Lateglacial and Holocene environmental changes in Portuguese coastal lagoons 2: microfossil multiproxy reconstruction of the Santo André coastal area

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Abstract: Benthic foraminiferal, ostracod, calcareous nannoplankton and diatom assemblages have been analysed from the 25.45 sedimentary succession of a borehole drilled in the Santo André lagoon (southwestern Portugal). The zones and subzones recognized according to their microfossil content have been used to define six palaeoenvironmental stages extending from the Lateglacial to the present. Stage A and the lower part of stage B (14.2 to 10.0 ka) represent a postglacial terrestrial environment when sea level was below present. Following eustatic sea-level rise, a normal marine, open-bay environment established during the upper part of stage B (10.0 to 5.4 ka). Before 5.4 ka, a coastal lagoon developed as a consequence of a sandy barrier formation. Since then, natural variation in the permeability of the detrital barrier through time has been the primary control of the physical, chemical and biological features of the lagoonal environment: during stage C (5.4 to 3.6 ka) as a freshwater-dominated lagoon, stage D (3.6 to 1.6 ka) as a brackish lagoonal environment, and stage E (1.6 to 0.5 ka) as a return to a freshwater-dominated lagoon. Finally, in the last 400 years (stage F), human intervention on the sandy barrier (artificial open- and closed-inlet conditions) has provoked rapid and dramatic environmental changes in Santo André.

Key words: Benthic foraminifera, ostracoda, calcareous nannoplankton, diatoms, coastal evolution, lagoon, sea-level rise, sandy barrier, human intervention, Portugal, Lateglacial, Holocene.

Introduction

The Santo André lagoon is located in the Tróia-Sines coastal area, SW Portugal (Figure 1). It is a semi-enclosed water body separated from the open sea by a sandy barrier. In order to prevent eutrophication and reclaim of the tributary alluvial plains for grazing, an inlet has been opened annually since at least the seventeenth century (Freitas et al., 1999b). Opening and closing the inlet control the physico-chemical parameters of the lagoon’s water, bottom-sediment distribution and microfaunal distribution and abundance (Freitas et al., this issue; Bao et al., 1999; Cearreta et al., 2002) and may have also controlled the evolution of the adjacent coastal lowland during the Holocene.

Only during the last decade have multidisciplinary studies been produced on the geological record of SW Portugal coastal lagoons (cf. Queiroz and Mateus, 1994; Freitas, 1995; Bao et al., 1999; Freitas et al., 1999b; Freitas and Andrade, 2003). These studies have indicated that most of the Portuguese coastal barriers developed after 4000-5000 BP, a period when the rates of sea-level rise were strongly attenuated. Decelerating rates of sea-level rise led to a decoupling between eustatism and transgression. In this scenario, the importance of previous global eustatic controls diminished, accentuating the role of local factors, such as sediment availability, local wave climate or land-management practices, as the dominant forcing factors in the coastal evolution during the late Holocene. Therefore, identification at the local scale of the effects of those factors primarily involved in the Holocene evolution of coasts subjected to high-energy conditions, such as the SW Portuguese coast, is necessary in order to correctly assess the environmental changes of these areas through time.

A continuous 25.45 m long sediment core (borehole LSA) was drilled in June 1998 from the alluvial plain of Azinhal in a distal
location from the tidal inlet (Figure 1) in order to study the environmental evolution of this coastal area. The coring site (UTM 29SNC18601511) is located at +2.743 m (local ordnance datum) and the borehole reached basement (Miocene sediments) at –21.33 m.

We used a multidisciplinary micropalaeontological approach involving the analysis of benthic foraminifera, ostracoda, calcareous nanoplankton and diatoms in order to reconstruct the palaeoenvironmental history of the marginal marine environment of Santo André since the Lateglacial. This multiproxy approach was adopted in order to obtain independent lines of evidence on past environmental changes. Details on the relative importance of the different global and local forcing factors governing the evolution of the system during the last 14 000 years are also presented. Microfossil assemblages also provide important evidence of the sea-level changes in this part of the Portuguese coast where Holocene sea level is poorly understood. The sedimentological and geochemical approach to the same core is contained in the paper by Freitas et al. (this issue) and its palynological interpretation is presented in Santos and Sánchez González (this issue).

Numerous studies on the European Atlantic coast show that certain species of benthic foraminifera characterize particular environments (cf. Murray, 1991, for a summary). Intertidal and subtidal brackish lagoons are characterized by high dominance of the hyaline species Ammonia beccarii, Haynesina germanica and Elphidium oceanensis, the species diversity being highly variable. In sandy areas, under almost normal marine conditions, Quinqueloculina seminula and other porcellaneous forms may also be abundant. Data for modern coastal foraminiferal assemblages and their application to palaeoenvironmental interpretation of borehole sequences in other coastal areas of the Iberian Peninsula are summarized elsewhere (Cearreta and Murray, 1996; Cearreta, 1998). The modern foraminiferal assemblages of the Santo André lagoon have been studied by Cearreta et al. (2002). A high abundance of individuals has been found after the artificial breaching of the sand barrier whereas low abundance of foraminifera is characteristic of closed-inlet conditions. Assemblages are permanently dominated by euryhaline A. beccarii, H. germanica and E. oceanensis, plus Q. seminula following the entrance of open-ocean water into the lagoon. Rapid and intense environmental changes that range from low-salinity and low-oxygen bottom water under closed-inlet conditions to brackish and well-oxygenated bottom water under open-inlet conditions seem to be responsible of foraminiferal assemblages characterized by extremely low species diversity, high species dominances, seasonal variable abundances and common deformed tests.

Ostracods live at the water-sediment interface or just below its surface in all coastal environments, the assemblages reflecting environmental constraints at the interface (Carbonel, 1988). Numerous studies show that ostracod faunas make important contributions in palaeoenvironmental reconstruction of borehole sequences (Carbonel and Jouanneau, 1982; El Hmaidi et al., 1998; 1999; Mazini et al., 1999). Present-day ostracods of the Santo André lagoon are very abundant, show low diversity, and are dominated by the brackish-water species Cyprideis torosa and Loxoconcha elliptica (that exceed 80% in all samples); Cypridopsis vidua and juveniles of Heterocypris spp. sporadically occur.

Because placoliths, helicoliths, caneloïds and pentaliths are coccolith types exclusively produced by marine Coccolithophore algae, coccolith abundance is a proxy for the degree of marine influence on silty-clay particles deposited in lagoons and estuaries (Freitas et al., 1999a). The modern sedimentation of these minute calcite scales in the Santo André lagoon, with sizes ranging from less than 3 μm to nearly 10 μm, depends on two major factors: closeness to the inlet and bottom hydrodynamic conditions. Results from present-day analogues show that coarse-grained sediment samples located close to the inlet may contain significant amounts of coccoliths, while samples located in inner areas of the lagoon only have significant coccolith content if the sand percentage is lower than 60%.

Diatoms are extremely sensitive to the factors, such as salinity, sediment availability and hydrodynamic conditions, which control the evolution of coastal water bodies (Cooper, 1999; Denys and De Wolf, 1999, for a summary). For this reason, they provide evidence of process-response thresholds controlled by local factors. For example, Bao et al. (1999) demonstrated the value of diatom assemblages in interpreting changes in the permeability of sandy barriers in both the present-day and late-Holocene sediment records in barrier-lagoon systems of the Portuguese coast.

**Methods**

Samples for micropalaeontological analyses were taken throughout borehole LSA at 30 cm intervals with denser sampling near clayey units and lithological boundaries. The 70 samples for benthic foraminifera, ostracods and calcareous nanoplankton analyses and 57 samples for diatom analysis were 1 cm thick.

In the laboratory, foraminiferal samples (10 cm³) were wet-sieved through a 74 μm mesh and dried. All foraminiferal tests from each sample were picked, mounted and identified under a stereoscopic binocular microscope (10 500 total foraminifera). Forty-seven samples were barren or contained too few tests (range 0–43 tests/sample). Only samples containing more than 100 foraminiferal tests were used for calculations.

For ostracoda analysis (procedures as for foraminifera) all valves and carapaces (1 individual = 1 carapace or 1 valve) from each sample were picked, mounted and identified under a stereoscopic binocular microscope (10 000 total valves). In each sample, the population age structure of each species was analysed. Only
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Figure 2. Sedimentary sequence, absolute abundance of foraminiferal tests (10 cm³), number of species, and distribution and relative abundance of the main foraminiferal species in the Santo André lagoon borehole. The foraminiferal assemblage zones and radiocarbon dates are indicated. Lithostratigraphic symbols follow Troels-Smith (1955).
Figure 3 Sedimentary sequence, absolute abundance of ostracod valves and carapaces (10 cm$^3$), number of species, and distribution and relative abundance of the ostracod species in the Santo André lagoon borehole. The ostracod assemblage zones and radiocarbon dates are indicated. Circles indicate abundance lower than 10 individuals per sample. Lithostratigraphic symbols follow Troels-Smith (1955).

Results
Foraminiferal and ostracod zones
In total, 37 different foraminiferal species (Appendix 1) and 19 ostracoda species (Appendix 2) have been found in this borehole. On the basis of foraminiferal and ostracod assemblages (in terms of species abundance, diversity and dominance), this borehole section can be divided into four different zones and seven subzones (Figures 2 and 3). At the base, foraminiferal and ostracod zone 1 (–21.33 m to –11.51 m) consists of 10 m of pebbly sand, sand and muddy sand with some mollusc fragments. Based on its microfossil abundance, this zone can be subdivided into three different subzones. Subzone 1A represents the lowermost 3.5 m of the core and is characterized by the absence of benthic foraminifers. The ostracod content is very scarce with only five transported juveniles of brackish species. Subzone 1B comprises the overlying 4 m and contains very scarce foraminiferal tests (range 0–30 tests per 10 cm$^3$, average 5 tests per 10 cm$^3$) as well as some typical inner shelf species like Quinquel...
oculina lata, Triloculina bermudezi, T. trigonula, Bulimina gibba, Asterigerinata mamillia, Brizalina britannica, B. spathulata, Cibicides lobatula, Elphidium crispum, E. excavatum and Haynesina depressula that will not be present in other zones of the borehole. This subzone is also characterized by the highest number of species found in the borehole (range 0–23 species per sample, average 13 species per sample) and a moderate content of porcellaneous tests (average 13%). Like foraminifers, ostracoda display an upward increase in species diversity with some barren intervals. The diversity is moderate (1–8 species per sample), but is also the highest found in the whole core. Most species are marine littoral or sublittoral, associated with sandy-muddy substrates and algae: Aurila convexa, A. arborescens, Loxoconcha rhomboidea, Carinocythereis whitei, Pontocythere elongata, Urocystheris britannica, Xestoleberis cf. nitida; a small number of the brackish-water forms C. torosa and L. elliptica are also present. At the top of this subzone (uppermost two samples) the ostracod diversity decreases.

Foraminiferal and ostracod zone 2 (−11.51 m to −2.51 m), of 9 m of mud with abundant mollusc fragments, can be divided in two different subzones based on its microfossil abundance. Subzone 2A consists of the basal 3.5 m and exhibits a low foraminiferal abundance, with few tests (range 0–32 tests per 10 cm³, average 7 tests per 10 cm³) of the species H. germanica and A. beccarii. The ostracod content is also poor (0–70 individuals per 10 cm³) with low diversity (2–4 species per sample). Most species are brackish forms of C. torosa and L. elliptica; euryhaline forms of non-marine origin such as C. vidua and Darwinula cf. stevensoni are also present but with frequency of less than 10 valves. Subzone 2B corresponds to the overlying 5.5 m and contains initially two narrow intervals of low foraminiferal abundance. However, as a whole, it contains the highest abundance of foraminiferal tests in the borehole (range 0–1373 tests per 10 cm³, average 491 tests per 10 cm³) and it has a foraminiferal assemblage primarily of H. germanica (range 65–99%, average 90%), A. beccarii (range 0.7–26%, average 8%), and E. oceanensis (range 0–9%, average 2%). This subzone contains a very low number of foraminiferal species (range 0–5 species per sample, average 3 species/sample), almost exclusively hyaline individuals, and frequent pyritized tests. The ostracod content changes sharply in this subzone. The diversity is low (1–4 species/sample), but the abundance is very high (198 to 1070 individuals per 10 cm³). Only C. torosa is generally present (always exceeding 92%), sometimes pyritized.

Foraminiferal and ostracod zone 3 (−2.51 m to +0.74 m) consists of 3 m of sand with some mollusc fragments. Most of it is included in subzone 3A, which contains a very low-abundance foraminiferal assemblage (range 0–37 tests per 10 cm³, average 5 tests per 10 cm³) with few E. oceanensis and A. beccarii tests. The ostracod assemblage of this subzone is also very poor (0–6 individuals per 10 cm³), except in two samples with low diversity (2–3 species/sample) but high abundance (157–624 individuals per 10 cm³), dominated by Heterocypris sp.; juveniles (over 73%). Subzone 3B consists of the upper 0.35 m and contains a more abundant foraminiferal assemblage (range 100–126 tests/10 cm³, average 113 tests per 10 cm³) composed of E. oceanensis (range 40–53%, average 46%), H. germanica (range 35–48%, average 41%) and A. beccarii (12%). This assemblage shows a very low
Figure 5 Sedimentary sequence, total counts of diatom valves, and distribution of the main diatom taxa in the Santo André lagoon borehole. The diatom zones and radiocarbon dates are indicated. Lithostratigraphic symbols follow Troels-Smith (1955). Ecological groups according to Vos and De Wolf (1993). nci = non-countable intervals; *= exclusive or almost exclusive presence of the taxon; black diamonds = dominance of the taxon. Dots indicate percentages of less than 0.5% or presence of the taxon in countable and non-countable intervals respectively.
number of species (range 3–4 species per sample, average 3 species per sample) and exclusively hyaline tests. The ostracods are relatively abundant (113–362 individuals per 10 cm$^3$), with low diversity (3–4 species per sample). Most individuals belong to the brackish-water forms $C$. torosa and $L$. elliptica ($C$. torosa always >81%); freshwater to slightly brackish forms such as $C$. vidua, Ilyocypris gibba and Eucypris cf. ornata are also present but only with few valves.

The uppermost zone 4 (+0.74 m to +1.74 m) consists of the upper 1 m of brown mud to sandy mud and is barren of foraminifers. The ostracod content, only represented by freshwater to slightly brackish species ($Ilyocypris bradyi$ and Darwinula cf. stevensoni), is not representative (less than 10 valves per sample).

### Calcareous nannoplankton zones

The coccolith abundance index (CAI) changes by three orders of magnitude throughout the borehole, ranging from none to more than 1400 (sample 39). In total, 10 coccolith species have been found (Appendix 3). The presence of small fragile placoliths indicates absence of postdepositional taphonomical dissolution.

According to the coccolith content, the LSA borehole may be subdivided into four CC (= coccolith) zones (Figure 4). The lowermost zone $CC_A$ (between –21.33 and –14.26 m) is almost barren. The zone $CC_B$ (between –14.26 and –12.19 m) is characterized by the occurrence of two thin intervals, $CC_B1$ (samples 46 and 47) and $CC_B2$ (samples 40 and 41), with high abundance and relatively high diversity of coccoliths. Their relatively high diversity (10 taxa) suggests that these coccolith assemblages may have been deposited in open marine sediments. They are dominated by $E$. huxleyi, a species that characterizes the $E$. huxleyi acme biozone, the last marine biostratigraphical unit that can be recognized by nannofossils. *Emiliania huxleyi* is a common species dwelling in Portuguese waters and, together with the common occurrence of *Syracosphaera* spp., suggests a location on the southwest Portuguese coast. The latter genus tends to be more frequent in the southern surface waters off Portugal (Cachão et al., 2000; Cachão and Oliveira, 2000).

### Diatom zones

The diatom record of the LSA borehole is very fragmentary (Figure 5). Most of the samples analysed (particularly lithostratigraphical units IA and IB) contained too few diatom fragments or/and values for quantitative analyses. Good preservation made identification of three diatom zones possible only in the –4.20 to –2.20 m and –1.05 to –0.96 m intervals. In the six non-countable intervals, only a qualitative interpretation of the palaeoenvironmental conditions was made.
The qualitative analysis of the diatom record of the upper lithostratigraphical subunit IB shows that between –16.06 and –15.56 m (non-countable interval 1) the diatom assemblages are mainly marine to marine/brackish taxa such as *Paralia sulcata* or *Fragilaria fasciculata*, although some epiphytic diatoms of brackish to freshwater character (*Cocconeis placentula* and *Epithemia adnata*) also occur. The base of lithostratigraphical subunit IC (non-countable interval 2, from –14.26 to –13.86 m) shows assemblages similar to those of the underlying subunit. It is dominated by marine planktonic diatoms (*P. sulcata*, *Chaetoceros* spp. resting spores and *Actinoptychus senarius*) and shows scarce freshwater epiphytes (*Fragilaria ulna*). The top of this subunit, non-countable interval 3 (–12.75 to –12.44 m), contains almost exclusively the marine planktonic diatoms *P. sulcata* and *Chaetoceros* resting spores.

The transition from lithostratigraphical unit I to unit II is characterized by the exclusive presence of the marine planktonic diatom *P. sulcata*. The upper part of subunit IIA (non-countable interval 4, from –11.98 to –9.36 m) contains marine to marine/brackish diatom assemblages (e.g., *P. sulcata*, *Chaetoceros* resting spores, *F. fasciculata*, *Amphora coffeaeformis*, * Mastogloia pumilla*) associated with other species such as *C. placentula*. The most significant feature of the base of lithostratigraphical subunit IIB (non-countable interval 5, from –8.26 to –4.20 m) is the disappearance of the previously dominant *P. sulcata* and an increase in the proportion of brackish/freshwater to freshwater diatoms such as *C. placentula*. Although qualitative analysis was not possible, the dominance of *C. placentula* and *Cyclotella* sp. aff. *meneghiniana* at –7.26 m and –6.26 m, respectively, suggests brackish conditions. The uppermost part of subunit IIB contains the best-preserved diatom assemblages in the borehole allowing quantitative analysis and the definition of diatom zone 1 (–4.20 to –2.51 m). This zone is mainly composed by marine, marine/brackish and brackish/freshwater diatoms, *C. placentula* being the dominant species. The dominance of epiphytic diatoms suggests shallow water with abundant macrophytes. In the –3.20 to –2.70 m interval a relative increase of the marine planktonic diatoms *Chaetoceros* spp. and *Thalassionema nitzschioides* is noticeable.

The transition of lithostratigraphical unit II to unit III is characterized by diatom zone 2 (–2.51 to –2.20 m), which shows a sharp increase in the abundance of marine/brackish epipelagic and epipsammic diatoms (*Achnanthes delicatula* and *Achnanthes lemmermannii*) typical of intertidal sand- and mudflats. Subunit IIIA is generally characterized by the almost complete disappearance of marine planktonic diatoms and the codominance of *C. placentula* and *Fragilaria construens* f. *salina* (non-countable interval 6, from –2.20 to –1.05 m, and diatom zone 3, from –1.05 to –0.96 m).

Lithostratigraphical unit IV is barren.

**Palaeoenvironmental interpretation and discussion**

According to the lithostratigraphic units defined by Freitas et al. (this issue) and the different microfossil zonations presented in the previous section, we define six distinctive palaeoenvironmental stages (A–F). These stages show the environmental evolution of this lagoon since the Late Glacial (Figure 6).

**Palaeoenvironmental stage A (after 14.2 to c. 12.4 ka)**

This stage is characterized by the complete absence of foraminifers, with only a few ostracods, calcareous nannoplankton and diatoms. Due to its very low microfossil content, we interpret this stage as a record of a postglacial terrestrial environment when sea level was well below present. This conclusion is also supported by the geochemical, mineralogical and sedimentological characteristics of this stage (cf. Freitas et al., this issue).

**Palaeoenvironmental stage B (c. 12.4 to 5.4 ka)**

The basal part of this stage (12 440 ± 60 to 10 020 ± 50 BP) was deposited under non-marine conditions, as indicated by the very scarce foraminiferal tests, no representative ostracods and no coccoliths. The coexistence of marine to marine/brackish with some brackish/freshwater to freshwater diatoms suggests that this interval probably records the progress of the Holocene post-glacial transgression.

The upper part of stage B (10 020 ± 50 to 5380 ± 50 BP) represents normal marine salinity conditions. This interpretation is supported by an abundant and diverse foraminiferal assemblage with a mixture of coastal and inner shelf species, an ostracod assemblage of marine littoral or sublittoral species of moderate diversity, and the almost exclusive presence of marine planktonic diatoms. As a whole, the upper part of stage B represents flooding of the coring site by the sea and the establishment of open-marine bay conditions.

The interpretations inferred from benthic foraminifers, ostracoda and diatoms match quite well with those inferred from the coccolith assemblages found in the CC5 coccolith sector. During episodes CC5b and CC5c the abundance of coccoliths exceeds that found in the present-day lagoonal sediments. The assemblages found in those sectors are similar in composition to those retrieved from surface samples on the Portuguese inner and middle shelf (Cachão, 1993) suggesting deposition under open-marine conditions.

Intervals barren of foraminifers and ostracoda coincide with the absence of calcareous nannoplankton and may represent short-term episodes of fluvialite sedimentation in the bay. Geochemical data support also terrestrial influence on these intervals (cf. Freitas et al., this issue) disregarding dissolution problems as the cause for the low microfossil content.

The uppermost part of stage B shows an upward decreasing trend in species diversity of ostracoda (foraminiferal and ostracod subzone 1C). Also, in the lower part of the CCb coccolith sector (–12.16 to –11.65 m) CAI and coccolith diversity are much lower than for the CC5b and CC5c episodes. Altogether, these data suggest that the environment became progressively more restricted during the latter half of this palaeoenvironmental stage.

This stage represents the progressive advance of the postglacial marine transgression and the arrival of the coastal zone to its present position. Initially, 10 ka ago, a normal-marine, open-bay environment developed in the area and it lasted until 5.4 ka when, due to a sandy barrier formation, this bay was isolated from the open sea and transformed into a coastal lagoon (see following palaeoenvironmental stages). The formation of a sandy barrier represents a common feature along this coastal area at this time and it has been invoked as responsible for the environmental evolution of other lagoonal areas during the late Holocene (Freitas, 1995; Bao et al., 1999; Freitas and Andrade, 2003).

**Palaeoenvironmental stage C (c. 5.4 to 3.6 ka)**

Stage C is characterized by a very low foraminiferal abundance suggesting deposition in a freshwater-dominated environment, formed by the establishment of a sandy barrier. The ostracod content, also of very low abundance and diversity, is almost exclusively represented by brackish-water species (*C. torosa* and *L. elliptica*), pointing to fresh to slightly brackish water conditions. Modern assemblages exhibit great and rapid seasonal variations in foraminiferal abundance between open- and closed-inlet conditions in the Santo André lagoon (Careta et al., 2002). This fact, together with the abundant presence of carbonate mollusc fragments, and the geochemical results of this stage (cf. Freitas...
The absence of coccoliths and very low foraminiferal and ostracod abundances in this stage represent another period of isolation from the sea due to restoration of an impermeable sandy barrier about 1.6 ka. The abundant freshwater to slightly brackish ostracod *Heterocypris* sp. population in samples at −1.05 and −0.96 m depth, although represented only by juveniles and therefore regarded as allochthonous (population age structure of type C in Whately, 1988), may indicate the presence of temporary pools close to the lagoon. Diatom zone 3, marked by a sharp increase in marine/brackish epipelic and epipsammic diatoms which acquire percentages typical of intertidal sand- and mudflats, has no corresponding zone in the foraminiferal and ostracod records. This could suggest allochthonous diatom valves. However, the coarse sand in lithostratigraphical subunit IIIA indicates that the epipsammic diatoms might be autochthonous, a conclusion that could not stand if clay was dominant (Vos and De Wolf, 1993). Nevertheless, the diatom assemblages of stage E are characterized by a decrease in the marine planktonics, indicating a decreasing marine influence. The dominance of the euryhaline *C. placenta* and the pioneering *F. construens* *F. subsalina* may point to salinity changes. High abundances of Fragilaria taxa are common under conditions of hydrological instability in coastal systems, strong changes in salinity being one of the main factors controlling their abundance (e.g., Denys, 1990; Stabell, 1985). Sedimentological and geochemical characteristics of this stage E (cf. Freitas *et al.*, this issue) indicate high-energy conditions and terrestrial terrigenous input into the lagoon at this time.

**Palaeoenvironmental stage F (c. 0.5 ka to present)**

During stage F brackish, restricted conditions were re-established, probably due to human intervention since the seventeenth century. The coccoliths reflect a short-term episode of marine input during *C* c (0.40 to +0.47 m), which is in agreement with a shift from fresh water to brackish water, indicated by benthic foraminiferal and ostracoda assemblages similar to modern lagoonal assemblages and geochemical results (cf. Freitas *et al.*, this issue). The uppermost part of this man-influenced stage is barren of foraminifera, representative ostracoda, calcareous nanoplankton and diatoms. Preservation problems of calcareous microfossils cannot be invoked as geochemical analysis show a significant increase in carbonate content for this lithostratigraphical unit IV (cf. Freitas *et al.*, this issue). It records the final thickness of sediment deposited in the southern part of the Santo André lagoon under alluvial plain conditions before recent land reclamation.

Based on this palaeoenvironmental interpretation, global eustatic sea-level rise can be considered as the main factor responsible for coastal development during the Lateglacial and first part of the Holocene (palaeoenvironmental stages A and B). However, it must be regarded as being of secondary importance during the last 5 ka after the sandy barrier formation. Natural variations in the permeability of the detrital barrier through time seem to be the primary control of the physical, chemical and biological features of the lagoonal environment (palaeoenvironmental stages C, D and E). These changes in the permeability are controlled by local coastal parameters (e.g., sediment budget and wave regime) although regional and global scale factors (sea-level change and long-term climatic variations) acted as background controls. Finally, at least during the last 400 years (palaeoenvironmental stage F) human intervention on the sandy barrier has provoked rapid and dramatic environmental changes in Santo André.

These conclusions are in accordance with studies of the sedimentary sequence in the Albufeira and Melides lagoons on the same SW Portuguese coast (Freitas, 1995; Bao *et al.*, 1999; Freitas and Andrade, 2003) where it was concluded that these lagoonal basins evolved also as barrier-controlled systems during the late Holocene.
Summary and conclusion

We interpreted foraminiferal, ostracod, calcareous nannoplankton and diatom assemblages in the sedimentary succession of one borehole drilled in the Santo André lagoon to identify six palaeo-environmental stages in the Lateglacial and Holocene history of the lagoon (Figure 6). Four major zones and seven subzones are recognized according to its foraminiferal and ostracod contents, four zones according to its calcareous nannoplankton content, and three zones plus six non-countable intervals according to the diatom content. These zones and subzones of each fossil group are used to define the palaeo-environmental stages. Stage A represents a terrestrial environment at Santo André contemporaneous of a low sea level and a distal shoreline. As a consequence of the postglacial sea-level rise (global forcing factor), a normal marine, open-bay environment characterized by a diverse and abundant foraminiferal assemblage (dominated by A. beccarii, H. germanica and Q. seminula with frequent inner-shelf species) and by a moderately diverse ostracod assemblage (dominated by marine coastal species such as L. rhomboidea, A. convexa, A. arborescens, C. whitei, U. britannica, P. elongata, P. cf. trigonella) during the period between 10 and 5 ka constitutes the most important feature of stage B. The diversity and abundance of the E. huxleyi-dominated coccolith content corroborates this interpretation, showing that neritic open-ocean sedimentation was present during CC B1 and CC B2 intervals. The dominance of marine planktonic diatoms also suggests the development of an open-bay system.

Before 5.4 ka, a coastal lagoon developed as a consequence of the sandy barrier formation, isolating the bay from the open sea. The development of this barrier is most probably a local effect of the marked deceleration of the sea-level rise at this time. The exclusive presence of the diatom P. sulcata at this boundary is an indication of this isolation event. In the following stage C, assemblages show that the lagoon was dominantly closed with freshwater to very slightly brackish conditions through the period 5.4–3.6 ka, followed by restricted, brackish conditions during 3.6–1.6 ka. This stage D probably began with a sea-level rise, and it is characterized by an abundant, low-diverse, pyritized foraminiferal assemblage (made by H. germanica, A. beccarii and E. oceanensis) and by a very abundant, low-diversity ostracod assemblage (highly dominated by C. torosa). During stages C and D, both the coccolith and diatom contents showed short-term episodes of strong marine influence alternating with long intervals of restricted freshwater or brackish conditions. The typical highly variable salinity during these stages is particularly reflected by the dominance of the diatom genus Fragilaria. Restoration of closed, freshwater conditions in the lagoon characterizes stage E during the period from 1.6 ka to the seventeenth century. In consequence, after 5 ka the lagoon environment evolved essentially as a function of local forcing factors, based on the frequency and efficiency of the exchanges with the open ocean which may have been concomitant with minor sea-level rises.

Finally, stage F, characterized at the base by very-low-diversity foraminiferal (made of E. oceanensis, H. germanica and A. beccarii) and ostracod (C. torosa and L. elliptica) assemblages and low abundance of calcareous nannoplankton (E. huxleyi, G. ericosii and Syracosphaera spp.), probably reflects human intervention on the lagoon since the seventeenth century. The upper part of stage F (equivalent to the uppermost part of CC B) is barren of foraminifera, representative ostracoda, coccoliths and diatoms, and it represents the final stage of terrestrial sedimentation before land reclamation.

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Appendix 1: Foraminiferal reference list

| Agglutinated species: |  |
|-----------------------|  |
| Trochammina inflata   |  |
| Porcellaneous species:|  |
| Adelosina costata     |  |
| Adelosina laevigata   |  |
| Massilina secsns      |  |
| Milolinella subrotunda|  |
| Quinquelocalina lata  |  |
| Quinquelocalina oblonga|  |
| Quinquelocalina quadrata|  |
| Quinquelocalina seminula|  |
| Triloculina bermudezi |  |
| Triloculina trigonula |  |

| Hyaline species:        |  |
|-------------------------|  |
| Ammonia beccarii        |  |
| Astacolus crepidula     |  |
| Asterigerinata mamilla  |  |
| Aubigyna perlucida      |  |
| Bolivina pseudoplicata  |  |
| Brizalina britannica    |  |
| Brizalina spatulata     |  |
| Brizalina variabilis    |  |
| Bulimina alazanensis    |  |
| Bulimina elongata       |  |
| Bulimina gibba          |  |
| Cibicides lobatusul      |  |
| Elphidium crispum       |  |
| Elphidium excavatum     |  |
| Elphidium gerthi        |  |
| Elphidium oceanensis    |  |
| Elphidium williamsoni   |  |
| Fissurina lucida        |  |
| Gavolinopsis praegeri   |  |
| Haynesina depressula    |  |
| Haynesina germanica     |  |
| Nonion boweanum         |  |
| Nonionella atlantica    |  |
| Patella corrugata       |  |
| Rosalina anomala        |  |
| Trifarina angulosa      |  |

Appendix 2: Ostracoda reference list

| Freshwater to slightly brackish-water species: |  |
|-----------------------------------------------|  |
| Cypridopsis vidua                            |  |
| Darwinula cf. stevensoni                     |  |
**Eucypris** cf. ornata  
**Heterocypris** sp.  
**Hyocypris bradyi**  
**Hyocypris gibba**  
**Limnoctythere inopinata**

**Brackish-water species:**  
**Cyprideis torosa**  
**Loxocochna elliptica**  
**Xestoleberis cf. nitida**

**Marine coastal species:**  
**Aurila arborescens**  
**Aurila convexa**  
**Bassleriites cf. hercioni**  
**Carinocythereis whitei**  
**Leptocythere mueller-fabaeformis**  
**Loxocochna rhomboidea**  
**Pontocythere elongata**  
**Propontocypris trigonella**  
**Urocythereis britannica**

**Appendix 3: Nanno/bullet6 oral reference list**

**Placoliths:**  
**Emiliania huxleyi**  
**Gephyrocapsa ericsonii**  
**Gephyrocapsa muellerae**  
**Gephyrocapsa oceanica**  
**Calcidiscus leptoporus**  
**Coccolithus pelagicus**

**Helicolith:**  
**Helicosphaera carteri**

**Caneoliths:**  
**Syracosphaera pulchra**  
**Syracosphaera sp.**

**Pentalith:**  
**Braarudosphaera bigelowi**

**Appendix 4: Diatom reference list**

**Marine plankton:**  
**Actinocyclus sp. aff. ehrenbergii**  
**Actinoptychus senarius**  
**Chaetoceros spp. (resting spores)**  
**Paralia sulcata**  
**Thalassionema nitzschioides**  
**Triceratium antediluvianum**

**Brackish/freshwater plankton:**  
**Cyclotella meneghiniana**  
**Cyclotella quetzingiana**  
**Cyclotella ocellata**  
**Cyclotella shumannii**

**Brackish/freshwater tychoplankton:**  
**Bacillaria paradoxa**  
**Fragilaria brevistriata**  
**Fragilaria construens f. subsalina**

**Marine epiphytes:**  
**Grammatophora marina**  
**Grammatophora oceanica**  
**Synedra crystallina**

**Marine/brackish epiphytes:**  
**Achnanthes brevipes**  
**Cocconeis scutellum**  
**Cymbella pusilla**  
**Fragilaria fasciculata**  
**Fragilaria pachellia**  
**Gomphonema exiguum var. minutissimum**  
**Mastogloia braunii**  
**Melosira lineata morph. juergensii**  
**Rhopalodia acuminata**  
**Rhopalodia gibberula**

**Brackish/freshwater epiphytes:**  
**Cocconeis placentula**  
**Rhoicosphenia abbreviata**  
**Rhopalodia gibba**

**Freshwater epiphytes:**  
**Achnanthes lanceolata**  
**Achnanthes minutissima**  
**Cymbella microcephala**  
**Cymbella silesiaca**  
**Cymbella tumida**  
**Epithemia adnata**  
**Epithemia sorex**  
**Epithemia turgida**  
**Fragilaria ulna**  
**Gomphonema gracile**  
**Nitzschia amphibia**

**Marine/brackish epipelon:**  
**Amphora coffeaeformis**  
**Amphora holsatica**  
**Amphora veneta**  
**Anomoeoneis sphaerophora**  
**Caloneis amphisbaena f. subsalina**  
**Diploneis didyma**  
**Diploneis subovalis**  
**Gyrosigma acumination**  
**Mastogloia ellipitca**  
**Mastogloia pumila**

**Freshwater epiphytes:**  
**Achnanthes brevipes**  
**Cocconeis scutellum**  
**Cymbella pusilla**  
**Fragilaria fasciculata**  
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