5.4	4.2	1
Upper-middle marsh	0.05	0.03	-33	1.6	-8.4	13.2	10.9	1
Lower-middle marsh	0.10	0.06	-33	-1.2	-7.2	6.0	5.5	0
Low marsh	0.13	0.05	-63	-14.9	-91.2	12.0	33.8	4
Watt	0.10	0.16	+67	196.4	-13.2	603.6	285.2	(recolinised by *Spartina*) -1
Tidal channel	0.43	0.43	0	-71.8	-304.8	10.8	75.0	2

(C)

Fig. 7. Short-term evolution of the lagoon marshes of the CDSA near Quinta do Lago footbridge, Ria Formosa, Southern Portugal. (A) Photograph looking upwards at low tide (November 2000). (B) Change in lagoon marsh elevation from July 2000 to March 2002. (C) Description of the sub-environments based on July 2000 observations (photograph: G. Arnaud-Fassetta).

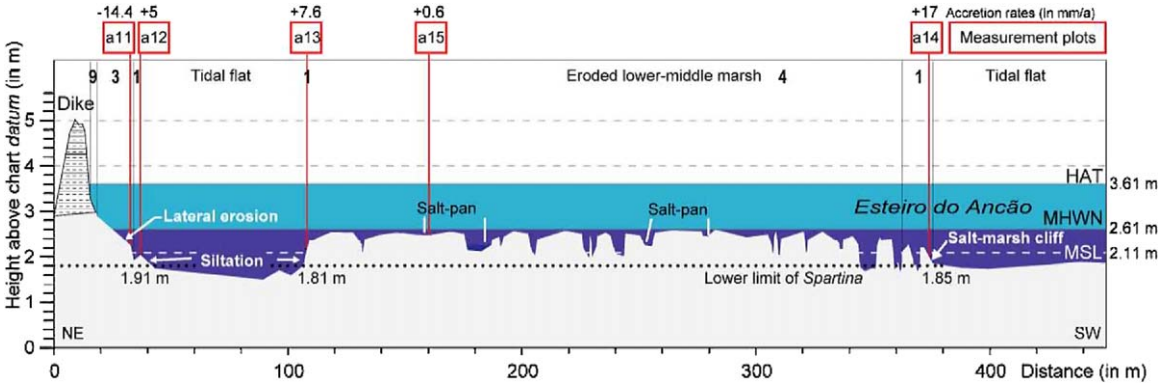


Fig. 8. Transversal transect (t2b) of the Ancão medio-lagoon marsh in front of the 1898 embankment. Short-term accretion/erosion rates (July 2000–March 2002).

whereas RSLR was estimated to ~0.3 mm/a (Pirazzoli, 1998). The dominant accretion of the lagoon marshes roughly kept pace with the RSLR.

- On the medium term (AD 1941–2000), average accretion rates were ranged from 8 to 9 mm/a, with an increase (12 mm/a) of accretion during the AD 1986–2000 period. These rates are 5–8 times higher than current estimates (1.5 ± 0.2 mm/a; Dias and Taborda, 1992) of RSLR in this area. Compared to the long-term marsh accretion rates, medium-term accretion rates are considerably higher, in response to probable effects related to auto-compaction of sediments.
- On the short-term (AD 2000–2002), an accretionary deficit was observed both in low marsh and lower-middle marsh, with average vertical erosion rates varying from −9.0 to −3.7 mm/a. If this negative trend confirms in the next years, the sedimentary dynamics of lagoon marshes could not compensate the effects of RSLR.

The effects of the human actions on the evolution of the marsh-sediment balance are also discussed. On the medium-term, the reduction of tidal volume by the Ludo impoundments induced a high eastwards migration of the Ancão spit between 1893 and 1923 (Andrade, 1990) that switched the direction of forces from transversal to longitudinal pattern and led to the connection of the CDSA to the Faro inlet. The loss of São Lourenço valley marshes was compensated in a large extent by the lengthening of the estuary and the incorporation of new retardation zones downwards, which probably tended to an excess of frictional dissipation ability over tidal energy and induced a significant decrease of tidal range. Therefore, the reduction of the capacity of the tidal channel induced the sudden sedimentary infilling of the CDSA. In the mean time, the width of intertidal surface suitable for marsh colonisation continued to reduce (fish ponds, golf courses).

In the late 1980s, the narrow fringe-marshes of the CDSA have probably approached an equilibrium height and width, as suggested by the asymmetric (e.g., ebb dominance in duration) tidal curve described by Andrade (1990). But since the artificial inlet opening in 1997 and the dredging of the western part of the lagoon in 2000 induced tides, which are now more in phase with those in the adjoining Atlantic Ocean, duration of flooding increased all over the saltmarsh surface involving physiologic stress for the plants and changes in sediment patterns.

Our field observations and measurements have shown that:

- The high marshes are well fixed by the vegetation, which limits sediment erosion, and prograding (Quinta do Lago footbridge). Some high marshes receive sandy inputs coming from washover fans, thus allowing them to maintain high vertical growth (Fig. 6). Sediment outputs are derived mainly from the dismantling of high marshes by micro-depressions and minor tidal channels.
- The middle and low marshes are in lateral and vertical erosion. Since the impoundments considerably reduced the sedimentary yield derived from the erosion of hillsides, and taking into account that fine-grained sediments entering in the lagoon basin through the inlets are little

Fig. 9. Field evidence of changes in habitats (photographs: G. Arnaud-Fassetta and F. Bertrand). (A) Upper section of the CDSA towards the mainland shoreline (1). Pioneer *Salicornia fragilis* (2) *Spartina maritima* (3) and communities are growing on the backbarrier marsh edge whereas vegetation is absent on the mid-lagoon mudflats despite the stabilisation of the sediment surface by the chlorophyte *Entermorpha clathrata* (4). (B) Photograph looking upwards along the Ancão steep-sided channel and illustrating the tidal-scour and fill process. Current-eroded microcliff formed by erosion of the middle salt marsh (1). The slumped blocks are eroded (2), so converting the marsh to bare mudflat (3) and allowing accretion on the tops (4). (C) Lower intertidal flats of the landward side of CDSA behind the footbridge. Note the absence of seagrass (*Zostera noltii*) possibly due to the gathering of mollusks taken by hand (1) and to the eutrophication of the lagoon marked by the green—*Entermorpha clathrata* (2) and red—*Graciliaria* sp., (3) macro-algal mats. (D) Erosional spur and grooves topography which surface is no more contiguous with the backbarrier fringe marsh (1). The cutting face of the marsh cliff (2) and the surface of the mudmounds (3) are devoid of vegetation. (E) Central section of the CDSA showing extensive tidal-channel marshes. Along the main channel margin, current action has undercut the marsh surface creating a cliff of variable elevation (1). Along more sheltered sites, *Spartina* may either extend down to the fronting mudflat (2) or colonise the eroded lower level surface (3). (F) Secondary annual glasswort swards (1) overlapping both the inter-creek basin perennial glasswort (2) communities and the fringing *Halimione* stands (3). Note the sandy layer (4) which underlies a cynaobacterial mat developed under anaerobic conditions (5) since this channel pan was left without outlet (arrows). (G) Backbarrier middle marshes developed on a storm-surge platform. Typical Mediterranean dwarf shrubs (1) contrast with the lower growths of the chamaephytic *Halimione portulacoides* (2) and the hemicryptophitic *Spartina* which is spreading on the floor of a shallow and elongate pan under conditions of accretion (3).

important, products of erosion of this lower part of the marsh constitute the main sedimentary source for the watts.

- The watts are both in strong extension and accretion, but they are the most unstable depositional sub-environment because the closest to the high-energy tidal channel.
- The tidal channels widen and deepen partially for anthropogenic causes (e.g., dredging). Sediments eroding from the marshes could temporally compensate the sedimentary deficit of tidal channels.

4.2. Spatial heterogeneity of present accretionary deficit

The present negative sedimentary balance of lagoon marshes is more marked upstream than downstream of the CDSA. Three causes can be evoked to explain this situation: firstly, the duration and the frequency of flooding are weaker upstream of the CDSA, so the fine-grained sediment supplies are less important; secondly, there are no fine-grained sediments yielding from the upstream part of the CDSA because of impoundments and disconnection with the catchment basin, that is not the case downstream where fine-grained sediment supplies are derived from the product of the erosion of marshes situated upstream of the CDSA; thirdly, the surfaces not covered by salt-marsh vegetation are in net progression in the upstream part of the CDSA. Therefore, the erosion and the remobilisation of fine-grained sediments are easier.

Furthermore, the present accretionary deficit or the negligible amount of accretion observed both in downstream and upstream parts of the CDSA suggest there is a negative relationship between accretion and elevation. Assuming that RSLR occurs at a rate of 1.5 ± 0.2 mm/a, the overall consequence is a strong increase of frequency and duration of the marsh surface flooding that contribute to marsh deterioration through osmoregulation problems and submergence effects on plant vigour. The present accretionnary deficit must be evaluated with respect to the dissipation ability and therefore the elevation of the antecedent saltmarsh surface. Considering the numerous marks of erosion both in the downstream (transect t2) and upstream (Quinta do Lago footbridge transect) parts of the CDSA, the negligible amount of accretion in the saltmarshes is certainly due to an excess of tidal energy over frictional dissipation ability of their surface which exhibits a very low elevation.

However, the present accretionnary deficit is not everywhere and some sites record a trend toward the accretion Field evidences, as middle marsh salt pans colonised by *Spartina* (Fig. 9G) indicate that higher elevations of marshes are more favourable to depositional process, because the presence of well-developed vegetation above the present mid-tide level stills current actions and encourages the retention of the flood-tide sediment influx. These areas are likely to get progressively shallower through upbuilding by uneven siltation, which is already suggested by the mosaic appearance of plant distribution associated with reccurrent microtopographic variations.

In the downstream part of the CDSA the eroded lower level surface is locally colonised by pioneer species, suggesting that new low-level secondary marsh may extent in the following years (transect t7). Conversely in the upstream part of it, the channel-bank is eroded back without producing any step-like bench and suitable habitat for pioneer growth of *Spartina*. Instead, the site of Quinta do Lago footbridge suggests a preferential sediment redeposition close to the main channel, leading to the formation of levees (Fig. 9B). Continued accretion on such sites means that spaced marsh stems, while acting as an effective baffle to current flow, may enhance accretion rate in the near-future in such a way to keep face locally with sea-level rise.

To conclude, we have compared the accretion/erosion rates of the CDSA with those acquired in the other parts of the Ria Formosa (Bertrand et al., in preparation). The results show that the trend toward a sedimentary deficit is confirmed on the studied sites as Barra Nova, Mar Santo and Gemidos, with average erosion rates varying from -2.6 to -1.5 mm/a (min. -13.8 mm/a; max. 16 mm/a) between July 2000 and March 2002. Finally, the sedimentary deficit observed in the CDSA is not specific to this zone but corresponds to a global context of dominant salt-marsh erosion in the whole Ria Formosa.

4.3. Preservation potential of the CDSA marshes

The eroding margins of the marsh are not a sufficient source of accreting matter, and accretion at lower marsh elevations not sufficient as well to maintain an overall equilibrium position in the intertidal zone. A response of the intertidal profile

to current and presumably future high-energy inputs would be to increase into length so as to extend the tidal wave-sediment interface. These adjustments are no more possible along the mainland where the impoundment of the former valley marshes limits marsh expansion landwards and where the most exposed reaches of the headland marshes are already reworked into tidal flats (Fig. 9C).

The preservation potential of mid-lagoon marshes seems to vary according to the changing character of the antecedent surface. Short-term accretion rates indicate that hammock marshes that surround relict beach ridges exhibit the highest—although little—vertical accretion (plot a15; Fig. 8) and may well evolve into marsh islands as the marsh spreads over the sandy substrate and its distal edges change into tidal flats. Field observations show that the maintenance of tidal-channel marshes is more hypothetical although accretion rates (levees) are able to maintain an elevation suitable for vegetation growth (Quinta do Lago footbridge transect). Locally, the tidal-marsh fringe becomes completely surrounded by water producing therefore typically *Spartina* dominated marsh islands (Fig. 9E). But presently, most of the dissected edge of the mid-lagoon marsh is bare of vascular plants as if the readvance of vegetation over the residual mud-mounds was durably inhibited (Fig. 9A). Considering the numerous sources of untreated domestic effluent as well as non-point runoff (agriculture, golf course) leading to episodic eutrophic condition (Newton et al., 2003) and dense algal growth (Fig. 9C), it is suggested that there may be a relationship between the general deterioration in water quality and the failure of *Spartina* to (re-)establish on present accretional surfaces.

Finally, the lagoon side of the peninsular spit is the only part of the CDSA where the rate of upbuilding could exceed the rate of RSLR and therefore assure the maintenance of the marsh. Upward growth of the marsh is permitted both by the intermittent cross-island sediment and the increased duration of flooding on the backbarrier region which allow high marshes to spread rapidly over a newly inundated surface, particularly as reworked sediment from the low-lying marshes is transported backwards (Fig. 9G). This transferring sediment process is no more possible in places such as Praia de Faro where the dune ridge has been destroyed by human occupation (Martins et al., 1996) and where infrastructures prevent water and sediment from spreading and flowing down the backbarrier into the lagoon. In such a case, the preservation potential of fringe marsh is annihilated moreover since the overtop sandy material is used as filler for backbarrier shoreline nourishment and furthermore creation of land (Cremona, 1998).

Beyond this attempt to estimate the preservation potential of various categories of marshes within the specified western part of the Ria Formosa lagoon, one can ask about the significance of the present negative sedimentary balance of CDSA lagoon marshes in term of overall sediment budget of the area. Changes in sedimentary trend and spatial heterogeneity of accretionnary deficit permitted to identify the marshes of the CDSA as both an important source and important sink for sediment. Fig. 1 shows that cross-shore aeolian sand transport (90,850 m^3) is by far the first sediment source in the backbarrier lagoon whereas fluviatile supplies (82 m^3 including sediment discharge of the Rio Seco) are insignificant. The cross-barrier marine transport cannot be considered as a major source of material, but this study has shown that the part of sediment deposited in lagoon marshes by over-washing is not neglictible. However, the total sedimentary budget of the CDSA appears very difficult to quantify because boundaries between the "barrier-island" and "lagoon-marsh" hydrosedimentary cells are hard to define precisely.

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