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The sedimentary record of recent (last 500 years) environmental changes in the Seixal Bay marsh, Tagus estuary, Portugal

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Abstract

The inner Tagus estuary is essentially a sedimentation basin that receives cohesive sediment from terrestrial, marine, biological and anthropogenic sources. Three short cores from one site in a marsh area of this estuary (Seixal Bay) were analysed for sedimentary, geochemical and micropalaeontological contents (benthic foraminifera and nannoplankton). The length of the cores represents about half a millennium of sedimentation. Textural analysis suggests a highly uniform mud sedimentation for most of the cores but geochemical, mineralogical and micropaleontological results indicate climatic and environmental changes and anthropogenic disturbance. Three Foraminifera zones were identified. The lower part of the lower zone indicates sedimentation in an open channel or a lower domain of an exposed high-energy sandflat. Sediments of the upper part of the lower zone and of the middle zone were deposited in a lower-energy environment, probably associated with a sheltered, vertically aggrading mudflat located within the Seixal Bay. Biological and mineralogical indicators suggest that periods of total or partial closure of this bay occurred. Clay minerals indicate that drier and colder conditions prevailed in the lower half of this zone evolving gradually to a wetter and warmer environment towards the top. The upper zone indicates persistence of low-energy sedimentation and evolution towards the present salt-marsh conditions. Anthropogenic pollution is clear in geochemical proxies at the top of the sedimentary column and was used for dating purposes.

Introduction

The Tagus estuary is located on the western coast of Portugal, near Lisbon, and occupies an area of approximately 320 km^2 (Figure 1). The main aspects of its functioning and geomorphology are described elsewhere (Freire 1993). This estuary is characterised by a particular setting, including a narrow and fault-controlled inlet channel that separates the outer, wave-dominated estuarine domain from the inner, broad and shallow, tide-dominated part of the estuary (Figure 1B). This inner estuary is characterised by extensive intertidal and subtidal sedimentation of cohesive sediments that are redistributed by tidal currents. These sediments are deposited in mudflats and salt-marshes that form most of the morphosedimentary units of the southern margin. The study area, the Alfeite marsh, is located in this margin, along the Seixal Bay, which is sheltered from the rest of the inner estuary by the Alfeite sand spit (Figure 1C). Sediments accumulated in this marsh are essentially products of weathering derived from upstream areas, anthropogenic inputs and in-situ biological production. Marine contributions to the inner-estuary sediment budget are negligible (Freire 1993).

It is well established that different climatic conditions may result in measurable differences in the weathering products generated in a catchment area; such products will ultimately reach the estuary as solid load delivered to intertidal sedimentation areas (Singer 1984, Jansen et al. 1986). In addition, changing climatic conditions will modify the physico-chemical constraints of the estuary, even for brief time periods, and should interfere with the living biocenoses that constantly adapt to abiotic environmental factors. The sedimentary record of the Tagus estuary is therefore

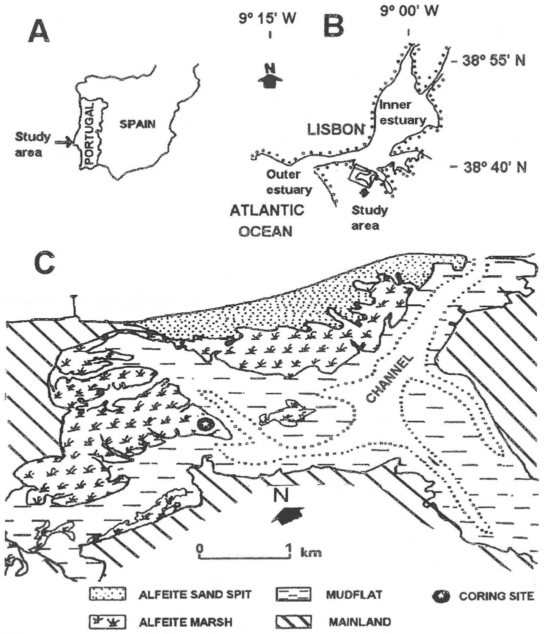

Figure 1. A–B) Location maps of study area; C) Seixal Bay in which the studied Alfeite marsh is situated.

expected to contain signals of environmental change in the geochemical, mineralogical, textural and biological facies. Due to the high sedimentation rate in this estuary which is partly related to a persistent subsidence since the late Pliocene, it is reasonable to expect that such a record is present even for short time scales, of the order of decades or centuries.

The present study is based on the combined records of mineralogical, chemical and micropalaeontological proxies retrieved from Tagus estuarine sediments and introduced both by natural and anthropogenic causes over 500 years.

Methods

Three short cores, located about 1 m apart, were taken from one site on the Alfeite high-marsh area (Figure 1C) using a steel, 50-mm-diameter and 1-m-long gouge auger, and a 34-mm-diameter Dachnowski sampler, down to a depth of 4.15 m below the marsh surface which stands 1.5 m above mean sea level. The sediment cores were wrapped in plastic foil, transferred to PVC liners, and taken for laboratory analysis. In the laboratory each core segment was opened longitudinally and both halves were sampled using steel spatulas. Sediment samples were oven-dried (50°C) and split. Results from the study of different sections of the three cores were combined to produce one single composite data column.

Organic matter was determined using about 1 g of dried sediment through oxidation with K-dichromate followed by titration using Fe-sulphate (Standard E-201, LNEC 1967). The sediment pH was estimated by the electrometric method (Head 1980) and classified following Gale & Hoare (1991). Grain-size analysis was undertaken on material < 250 μm, using a Fritsch laser particle analyser. Coarse-grained sediment was sieved by standard methods. Moisture contents and bulk dry weight were estimated using 2 cm^3 of wet sub-samples extracted from the halved cores with a set of syringes. This sediment was used for counting benthic Foraminifera (number of Foraminifera per cm^3 – FCC), along with a second sample of 10 cm^3, taken with identical procedures, used for species determination. Foraminifera were determined by sampling every 5 cm down to 4.0 m with the exception of the top 15 cm of the core where contiguous 1-cm samples were analysed. These were coloured with Bengal-rose and used to determine living Foraminifera associations. A second set of determinations was made in every sample replica that was used for geochemical analysis. The Foraminifera were determined using 100 individuals picked under the binocular microscope. The Foraminifera assemblages were identified and interpreted according to Murray (1991), Boomer & Godwin (1993) and Alve & Murray (1994). Two surficial sampling transects of the Seixal Bay were made to study the living Foraminifera associations and to provide a basic data set for the interpretation of the core data. Details of this study and of the core analysis can be found in Moreno & Fatela (1996).

A set of 22 samples was prepared for nannoplankton analysis. Small portions of the sediment were directly spread on a slide cover. Rippled spreading was achieved across the slide in order to produce alternating rows of high an low relative particle density. Slides were finished by applying a synthetic mount medium (Entellan®). The search for coccoliths was undertaken using a petrographic microscope with cross-polarising light and immersion objective, with a magnification of × 1250, over a 30-mm row of spread sediment. Samples were considered barren if no coccoliths were found in a complete row.

Geochemical analysis was performed by ACTILABS LTD (Canada) on dried and agate-mortar-powdered samples. Major oxides were determined by fusion-inductive coupled plasma emission spec-

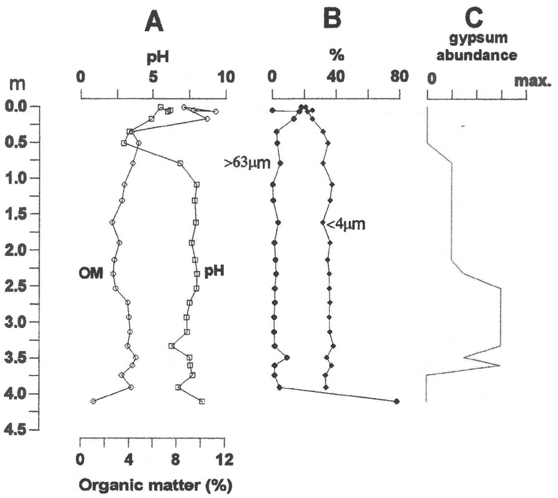

Figure 2. Profiles of A) pH and organic matter, B) grain size, and C) relative gypsum abundance in the composite Alfeite column.

trometry (ICP). Trace elements including transition elements were determined by ICP/mass spectrometry.

Clay minerals were investigated in the sediment fraction finer than 2 μm. These fractions were obtained by wet screening of the whole sample through a 53 μm sieve followed by controlled decantation according to Stokes' law and elimination of organic matter. Clay minerals were determined using a Philips PW1011 X-ray diffractometer equipped with a CuK α radiation source filtered through a Ni screen. Samples (oriented aggregates) were run in continuous scan mode over the range of 2 to 30° (1°/min). Three different diffractograms were obtained from each sample: natural, after glycolation with ethylenoglycol for 24 hours, and after burning (550°C). The determination of clay minerals followed the criteria of Lucas et al. (1959) and Brindley & Brown (1980). A semi-quantitative determination of clay minerals was undertaken according to Schultz (1964) and Barahona (1974), and the crystallinity of illite was investigated following Dunoyer de Ségonzac (1969).

Results

Texture, organic matter, pH and density

The sediments cored are essentially mud (Figure 2). The muddy section extends from the surface to 3.99 m where a sharp contact separates it from a lower sandy unit that prevented corer penetration below 4.15 m.

The mud consists of clayey silt. The clay content ($\leq$ 4 μm) typically ranges between 21 and 39% of the total dry sample. The mud contains small amounts of sand-sized particles. These particles represent up to 10% of the dry samples in the topmost 20 cm of the core, where they totally consist of plant debris. Further downcore the sand-sized particles include rare plant debris, Foraminifera and/or Ostracoda tests as well as small shells of Lamellibranchia and Gastropoda together with muscovite flakes, pyrite and very fine quartz grains.

In addition, a layer rich in shell-fragments occurs between 3.46 and 3.56 m containing whole shells of *Cerastoderma edule* and gastropods, and including about 10% of medium-grained sand or coarser particles.

Euhedral gypsum crystals occur throughout the column below 0.78 m and are particularly abundant between 2.42 and 3.61 m (Figure 2). Below this depth no gypsum was found.

Below 3.99 m sand-sized sediment accounts for more than 78% of the total sample. It includes quartz sand, gastropods and bivalves (whole shells and shell debris), ostracods, fish remains (vertebra and teeth), sponge spiculae, diatoms and plant debris.

The sediment pH is consistently mildly to moderately alkaline or neutral below 0.78 m (Figure 2). Towards the surface the sediment is slightly to extremely acid, with minimum pH values (2.95–3.34), between 0.34 and 0.52 m. These values probably result from respiration associated with rootlet masses.

The basal sandy unit, below 3.99 m, presents the lowest organic-matter contents, about 1% (Figure 2). The overlying middle section, from 3.99 to 0.34 m, exhibits organic-matter contents ranging between 2.6 and 4.8%, figures that are typical for mudflat areas in this region. Finally, the upper section contains organic matter between 9 and 11%.This consists of poorly packed plant debris, as well as living stems, roots, leaves and decaying plant remains, together with some fine-grained sediment.

The surficial layer, between 0 and 0.25 m, can be readily distinguished by the low values of dry bulk weight that range from 0.31 to 0.63 g/cm^3 (Figure 3). A second interval, extending down to 1.05 m depth, exhibits a variable bulk density that ranges between typical figures for unconsolidated muds (about 0.7 g/cm^3) and values as low as 0.4 g/cm^3 in locations bioturbated by rootlets. Farther down the bulk density remains fairly constant and averages 0.7 g/cm^3. In the

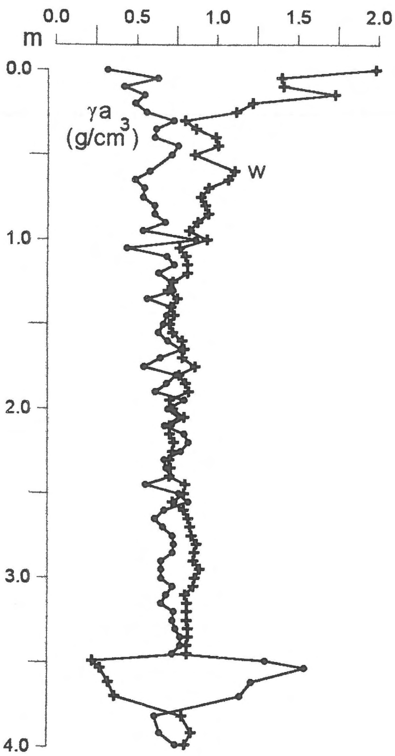

Figure 3. Profiles of moisture content (w – adimensional figure) and bulk dry weight (γa) in the composite Alfeite column.

sandy layer between 3.46 and 3.56 m it is about 1.3 g/cm^3.

Benthic Foraminifera

On the basis of the benthic Foraminifera associations, the column may be divided in three zones (Figure 4).

A *basal zone*, extending from the bottom of the core to 3.48 m, in which the dominant species are *Haynesina germanica* (a few individuals may correspond to *H. depressula)* and *Ammonia beccarii.* The latter is dominant in well-defined intervals at 3.50–3.63 m and 3.70–3.73 m.

Specimens of *Elphidium oceanenses* or *E. excavatum* occur in low percentages in this basal zone, attaining 4–8% of the total number of Foraminifera (TNF) between 3.52 and 3.73 m. Also, low numbers of *Jadammina macrescens* and *Trochammina inflata* occur. Both species are slightly more abundant towards the base of the core in association with mud laminae.

A *middle zone*, extending from 3.48 to 0.90 m, in which the dominant species is *H. germanica*, followed by *A. beccarii.* However, the latter predominates at 2.40 and 1.80 m. *Elphidium oceanenses* and/or *E. excavatum* f. *clavata* represent 4 to 8.5% at 3.15, 2.35, 1.70, 1.55 and 1.25 m. Two intervals of larger abundance of Foraminifera are present between 2.55 and 1.95 m (maximum at 2.40 m) and between 1.70 and 1.25 m (maxima at 1.45 and 1.60 m). *Elphidium excavatum* f. *clavata* occurs in percentages > 11% above 1.20 m and at 1.10 m it is the dominant species. The abundance above 1.20 m of *A. beccarii*, 25–32% of the TNF, correlates with that of *E. excavatum* f. *clavata*, whilst *H. germanica* shows an opposite behaviour. Within the same depth range *Quinqueloculina* sp. and *Fissurina marginata* exhibit maximum abundance. Above 1.05 m the association is clearly dominated by *H. germanica* (> 70%) whilst *E. excavatum* f. *clavata* is reduced to < 1% at 0.90 m. The number of (genetically) deformed individuals increases above 1.0 m attaining 47% between 0.90 and 0.95 m.

An *upper zone* extends from 0.90 m to the surface. The dominant species, *H. germanica,* increases in abundance between 0.90 and 0.85 m, and at 0.76–0.78 m (> 80%). Above 0.76 m the abundance of plant debris increases and pyrite grains or pyrite-filled foraminiferal tests are frequent together with perforated mollusc shells and glass shards. At 0.85 m the percentage of deformed individuals is quite high (40%).

Above 0.85 m the FCC figure is too low for systematic determination (probably due to low pH); this tendency persists up to 0.25 m depth. This interval is characterised by the abundance of pyrite and iron-oxide grains and pyritized plant debris. The study of the remnants of Foraminifera tests suggests that the association was probably dominated by *H. germanica* and *A. beccarii* up to 0.65 m, and by agglutinating forms, typical of saline to brackish marsh surfaces, such as *Reophax sp.*, *Miliammina fusca*, *J. macrescens* and *T. inflata*, above this depth. The topmost 0.25 m contains exclusively agglutinating forms and is dominated by *J. macrescens* in percentages > 90%. *Miliammina fusca* occurs in significant percentage at 0.03 m. Above this depth *T. inflata* becomes dominant and is accompanied by a few specimens of *H. germanica* and *A. beccarii* (< 1%). The study of deformed individuals was not possible in the uppermost 0.80 m because of the poor preservation of carbonate tests.

Calcareous nannoplankton

Coccolith specimens and taxa were counted for each of the 22 samples analysed (Figure 5). The diversity

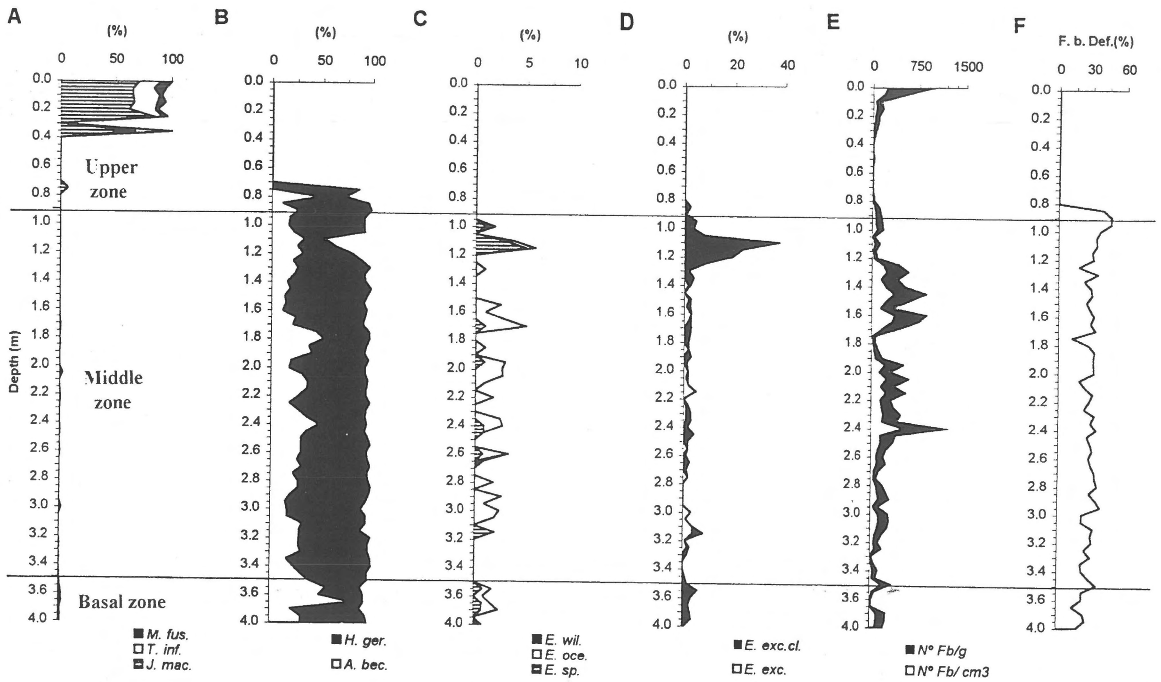

Figure 4. Distribution of Foraminifera in the composite Alfeite column. A–D) Foraminifera in % TNF: *Ammonia beccarii* (A. bec.), *Elphidium excavatum* (E. exc.), *Elphidium excavatum* f. *clavata* (E. exc. cl.), *Elphidium oceanenses* (E. oce.), *Elphidium* sp. (E. sp.), *Haynesina germanica* (H. ger.), *Jadammina macrescens* (J. mac.), *Miliammina fusca* (M. fus.), *Trochammina inflata* (T. inf.); E) number of individuals/cm^3 (N° Fb/cm^3), number of individuals/gram (N° Fb/g). F) % TNF of deformed calcareous individuals (F. b. Def.). Note change of scale below 3.5 m.

is always low and the coccolith forms are dominated by small placoliths of *Gephyrocapsa*, *Reticulofenestra haqii-minutula* and *Emiliania huxleyi*. *Gephyrocapsa oceanica*, *Coccolithus pelagicus* and *Helicosphaera carteri* occur also but are very rare (1 to 3 specimens per row).

The curves showing the estimated abundance and diversity follow each other, showing peaks alternating with barren intervals. The bottom sample (4.15 m) revealed a relative maximum abundance (14 coccoliths per column). It is overlain by an interval of small variations in coccolith content (3.8–2.8 m). Immediately above, the coccolith abundance recovers twice, around 2.5 m and between 1.6 and 1.2 m, matching increases in the number of forams/g (Figure 4E). The interval above 0.6 m is barren.

The taphonomic interpretation of the coccolith content has to consider the effect of early diagenesis, particularly in the interval 0.6–0.1 m where the pH ranges between extremely and medium acid. Under these conditions coccoliths are probably dissolved.

Below 1.0 m, pH values become more or less stable around the neutral point (Figure 2). The presence of small, well-preserved coccoliths corroborates the absence of corrosion. The coccolith contents can be directly related to a varying marine influence. Thus, increased coccolith contents reflect less sheltered conditions.

Clay mineralogy

Illite (I) and kaolinite (K), both essentially detrital, dominate the clay-mineral assemblage, followed by smectite (Figure 6). Traces of vermiculite-interlayered minerals and palygorskite were also detected. The distribution of clay minerals with depth displays oscillations. The I/K ratio shows a clear tendency to increase towards the bottom, but the trend is disturbed by regular positive and negative oscillations of increasing amplitude.

The plot of the illite crystallinity index shows three peaks of apparently low crystallinity: at 1.25–1.75 m, 2.75 m and 3.60–3.80 m. They were interpreted as representing overlap with the palygorskite 10 Å peak, causing its apparent enlargement. Electron microscope scanning analysis of clay minerals from 3.60–3.80 m depth indicates that palygorskite fibres are indeed present.

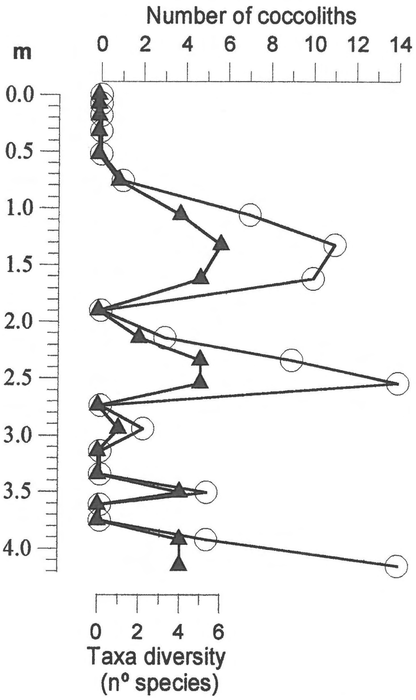

Figure 5. Calcareous nannoplankton content in the composite Alfeite column. ○ = number of coccoliths/row of the smear slide (30 mm length); ▲ = number of identified species.

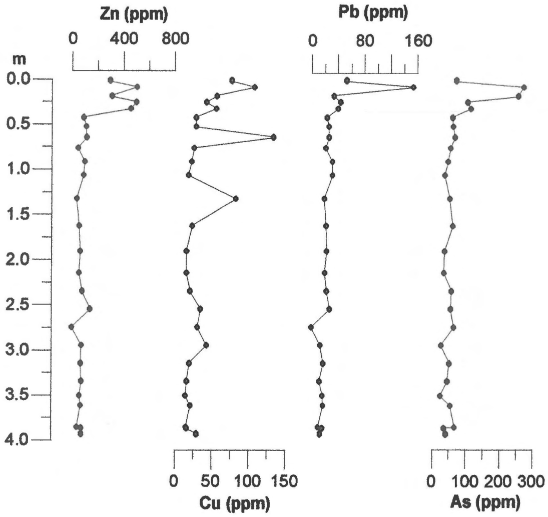

Figure 7. Profiles of Zn, Cu, Pb and As in the composite Alfeite column.

Elemental analysis

Sedimentation in the Tagus estuary reflects the general input derived from adjacent land sources or the main river channel, production from organisms living *in situ*, and the activities of man. Human activities in the present century contributed heavy metals and other elements as well as organic pollutants to these sediments (Vale et al. 1990, Vale 1990). A few elements, apparently not related to human activities (including marine contributions), were also used to identify changes in source areas or environmental conditions.

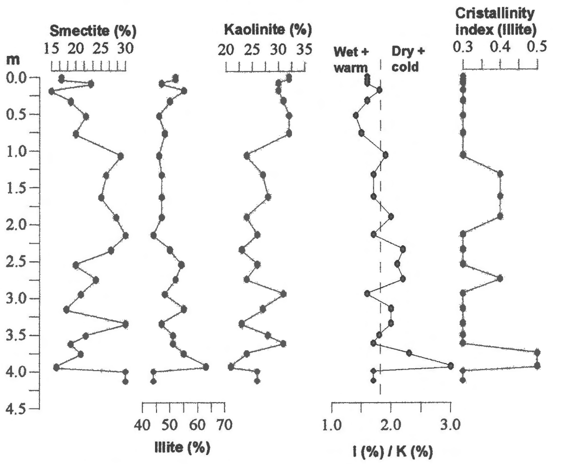

Figure 6. Profiles of clay minerals, illite/kaolinite (I/K) ratio and illite cristallinity index in the composite Alfeite column. Climatic interpretation is based on Singer (1984b).

Anthropogenic elements: The Tagus estuarine plain is known to have been occupied a long time ago, because of its climatic and strategic features and availability of food resources. However, the establishment of heavy industry and accelerated demographic expansion of this area are features of the present century (Cruz 1973).

Several elements (Zn, Cu, Pb, As, Sn, Sb and P) were identified as indicators of human activities. Figure 7 shows the concentrations for Zn, Cu, Pb and As, which tend to increase nonlinearly towards the surface. Analytical results obtained between the base of the core and 1 m depth were used to evaluate average values and standard deviations of background concentrations of these elements (Table 1). Contamination was considered to exist in the first sample that showed a concentration higher than average plus 3 standard deviations. However, the Cu peak at c. 60 cm is dubious as it is not related to industrial contamination and might either represent an analysis error or an isolated Cu input of unknown origin. Accordingly, the contaminated section of the core extends down to 38 ± 5 cm depth. This section shows an enrich-

Table 1. Concentration of metals and As in 26 samples from the composite sediment core in the Alfeite marsh. Background concentration from samples below 1 m. Contaminated section is above ca. 0.38 m, see text.

	Background concentration (ppm)				Concentration in contaminated section (ppm)			
	Pb	Zn	Cu	As	Pb	Zn	Cu	As
Average	18.0	66.5	25.7	46.5	64	411	67	162
Standard deviation	6.9	27.9	16.6	12.8	--	--	--	--

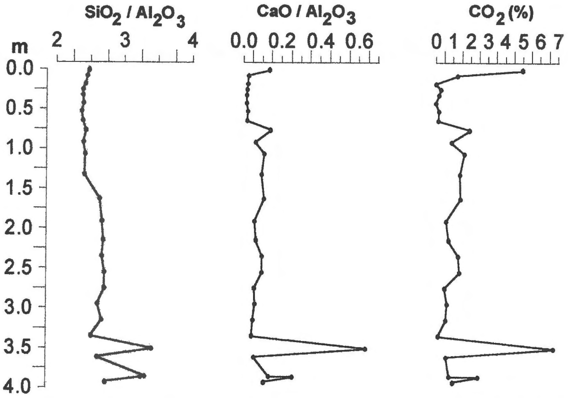

Figure 8. Profiles of SiO_2/Al_2O_3 and CaO/Al_2O_3 ratios and of CO_2 content in the composite Alfeite column.

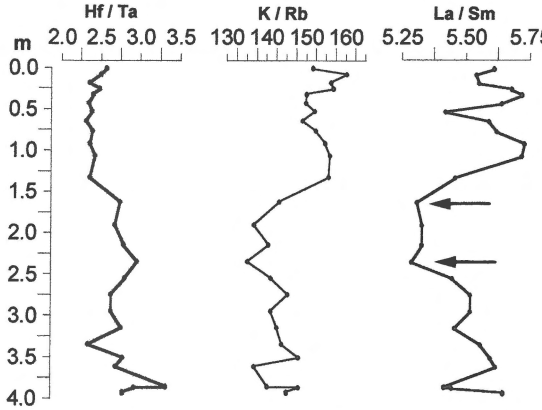

Figure 9. Profiles of Hf/Ta, K/Rb and La/Sm ratios in the composite Alfeite column. Arrows show compositional breaks mentioned in text.

ment factor of about three to six times the background concentration.

Within the contaminated section, the concentration curves drop at the surface sample. The abundance of plant debris in this sample and/or the implementation of recent environmental protection legislation (cf. Baird 1995) may account for this effect.

Non-anthropogenic elements: The geochemical analysis of variations in major and trace elements of the section not influenced by human activities, indicates relatively homogeneous concentrations, in accordance with the dominant silty to clayey composition of the sediments. Except for near-surface perturbations, compositional breaks are limited to lithological transitions; this is well illustrated by the shell-fragment-rich layer at 3.46–3.56 m where SiO_2/Al_2O_3, CaO/Al_2O_3 and CO_2 all strongly increase with increasing carbonate content (Figure 8).

Subtle variations were detected for the K/Rb, La/Sm and Hf/Ta elemental ratios (Figure 9). These elemental pairs have similar crystallochemical properties and changes of the ratios should thus primarily reflect variations in sediment source. Indeed, changes in the ratios K/Rb, La/Sm and Hf/Ta correlate fairly well with those derived from calcareous nannoplankton studies.

Sedimentation rates and dating

The sedimentation episodes preserved in the cores were dated by combining different approaches. One accelerated-mass-spectrometry ^{14}C radiometric determination was obtained from Beta Analytic Inc., U.S.A. (laboratory number Beta-88443), on a whole *Cerastoderma edule* shell, collected in living position at 3.54 m depth. The calibrated age of this sample is AD 1490 (cal AD 1460 to 1530, 1σ calibrated results). This dating implies an average rate of sedimentation of 7 $\pm$ 0.6 mm/year for the last five centuries. Extrapolation of this rate suggests an age of ca. AD 1420 $\pm$ 35 for the contact at 3.99 m between the basal sands and the mudflat deposits. This is probably contemporaneous with the setting up of the Alfeite sand spit and of a sheltered sedimentary environment south of this spit.

Freire & Andrade (1993) investigated present rates of sedimentation in the Tagus estuary using methods of bathymetric comparison. Their work was essentially conducted on the subtidal area and yielded an average rate for the period 1928–1986 of 12 mm/year.

Documentary evidence suggests that although the Tagus estuary has been colonised for a long period of time, high levels of pollution associated with the installation of heavy industry became important after 1900 and especially after 1930. The analysis of the vertical profiles suggests that anthropogenic metal concentrations are present in the upper 0.38 m of sediment. This implies a sedimentation rate of about 4–6 mm/year for the last century. If the P_2O_5 content is taken as an indication of widespread use of detergents then a second estimated rate of about 8 mm/year may be derived for the last 36 years. Actually, the P_2O_5 content increases from a background of 0.09–0.14% up to 0.39% in the uppermost 0.29 m of the core.

Taken together, this information suggests that the rate is largest in subtidal areas of the estuary. Tidal marshes record lower rates, probably because of emergence periods. This factor seems to overprint the expected increase of the rate in these marshes associated with both the trapping effect of the plant cover and the anthropogenic input of solids.

Discussion

Basal zone

The sandy unit below 3.99 m was probably deposited in a high-energy environment, preceding the sheltering provided by the Alfeite spit. The dominant foraminifera *Haynesina germanica* (including specimens of *H. depressula*) and *Ammonia beccarii*, together with the occurrence of *Elphidium excavatum* f. *clavata* and/or *E. oceanenses* (4–8%) and Miliolidea, as well as the high coccolith abundance, all suggest that salinity levels were considerably higher than presently and close to average marine conditions. *Ammonia beccarii* is considered a moderately euryhaline species, less tolerant to low-salinity conditions than *Haynesina germanica* (Murray 1991). This unit is therefore interpreted as having been deposited in an open channel or in the lower domain of an exposed high-energy sand flat.

Between 3.99 and 3.48 m some sheltering by the Alfeite spit, indicated by low coccolith and high gypsum abundances in muddy sediments, reduced the energy levels. The foraminifera associations, however, remained essentially the same.

Middle zone

Between 3.48 and 0.90 m, sedimentation took place in a low-energy environment, dominated by deposition of mud, and sheltered from the more open part of the inner estuarine domain. Foraminifera tests are frequently corroded, unpolished and fragile, indicating reducing conditions. The associations suggest that sedimentation evolved in the upper zone of a vertically aggrading mudflat in a brackish environment. They are dominated by *H. germanica*, *A. beccarii* and *E. excavatum*. The biological and mineralogical indicators suggest that this zone corresponds to a period of alternation between total and partial closure of Seixal Bay. Two periods of total closure occurred (at approximately 1.90 m and 2.75–3.40 m), characterised by the virtual absence of coccoliths, together with foraminiferal associations typical of less marine conditions. These periods alternate with less restricted conditions marked by high coccolith abundance, peaks of *A. beccarii* at 2.40 and 1.80 m, and low occurrence of gypsum. Between 1.20 and 1.10 m a peak in the occurrence of *E. excavatum* f. *clavata* is noticeable, associated with *H. germanica* and *A. beccarii* as dominant species. *Elphidium oceanenses* and *E. williamsoni*, as well as *H. depressula* are present in low frequencies. This association confirms a temporary return to a higher salinity, close to average marine conditions. The sudden bloom in *E. excavatum* f. *clavata* may also indicate a lower temperature (Boomer & Godwin 1993). Above 1.05 m, *H. germanica* becomes the dominant species indicating an upper mudflat environment. The transition to the upper zone is marked by an increase in the number of deformed individuals and in the frequency of plant debris suggesting the setting of an incipient low-marsh facies.

In general, geochemical compositional breaks found in the La/Sm, K/Rb and Hf/Ta ratios agree fairly well with abundance peaks of coccoliths, suggesting that the geochemical indicators were sensitive to changes of the source areas.

The presence of palygorskite suggests authigenic deposition promoted by climatic control. According to Singer (1984a), palygorskite is a quite fragile mineral, characteristic of arid environments (rainfall < 40 mm/year), which occurs commonly in Holocene soils, including alluvial sediments of mildly alkaline pH. Singer also reports the usual coexistence of gypsum crystals and palygorskite, a feature that was observed in this case essentially below 2.72 m.

According to Singer (1984b), Jansen et al. (1986) and Delgado et al. (1994), the illite/kaolinite ratio, together with the variation of the illite crystallinity index, may reflect environmental modifications in the average temperature and moisture. These indicators suggest that drier and colder conditions prevailed in the lower half of the middle zone, evolving gradually to wetter and warmer conditions towards the top (Figure 6). High I/K ratios between 2.25 and 2.75 m, and also at 3.75–4.0 m in the basal zone correlate fairly well with the nannoplankton data but somewhat less with the foraminifera ones.

According to Tullot (1986), Little Ice Age conditions affected quite suddenly the Iberian Peninsula at the turn of the 15th to the 16th century. If the radiocarbon dating of AD 1490 at 3.54 m is accepted as correct then the sand at the base of the core is probably contemporaneous with the preceding Little Optimum (Goudie 1992). The middle zone seems to have been deposited during or shortly after the development of the Alfeite sand spit. Dabrio et al. (1996, this issue) indicate a pronounced change of the wind regime ca. 500 BP when this regime became similar to that of the present-day Atlantic. According to Andrade & Freitas (1996) such a change is crucial in allowing coarse sediment mobilisation in the inner Tagus estuary and development of the Alfeite sand spit. The origin of this spit roughly coincides with the beginning of the Little Ice Age in the Iberian Peninsula. According to Tullot (1986) this period was characterised by cold and arid conditions along the Atlantic margins of Iberia. Both aspects are quite well preserved in the clay-mineral record of the lower half of the middle zone. Contrasting with the apparently sharp definition of the onset of the Little Ice Age in this core at 3.99 m depth, the waning of this episode seems to be diffuse, marked by a general warming-up trend recorded in the upper half of the middle core section. This is in general agreement with the conclusions of Tullot (1986) who suggests an ending of the Little Ice Age for the Iberian Peninsula in the beginning of the 18th century. The 18th and 19th centuries were less adverse from a climatic point of view and included periods of clear thermal recovery.

Upper zone

The upper zone, above 0.90 m, results from persistent low-energy sedimentation in an intertidal area. Its lower part exhibits a pronounced degradation of environmental conditions marked by reductions in the FCC and the number of deformed Foraminifera. Part of this reduction may derive from post-depositional corrosion of carbonate tests under low pH values. Taken together with the geochemical results on anthropogenic contamination, this information suggests that although pollution of the area may be recorded in the uppermost 0.38 m of the sediment column, less favourable living conditions already occurred from 0.90 m upward. The interval 0.76–0.40 m shows *Reophax* sp. as the most abundant species and above 0.40 m the associations are essentially represented by *Jadammina macrescens*, *Trochammina inflata* and *Reophax* sp. This latter change probably reflects the transition from a low to a high-marsh environment. Between 0.25 and 0.04 m, *J. macrescens* is dominant and associated with *T. inflata* and *M. fusca*. According to Boomer & Godwin (1993) this association typifies the lower zone of the high marsh in low-energy environments associated with large amounts of plant debris and brackish water. At 3–4 cm depth a sudden blooming of *M. fusca* is noticeable (20%) but above this level *T. inflata* dominates and characterises an association typical of the upper high-marsh area.

The study of deformed Foraminifera was undertaken to correlate this pattern with environmental stress induced by natural or man-related causes, the latter being essentially represented by chemical and organic pollution of the estuary (Sety & Nigam 1984, Sharifi et al. 1991, Alve 1991, Yanko et al. 1994, Gonzalez-Regalado et al. 1996). Although pollution may be one cause for the ocurrence of deformed Foraminifera, the number of these individuals is also quite high in pre-industrial sections of the core. This suggests that part of these individuals acquired their deformations by natural causes. It must also be noted that the basic data set may be biased because of the size range of the tests counted (> 63 μm), probably including larger numbers of juveniles than other countings quoted in the literature.

Anthropogenic contamination is clearly indicated by the geochemical record, and allows the assessment of sedimentation rates in industrial times. The amount of anthropogenic contaminants in the marsh sediments above 0.38 m is quite high when extrapolated to the whole Tagus estuarine surface (ca. 320 km^2). Considering the estimated sedimentation rates, the figures obtained for anthropogenic contaminants translate to yearly inputs into the Seixal Bay ($\approx$ 3 km^2) of Pb = 1.4 t, Zn = 10.3 t, Cu = 1.2 t and As = 3.6 t. However, these amounts represent only about 10% of the total estimated industrial input into the Tagus estuary (Adriano 1986), suggesting that a large quantity of pollutants is available for incorporation in the food chain.

Conclusions

The results of sedimentological and palaeoecological interpretation of a composite core taken from the Alfeite marsh area suggest that this marsh evolved in close dependence of the Alfeite sand spit.

The sandy unit below 3.99 m was probably deposited in a high-energy environment, in an open channel or in the lower domain of an exposed high-energy sand flat, preceding the sheltering provided by this spit. Salinity levels were considerably higher than presently and close to average marine conditions. Extrapolation of a radiocarbon dating indicates that the base of the core is probably contemporaneous with the Little Optimum. During the deposition of the interval between 3.99 and 3.48 m some sheltering provided by the Alfeite spit was probably present and reduced the energy levels but other ecological conditions remained essentially unchanged. Sedimentation of the interval between 3.48 and 0.90 m took place in a sheltered, low-energy environment, dominated by deposition of mud, probably corresponding to the upper zone of a vertically aggrading mudflat in a brackish environment. The biological and mineralogical indicators suggest that this zone corresponds to a period of alternation between total and partial closure of Seixal Bay. Two periods of total closure occurred (c. 1.90 m and 2.75–3.40 m), characterised by the virtual absence of coccoliths, together with foraminiferal associations typical of less marine conditions. The interval between 1.05 and 0.90 m represents sedimentation which shifted to an upper-mudflat environment and finally to an incipient low-marsh facies. The upper zone, above 0.90 m, exhibits a pronounced degradation of foraminiferal environmental conditions. Above 0.65 m a transition from a low to a high-marsh environment is recorded.

The geochemical compositional breaks found in the La/Sm, K/Rb and Hf/Ta ratios, probably reflect changes of the source areas. The illite/kaolinite ratio, together with the variation of the illite crystallinity index, reflects modifications in the average temperature and moisture. Drier and colder conditions prevailed in the lower half of the middle foraminiferal zone, evolving gradually to wetter and warmer conditions towards the top. Contrasting with the apparently sharp definition of the onset of the Little Ice Age at 3.99 m in this core, the waning of this episode is not clearly marked in the general warming-up trend recorded in the upper half of the core section.

Anthropogenic contamination is indicated by the geochemical record above 0.38 m, and suggests a sedimentation rate of 4 to 6 mm/year in industrial times. The amount of anthropogenic contaminants in the marsh sediments is quite high and translates to significant yearly inputs of heavy metals to the Seixal Bay sediments. However, this amount represents only a small fraction of the pollutants still available for incorporation in the food chain.

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