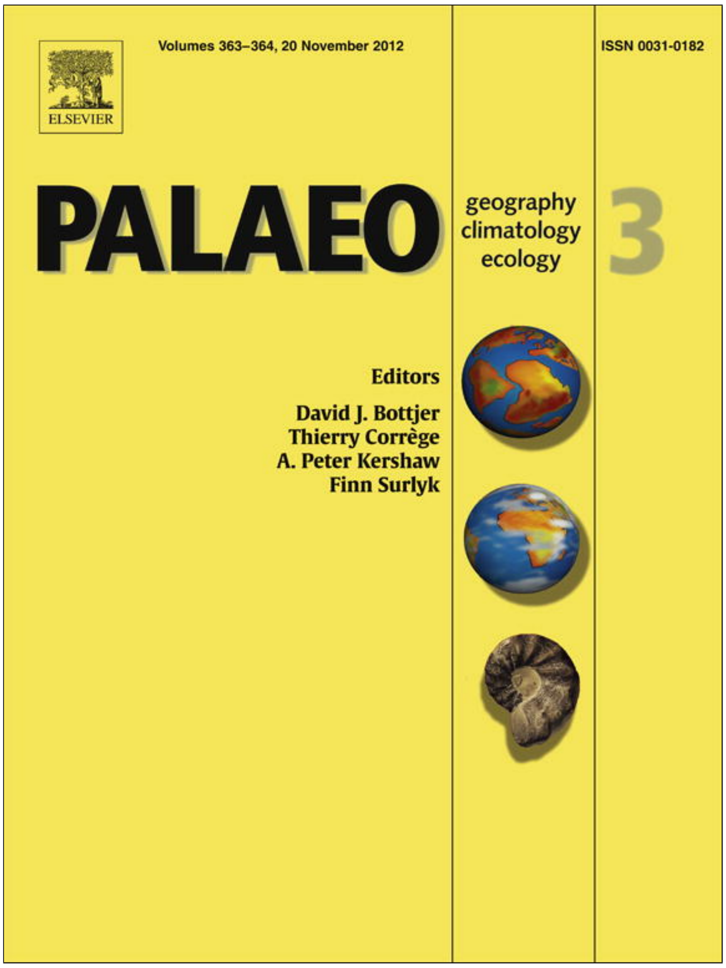
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Late Quaternary vegetation and coastal environmental changes at Ilha do Cardoso mangrove, southeastern Brazil

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ABSTRACT

A 190 cm mangrove sediment core from the Ilha do Cardoso State Park, State of São Paulo, southeastern Brazil was analyzed for pollen, diatoms as well as carbon and nitrogen isotopes. The goal was to determine the dynamics of the coastal terrestrial/aquatic ecosystems, vegetation history and climate change in this region of the Brazilian Atlantic rainforest, during the Late Pleistocene and Holocene.

The values for total organic carbon—TOC (from ~3 up to 40%), C/N ratios (from ~10 up to 130), and $\delta^{15}N$ (~0 to >8) are associated with well preserved aquatic and terrestrial organic matter and possibly influenced by nitrogen cycling (e.g., denitrification) that caused ^{15}N enrichment between >40,000 cal yr B.P. and ~23,000 cal yr B.P. Depleted $\delta^{13}C$ values (~ -28.0‰) are also observed and indicate the predominance of C_3 plants. During this time interval, the pollen analysis reveals the presence of the genera *Ilex*, *Alchornea*, *Weinmannia*, *Myrsine*, *Symplocos*, *Drimys* and *Podocarpus* on a site currently occupied by mangrove vegetation. These data suggest that in the past prevailed a colder and more humid climate than today, with a low relative sea-level. From ~23,000 cal yr B.P. to ~2200 cal yr B.P. a sedimentary hiatus likely occurred, related to an erosive event associated to the post glacial sea-level rise. Since at least ~2200 cal yr B.P., sediments are marked by relatively low C/N ratios (from 2 to 27), exhibit more enriched $\delta^{13}C$ (from ~-26.0‰ to −24.0‰) and $\delta^{15}N$ (up to ~7) values and are characterized by the presence of marine diatoms. This indicates the return of the marine coastal line to its current position, and consequently the development of mangrove.

1. Introduction

Climatic fluctuations (e.g. Ledru et al., 1996; Behling et al., 2007) and the post glacial sea-level rise (Shackleton and Opdyke, 1973; Martin et al., 1996; Angulo et al., 2006) provoked dramatic habitat changes along the Brazilian coast during the Late Pleistocene and Holocene (e.g. Giannini et al., 2007; Guedes et al., 2011). Tropical rainforests and savannas are expected to have responded to climate change in the glacial-interglacial cycles, as observed in the Amazon region (Freitas et al., 2001). Pollen records in tropical regions of Africa, America and the western Pacific indicate that tropical vegetation changed during the glacial period, with a clear movement of montane trees to lower altitudes in most locations (Bush and Flenley, 2007).

In the case of mangrove systems, which in Brazil extend from the northern coast to the southernmost limit of the State of Santa Catarina, their distribution is interpreted as reflecting the change in variables which control coastal geomorphology (e.g. Blasco et al., 1996, Lara and Cohen, 2009). Indeed, mangrove development is regulated by continent-ocean interactions, and their expansion is determined by the topography relative to sea-level Chapman, 1960; Woodroffe, 1982; Gornitz, 1991; Cohen and Lara, 2003). Therefore, mangroves may migrate according to sea-level changes. Following a sea-level rise, the Brazilian Atlantic rainforest will be subjected to boundary adjustments since mangroves will migrate to higher locations and could invade them (e.g. Cohen and Lara, 2003). Thus, mangroves can be considered highly susceptible to climatic and sea-level changes (e.g., Gornitz, 1991; Alongi et al., 2000; Cohen et al., 2008; Krauss et al., 2008; Cohen et al., 2009; Lara and Cohen, 2009).

This study concerns a mangrove located in the State of São Paulo's southern coast. The widespread occurrence of mangrove ecosystems along the Brazilian coast provides many opportunities for the characterization of these environments and paleoenvironmental reconstructions using isotope (^{12}C, ^{13}C and ^{14}N, ^{15}N), pollen and diatom records. $\delta^{13}C$ and $\delta^{15}N$ are good indicators of environmental change, since they provide information on the origin of organic matter and

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the abundance of various types of biota which produced it (Meyers, 1997, 2003; Schidlowski et al., 1994), and such data can be successfully used to reconstruct relative sea level (RSL) (Wilson et al., 2005). However, few studies have focused on such reconstructions, and they are restricted to a small number of specific locations. Previous studies of pollen records in Brazilian mangroves have demonstrated that palynological analysis can provide important information about the vegetation history of this particular ecosystem (Grindrod et al., 2002; Amaral et al., 2006; Pessenda et al., 2008; Cohen et al., 2009; Francisquini, 2011; Smith et al., 2011, 2012; Guimarães, et al., 2012).

Bulk organic carbon isotope ($\delta^{13}C$) analysis has been used to determine the provenance of organic matter in coastal sediments (Fry et al., 1977; Ember et al., 1987; Wilson et al., 2005). Bulk sediment $\delta^{13}C$ directly reflects the relative amounts of isotopically distinct parent source materials in the sediment. This arises because the mean $\delta^{13}C$ value of C_3 vascular vegetation and freshwater phytoplankton is −27‰, and thus distinguishable from C_4 plants and marine phytoplankton with a $\delta^{13}C$ signature of approximately −20‰. Variation in the isotopic composition of the organic matter in coastal sediments has been used as a proxy for environmental change resulting from changes in paleoriver discharge and/or RSL (Wilson et al., 2005).

In dynamic coastal environments such as estuaries, there is a variable influx of freshwater phytoplankton from riverine sources as well as terrigenous organic matter. Freshwater phytoplankton is isotopically indistinguishable from C_3 vascular vegetation, therefore an interdisciplinary approach is necessary to distinguish between these two sources of organic carbon in estuarine saltmarsh sediments (Thornton and McManus, 1994; Graham et al., 2001). Organic carbon to total nitrogen (C/N) ratios can be measured alongside $\delta^{13}C$ in an effort to distinguish between C_3 vascular vegetation and freshwater phytoplankton. In fact, C_3 vascular vegetation has higher C/N ratios of around 12 and over, in contrast to phytoplankton, which tends to be nitrogen rich and to have lower ratios between 5 and 7 (Wilson et al., 2005). In estuarine saltmarsh sediments, organic carbon may be derived from C_4 and C_3 vascular vegetation and from marine and freshwater phytoplankton.

Thus, this work includes a detailed description of paleovegetation changes according to RSL and climatic change during the last >40,000 cal yr B.P. in an area currently under mangrove vegetation, using palynological, diatom, $\delta^{13}C$, $\delta^{15}N$ and C/N analyses. The goal was to contribute to knowledge on the impact of glacial and interglacial events in the Brazilian Atlantic rainforest and mangrove areas of southeastern Brazil.

2. Study area

2.1. Origin of the Cananéia lagoon estuarine system

Samples were collected from the Sítio Grande mangrove (MSG, 25º05′S, 47º56′W), on Cardoso Island which is located in the Cananéia lagoon estuarine system on the coast of southern Brazil (Fig. 1). This estuary is surrounded by mangroves and comprises a total area of 110 km^2. It is connected to the South Atlantic Ocean by the Cananéia and Icapara inlets/estuaries, located in the southern and northern parts of the system, respectively. Tides and inflow of freshwater from continental drainage of several small rivers regulate water circulation in the estuary channels. The geology of the surrounding areas consists of a pre-Cambrian metamorphic basement dominated by rocks such as slates, gneisses and mica-schists (Souza et al., 1996). In terms of quaternary depositional systems, the evolution of this coastal plain system is basically related to the progradations which followed two separate transgressive events (Martin and Suguio, 1978). The first, in the Late Pleistocene, is related to the high RSL (+8±2 m) of the last interglacial near 120,000 yr B.P. Published curves propose that the present mean sea-level was exceeded for the first time during the Holocene at ca. 7800 to 6600 cal. yr B.P., on the southeastern Brazilian coast. These curves also suggest that the highest relative sea-level was reached at ca. 5500 cal. yr B.P., with a maximum height of 2 to 5 m above present mean sea-level. After this maximum was reached, the relative sea-level showed a major tendency to decrease toward its modern height (Martin et al., 2003; Angulo et al., 2006).

2.2. Climate and vegetation

In southern and central Brazil, seasons are controlled by the position of the Inter Tropical Convergence Zone (ITCZ). In winter the ITCZ remains north of the Equator and the South Atlantic high pressure cell covers a large part of Brazil. Polar air masses advect toward the Equator where they come in contact with warm tropical air at latitude of 25–30ºS, and induce precipitation. In contrast, the central region of Brazil experiences a long dry season lasting 3 to 5 months. In summer the ITCZ moves to its southern position, south of the equator. The South Atlantic high pressure cell is weakened and moves offshore, bringing summer precipitation to latitudes of 15–25°S.

Cardoso Island covers an area of ~150 km^2 and is located between the latitudes of 25°05′–25°15′S and longitudes of 47°53′–48°06′W. Mean annual temperature oscillates between 20 and 22 °C, and mean annual precipitation is 2250 mm. Highest precipitations occur during the summer (December to March) and the lowest in winter (July to August), although there is no well-defined dry season.

The topography of the island is largely mountainous; the center is dominated by a massif of over 800 m (Fig. 1). Soils of the coastal plain result from recent sea sedimentation and are classified as Spodosols. In the middle and upper slopes soils are classified as Oxisols, according to American soil taxonomy, USDA classification (Soil Survey Staff, 1999).

The vegetation of Cardoso Island consists of mangrove, coastal plain rainforest and lowland to cloud tropical rainforest. Schaeffer-Novelli et al. (1990b) determined the dominant species at Sítio Grande mangrove to be *Rhizophora mangle* (Rhizophoraceae), *Avicennia schaueriana* (Acanthaceae) and *Laguncularia racemosa* (Combretaceae). In the outlying zones the arboreal taxon *Hibiscus pernambucensis* (Malvaceae) and the herbs *Spartina ciliata* (Poaceae) and *Acrostichum* sp. (Lomariopsidaceae) are also found.

Fig. 1 show a longitudinal transect with the main topographical features and vegetation. A mud plain positioned ~0.5 m above the mean sea-level and influenced by the tide (tidal range ~1.5 m) is found along the margin of Dolphin Bay and Arapira Channel. This tidal plain is colonized by mangrove with 16.3 km^2 only in the Cardoso Island. The Atlantic Rainforest begins in areas not under tidal influence. The vegetation of the neighboring arboreal/shrubby Restinga, which grows on sandy coastal plains, is characterized by a wide variety of palm trees, as well as orchids and bromeliads that grow on trunks and branches of larger trees (Barros et al., 1991). Sampaio (2003) identified 117 species from 84 genera and 43 families in the arboreal Restinga of Cardoso Island. According to this author, the dominant plants are represented by the following families: Myrtaceae (*Calyptranthes concinna*, *Eugenia* sp., *Myrcia* sp., *Psidium cattleyanum*, *Siphoneugena guilfoyleiana*), Lauraceae (*Nectandra* sp., *Ocotea pulchella*), Arecaceae (*Astrocaryum aculeatissimum*, *Bactris setosa*, *Euterpe edulis*, *Geonoma schottiana*), Euphorbiaceae (*Alchornea triplinervia*, *Pera glabrata*, *Maprounea guianensis*), Myrsinaceae (*Cybianthus peruvianus*, *Myrsine* sp.) and Melastomataceae (*Miconia* sp., *Tibouchina trichopoda*).

The Serra do Mar tropical rainforest is located on the hillsides and summit of the massif's mountainous ecosystem and occupies the largest extension (approximately 74%) of the area (Barros et al., 1991). Dominant species in this ecosystem include *Euterpe edulis* (Arecaceae), *Psychotria nuda* (Rubiaceae), *Rudgea jasminoides* (Rubiaceae), *Cryptocarya moschata* (Lauraceae), and *Malouetia cestroides* (Apocynaceae). In the

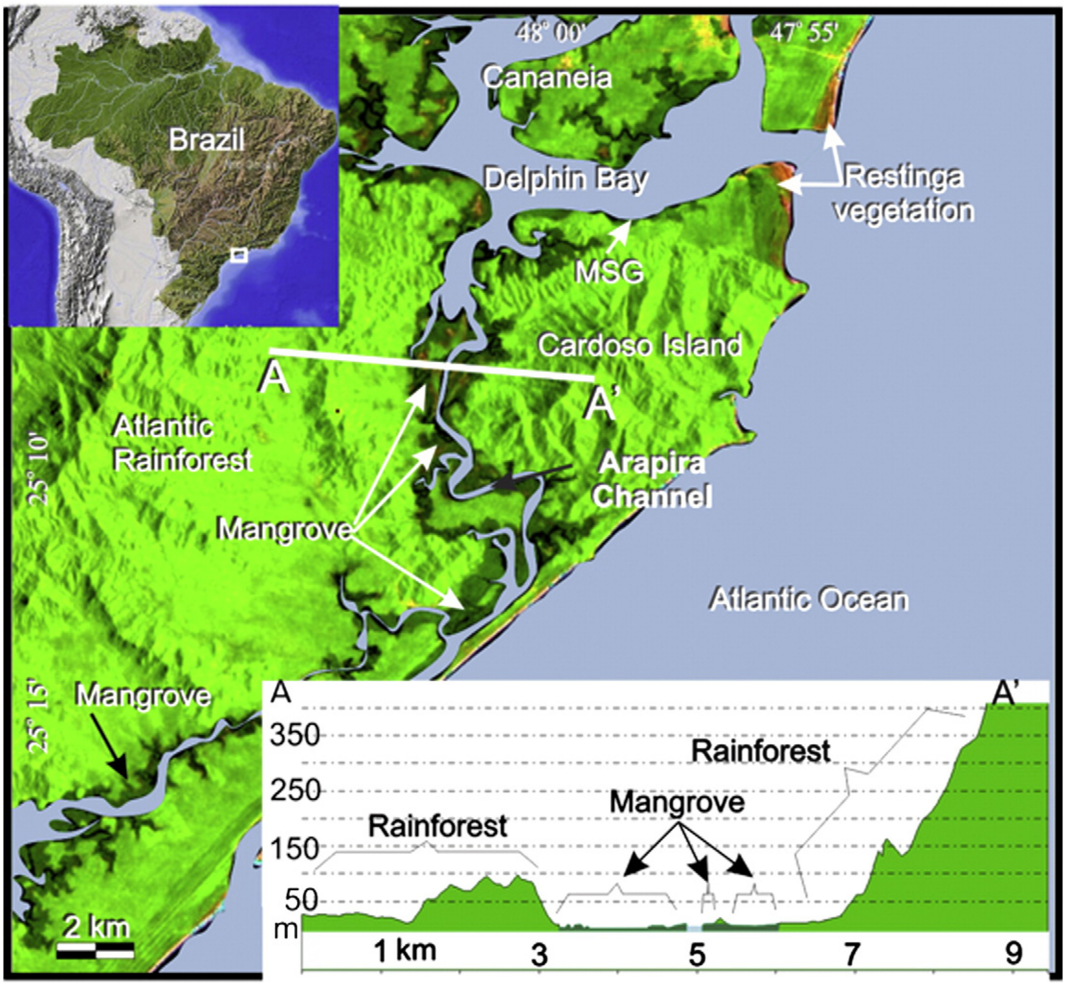

Fig. 1. Vegetation distribution at the MSG study site and sampling location.

highest areas the main herb species are *Fuchsia regia* (Onagraceae), *Leandra quinquedentata* (Melatomataceae) and *Vriesea heterostachyus* (Bromeliaceae) (Barros et al., 1991; Mello and Mantovani, 1994).

3. Materials and methods

A LANDSAT image obtained on February 2010 was acquired from INPE (National Institute for Space Research, Brazil). A three-color band composition (RGB 543) image was created and processed using the TerraAmazon 4.2.1 image processing system. Topographic data are derived from SRTM-90 data. These were downloaded from the USGS' Seamless Data Distribution System (http://srtm.usgs.gov/data/obtainingdata.html). The interpretation of elevation data was made possible by the use of the Global Mapper 12 software.

A 190 cm mangrove sediment core was collected using a vibro-corer (Martin and Flexor, 1989) at the MSG location (Fig. 1). Upon opening the core, color changes, grain size, roots and other fragments of vegetation were recorded. Sediment samples were collected at 2 cm depth intervals for isotope (carbon and nitrogen) and pollen analyses and at 10 cm depth intervals for diatom analysis. Twelve radiocarbon dates were obtained on mangrove samples.

Total organic carbon, total nitrogen and isotope (^{13}C, ^{15}N) analyses were carried out at the Stable Isotope Laboratory of the Center for Nuclear Energy in Agriculture (CENA). Organic carbon and nitrogen results are expressed as percentages of dry weight. Carbon and nitrogen isotope ratios of bulk organic matter were measured at the same laboratory and results are expressed in delta per mil notation, with an analytical precision better than 0.2‰. ^{13}C results are expressed as $\delta^{13}C$ with respect to the VPDB standard, and ^{15}N results are expressed as $\delta^{15}N$ with respect to the atmospheric N_2 standard.

The ^{14}C analyses were carried out by Accelerator Mass Spectrometry (AMS) at the Isotrace Laboratory of the University of Toronto, Canada and Erlanger Labor ^{14}C, University Erlanger-Nürnberger, Germany, and using the benzene synthesis liquid scintillation counting method (Pessenda and Camargo, 1991) at the ^{14}C Laboratory of the Center for Nuclear Energy in Agriculture (CENA). Based on an international convention, radiocarbon ages are expressed as ^{14}C yr B.P. (Before Present) normalized to $\delta^{13}C$ of −25‰ PDB (Stuiver and Polach, 1977), at present denoted as VPDB. We also present the results in Table 1 as calibrated ages (cal yr B.P.), 2σ (Reimer et al., 2009) and use the median of the range for discussing our and other authors data in the text.

Pollen analyses followed the methodology described by Faegri and Iversen (1989) and Colinvaux et al. (1999): mineral removal with 50% hydrofluoric acid for 18 h, followed by a 50% HCl treatment in a hot water bath and by a 10% KOH solution. Palynomorphs were extracted using a $ZnCl_2$ solution of density 2 and mounted in glycerine for light microscopy. Pollen and spores were identified by comparison with our reference collections of about 4000 Brazilian forest taxa and various pollen keys (Salgado-Labouriau, 1973; Absy, 1975; Markgraf and D´Antoni, 1978; Roubik and Moreno, 1991; Colinvaux et al., 1999). At least 300 arboreal pollen grains were counted at each level. Due to the similarity of their pollen grains, the Melastomataceae and Combretaceae families were not distinguished here. The results are presented in two types of diagrams (Figs. 4 and 5). Fig. 4 provides

Table 1
Radiocarbon dating of mangrove organic matter and woody fragments collected at MSG.

Sample	Depth (cm)	Laboratory number	Age (14C yr B.P.)	Age (cal yr B.P., 2σ)	Mean calibrated age (cal yr B.P.)
Woody fragment	23–33	TO-12695	300 ± 40	289–474	~380
Sediment	23–33	TO-12696	1010 ± 50	793–1003	~900
Sediment	60–69	TO-12697	1480 ± 50	1296–1422	~1360
Sediment	70–74	Erl-10807	2069 ± 38	1946–2142	~2040
Sediment	76–80	Erl-10808	2238 ± 32	2153–2274	~2200
Sediment	80–84	Erl-10809	19,658 ± 85	23,121–23,861	~23,500
Sediment	86–90	Erl-10810	24,174 ± 165	28,510–29,430	~29,000
Sediment	93–98	CEN-968	35,900 ± 140	40,662–41,532	~41,000
Sediment	123–130	TO-13044	25,420 ± 350	29,526–30,894	~30,200
Sediment	150–156	TO-12698	23,880 ± 200	28,160–29,309	~28,700
Woody fragment	175–180	TO-12699	28,060 ± 260	31,540–33,026	~32,200
Sediment	190–196	CEN-967	> 40,000	> 40,000	> 40,000

TO—Isotrace Laboratory, Toronto, Canada.
CEN-14C Laboratory, Center for Nuclear Energy in Agriculture, Brazil.
Erl—AMS-Labor Erlanger, Germany.

detailed pollen data expressed as percentages of each *taxon* in relation to the sum of arboreal (AP) and non-arboreal (NAP). Fig. 5 provides percent values for summarized pollen groups and spore concentration, based on plant form and habitat type. Relative frequencies of arboreal, herb, undetermined and aquatic pollen were calculated in relation to the total pollen sum. The concentration values (pollen grains per gram of wet sediment) were calculated using the volumetric method of Cour (1974).

Diatom analyses followed the standard techniques (Batarbee, 1986), using 30% H_2O_2 solution for 24 h for organic matter removal. Permanent slides were mounted in Zrax Mounting Medium for light microscopy analyses. Diatoms were identified based on published diatom keys (Moreira-Filho, 1960; Patrick and Reimer, 1966, 1975; Bicudo and Bicudo, 1970; Round et al., 1990; Silva-Cunha and Eskinazi-Leça, 1990; Moro and Fürstenberger, 1997; Fürstenberger, 2001). Diatom concentration (diatoms per cubic centimeter) was determined by the addition of exotic *Lycopodium clavatum* spores according to the technique described by Stockmarr (1971). Diatom percentage and concentration diagrams were prepared using the Tilia and TiliaGraph softwares (Grimm, 1987, 1992). These results are presented in Figs. 6 and 7. Percentages of the numerically most important elements are shown for marine, salt and freshwater taxa in Fig. 6, whereas Fig. 7 presents a summary of concentration values for diatom categories.

4. Results and discussion

4.1. Age of mangrove samples

The radiocarbon dates obtained on mangrove samples are presented in Table 1 and Fig. 2. The base of the sediment core (196–190 cm) presented an age of > 40,000 cal yr B.P. and age inversions were observed up to shallow layers. The woody fragment collected in the 180–175 cm layer had an age of 28,060 ^{14}C yr B.P. (~32,200 cal yr B.P.), whereas samples from 156–150 cm, 130–123 cm and 98–93 cm depths were dated at 23,880 ^{14}C yr B.P. (~28,700 cal yr B.P.), 25,420 ^{14}C yr B.P. (~30,200 cal yr B.P.) and 35,900 ^{14}C yr B.P. (~41,000 cal yr B.P.), respectively. The 130–100 and 97–83 cm intervals reveal very dark gray sediment with frequent roots and bioturbation (ichnofossils), which could have enhanced the transport of allochthonous materials and contributed to date inversions. In addition, the presence of dead/old carbon mainly in layer 98–93 cm (~41,000 cal yr B.P.) cannot be discarded. This suggests the presence of dead/old carbon that remains strongly absorbed and naturally contaminated the organic matter. The physical and chemical pretreatments applied to all samples eliminate only adsorbed and/or soluble acid/alkaline dead and/or old inorganic/organic carbon. A hiatus of *ca.* 17,400 ^{14}C yr (~21,300 cal yr B.P.) is recorded within the 84–75 cm interval (19,658–2238 ^{14}C yr B.P. or ~23,500 cal yr B.P.–~2200 cal yr B.P.). This should represent an erosive event associated to the eustatic sea-level rise, which began at ~17,000 ^{14}C yr B.P. (~20,000 cal yr B.P.), reaching a maximum at ~5000 ^{14}C yr B.P. or ~5800 cal yr B.P. (Suguio et al., 2005). An age of 1010 ^{14}C yr B.P. or ~900 cal yr B.P. was obtained from the surface (33–23 cm) of the core. The woody fragment in the same layer gave an age of 300 yr B.P. or ~380 cal yr B.P., which can be associated to the transport of this material from surface layers likely through biological activity (crabs).

4.2. Total organic carbon (TOC), C/N, δ^{13}C and δ^{15}N values of mangrove samples

The TOC content added up to 2.6% in the deeper section of the profile (196–194 cm) (Fig. 2). A trend toward higher values (between 3.4 and 40.2%) is observed in the 192–174 cm depth interval. In the 182–180 cm interval, a high concentration of pollen grains was found (33,000 grains per gram of sediment) as well as a relative frequency of arboreal pollen of 87% (Fig. 5), probably associated to the high TOC content. A decrease in TOC content was observed from the 174–172 cm (29%) to the 156–154 cm layer (2.1%), with a simultaneous decrease in pollen grain concentration, from 6000 to 2000 grains per gram of sediment (Fig. 5). A new increase in TOC content was observed in the interval from 154–152 cm to 144–142 cm, with values between 12.3% and 19.4%, respectively. From 142 cm depth to the surface layer the values decrease, varying between 0.3% and 5.7%.

The C/N values varied significantly throughout the profile, from ~17 at 192 cm up to ~62 at 184 cm (Fig. 2). Then, a trend towards higher values (between 44 and 107) is observed in depth interval 182–158 cm, changing to lower values as low as 7 between 158–154 cm, and returning to higher values (~130) between 154–74 cm. These changes indicate the predominance of land plants (Meyers, 1994; Wilson et al., 2005) at the location presently occupied by the mangrove. This is likely associated to RSL changes. Based on pollen diagrams (Figs. 4 and 5), land plants are represented by trees and herbs from > 40,000 cal yr B.P. to ~23,000 cal yr B.P. C/N values ranging from 2 to 27.5 are observed from 74 cm depth to the surface, thus indicating a stronger influence of phytoplankton as a source of organic matter in the last ~2200 cal yr B.P.

Isotopic values tended to be more depleted in the lower part of the profile (196–130 cm), with most of the δ^{13}C values near −28.5‰ (Fig. 2). A trend toward more enriched δ^{13}C values is observed in the upper section (from 128 cm to the surface) (~−24.5‰). The higher but still depleted δ^{13}C values associated with lower values of TOC (from 0.3% to 6%) and C/N ratios (from 2 to 27), indicate the presence of phytoplankton (C/N < 10), and a mixture with land plants

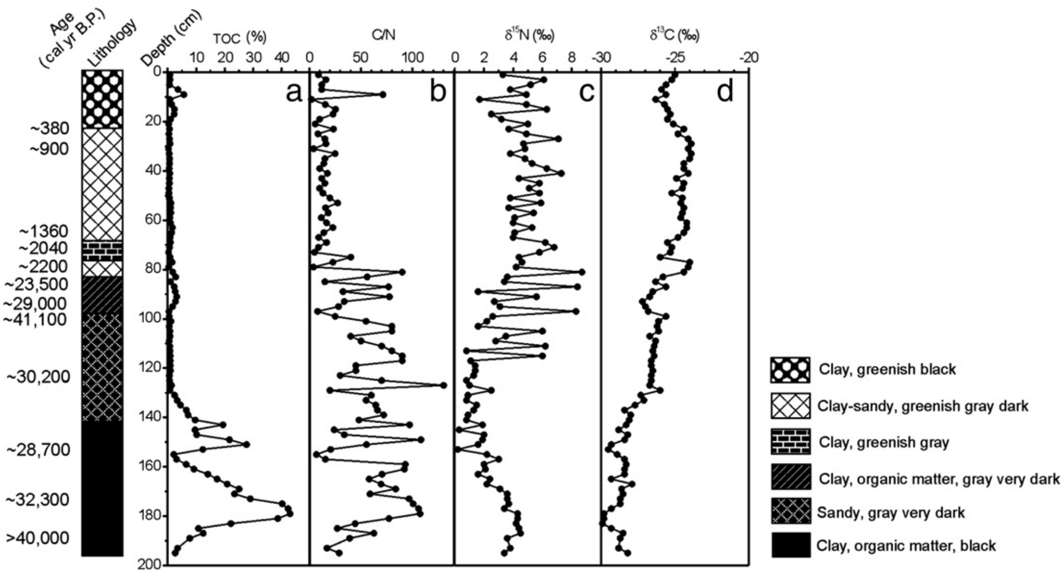

Fig. 2. ^{14}C age, lithology, total organic carbon (TOC), C/N, δ^{13}C and δ^{15}N values of mangrove samples in relation to depth.

(C/N > 10), possibly associated to the return of the mangrove to its current position since at least 2200 cal yr B.P.

The δ^{15}N values in the 196–76 cm interval (>40,000 cal yr B.P. and ~2200 cal yr B.P.) varied from approximately +0.8‰ to +9.0‰ (Fig. 2). These results can be linked to nitrogen cycle processes such as denitrification, which fractionates N with a loss of light N and a consequent enrichment of heavy N (Altabet et al., 1994). In addition to the influence of nitrogen cycle processes, enriched δ^{15}N values can also be associated to the presence of phytoplankton (values up to ~9‰) in the composition of the organic matter, probably freshwater phytoplankton, due to the retreat of the coast line during that period. Since the previously mentioned values of C/N and δ^{13}C indicate the presence of land C_3 plants at the study site between >40,000 cal yr B.P. and ~19,000 ^{14}C yr B.P. or ~23,000 cal yr B.P., a small pond/peatland might have existed at this location or the soils remained flooded over certain periods. In the interval between 76 cm depth and the surface (~2200 cal yr B.P. until present), values from +2.5‰ to +7.5‰ are characteristic of a mixture of land plants and phytoplankton. These values suggest a greater influence of C_3 land plants from ~>40,000 cal yr B.P. to ~19,000 ^{14}C yr B.P. or ~23,000 cal yr B.P., and a mixture of the two sources of nitrogen in the Sítio Grande mangrove sediments up to the present.

4.3. C/N × δ^{13}C

The distribution of C/N values associated with δ^{13}C values clearly indicates the predominance of land C_3 plants since >40,000 cal ^{14}C yr B.P. at the location presently occupied by mangrove (Fig. 2). Only very few points with lower C/N values (~10) and more enriched δ^{13}C values (~−24/−25‰) suggest an influence of phytoplankton (probably marine) in the composition of the organic matter (Fig. 3).

4.4. Pollen analysis

The results of pollen analysis of the core sample are presented in Figs. 4 and 5. The palynological content of the samples revealed the presence of 72 pollen taxa of which 71 are angiosperms and one is an gymnosperm (*Podocarpus*), as well as 11 pteridophytic spore taxa. Three zones may be distinguished. The first includes samples taken between depths of 196 and ~140 cm, equivalent to the period of ~40,000 ^{14}C yr B.P. or >40,000 cal yr B.P. to ~24,650 ^{14}C yr B.P. (this is the mean of ~23,880 ^{14}C yr B.P. at 156–150 cm and ~25,420 ^{14}C yr B.P. at 130–123 cm, or ~29,500 cal yr B.P. The second pollen zone corresponds to the layer between 140 and 80 cm (~24,650 ^{14}C yr B.P. to ~19,000 ^{14}C yr B.P. or ~29,500 cal yr B.P. to ~23,000 cal yr B.P.) and the last zone is characterized by the absence of pollen and spores taxa.

4.4.1. Zone I: 196–140 cm (~>40,000 ^{14}C yr B.P. or >40,000 cal yr B.P. to ~24,650 ^{14}C yr B.P. or ~29,500 cal yr B.P.)

This zone is mostly composed of organic rich clay and clayey-sandy sediments, and includes the base of the core (Fig. 4). Pollen concentrations varied between ~2500 and 24,000 grains per gram of sediment (Fig 5), except in layers 182–180 and 144–142 cm which contained 33,200 and 37,800 grains per gram of sediment, respectively. This zone is characterized by the stable presence of forest (51 to 87% of the total), herbs and grasses (4 to 31%) and fern spore elements (13 to 37%). Aquatic herbs represent about 4% of the total.

Among arboreal elements, the most common taxa are *Ilex* (7–32%), Myrtaceae (7.5–30%), *Alchornea* (1–17%), *Weinmannia* (1–17%), *Miconia* types (1–10%), *Symplocos* (1–7%), *Myrsine* (1–6%) and

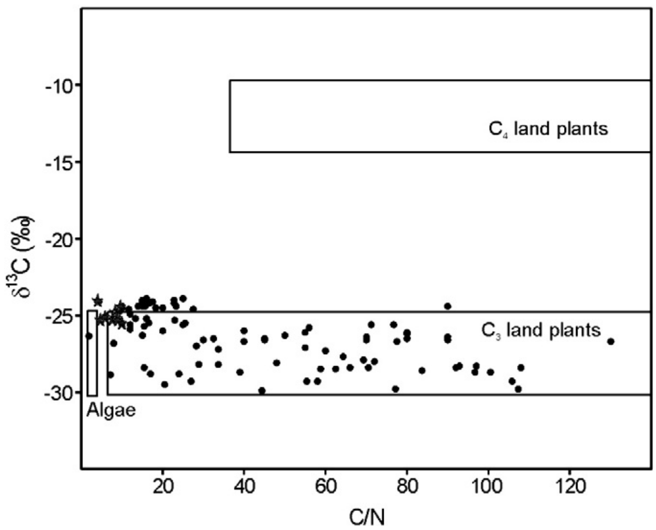

Fig. 3. C/N x δ^{13}C values of mangrove organic matter. Star dots suggest marine phytoplankton influence.

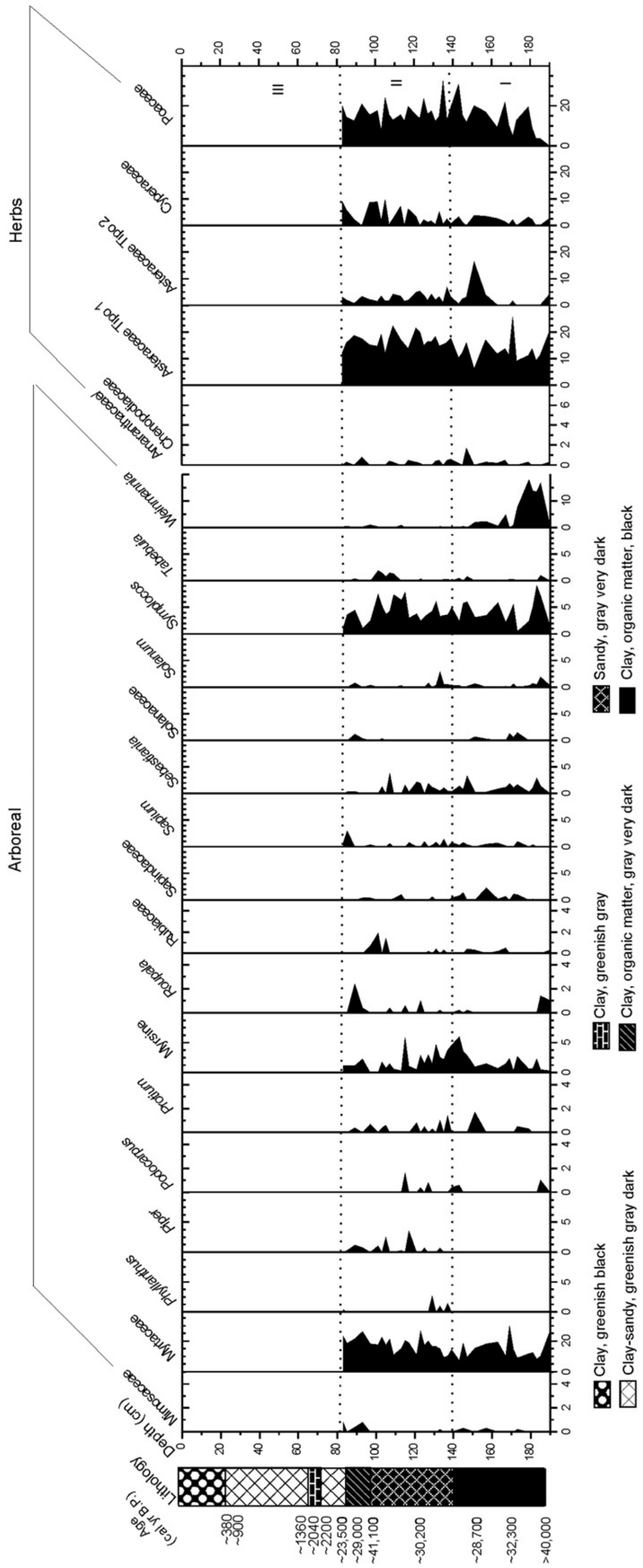

Fig. 4. Detailed pollen diagram expressed as percentages of each taxon in relation to the sum of arboreal and non-arboreal elements.

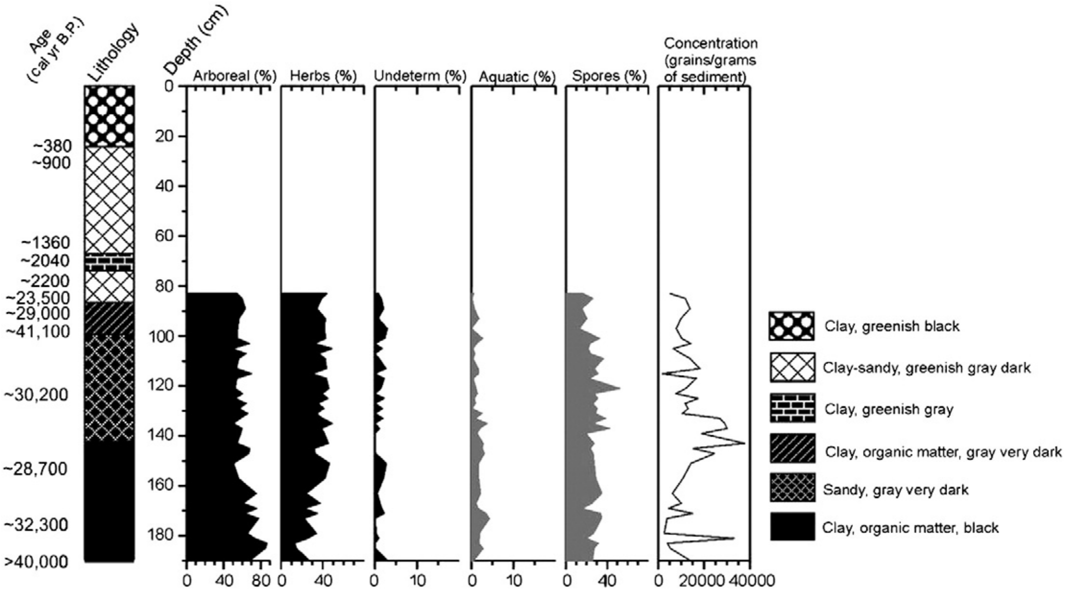

Fig. 5. Percent values for summarized pollen groups and spore concentrations, based on plant form and habitat type.

Melastomataceae/Combretaceae (1–4%). Non arboreal vegetation is dominated by the Poaceae (4–31%) and Asteraceae (6–26%). *Cyathea* (7–25%) and *Polypodium* (8–12%) were the dominant ferns.

The high percentage of Myrtaceae, *Alchornea*, *Weinmannia*, Melastomataceae/Combretaceae, *Symplocos* and *Myrsine* (Fig. 4), together with the presence of *Hedyosmum* (1.4%), *Podocarpus* (1%), aquatic herbs and typical ferns of forest formations (Fig. 4) during the period from 40,000 to 24,000 ^{14}C yr B.P. or ~29,000 cal yr B.P. suggest the presence of a cooler climate and humid forest where the mangrove currently occurs. The association of Myrtaceae, *Alchornea*, *Myrsine* and *Symplocos* has been found in other pollen records of tropical forests, and was related to the presence of forest under humid and cool conditions (De Oliveira, 1992; Ledru, 1993; Colinvaux et al., 1996, 1999; Ledru et al., 1996). Members of the family Poaceae, which are mostly C_3 grasses (based on depleted δ^{13}C values) and which represent a high percentage of the vegetation (30%), are known as prolific producers of windborne pollen (Colinvaux et al., 1999). Therefore, the paleoenvironmental interpretation for Zone I is of a tropical forest under a more humid and cooler climate than the present.

4.4.2. Zone II: 140–80 cm (~24,650 ^{14}C yr B.P. to <19,000 ^{14}C yr B.P., or ~29,500 cal yr B.P. to <~23,000 cal yr B.P.)

This zone is composed mostly of sandy sediments (140–90 cm) which gradually become organic rich (97–83 cm). In this interval pollen concentrations varied from 30,000 to 5000 grains and present a notable similarity with the previous zone, in the constant presence of forest elements (49 to 70%) such as Myrtaceae (9–26%), *Ilex* (6–21%), Melatomataceae/Combretaceae (1–10%), *Miconia* type (1–9%), *Symplocos* (1–7%) and *Myrsine* (1–6%). Although values for many tree taxa remain similar to those recorded in Zone I, some other taxa which were present in relatively high concentration in Zone 1, such as *Weinmannia* and *Alchornea* decrease in this zone, from a maximum of 17% to 1% and from 17% to 6%, respectively. The frequency of others increases: *Drimys* (from 0.2% to 2%), *Hedyosmum* (from 1.4% to 3%) and *Podocarpus* (from 1% to 2%). An increase in the frequency of fern spores and NAP elements is observed (from 35% to 53% and from 31% to 50%, respectively).

The high percentage of Poaceae (up to 50%), Cyperaceae, aquatic herbs and ferns suggest the presence of a humid and/or flooded environment. Based on δ^{13}C values, most Poaceae species represent C_3 grasses, plants commonly found in humid terrains. The percentage of Cyperaceae, herbs found mainly in flooded areas (Souza and Lorenzi, 2005), varied significantly in this interval (between 0.5% and 9.0%), probably indicating periods of greater or lesser humidity at the site. Within the 120–115 cm interval there was an increase in the percentage of *Drimys* (2%), *Hedyosmum* (3%) and *Cyathea* (40%), denoting a period of increased humidity. The C/N varied from ~40 up to ~90, indicating the dominance of land plants and the δ^{15}N values varied from ~2 (mixture of land/aquatic plant sources in the organic matter, with greater terrestrial influence) up to 6 (mixture of organic matter sources, but with greater aquatic influence). Considering the high values of C/N, the enriched δ^{15}N values are likely not only connected with the phytoplankton's influence, but also with isotopic fractionation (^{15}N enrichment) due to denitrification (Altabet et al., 1994). This interval is chronologically located within the period of the Last Glacial Maximum (LGM) that began approximately 25,000 yr B.P. or ~30,000 cal yr B.P., when glaciers expanded in the north and at high elevations of the southern hemisphere and under depressed temperature regimes and relative sea levels approximately 100 m below those of the present (Dawson, 1992; Colinvaux et al., 1996; Suguio et al., 2005). The taxa found in this interval, together with the increase in the proportion of *Drimys* and *Podocarpus* reinforce the interpretation of a cool climate forest in the area in the period from ~29,500 cal yr B.P. to ~23,000 cal yr B.P., probably with more variable humidity levels than during the previous period. Isotopic studies also indicated a cool and humid climate in the Serra do Mar State Park- Núcleo Curucutu (SP) in similar period, which is located ~170 km north of Cardoso Island. This was corroborated by the presence of arboreal pollen belonging to *Alchornea*, *Araucaria*, Arecaceae, Ericaceae, *Hedyosmum*, *Ilex*, Melastomataceae, *Maytenus*, *Podocarpus*, *Symplocos* and *Weinmannia* (Pessenda et al., 2009).

4.4.3. Zone III: 80–0 cm (~2200 cal yr B.P. to present)

Due to a sedimentary hiatus, the period between ~23,000 cal yr B.P. and ~2200 cal yr B.P. cannot be described. In addition, the sediment accumulated over the past ~2200 cal yr B.P. (80 cm to the surface) did not include palynomorphs. A hypothesis for the absence of pollen grains and spores would be the probable washing effect of tides during high sea level periods of the early Holocene, as indicated by the ascending curves of Martin et al. (2003) and Angulo et al. (2006). Support for this hypothesis is found in a palynological study conducted by Behling et al. (2002) on marine sediments collected in Vitória, Espírito Santo

State (Brazil). These authors observed larger amounts of pollen grains in sediments of the glacial period, when the sea level was lower than during the Holocene.

The lack of palynomorphs in the upper sediments of the core might also be explained by the presence of oxidizing conditions within the modern mangrove, which is continuously submitted to alternating oxic/anoxic conditions controlled by tides.

In the Pai Matos mangrove, located in the Cananéia-Iguape region of São Paulo State, biogeochemical studies indicated oxic conditions at the surface and anoxic conditions in the deeper sediments, where the authors observed a decrease in plant root density (Ferreira et al., 2007). Therefore, tidal effects in conjunction with the oxic conditions prevailing in surface sediments provide a reasonable explanation for the loss of palynomorphs in the upper section of the studied core.

4.5. Diatom analysis

Well preserved diatoms are found in the upper 76 cm of the core (Fig. 6), in contrast to a complete absence of frustules at depths ranging from 196 to 80 cm.

A total of 75 taxa were recorded, which allowed the distinction of three diatom ecological zones:

4.5.1. Zone I: 196–80 cm (>40,000 cal yr B.P. to ~23,000 cal yr B.P.)

This zone is characterized by the absence of diatom frustules. Gaps in diatom deposition in South American sediments are not uncommon (Bradbury et al., 1981; De Oliveira et al., 1987). The previously discussed elementary (C and N), isotopic (δ^{13}C and δ^{15}N) and pollen data for this time period suggest continental conditions influenced by humidity and forest vegetation.

Diatoms can be found in all types of aquatic environments, and in some cases in humid environments such as soils and swamps where light, temperature and chemical conditions are adequate (Patrick and Reimer, 1966). Since diatoms can thrive in humid soils and swamps (Patrick and Reimer, 1966), an alternative hypothesis for their absence in this zone is that reduced light intensity severely restricted their growth (Hudon and Bourget, 1983; Whitehead and McMinn, 1997).

4.5.2. Zone II: 80–20 cm (~2200 cal yr B.P. to ~900 cal yr B.P.)

In this zone marine taxa prevail (75% - 90%) over salt-tolerant taxa or diatoms that thrive in brackish (2%) and freshwater (5%), as shown in Fig. 6.

Numerically, the most important were the marine taxa *Actinoptychus splendens* (5% to 10%), *Coscinodiscus marginatus* (5% to 20%), *Cyclotella striata* (5 to 10%), *Diploneis gruendleri* (3 to 8%) and *Paralia sulcata* (10 to 25%).

Also present was *Coscinodiscus lineatus* with values of 1 to 6%, and a significant concentration of 30,000 valves/cm^3.

Despite low percentage values, high concentrations of *Cocconeis disculus*, a periphytic freshwater diatom ranging from 21,600 to 14,450 valves/cm^3, also indicates a source of continental water for samples taken at depths of 40, 50 and 76 cm. Since this taxon is known as oligothermal (Juse and Von, 1966; Moro and Fürstenberger, 1997), meaning it is commonly found in water with temperature ranging from 0 °C to 15 °C, it can be assumed that the diatom community in this zone is indicative of an estuarine-lagoonal system under strong marine influence.

4.5.3. Zone III: 20–0 cm (~900 cal yr B.P. to present)

The assemblages found in this zone are composed of ~80% marine taxa, ~5% brackish water diatoms and 2% freshwater elements, as shown on Fig. 6. Within the marine group, the best represented taxa

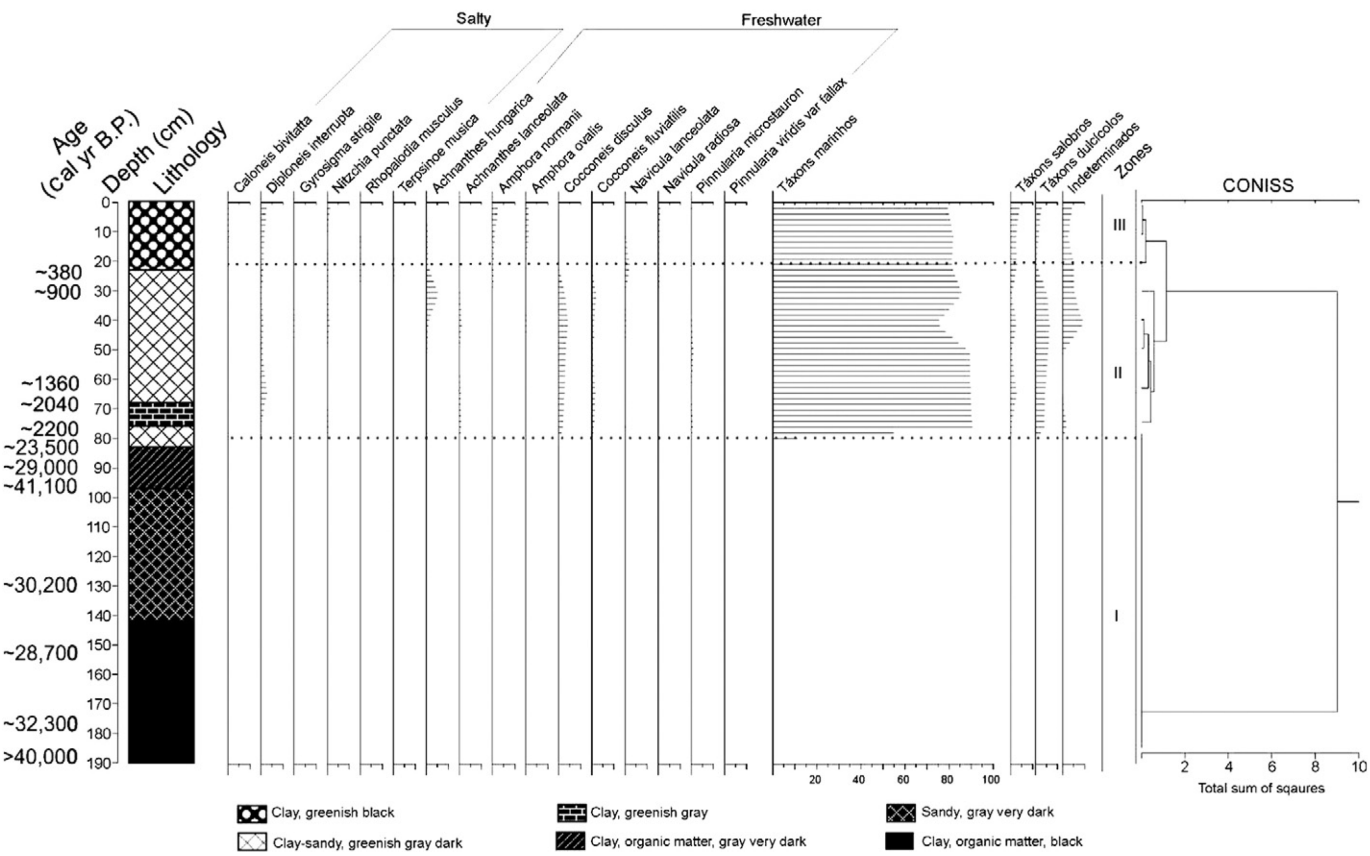

Fig. 6. Percentage of the numerically most important diatoms of marine, salt and freshwater taxa.

are *Actinoptychus campanulifer* (~5%), *Coscinodiscus marginatus* (~10% to 15%) and *Cyclotella striata* (~15%).

The concentration of freshwater taxa was lower than in the previous interval, varying from a maximum value of 30,000 valves/cm^3 at 40 cm to 5000 valves/cm^3 at 20 cm, and reaching 30,000 valves/cm^3 at the surface (Fig. 7). In this zone, the environment continues to be characterized as estuarine-lagoonal, probably similar to the present. In spite of the presence of slightly lower percentages of marine taxa (80%) in relation to the previous zone (90%), concentration values of marine taxa were higher, ranging from ~630,000 valves/cm^3 (76 cm sample) to ~940,000 valves/cm^3 at the surface (Fig. 7). The same can be observed for the salty taxa that increased from ~14,000 valves/cm^3 (40 cm sample) to ~50,000 valves/cm^3 at the surface.

4.6. Paleoenvironmental history

The data collected in this study allows the characterization of the climate of Cardoso Island between >40,000 cal yr B.P. and ~23,000 cal yr B.P. as a wet and cool, while it has been wet and warm since ~2200 cal yr B.P., similar to the present. A climatic interpretation could not be formulated for the period spanning ~23,000 cal yr B.P. to ~2200 cal yr B.P., due to a sedimentary hiatus.

Despite the fact that the study site is located between two adjacent hills, which allow more humid microclimate conditions to be maintained when compared to the regional climate, the study area should have been influenced by the climate of southeastern Brazil during the time span considered. Indeed, palynologycal studies of the southern tableland of Brazil also indicate a rise in humidity between ~48,000 cal yr B.P. and ~35,000 cal yr B.P. (Ledru et al., 1996). During the ~20,000 cal yr B.P. to ~9500 cal yr B.P. time interval, the region experienced a series of climate fluctuations dominated by cool, dry conditions interrupted by a brief period of higher humidity from ~15,800 cal yr B.P. to ~13, 000 cal B.P. (Ledru, 1993). Pollen analyses of lake sediments at Serra Negra, São Paulo State (19°S), from ~35,000 cal yr B.P. to ~24,000 cal yr B.P. and ~15,800–12,500 cal yr B.P. reveal that the climate was cooler and humid and very humid, respectively, with short dry phases (De Oliveira, 1992). Studies of several sites in the Brazilian Amazonian region (Colinvaux et al., 1996; Haberle, 1997; Freitas et al., 2001; Bush et al., 2004), southeastern (De Oliveira, 1992; Cruz et al., 2006, 2007; Siqueira, 2006; Wang et al., 2006; Pessenda et al., 2009), and northeastern Brazil (Auler and Smart, 2001; Pessenda et al., 2004, 2010; Wang et al., 2004) indicate the presence of a wetter climate during the LGM.

However, drier climatic conditions were recorded during the late Pleistocene and early Holocene at several sites in central (Ferraz-Vicentini, 1993; Ferraz-Vicentini and Salgado-Labouriau, 1996; Barberi, 2001), southeastern (Ledru, 1993; Behling, 1995; Ledru et al., 1996; Behling and Lichte, 1997; Behling et al., 1998; Gouveia et al., 2002) and southern Brazil (Roth and Lorscheitter, 1993; Stevaux, 1994, 2000; Behling, 1995; Lorscheitter and Mattoso, 1995; Neves and Lorscheitter, 1995; Behling and Lichte, 1997). Pollen data from Morro de Itapeva, São Paulo State (1850 m elevation) show that during the last glacial period, from about ~40,000 to 21,000 cal yr B.P., the Campos do Jordão highland region was cooler and drier than it is today (Behling, 2002). Between ~11,000 and ~6000 cal yr B.P. temperatures continued to be low, but humidity began to rise favoring the presence of *Araucaria* associated with species of the genera *Symplocos*, *Drimys*, *Lithraea*, *Podocarpus*, *Myrsine* and *Alchornea* (Ledru, 1993). Studies also report a dry period in Amazonia, as demonstrated in work by Absy et al. (1991), Cordeiro, et al. (2011), Ledru et al. (1998), Van der Hammenn and Absy (1994), Van der Hammen and Hooghiemstra (2000), Whitney et al. (2011), and this dry period is also associated with cooler temperatures (Van Der Hammen, 1974; Bush, et al., 1990; Colinvaux et al., 2000).

In isotopic studies of soil from a small semideciduous forest fragment (1.0–2.0 km^2) in southwestern São Paulo State, C_4 plants predominated from the late Pleistocene to the early Holocene and the predominance of C_3 plants marked the rest of the Holocene (Pessenda et al., 1996a,b,c 1998; Gouveia et al., 2002; Saia et al., 2008). Using pollen and carbon isotope analyses in a peat record of Curucutu Natural Reserve, a higher altitude mosaic of Atlantic forest and grassland located ~170 km northern of Ilha do Cardoso, Pessenda et al. (2009) observed the presence of glacial *Araucaria* forests with aquatic elements and herbs, and the predominance of C_3 plants (trees and herbs) during the period of ~32,000 to ~18,000 cal yr B.P. These results indicate the presence of a cool and humid climate. From ~18,000 cal yr B.P. to the present, the predominance of C_3 plants and the increase in arboreal

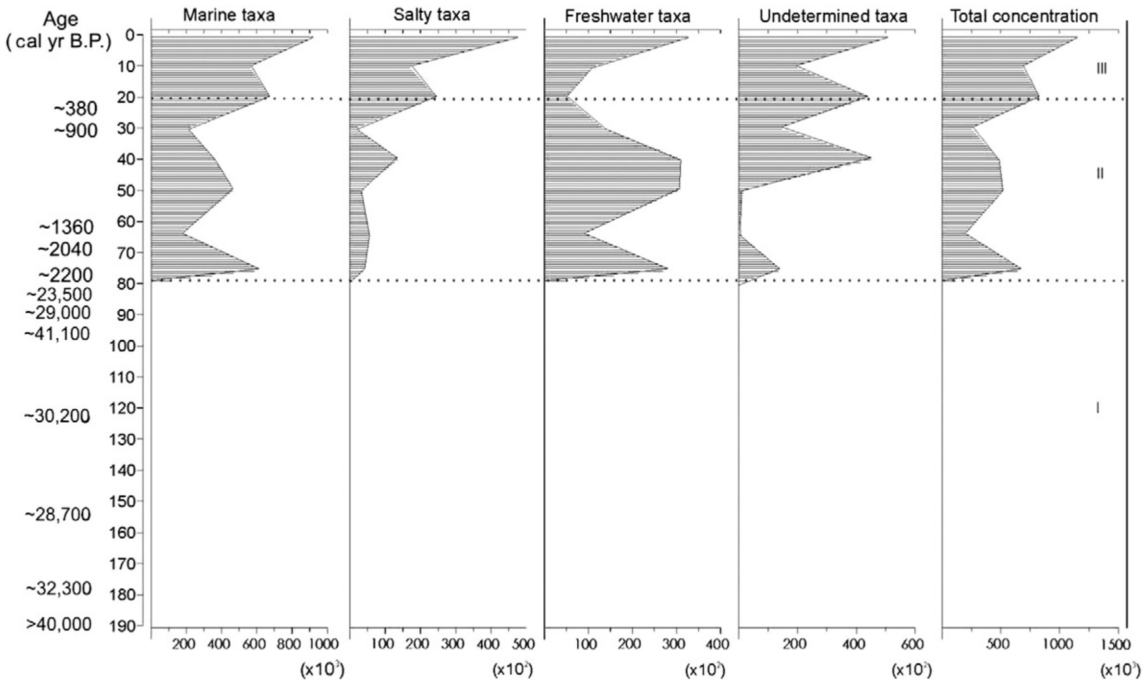

Fig. 7. Summary of concentration values for diatom categories.

species in the peat record, as well as a mixture of C_3 and C_4 plants in several soil organic matter profiles, were related to the prevalence of climatic conditions which were more humid and warmer than during the previous period.

Isotope studies of soils of the Atlantic Forest region, in southern São Paulo State (~24°S) also indicated the presence between ~29,000 to ~17,000 cal yr B.P. of more open vegetation than what is currently observed, with a probable mixture of C_3 and C_4 plants suggesting the prevalence of a drier climate during that period. From ~17,000 cal yr B.P. to the present, a significant predominance of C_3 plants was observed and associated with a more humid climate than during the previous period (Saia et al., 2008).

4.7. Post glacial sea-level rise

During the Last Glacial Maximum around ~20,000 cal yr B.P., a worldwide lowering of the eustatic sea-level occurred, resulting from the expansion of polar ice sheets (Murray-Wallace, 2007). Evidence of the lowering of the eustatic sea-level and the resulting regression of the ocean on the southern Brazilian coast during the LGM were obtained by Corrêa (1996). From ~20,500 to ~19,000 cal yr. B.P., at ~130 m below the current mean sea-level, the southern portion of the Brazilian continental shelf was almost entirely exposed, placing the coastline at some sites more than 100 km east of its present position (Corrêa, 1996). A similar scenario may have occurred on the shallow continental shelf of São Paulo State, as indicated by the geomorphologic analysis carried out by Conti and Furtado (2006). Our paleoenvironmental interpretation of results obtained at the MSG site for the time interval from ~>40,000 to ~19,000 yr B.P. (~23,000 cal yr B.P.) reflects the regression of the ocean during the last glacial period. During this period, forest vegetation adapted to a cool and humid climate became established at the study site and no marine water influence is observed in the sediment. The climatic mechanisms resulting in enhanced humidity during the last glacial period include mainly the influence of changing land-sea temperature contrasts on atmospheric circulation patterns, which control the South American summer monsoon (SASM) over South America (Cruz et al., 2007). The speleothem records of subtropical Brazil indicate that periods of more abundant monsoonal rainfall coincide with (i) high summer insolation phases on Milankovitch timescales (Cruz et al., 2006), (ii) cold periods in the northern hemisphere during Heinrich events (Cruz et al., 2006; Wang et al., 2006), and between >70,000 cal yr B.P. and ~20,000 cal yr B.P. during marine oxygen isotope stages 4 to 2 (Cruz et al., 2007). Both factors positively affect the mean location and/or the convective activity of SASM, resulting in enhanced transport of moisture from the Amazon Basin into southeastern and southern Brazil. This occurs because continental heating results from increased incoming solar radiation or cooler surface sea temperatures in the northern tropical Atlantic.

During the Holocene the global eustatic sea-level reached its present level at ~7000 cal. yr B.P., with local and regional variations attributed to a variety of factors including tectonics, isostatic adjustments and geoid changes (Murray-Wallace, 2007). Relative sea-level reconstructions for the southeastern Brazilian coast (Martin et al., 2003; Angulo et al., 2006) reveal that the present mean sea-level was exceeded for the first time during the Holocene at ~7800 to 6600 cal. yr B.P., and reached its maximum height (2 to 5 m above the present mean sea-level) at 5500 cal. yr B.P. Since then, the relative sea-level decreased to its modern height, with high-frequency oscillations (Martin et al., 2003) or without oscillations (Angulo et al., 2006). At the MSG site, sediment records of Holocene eustatic fluctuations are absent until ~2200 cal. yr B.P. The sedimentary hiatus in the core between ~23,000 cal yr B.P. to ~2200 cal yr B.P. may be the result of erosive events, since abrupt processes were recorded at 84–80 and 80–76 cm sediment depths (Table 1). Such events were likely caused by the low sea-level during the LGM and by relative sea-level changes during the Holocene (Suguio, 1993), and/or by a tectonic event occurring in the region (Vidotto, 2008). Nonetheless, data from the last ~2200 cal. yr B.P. show that an estuarine/lagoonal environment similar to the present one was maintained.

5. Conclusions

An interproxy approach shows a mixture of terrestrial and aquatic organic matter preserved in a flooded/humid environment (peatland) from >40,000 cal yr B.P. to ~29,500 cal yr B.P. During this time interval, C_3 land plants and arboreal elements of a humid forest in a cool environment predominated at the study site. Between ~29,500 and ~23,000 cal yr B.P. our data continues to indicate the prevalence of C_3 land plants forming a humid forest in a cool climate, under continental influence, at Ilha do Cardoso.

It is likely that the post-glacial sea-level rise produced erosion of the continental sedimentary deposits, thus from ~23,000 to ~2200 cal yr B.P. it was not possible to obtain a continuous stratigraphic record due to the existence of a sedimentary hiatus. However, near 2200 cal yr B.P. sediment accumulation was restored, and the records suggest the occurrence of a marine coastline occupied by mangrove as observed today.

Acknowledgments

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