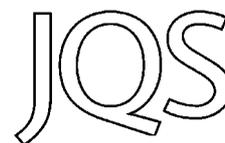


Paleoenvironmental reconstruction of a Late Quaternary lagoon system in southern Brazil (Jaguaruna region, Santa Catarina state) based on multi-proxy analysis



PAULA GARCIA CARVALHO DO AMARAL,^{1,2*,†} PAULO CÉSAR FONSECA GIANNINI,¹
FLORENCE SYLVESTRE² and LUIZ CARLOS RUIZ PESSEDA³

¹Instituto de Geociências, Departamento de Geologia Sedimentar e Ambiental, Universidade de São Paulo, São Paulo, Brazil

²CEREGE, Aix-Marseille Université-CNRS-IRD, Aix-en-Provence, France

³Laboratório de Carbono 14, CENA/USP, Piracicaba, SP, Brazil

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ABSTRACT: This paper provides a paleoenvironmental reconstruction of a Late Quaternary lagoon system in the Jaguaruna region of Santa Catarina state, southern Brazil. Integrated results of bulk sedimentary organic matter characterization ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C/N), microfossil (pollen and diatom) and grain-size analysis from three shallow cores (~2.5 m depth) allowed us to propose an evolving paleogeographic scenario in this coastal region for the last ca. 5500 cal a BP. The lagoonal system in this area was more extensive during the mid-Holocene than today, with a gradual and continuous lagoon–sea disconnection until the present. We add to the debate regarding relative sea-level (RSL) variations for the Brazilian coast during the Holocene and discuss the importance of sedimentary dynamics for interpreting changes in coastal ecosystems. The multi-proxy analysis suggests that changes in coastal ecosystems could be directly related to local sedimentary processes, which are not necessarily linked to RSL fluctuations and/or to climatic variations. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: Late Quaternary; lagoon system; sedimentary dynamics; geochemistry; diatom analysis; pollen analysis.

Introduction

The high variability of energy and depositional processes in coastal zones produces rapid spatial and temporal changes. Paleoenvironmental reconstructions in these zones should be based on multi-proxy analyses, including biological, geochemical and sedimentological indicators. Fortunately, coastal regions contain a large number of paleoenvironmental proxies, including sedimentary facies, pollen, spores, seeds, charcoal fragments from land plants and ecosystems which occur exclusively in these areas (e.g. mangroves), diatoms, foraminifera and geochemical parameters. Among these proxies, microfossils have good potential in paleoenvironmental reconstructions, although they can be poorly preserved, scarce or absent in coastal sediments (Wilson *et al.*, 2005). Additionally, paleoenvironmental interpretations based only on microfossil assemblages can be complicated by the effects of syn- and post-depositional processes, which influence the distribution and preservation of microfossils within sedimentary records. For this reason, combining microfossil studies with sedimentological analyses and organic matter characterization could fill gaps in information from the microfossil record as well as complement evolution models in coastal regions.

Here, we present the results of bulk organic matter characterization, grain-size analysis and microfossil (pollen and diatom) studies carried out in three shallow cores (~2.5 m in depth for each) collected from paleo-lagoon sediments in southern Brazil. On the Brazilian coast, environmental reconstructions based on multi-proxy analysis are still scarce, and the response of coastal ecosystems to Quaternary climate and sea-level changes remains poorly known due to the paucity of data. In addition, relative sea level (RSL) changes on the

Brazilian coast during the Holocene remain of debate, so new paleodata can bring novel insight regarding this subject. The two RSL curves proposed for the Brazilian coast have in common a mid-Holocene sea level maximum followed by a subsequent fall (e.g. Suguio *et al.*, 1985; Angulo *et al.*, 1999). However, the height of the maximum sea level rise and the nature of the Late Holocene sea level fall differ significantly in the two curves (Angulo *et al.*, 2006). In this context, the goal of this study was to reconstruct the paleogeographic evolution of a Quaternary lagoon system in southern Brazil based on a multi-proxy analysis, and to provide new elements to the Holocene RSL debate.

Study area

Quaternary depositional systems at the mid-south coast of Santa Catarina state

The Quaternary sediments at the mid-south coast of Santa Catarina state (southern Brazil) display a diversity of depositional facies, related to a mosaic of interdependent eolian, lagoonal and marine processes. The coastal facies are grouped into four depositional systems (Fig. 1): barrier, strandplain, lagoonal and eolian (Giannini, 1993; Giannini *et al.*, 2007). The barrier system is currently covered by the eolian deposits.

Three specific sites were selected for shallow coring (~250 cm in depth) and represent different morphological aspects of the lagoon system. The first site, Figueirinha Lake (core FIG, drilled in a peat surrounding the lake, Figs. 1 and 2a), corresponds to a residual lake from an ancient bay-lagoon system formed behind a transgressive barrier during Holocene maximum flooding; it is placed where the southern tip of a Holocene barrier was probably anchored in the Pleistocene strandplain (Giannini, 1993). The two other sites, the Riachinho and the Sangão River valleys, represent the outer and the inner portions, respectively, of a valley-lagoon (Figs. 1 and 2). The Riachinho valley is a dissection valley incised into pre-existing

*Correspondence: P. G. C. Amaral, at †present address below.

E-mail: amaral@cerege.fr

† Present address: CEREGE, Europôle de l'Arbois BP 80, 13545, Aix-en-Provence Cedex 4, France.

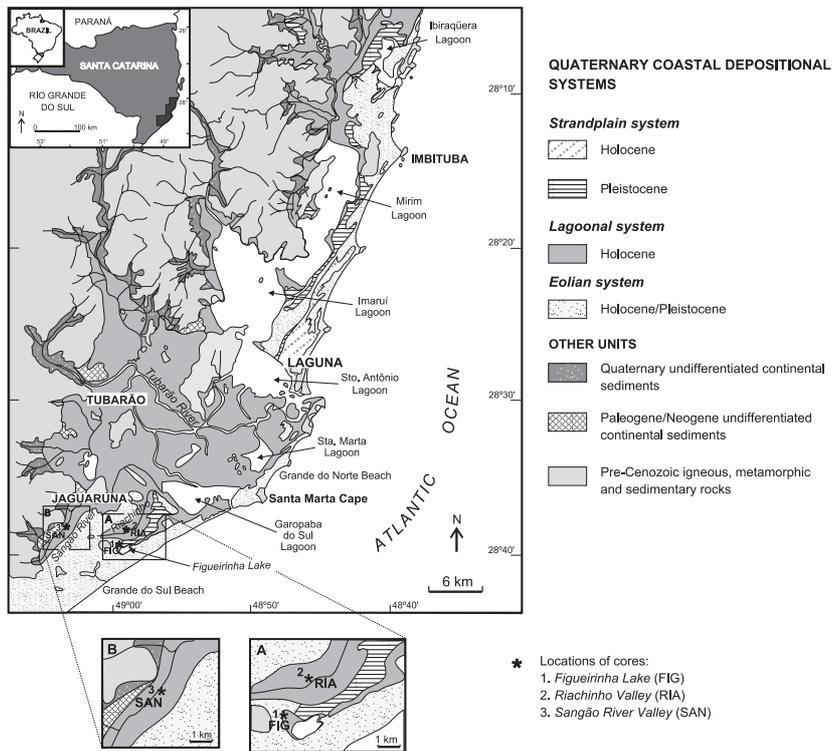


Figure 1. Map of the Quaternary depositional systems from the mid-south coast of Santa Catarina state (southern Brazil). Modified from Giannini (1993). Boxes A and B show the location of the two images of Fig. 2.

regressive marine Pleistocene terraces that were drowned and transformed into a lagoon during the maximum Holocene RSL rise, and later became mud filled (core RIA, Figs. 1 and 2a). The Sangão River valley is similar in origin to the Riachinho valley and was incised between the pre-Cenozoic basement and marine Pleistocene terraces (core SAN, Figs. 1 and 2b).

Climate and vegetation

The climate of the region is subtropical humid mesothermal, without a dry season and with annual average temperature of 19 °C. The area has high relative humidity (~85%), with annual precipitation between 1250 and 1400 mm (Giannini *et al.*, 2007). The South Atlantic Tropical Anticyclone (warm air) predominates during the spring and summer months, and is related to trade winds from the north-east.

In autumn and winter, the Polar Migratory Anticyclone is more active, with the predominance of winds from the south to the south-west. In general, rainy days are associated with winds coming from the southern quadrants (Nimer, 1989).

A mosaic of coastal vegetation characterizes the region. In some places it is dominated by herbaceous plants (e.g. on the foredunes, and surrounding the lagoons), and in other places by dense arboreal vegetation including trees up to 10 m in height (lowland forest). The foredune vegetation is characterized by a low diversity of species that live under specific conditions of variable temperature within the surface soil, low soil humidity and constant movement of sand (Cordazzo and Seeliger, 1995). The dominant families are Amaranthaceae, Poaceae, Asteraceae and Apiaceae. Among the vegetation surrounding the lagoons, swamps and peatboags the main families are



Figure 2. Satellite images of the Jaguaruna region (Santa Catarina state) with the coring sites indicated: Part (a) shows core FIG which was drilled in peat around the lake (see 1), and core RIA (see 2); part (b) shows core SAN (see 3). Dashed line shows the limits of the Holocene lagoonal system. Images from Google Earth, 2011. This figure is available in colour online at wileyonlinelibrary.com.

Droseraceae, Lentibulariaceae, Eriocaulaceae, Juncaceae, Polygalaceae, Cyperaceae and Poaceae.

The lowland forest is characterized by a high diversity of species, with a large number of epiphytes, lianas and several types of ferns. The dominant trees are in the families Euphorbiaceae (*Alchornea*), Moraceae, Fabaceae, Malpighiaceae (*Byrsonima*), Aquifoliaceae (*Ilex*), Urticaceae (*Cecropia*) and Myrtaceae.

Material and methods

Three sediment cores were collected with a vibrocorer (Martin *et al.*, 1995). The cores were subsampled every 5 cm for diatom and grain-size analysis, and every 10 cm for organic geochemistry and pollen analysis.

Grain-size analysis was undertaken using standard pipette-sieve methods (Galehouse, 1971; Ingram, 1971). Samples were pipetted in 1.0 ϕ intervals (on the Krumbein *phi* scale) for both silt and clay fractions, while fractions greater than 62.5 μm were dry sieved in 0.5 ϕ intervals. Results of the grain-size distribution were converted into statistics (mean diameter, standard deviation, skewness and kurtosis) using Pearson's moments method.

Samples for pollen analysis were prepared using the method described by Faegri and Iversen (1989), while diatom preparations followed the procedures described in Battarbee (1986). For each sample, 250–300 pollen grains and a minimum of 400 diatom valves were counted. Pollen grains were identified using various pollen keys (e.g. Salgado-Laboriau, 1973; Colinvaux *et al.*, 1999). Diatom taxa identifications were primarily based on Peragallo and Peragallo (1897–1908), Germain (1981) and Witkowski *et al.* (2000). Ecological diatom species requirements were based on Carpelan (1978) and Moro and Fürstenberger (1997). Salinity classification follows Gasse *et al.* (1987). Factorial correspondence analysis (FCA) was performed for the diatom dataset from the RIA core using PAST software (Hammer *et al.*, 2001).

Elemental and isotopic carbon and nitrogen analyses were carried out at the Stable Isotope Laboratory of CENA/USP (University of São Paulo, Brazil). The total organic carbon (TOC) content, the total nitrogen (TN) content, and the stable isotopes of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) were analysed

with an ANCA SL 2020 mass spectrometer (Europa Scientific, Crewe, UK). TOC and TN results are expressed as percentage of dry weight. Isotope ratios were determined with respect to the VPDB standard for $\delta^{13}\text{C}$ and atmospheric air for $\delta^{15}\text{N}$, with an analytical precision of $\pm 0.2\%$ for both. The correlation coefficient (*r*) between TOC and TN was used to evaluate whether the TN content of the samples was predominantly organic and therefore if it could be utilized to characterize the origin of the organic matter in the sediments (Hedges *et al.*, 1986).

Chronological control was based on 30 accelerator mass spectrometry (AMS) ^{14}C measurements (Beta Analytic Inc, Miami, FL, USA). AMS dates were made on peat, wood and on the bulk organic matter within intervals of the cores that did not contain macrofossils. Pretreatment washing used acid/alkali/acid for the peat and wood, and acid for the organic sediments. Calibration dates were estimated using CALIB 6.0 and Reimer *et al.* (2009).

Results

Lithology and chronology of the cores

The core collected from the peat surrounding Figueirinha Lake (core FIG, Fig. 3a) was divided into three facies, from base to top: (i) fine sand with plane-parallel laminations, (ii) massive muddy fine sand and (iii) sandy mud with plant debris. Grain-size analysis showed a clear difference between the basal facies and the other two facies, which have higher silt and clay mass concentrations. Radiocarbon ages (Table 1) showed that this core represents a sedimentary record of more than 25 600 cal a BP. The bottom of the column was not dated by ^{14}C due to the low organic carbon content (TOC < 0.1%).

The core collected in the Riachinho valley (core RIA, Fig. 3b) revealed two facies: (i) massive sandy clay and (ii) organic mud with plant debris. The transition between the two is abrupt and irregular. Results obtained from radiocarbon analysis (Table 1) indicate that the sediments were dated to at least 5170 cal a BP. An age inversion was observed between samples above and below the facies contact (Fig. 3b). However, when dating precision is considered, these dates overlap. This suggests that the sedimentary processes that formed the two facies occurred during the same time interval, or that the difference in age

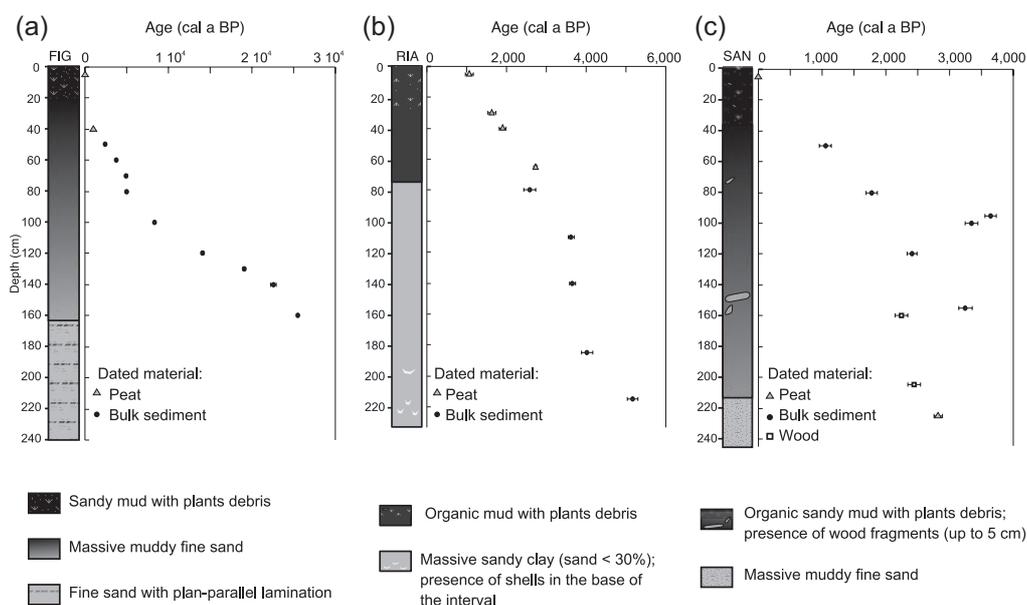


Figure 3. Schematic columnar sections showing the sedimentological variations and calibrated ages with depth in the three cores collected in the Jaguaruna region: (a) core FIG, (b) core RIA and (c) core SAN.

Table 1. Depth, material, $\delta^{13}\text{C}$ and ^{14}C conventional and calibrated ages (using Calib 6.0; Reimer *et al.*, 2009) for the FIG, RIA and SAN core samples.

Core and Sample (Beta) code	Depth (cm)	Material	$\delta^{13}\text{C}$ (‰)	Conventional radiocarbon age, ^{14}C a BP	Age range with 2σ deviation, cal a BP [†]	Median of age range (cal a BP)
FIG						
205084	-5	Peat	-22.3	109.2 ± 0.5 *pMC	Modern	
205085	-40	Peat	-25.3	1070 ± 40	930–1060 (1.0)	995
224106	-50	Bulk sed.	-21.8	2340 ± 40	2310–2490 (0.95)	2400
224107	-60	Bulk sed.	-18.7	3480 ± 40	3640–3850 (1.0)	3745
205086	-70	Bulk sed.	-18.7	4380 ± 40	4850–5050 (0.99)	4950
224108	-80	Bulk sed.	-18.1	4410 ± 40	4860–5070 (0.85)	4965
224109	-100	Bulk sed.	-18.3	7570 ± 40	8320–8430 (1.0)	8375
224110	-120	Bulk sed.	-17.9	12 210 ± 60	13890–14230 (1.0)	14 060
205087	-130	Bulk sed.	-19.1	15 880 ± 60	18930–19250 (1.0)	19 090
224111	-140	Bulk sed.	-18.9	19 020 ± 120	22270–22880 (1.0)	22 575
224112	-160	Bulk sed.	-21.2	21 150 ± 20	25380–25610 (0.95)	25 495
RIA						
205093	-5	Peat	-27.5	1160 ± 40	970–1170 (1.0)	1070
224099	-30	Peat	-26.4	1740 ± 40	1540–1740 (0.99)	1640
205094	-40	Peat	-26.3	1930 ± 40	1810–1990 (0.97)	1900
205095	-65	Peat	-26	2580 ± 40	2690–2770 (0.67)	2730
205096	-80	Bulk sed.	-26	2490 ± 40	2430–2730 (0.95)	2580
224100	-110	Bulk sed.	-18.9	3370 ± 40	3550–3700 (0.87)	3625
205097	-140	Bulk sed.	-16.3	3430 ± 40	3580–3730 (0.76)	3655
243984	-185	Bulk sed.	-17.9	3700 ± 50	3890–4160 (0.98)	4025
243985	-215	Bulk sed.	-19.5	4500 ± 40	5040–5300 (0.98)	5170
SAN						
205099	-5	Peat	-23.9	102.3 ± 0.5 *pMC	Modern	
224101	-50	Bulk sed.	-28.9	1140 ± 40	960–1150 (0.96)	1055
224102	-80	Bulk sed.	-28.4	1830 ± 40	1690–1870 (0.97)	1780
243981	-95	Bulk sed.	26.4	3410 ± 40	3560–3730 (0.9)	3645
205101	-100	Bulk sed.	-27.3	3120 ± 50	3240–3440 (0.98)	3340
224103	-120	Bulk sed.	-28.3	2370 ± 40	2330–2490 (0.92)	2410
243982	-155	Bulk sed.	-27.1	3040 ± 40	3140–3360 (0.99)	3250
224104	-160	Wood	-29.8	2220 ± 40	2150–2340 (1.0)	2245
224105	-205	Wood	-28.6	2430 ± 40	2350–2550 (0.7)	2450
243983	-225	Peat	-27.5	2730 ± 40	2760–2890 (0.96)	2825

*pMC is the percentage of modern carbon relative to the modern reference standard, indicating a post-0 BP age (i.e. the material was living within the last 50 years); [†]the numbers in parentheses are the relative areas under the probability distribution; sed. = sediment.

represents a difference in the dating material (peat vs. bulk sediment).

Two facies were described in the Sangão River valley core (core SAN, Fig. 3c): (i) massive muddy fine sand and (ii) organic sandy mud with plant debris. Between 160 and 80 cm, an increase in the amount of sand was observed in the macroscopic analysis and this was confirmed by grain-size analysis. An age inversion was verified in this interval (Fig. 3c, Table 1), attributed to an episodic event with deposition of reworked sediments. The radiocarbon age obtained near the base, at 225 cm (Table 1), indicated that the core records at least the last 2825 cal a BP.

Micropaleontological and geochemical indicators

Figueirinha Lake – core FIG

Core FIG had low pollen and diatom content. Diatom analysis was carried out for the upper 20 cm (Fig. 4) showing no significant ecological changes. The diatom taxa association, dominated by *Brachysira serians*, *B. brebissonii*, *Frustulia rhomboides* and *F. crassinervia*, is typical of shallow oligosaline acidic water and indicates conditions similar to those currently observed in the peat where the core was collected.

Pollen analysis was only possible in portions of the core with more than 15% silt and clay (Fig. 4). The pollen record indicated that around 4000 cal a BP the vegetation may have been less diverse than today, with a dominance of Poaceae (59%). Pollen assemblages indicated that vegetal diversity increased upwards. Typical peat taxa (*Drosera*, Eriocaulaceae, Polygalaceae and Alismataceae) displayed their highest frequencies in the top of the core.

TOC values varied from 0.02 to 9%, and TN from 0.001 to 0.9%, with the highest concentrations found in the upper part of the core. C/N ratios were variable (from 10 to 45), with most of values in the range 11–20 (Fig. 4). The range of C/N ratios indicates a combination of algae and land plants as source of the organic matter (Meyers, 1997; Meyers and Lallier-Vergès, 1999; Sifeddine *et al.*, 2004). $\delta^{13}\text{C}$ results varied between -23.2 and -17.8‰. An isotope-enriched layer was observed between 160 and 60 cm, with a mean value of -18.4‰. $\delta^{15}\text{N}$ varied from -5.7 to 5.2‰, increasing upwards (with an exception of -11.1‰ found at 190 cm). A mixed origin for the sedimentary organic matter could be inferred from both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analyses, with contributions from algae and land plants (C₃ and C₄).

The correlation coefficient obtained between TOC values and TN values ($r=0.98$; Fig. 5a) indicates that the nitrogen analysed was predominantly organic. The plot of $\delta^{13}\text{C}$ vs. C/N (Fig. 5b) confirmed a mixed organic matter source.

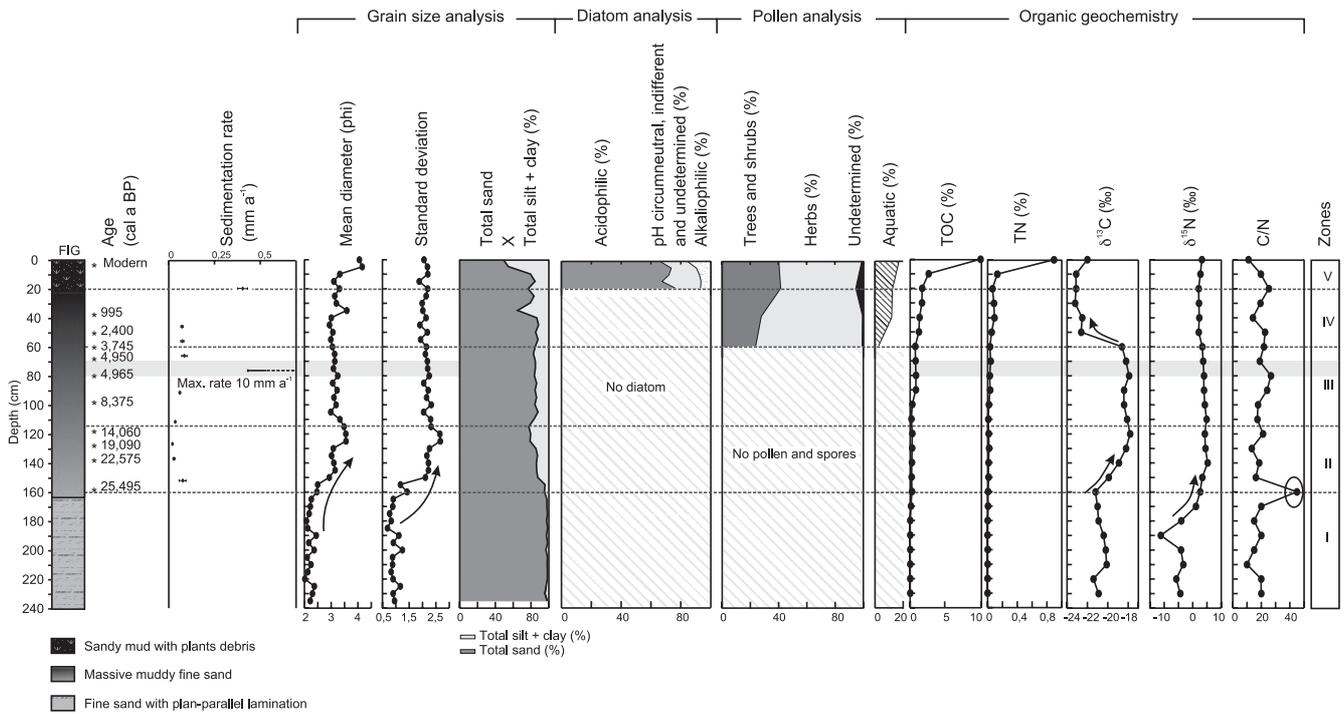


Figure 4. Summary results for core FIG: variation as a function of the core depth from the chronological, sedimentological, micropaleontological (diatom and pollen analysis) and geochemical variables. The arrows and circle indicate the variations discussed in the text.

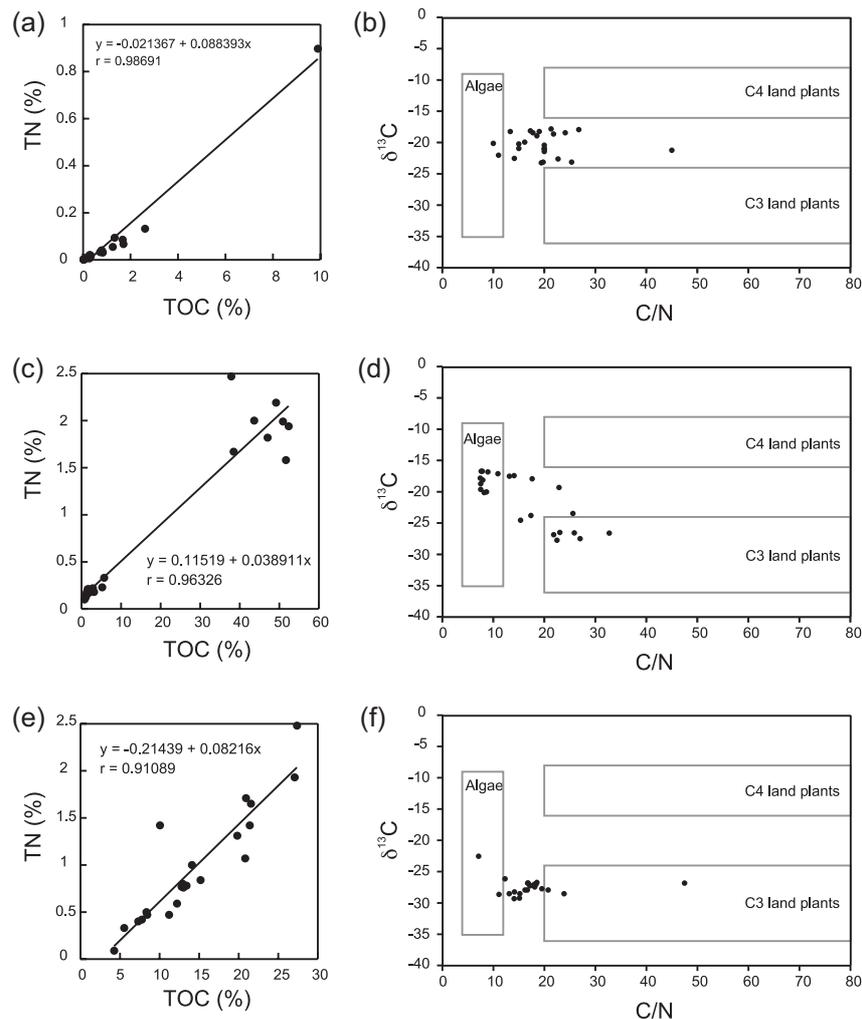


Figure 5. Scatter plots between TOC and TN, and $\delta^{13}\text{C}$ vs. C/N for the different studied cores: (a,b) core FIG, (c,d) core RIA and (e,f) core SAN. The solid line and the function in TOC and TN scatter plots refer to the linear regression. The different fields in the $\delta^{13}\text{C}$ vs. C/N plots correspond to end-member sources for organic matter preserved in sediments (modified from Meyers, 1994 by Sifeddine *et al.*, 2004).

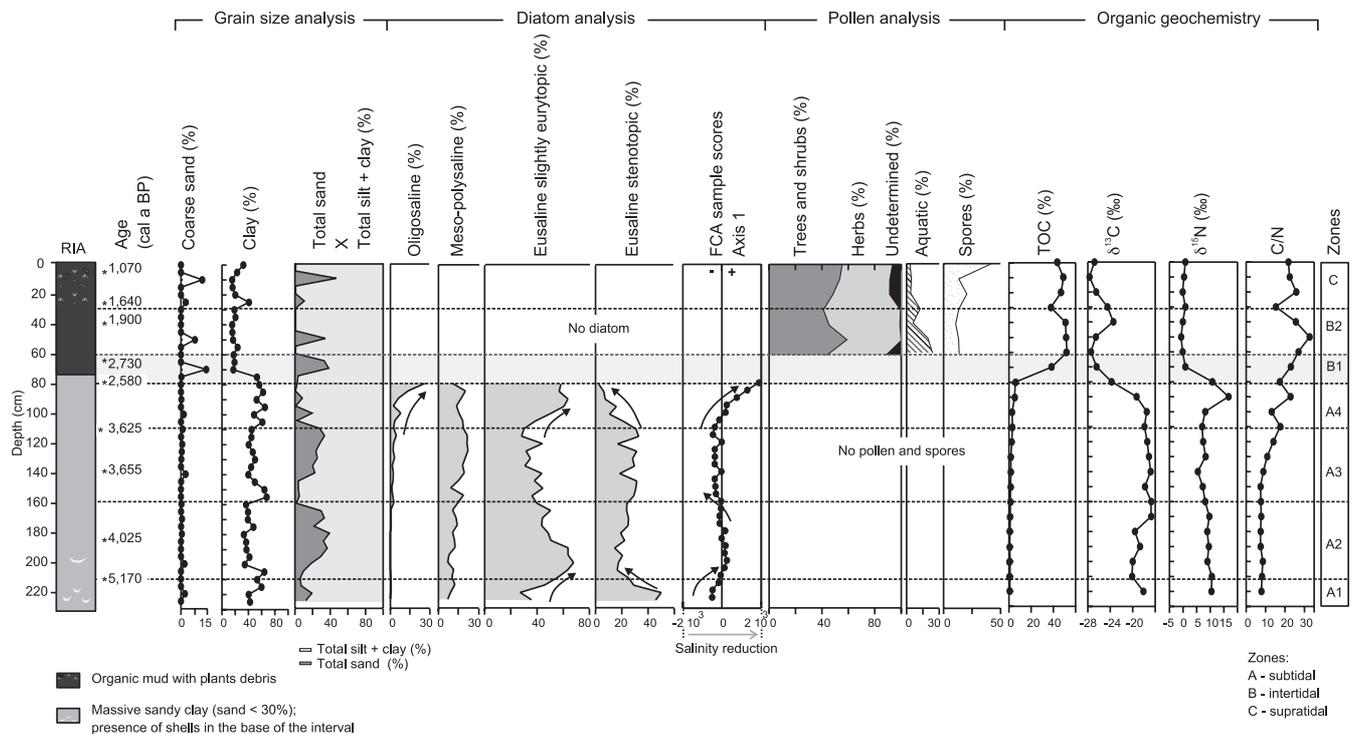


Figure 6. Summary results for core RIA: variation as a function of core depth from the chronological, sedimentological, micropaleontological (diatom and pollen analysis) and geochemical variables. Arrows indicate the variations discussed in the text.

Riachinho valley – core RIA

Diatom analysis from core RIA was carried out in the basal facies (Fig. 6). In the upper facies, diatoms were rare and essentially occurred as valve fragments. Diatom assemblages were mainly composed of marine eusaline slightly eurytopic species (with a range from marine to meso-metasaline waters; e.g. *Paralia sulcata*, *Biddulphia pulchella* and *Cyclotella striata*), and eusaline stenotopic species (growing in water with 30–40‰ salt content; e.g. *Cymatosira belgica*, *Thalassiosira oestrupii* and *Dimeregramma minor*). Oligosaline taxa, such as *Cyclotella stelligera*, *Caloneis bacillum* and *Nitzschia tryblionella*, occurred at frequencies higher than 5% only above 100 cm depth. FCA was undertaken on the diatom data set, comprising 123 diatom species from 30 samples. FCA results showed different sample groups in Axis 1 (Fig. 6) with salinity as the main factor explaining the composition of the diatom assemblages. The results suggest an important decrease in water salinity above 110 cm, as indicated by an increase in oligosaline taxa, which account for 26% of the total diatom species.

Pollen analysis was carried out from 60 to 0 cm (Fig. 6). From the base of the core to 60 cm, pollen grains were scarce or absent, probably due to geochemical and depositional conditions not suitable for pollen preservation. In the interval between 60 and 30 cm, pollen of aquatic plants, mainly represented by *Juncus*, was found at its highest frequency (23–5%). Pollen concentration in this interval was on average 4.5×10^3 grains cm^{-3} . Herbaceous taxa varied from 44 to 57% with a predominance of Poaceae, Cyperaceae and Amaranthaceae/Chenopodiaceae. Above 30 cm, the relative frequencies of aquatic plant pollen decreased (>5%), and pollen concentration increased ($\sim 1.5 \times 10^4$ grains cm^{-3}). The composition of the pollen spectra was characteristic of lowland forest, represented mainly by Moraceae, *Ilex*, *Byrsonima*, *Cecropia*, Myrtaceae and Apocynaceae.

Geochemical results showed significant contrast between the two depositional facies (Fig. 6). The basal facies was

characterized by: (i) low values of TOC (0.9–5.7%) and TN (0.1–0.3%), with a progressive upward increase in both; (ii) $\delta^{13}\text{C}$ values between -17.1 and -23.7 ‰, with depleted values above 100 cm; (iii) $\delta^{15}\text{N}$ values varying from 5.3 to 16.7‰ (mean > 9‰); and (iv) a C/N < 20 (except for the value obtained at 90 cm, C/N = 22.8). The upper facies displayed opposite characteristics for the elemental and isotopic C and N analyses. This facies had high TOC (> 37.8%) and TN (> 1.5%), lower values of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ (< -23.4 and < 0.8‰, respectively), and C/N ratios between 15.3 and 32.7.

A high correlation coefficient was observed between TOC and TN ($r = 0.96$; Fig. 5c). In the plot of $\delta^{13}\text{C}$ vs. C/N (Fig. 5d) three main groups of samples were distinguished. The first group (from the base of the core up to 130 cm) was characterized by a predominance of organic matter from marine phytoplankton, with $\delta^{13}\text{C}$ values from -17.1 to -20 ‰ (Emerson and Hedges, 1988; Meyers, 1997; Tyson, 1995). In the second group (samples from 120 to 80 cm), the organic matter was a mixture of both phytoplankton and land plants. The third group (samples from 70 to 0 cm) represented the dominance of C_3 land plants as the source of sedimentary organic matter. The plot of $\delta^{13}\text{C}$ vs. C/N shows a gradual change in the source of the organic matter from marine phytoplankton (basal facies) to dominant land plants (upper facies).

Sangão river valley – core SAN

Diatom analysis of core SAN was carried out from 35 samples. Between 160 and 100 cm, diatoms were absent or present as valve fragments (Fig. 7). The main diatom genus in the whole core was *Eunotia* (represented by 34 species). This predominance indicates that the environment probably did not have large variations in salinity, as *Eunotia* is mainly found in freshwater/oligosaline waters (salinity < 5‰). Additionally, the sum of meso-polysaline, eusaline and extremely eurytopic taxa represented only 5% of the diatom assemblages throughout the sedimentary column. Diatom assemblages thus suggest a shallow acid water body (pH < 7). The upwards decrease in

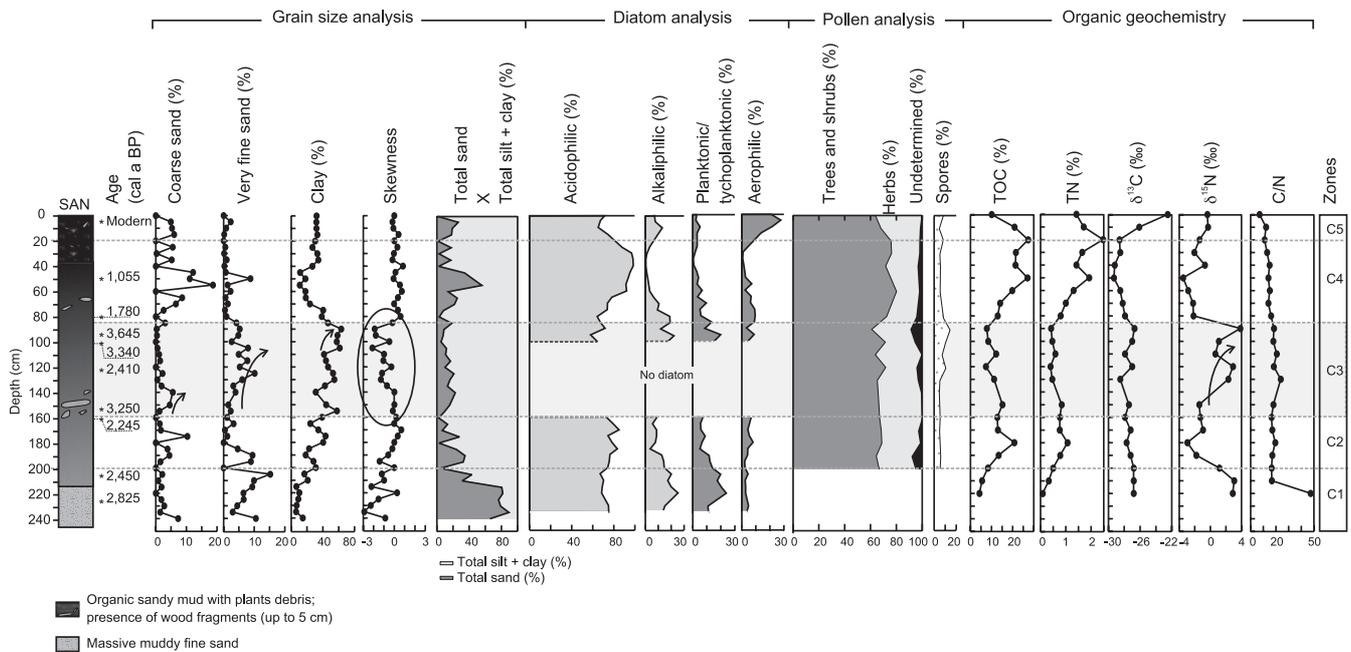


Figure 7. Summary results for core SAN core: variation as a function of core depth from the chronological, sedimentological, micropaleontological (diatom and pollen analysis) and geochemical variables. The arrows and the circle indicate the variations discussed in the text.

percentage of planktonic/tychoplanktonic taxa (*Staurosirella pinnata*, *Cyclotella meneghiniana* and *C. kutzingiana*), as well as an increase in aerophilic taxa (*Hantzschia amphioxys*, *Navicula mutica*, *Pinnularia borealis* and *P. divergentissima*), indicates a progressive reduction in water column depth.

Pollen analysis was possible along the entire core, except for below 200 cm. The summary pollen diagram (Fig. 7) indicates the predominance of arboreal pollen (tree and shrub, 63–80%), with no significant variation. Arboreal pollen mainly includes Myrtaceae, *Ilex*, *Alchornea*, Melastomaceae/Combretaceae, *Byrsonima*, *Sloanea* and *Myrsine*. The pollen spectra suggest the presence of lowland forest at the core site since at least 2825 cal a BP.

TOC values varied between 4.2 and 27.3%. The highest values were found above 60 cm, with an exception from the top of the core where TOC was 10% (Fig. 7). TN variation (0.09–2.4%) displayed the same trends as observed for TOC.

$\delta^{13}\text{C}$ varied from -29.3 to -22.5‰ , with most values $\geq -27\text{‰}$ (Fig. 7). The top of the core contained the most enriched value (-22.5‰). $\delta^{15}\text{N}$ values ranged from -3.4 to 3.8‰ , with an isotopic enrichment observed from 160 to 90 cm (-2.9‰ at 180 cm to 3.8‰ at 90 cm). C/N ratios varied from 47.4 to 7.07. However, most of the sample ratios ranged between 11 and 20, which reflects a mixture of algae and land plants as sources for the organic matter. A high correlation coefficient was observed between TOC and TN ($r=0.91$; Fig. 5e). The plot of $\delta^{13}\text{C}$ vs. C/N (Fig. 5f) provides evidence of the mixing of organic matter from C_3 land plants and freshwater phytoplankton.

Interpretations and discussion

Figueirinha lake – core FIG

Due to the low microfossils content of core FIG, its interpretation was based in particular on sedimentological and geochemical results, from which five zones (I to V) were distinguished (Fig. 4). Zone I corresponds to the basal facies, older than 25 000 cal a BP. Owing to the sedimentological characteristics and the depositional context of the sampling, closed to regressive marine terraces (see Fig. 1), we propose that Zone I corresponds to the Pleistocene regressive strandplain

system, possibly represented by swashing deposits. The strandplain system would have formed after the maximum RSL rise during the Last Pleistocene Interglacial (approximately 120 ka), which reached 8 ± 2 m above present along the south-southeast coast of Brazil (Martin *et al.*, 1988). In the transition between Zones I and II, at approximately 25 000 cal a BP, RSL was fast decline (up to 130 m below present sea level at ca. 17 000 ^{14}C a BP, according to Correa, 1996), and the low erosion base level would favour the development of incised fluvial valleys in the Pleistocene strandplain system. Changes in both sedimentological and geochemical parameters (Fig. 4) recorded the beginning of fluvial floodplain processes. A strong increase in C/N ratios in the transition between Zones I and II suggests an input of carbon-enriched material. Beside this, the increase of fine and less sorted sediments in Zone II (ca. 25 000 to ca. 14 000 cal a BP; Fig. 4) seems to show a response to the increasing fluvial flood supply.

In Zone III (from ca. 14 000 to 3745 cal a BP), no significant changes were observed in the sedimentological and geochemical results. This zone is within the last post-glacial RSL rise, which reached the studied area around 6000 cal a BP (Suguio *et al.*, 1985; Martin *et al.*, 1988; Angulo *et al.*, 1999, 2006). Therefore, it is possible that the maximum RSL is indicated by the peak in the sedimentation rate (Fig. 4) observed at ca. 5100 cal a BP.

The transition between Zones III and IV is recorded by the $\delta^{13}\text{C}$ values, with a shift of $\sim -4\text{‰}$. Even with this shift, $\delta^{13}\text{C}$ values in Zone IV indicate an important contribution of C_4 plants, in agreement with pollen analysis. Zone IV (from ca. 3745 to 500 cal a BP) indicated the beginning of plant colonization surrounding Figueirinha Lake. The dominance of Poaceae as seen in pollen analysis is possibly related to the presence of swamps around the lake. Vegetation decomposition in these swamps probably triggered the process of peat formation. The progressive percentage increase in Cyperaceae and other aquatic taxa typical in peats (Eriocaulaceae, *Juncus*, *Drosera*) in the top of this zone supports this interpretation.

Zone V represents approximately the last 500 cal a BP. The soil humidity associated with peat formation favored the development and preservation of diatom frustules. The presence of diatoms is coincident with a decrease in the C/N ratio that is attributed to an increase in the contribution of nitrogen-enriched

algae organic matter. Both diatom and pollen analyses indicate the settlement of modern conditions at the core location.

Riachinho valley – core RIA

Figure 8 shows the paleoenvironmental evolution proposed for the Riachinho valley. The multi-proxy analysis allowed us to divide the sedimentary column into three intervals, Zones A, B and C, which correspond to deposition in subtidal, intertidal and supratidal areas, respectively (Fig. 8a). These three zones are clearly separated in the geochemical data set (Fig. 5d), with a gradual shift from strong marine influence to continental influence.

Subtidal deposits (Zone A) were found from ca. 5500 to 2580 cal a BP. The subdivisions proposed for this interval (Fig. 6) are based on changes in diatom assemblages and reflect variations in lagoon salinity. Subzone A1 (ca. 5500 and 5170 cal a BP) recorded the predominance of marine stenotopic species, and indicates salinity values between 30 and 40‰ in the lagoon (Gasse *et al.*, 1987). The predominance of marine stenotopic taxa could be related to the maximum Holocene RSL rise, and with the formation of the lagoon system in the sampling area, which involved the drowning of pre-

existing fluvial dissection valleys (Giannini, 1993; Giannini *et al.*, 2007).

Changes in diatom assemblages suggest a decrease in the salinity of the lagoon in subzones A2 and A4 (from ca. 5170 to 3950 and from ca. 3625 to 2580 a cal BP), which may reflect an increase in freshwater input related to higher precipitation rates in the continent, and/or the temporary closure of the inlets that linked the lagoon to the ocean.

To test the first hypothesis our data were compared with records of $\delta^{18}\text{O}$ (Cruz *et al.*, 2006; Wang *et al.*, 2006), Sr/Mg and Mg/Ca (Cruz *et al.*, 2007) obtained from speleothems from Botuverá cave located approximately 160 km north-east of the study area. The records from Botuverá cave indicate a higher frequency and higher intensity of summer rainfall within the two time intervals that represent subzones A2 and A4. This increase in rainfall could explain the major input of freshwater from continental drainage inside the lagoon, with a consequent reduction in salinity. However, this hypothesis does not exclude the possibility of a temporary inlet closure reducing the influence of saltwater inside the lagoon.

We also compared our record with studies based on diatoms (Sylvestre *et al.*, 2005; Laslandes *et al.*, 2006) and charcoal analysis (Scheel-Ybert, 2000) from Cabo Frio (Rio de Janeiro

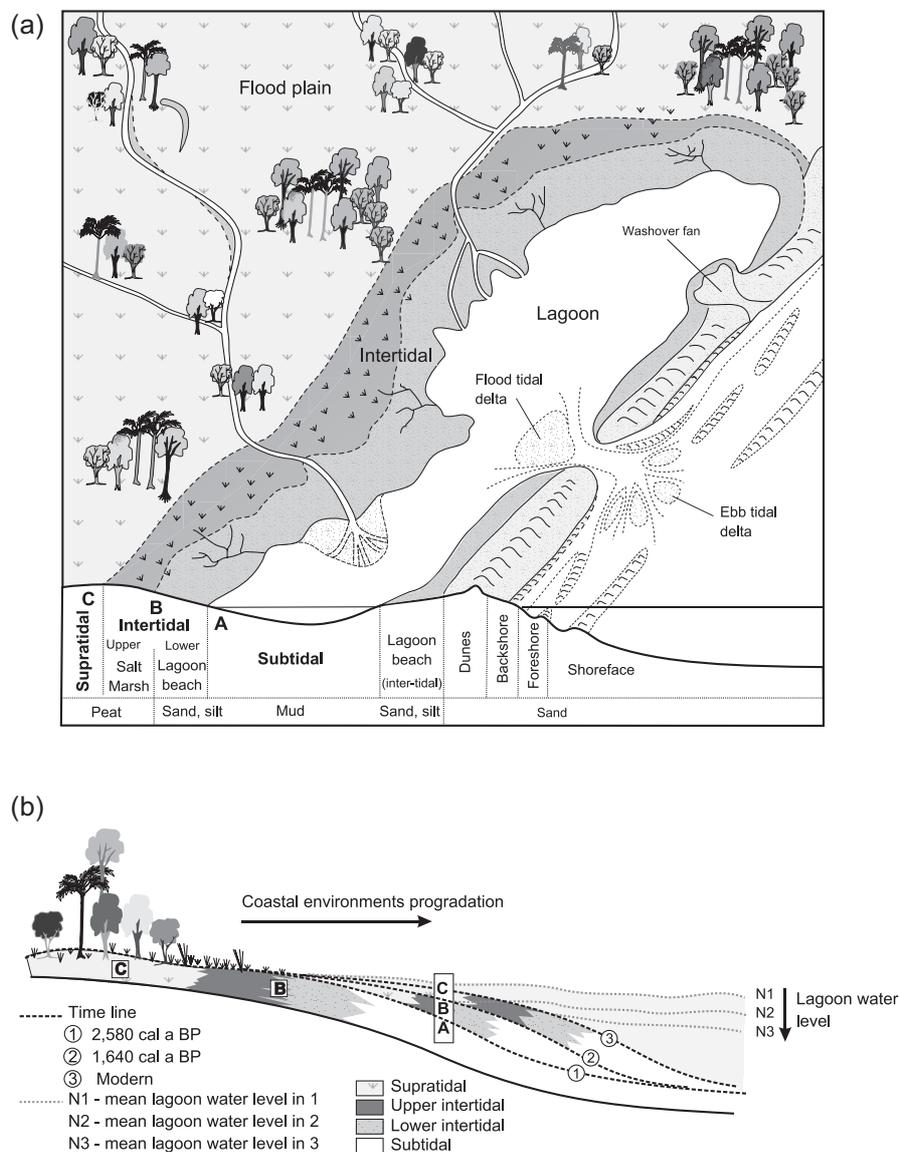


Figure 8. The paleoenvironmental evolution proposed for the core from Riachinho valley. (a) Reconstruction model of the depositional environments at the coastal zone (modified from Reineck and Singh, 1980). (b) Schematic section transverse to the lagoon margin showing the facies succession in core RIA.

State, Brazil). These studies showed evidence of drier phases in the region in the same two time intervals (A2, A4) that are believed to represent a precipitation increase in Santa Catarina. These contrasting conditions in different zones of the Brazilian coast can be explained by wide-scale climatic events. Arid conditions in Cabo Frio are controlled by the presence of a local resurgence zone induced by the higher frequency of north-east winds (Sylvestre *et al.*, 2005, Laslandes *et al.*, 2006). Also, in Cabo Frio, prolonged periods of resurgence could be related to strong El Niño events (Laslandes *et al.*, 2006). During El Niño years, the polar fronts are blocked by an intensification of the subtropical jetstream in the area stretching from southern Peru to southern Brazil (Martin *et al.*, 1993). During these events, anomalously high rainfall occurs in the blocking zone of polar fronts (which includes the Santa Catarina region) and drier conditions are reported to the north of this zone, including eventually the Cabo Frio region. Although the relationship between our data and El Niño events requires further investigation, the pattern observed may be a real one, and the relationship between El Niño and local variations in humidity should be pursued in future work.

In subzone A4, less influence from seawater and greater continental inputs are also supported by variations in $\delta^{13}\text{C}$ and C/N values, indicative of mixed organic matter containing phytoplankton, and C_4 and C_3 land plants. Subzone A4 is interpreted as the transition between subtidal and intertidal deposition. The transition would have occurred at approximately 2580 cal a BP, in the context of RSL decline, with consequent fall in the lagoon water level and gradual sedimentary filling by its progradation (Fig. 8b).

Zone B (from ca. 2580 to 1640 cal a BP) may be divided into two subzones (B1 and B2), which, respectively, refer to deposition in the lower and upper intertidal flats (Fig. 8a). Subzone B1 is characterized by: (i) an increase in the coarse sand concentrations attributed to the occurrence of vegetal bioclasts; (ii) a decrease in the percentage of clay (fine sediments represented mainly by silt classes); (iii) low pollen and diatoms percentages; and (iv) $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C/N values suggesting a strong contribution from C_3 land plants. This subzone could represent a lagoon beach that was subjected to alternation of desiccation and flooding related to tidal variations; such conditions would not allow the preservation of pollen and diatoms. Subzone B2 is correlated with the upper intertidal flat covered by salt marsh vegetation. The pollen record, composed predominantly of *Juncus*, *Poaceae* and *Cyperaceae*, supports this interpretation.

The transition between Zones B and C (1640 cal a BP) indicates an expansion of the lowland forest in Riachinho

valley, which is clearly documented by the increase in the percentage of arboreal taxa pollen. No significant changes were observed during the time interval corresponding to Zone C (ca. 1640 cal a BP to the present day). The development of the lowland forest in previous salt marsh areas (subzone B2) reinforces the idea of coastal progradation completely filling the paleolagoon at the core site, which resulted in the modern landscape of the Riachinho valley.

Sangão River valley – core SAN

Figure 9 presents the paleoenvironmental evolution proposed for the Sangão River valley during the last ~3000 cal a BP. Core SAN is interpreted as representing the depositional record of a supratidal zone outside of tidal influence, essentially from the fluvial floodplain. The Sangão River valley would have lost its connection with the lagoon earlier than the Riachinho valley. This interpretation is supported by: (i) the absence of marine and the predominance of acidophilic diatom species throughout the core (Fig. 7); and (ii) geochemical data indicative of a sedimentary organic matter contribution from C_3 land plants and freshwater phytoplankton (Fig. 5f).

Two hypotheses are possible to explain the sandy facies at the base of the core (subzone C1, sediments older than ca. 2600 cal a BP; see boxes 1 and 2 in Fig. 9): (i) point-bar deposits as records of fluvial channel migration; or (ii) channel or oxbow lake deposits. For both hypotheses, a water body relatively deeper than the other subzones would have formed. Both hypotheses justify higher percentages of planktonic/tychoplanktonic diatom species. Gradual sedimentary filling by fine sediments allows pollen grains to be preserved, which began to be recorded in subzone C2.

Subzone C2 (from ca. 2600 to 2245 cal a BP) is characterized by: (i) an increase in the percentage of fine sediments; (ii) a decrease in the percentage of planktonic/tychoplanktonic and alkaliphilic diatom species, indicating both a gradual decrease in water column depth and a reduction in pH; (iii) an increase in TOC and depleted $\delta^{15}\text{N}$ values as a result of a greater contribution of organic matter from land plants; and (iv) pollen record indicating floodplain vegetation characteristic of lowland forest. The subzone indicates a progressive sedimentary filling of the basin and the formation of a swamp. The transition between subzones C2 and C3 is marked by the disappearance of diatoms and by an age inversion.

Subzone C3 represents the portion of the core where there is an increase in the percentage of very fine sand, negative grain-size skewness values and an inversion in the chronological profile (Fig. 6). This interval is interpreted as a distal facies of a

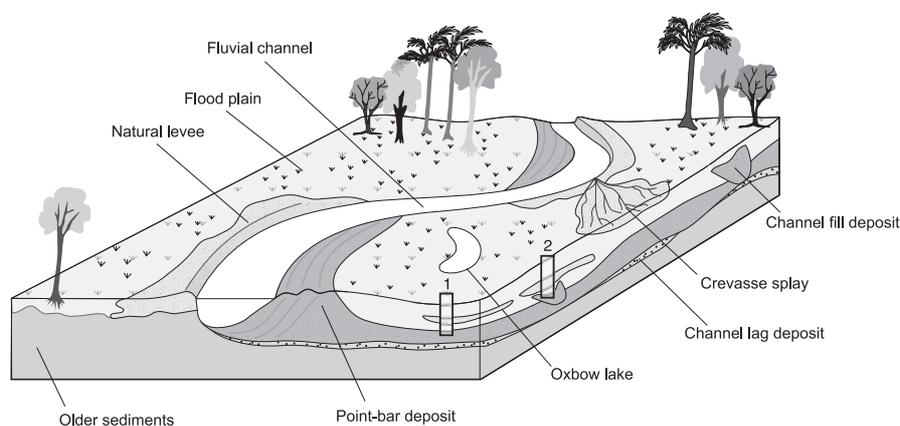


Figure 9. Paleoenvironmental evolution proposed for the core collected in the Sangão river valley during the last 3000 cal a BP (the block diagram indicates the sedimentary deposits found in a typical fluvial floodplain, modified from Allen, 1964). Based on the facies succession in core SAN, two possible positions for the core are indicated (boxes 1 and 2).

crevasse splay deposit, related to the recurrent process of natural levee rupture during flooding episodes. In this type of process there is erosion and re-sedimentation of levee sediments, which could explain the age inversion. The existence of the crevasse splay deposit may also explain the lacuna in the diatom record as levee sediments (the source of the crevasse splay) are typically formed in subaerial conditions, not favourable for the presence of algae. In addition, no significant changes were observed in the diatom assemblages below and above this core interval. This suggests a temporary interruption in the diatom record, also compatible with the idea of an episodic local change in depositional conditions.

In subzone C3, a clear change in $\delta^{15}\text{N}$ would represent the difference in the isotopic signature between the levee/crevasse and other parts of the floodplain, as the levee must show enriched $\delta^{15}\text{N}$ values due to the smaller amount of vegetation debris. Therefore, for this case, the shift in $\delta^{15}\text{N}$ values suggests a change in the proportion of land-plant debris, rather than changes in the source of the organic matter.

Subzone C4 (ca. 1780 to 425 cal a BP) shows a return to muddy sedimentation after the crevasse splay. The greater input of vegetal debris observed in the core is confirmed by an increase in TOC values and depleted $\delta^{15}\text{N}$ values. Subzone C4 represents a shallow water body (several centimeters in depth). Possible periods of subaerial exposure are indicated by an increase in the percentage of aerophilic diatom species in the top of this subzone. The pollen data indicate a vegetation cover of lowland forest.

Subzone C5 (ca. 425 cal a BP to the present day) reflects the anthropogenic influence at the core site over the last few centuries. Many arboreal taxa decrease in frequency while exotic species, such as *Pinus*, start to appear. The increase in percentage of aerophilic diatoms is related to an exposed substratum and to a lower soil humidity, probably related to the artificial deviation of the course of the Sangão River over the last century.

Regional scenario

Among the three cores, only core FIG reached Pleistocene sediments and had the potential to describe environmental changes over longer periods of time. However, because of the absence of microfossils in most parts of the core, it is difficult to determine a paleoenvironmental model that spans the Pleistocene to Early Holocene. Therefore, the integrated dataset from the three cores was used to draw conclusions regarding the regional coastal evolution for the last ca. 5500 cal a BP.

At ca. 5500 cal a BP, the lagoon system in this area was more extensive than today. The maximum Holocene RSL rise is possibly reflected in the higher sedimentation rate observed at ca. 5100 cal a BP within core FIG. During this period, the Figueirinha depression was linked to the Garopaba Lagoon, in the southern extension of the lagoon system (see Fig. 1). This connection lasted for a short period of time. Therefore, once the lagoon system connection was interrupted, the Figueirinha depression became an independent lake. In the Riachinho valley, the existence of the lagoon is recorded from ca. 5500 to 2580 cal a BP by the presence of marine diatoms and by elemental and isotopic signatures of the sedimentary organic matter. The sediment record in the Sangão River valley did not display a lagoonal phase, which should have occurred before 3000 cal a BP, at this location.

A controversial question in Brazilian coastal studies relates to the behaviour of RSL for the last 7000 years, including the difference in the highstand elevation and the existence of high-frequency oscillations. According to Suguio *et al.* (1985) and Martin *et al.* (1988), two regressive phases would have occurred during the Late Holocene, when it is proposed that

sea level was below its present elevation at approximately 4200–3700 and 2700–2100 cal a BP. However, other studies have suggested a regular decline in the RSL without a noticeable oscillation after 6000 cal a BP (Angulo *et al.*, 1999, 2006; Ybert *et al.*, 2003). In this respect, our data do not confirm the existence of two negative oscillations in the RSL during the Late Holocene and suggest that the lagoons in this region would have had a continuous and gradual sea disconnection over the last 5000 cal a BP. However, during this period, environmental reconstructions of coastal areas based on the presence/absence of microfossil and/or sedimentary organic matter data should be considered carefully. Environmental changes in coastal ecosystems can occur due to variations in coastal processes (opening and closing of a lagoon mouth, bayhead delta progradation, etc.), which are not necessarily associated with RSL changes. For this reason, in this type of record, environmental changes caused exclusively by RSL oscillations are difficult to identify and disentangle from those caused by variations in local sedimentary dynamics.

The major vegetation changes observed from pollen analysis seem to indicate the progradation of coastal ecosystems, without direct climatic influence. However, the relationship between climate and vegetation in coastal regions is difficult to establish due to the locally strong edaphic influence of the substrate. The edaphic-dependent character of coastal environments makes coastal formations much more resistant to climate variations and less sensitive to climate change (Scheel-Ybert, 2000). Synthesis of the palynological data indicated that no major changes in the mainland vegetation ecosystem have taken place at least since 4000 cal a BP. The result is in agreement with previous studies based on palynological and charcoal analysis conducted in coastal areas in south and south-eastern Brazil (Scheel-Ybert, 2000; Behling and Negrelle, 2001; Ybert *et al.*, 2003), which also show the stability of coastal vegetation spanning the last 6000 cal a BP.

Conclusions

The multi-proxy analysis from three cores collected in the coastal region of Jaguaruna (southern Brazil) allowed us to trace the evolution of coastal ecosystems during the Late Quaternary. Elemental and isotopic C and N analyses of bulk sedimentary organic matter were successfully used as complementary tools for paleoenvironmental reconstructions in paleolagoon sediments, especially to distinguish between subtidal, intertidal and supratidal zones.

At ca. 5500 cal a BP, a larger complex of interconnected lagoons characterized the study area. This is verified in the cores by the record of paleolagoon deposits in areas currently occupied by lowland forest. The connection of this larger lagoon system with the sea was demonstrated by the presence of marine diatoms and by the composition of the sedimentary organic matter (indicative of marine phytoplankton). Our results suggest gradual and continuous lagoon–sea disconnection over the last 5000 cal a BP. The existence of two regressive phases during the Late Holocene, as assumed in previous studies on RSL, was not confirmed. A synthesis of palynological data indicated that no major change in the mainland vegetation ecosystem took place, at least since 4000 cal a BP. Our results are in agreement with other palynological studies and charcoal analysis conducted in coastal areas in south and south-eastern Brazil. The multi-proxy analysis suggests that changes in coastal ecosystems could be directly related to local coastal dynamics, and not necessarily linked to RSL fluctuations and/or climate variations, as often assumed.

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Abbreviations. AMS, accelerator mass spectrometry; FCA, factorial correspondence analysis;; RSL, relative sea level;; TN, total nitrogen;; TOC, total organic carbon.

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