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Indicators of Holocene sea level changes along the coast of the states of Pernambuco and Paraíba, Brazil

Indicadores de variações holocênicas do nível do mar ao longo da costa dos estados de Pernambuco e Paraíba, Brasil

Kenitiro Suguio[1], Alcina Magnólia Franco Barreto[2], Paulo Eduardo de Oliveira[3], Francisco Hilário Rego Bezerra[4], Maria Cristina Santiago Hussein Vilela[5]

[1]Instituto de Geociências, Universidade de São Paulo - USP, Rua do Lago 562 - Cidade Universitária, CEP 05508-080, São Paulo, SP, BR (kenitirosuguio@hotmail.com)

[2]Departamento de Geologia, Centro de Tecnologia e Geociências, Universidade Federal de Pernambuco - UFPE, Recife, PE, BR (alcinabarreto@gmail.com)

[3]Universidade São Francisco - USF, Bragança Paulista, SP, BR (paulo@bjd.com.br)

[4]Departamento de Geologia, Centro de Ciências Exatas e da Terra, Universidade Federal do Rio Grande do Norte - UFRN, Natal, RN, BR (bezerrafh@geologia.ufrn.br)

[5]Pós-graduação em Análise Geoambiental, Universidade de Guarulhos - UnG, Guarulhos, SP, BR (cristina.sh@click21.com.br)

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Abstract

This study deals with the Holocene relative sea level (RSL) changes along the Brazilian northeastern coast, in particular along the states of Pernambuco and Paraíba. It presents 25 sea level superficial indicators, dominantly of a biological nature (i.e., vermetid gastropod tubes encrusted on rocky surfaces, as well as mollusk shells in live positions contained within beachrocks and paleomangrove deposits). Moreover, diatomological and palynological analyses have been carried out on a drilling core obtained from the Olhos d'Água lagoon (Southeastern Recife, Pernambuco state) with a length of about 2.7 m and age of about 8,300 cal yr BP at the base. The envelope RSL change curve obtained through the interpretation of the data indicates that, after reaching the current level ~ 7,400 cal yr BP, a sea level culmination of ~ 3 m above sea level was attained between 4,000 – 5,000 cal yr BP, and a general trend of sea level drop occurred until the present, with possible phases of slight oscillations. This is consistent with the oscillation frequency of microscopic marine and freshwater organisms in the sediment core.

Keywords: Borehole data; Holocene; Mesotidal; Sea level changes.

Resumo

Este estudo apresenta variações relativas do nível do mar no Holoceno ao longo do litoral do Nordeste brasileiro, em particular nos Estados de Pernambuco e Paraíba. O trabalho apresenta 25 indicadores superficiais do nível do mar, predominantemente de natureza biológica (i.e., tubos de gastrópodes vermitídeos encrustados em rochas, bem como conchas de moluscos em posição de vida em *beachrocks* e paleomangues). Além disso, análises de diatomológicas e palinológicas foram feitas em um furo na Lagoa Olhos d'Água (sudeste de Recife, Estado de Pernambuco) com um comprimento de aproximadamente 2,7 m e com uma idade de 8.300 anos cal. AP na base. A curva envelope obtida por meio da interpretação dos dados indica que, após ~ 7.400 anos cal. AP, o nível do mar atingiu o máximo de ~ 3 m acima do nível do mar entre 4.000 – 5.000 anos cal. AP, e uma tendência geral de queda do nível do mar ocorreu até o presente, com possíveis fases de pequenas oscilações. Esse padrão é consistente com a frequência das oscilações de organismos microscópicos marinhos e de água doce no furo coletado.

Palavras-chave: Dado de poço; Holoceno; Mesomaré; Variações do nível do mar.

INTRODUCTION

The sea level changes associated with the mesotidal regime in northeastern Brazil have been investigated during the past four decades. Delibrias and Laborel (1971) presented the first study on the relative sea level (RSL) change in the region, based mainly on the biological proxy records of vermetid tubes, coral remains, and oyster shell radiocarbon dates. This study included 18 samples from the Brazilian coast between the Ilha Grande (23° 10'S latitude) and Recife (8° 04'S latitude). These authors did not delineate any sea level curve, most likely due to the high vertical uncertainty. Nevertheless, as opposed to the world-wide sea level curve presented at the time (Bloom, 1971), the data in Delibrias and Laborel (1971) indicated that, during the last 6,000 years, the sea level was approximately 3 m above its present position. The same pattern was corroborated by a sea level curve presented by Fairbridge (1976) for the Brazilian coastline, which was mainly based on shell-middens. Martin et al. (1979) presented the Salvador Curve, which is one of the most representative amongst the Holocene curves outlined for the Brazilian coastline, because it was based on various proxy records. Dominguez et al. (1990) also presented a sea level curve, which they associated with the Salvador curve proposed for the littoral zone north of Salvador. They concluded that the region was subjected to a RSL rise in the Holocene, which was mainly caused, among other factors, by the global warming in the hypsithermal age. Angulo and Lessa (1997) presented a sea level curve for the coast of southern Brazil, which indicated that the sea level fell steadily after the Holocene highstand at ~5,000 cal. yr BP. Their study and the one on the Salvador sea level curve presented opposite interpretation about minor oscillations along the Brazilian coast in the Holocene, indicating a possible ambiguity in the Brazilian sea level data. Bezerra et al. (2003) proposed a sea level curve off the state of Rio Grande do Norte, which does not solve the ambiguity related to the minor sea level oscillations during the Holocene. More recently, Angulo et al. (2006) reviewed studies that presented sea level curves along the Brazilian coast. They concluded that there is evidence for a progressive decline, possibly with uneven rates, of relative sea level since the end of the mid-Holocene sea level maximum. These studies indicate the need of additional data to understand the evolution of the Brazilian coast during the Holocene. Thus, the main goal of this study was to compare the Holocene relative sea level change indicators along the littoral zone of the states of Pernambuco and Paraíba with palynological and diatomological data from a lagoon borehole close to the coastline (Figure 1).

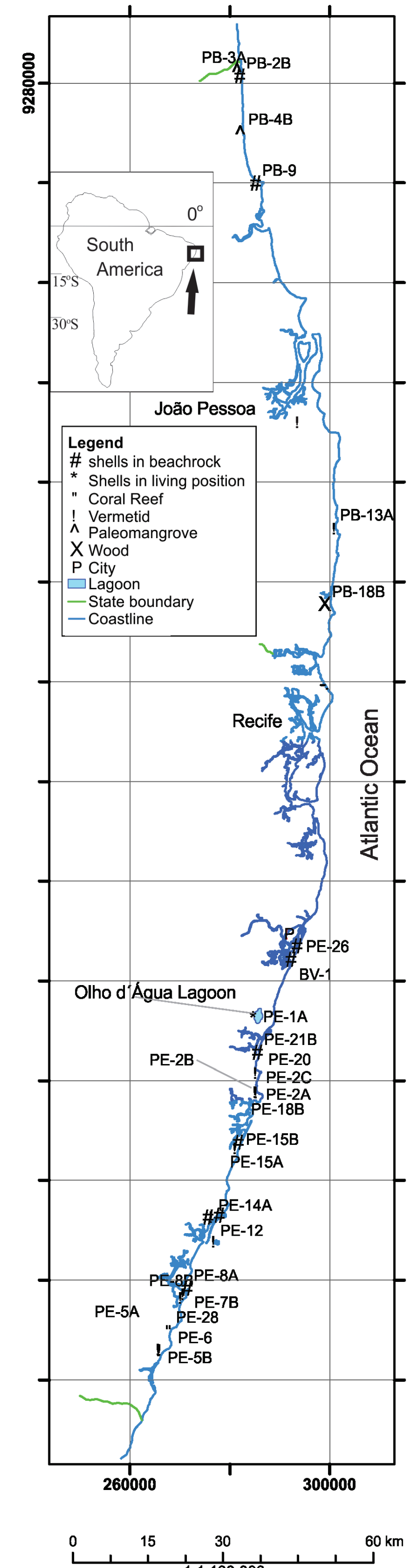


Figure 1. Map showing sample locations. Inset: the South American continent and location of study area.

GEOGRAPHIC AND GEOMORPHOLOGIC CHARACTERIZATION

The study area is located between 06° 29' S and 08° 55' S latitude and 34° 58' W to 35° 10' W longitude; it extends for approximately 270 km along the coastline roughly in a north-south direction (Figure 1). The study area has a wet tropical coastal climate with an average annual temperature of 22 – 32°C and an annual rainfall of 1,200 – 2,050 mm. The area has a semidiurnal mesotidal regime with tides from 2.0 and spring tides of 2.4 m (Brazilian Navy, 2010). The wind is usually from southeast and east and over the course of the year typical speeds vary from 0 to 7 m/s.

This sector of the Brazilian coastline is characterized by small to medium scale ephemeral rivers in the order of 50 – 200 km that carry negligible sediment load during the greater part of the year (Bittencourt et al., 2002). The perennial and major scale rivers in terms of length and volume of water are the Paraíba, in the state of Paraíba, as well as the Capibaribe and Beberibe rivers in the state of Pernambuco, all of which flow into lagoon-estuarine environments.

The most important geomorphic units of this coastline are the shelf, the coastal plain, and the coastal tablelands (RADAMBRASIL, 1981). In the adjacent submerged portion of the studied coastline, one of the narrowest continental shelves in Brazil is found, whose average width is about 80 km. The Quaternary coastal plain exhibits a width that ranges from approximately 0.1 – 30 km, which has developed on Quaternary shallow marine to fluvial estuarine deposits, composed of the following geomorphological subunits: beach-ridge plain, complex reef alignment (beachrocks with organic incrustations), present beach and tidal plain. The Quaternary coastal plain altitude ranges from a few centimeters above the present sea level to as high as 10 m. On the other hand, the Neogene (Miocene-Pliocene) coastal tablelands range from 50 – 100 m in altitude and occur throughout the littoral zone, almost continuously bordered by steeply sloped sea cliffs.

The coast of these states is a part of the oriental northeastern coast of Silveira (1964) and Cruz et al. (1985), which is also known as the Barreiras coast. It extends from the Calcanhar Cape (state of Rio Grande do Norte) to the Baía de Todos os Santos (state of Bahia). The shape of the coast was controlled by the breakup between Africa and South America in the Jurassic-Cretaceous, and its present characteristics were mainly shaped by eustasy and climate (Dominguez and Bittencourt, 2010). This coast exhibits beachrock units that support organic reef build-up composed of calcareous algae, bryozoans, and corals. The beachrock reefs protect the coastline against the dynamic coastal erosion effects from waves and tidal currents (Villwock et al., 2005).

MATERIALS AND METHODS

Our determination of sample sites heights from former RSL positions takes into account several sources of error, as in Bezerra et al. (2003). These are possible source of errors. The vertical uncertainty range includes (a) elevation error due to the transportation of local harbor predictions to sample sites; (b) possible discrepancies between the observed sea level and tide predictions; and (c) the accuracy of the RSL indicator used. The elevation of the sample sites from the current sea level was determined by using theodolite leveling, which has negligible error. These errors are discussed in more detail in Bezerra et al. (1998, 2003).

Sample heights and locations were determined using the procedures recommended by Admiralty Hydrograph Department (1996). The zero level from which all measurements and corrections were made was the Brazilian Córrego Alegre National datum. The geographic coordinates were determined using a pocket global positioning device with an accuracy of 10 m. The altitudes discussed in the text are expressed in terms of the mean sea level (msl). Sample heights were surveyed to tide levels and normalized to msl using the tide-table predictions by the Brazilian Navy (2010).

We used several sea level indicators to constrain relative sea level changes in our study area. Because the efficiency of sea level proxy records is quite changeable according to their nature (geological, geomorphological, biological, prehistorical etc.), the use of various simultaneous proxy records, as much as possible, is recommended. When convergence of evidence is found using different criteria, certainly, this evidence is not a mere coincidence, but it suggests that the result obtained is correct.

We used ports as the reference datum because living indicators were not homogeneously distributed in the study area. The application of the tidal prediction from local ports (Cabedelo, Recife, and Suape) to other areas was carried out using interpolation. Heights of the tidal levels at local ports were obtained from the Brazilian Hydrographic and Navigation Division website (Brazilian Navy, 2010). We assumed that interpolating these data could result in an error of about ± 20 cm, as already explained in Bezerra et al. (1998).

A possible difference between the observed sea level at the sample sites and the sea level interpolated from the local harbors may occur. The mean sea level may remain as much as 0.3 m above or below the average for as long as a month (Admiralty Hydrograph Department, 1996). This possible source of vertical error was added to the estimated vertical uncertainty.

We drilled a core 2.6 m deep in the Olhos d'Água lagoon and sampled sediments. The procedures used to clean the RSL indicators are given in detail in Bezerra et al. (1998, 2003). We carried out pretreatment to eliminate contamination. We selected shells that showed original colors and lacked any features to be expected from prolonged transportation. We began our screening with optical microscopy. If the contamination was at the surface, we tried to remove it mechanically or by acid washes and then reassess the specimen. We used X-ray diffraction (XRD) and scanning electron microscopy (SEM) if any suspected contamination were found. These procedures were described in detail in Bezerra et al. (2000). Samples from both the littoral zone and the lagoon were dated at Beta Analytic, USA, using the conventional radiocarbon method. The calibration method used the software INTCAL 98 as well as the studies of Talma and Vogel (1993) and Stuiver et al. (1998).

EVIDENCE OF HOLOCENE RELATIVE SEA LEVEL CHANGES

We dated 25 biological and geological RSL indicators along the littoral zone of the study area (Table 1): 15 vermetid gastropod samples (7 incrustation samples on Cretaceous granite, 6 incrustation samples on beachrock units, 1 incrustation sample on the sandstones of the Barreiras Formation, and 1 incrustation sample on the volcanic rocks of the Cabo Formation), 6 death assemblages in beachrock, 1 wood in peat deposit, 1 coral, and 1 bivalve shell in living position in peat deposit.

A RSL envelope curve for the study area is presented in Figure 2. It indicates that the RSL attained the present level at ~7,400 cal yr BP. The RSL reached its peak 2 – 3 m above the present level between 5,000 – 4,000 cal yr BP. The RSL has dropped since then to the present position. However, minor RSL oscillations could have occurred from 3,400 – 2,100 to 600 cal yr BP, but the envelope nature of the curve does not allow us to confirm these falls. Next we describe the main sea level indicators used in our study area.

Beachrock as a past relative sea level indicator

In spite of the current idea that beachrock units can be strictly formed within the intertidal zone, its upper limit of carbonate cementation is still uncertain, mainly in meso to macrotidal areas (Hopley, 1986). Beachrock is a useful tool as a past RSL indicator for areas where high tidal ranges do not occur and where there is limited upward movement of water capillarity despite a local dry climate (Pereira and De Ros, 2006; Vieira et al., 2007). The maximum age of a beachrock unit can be measured from its organic material (*e.g.*, mollusk shells) and its minimum age can be determined through cement dating. The utility of beachrock units as sea level indicators has been explained by Flexor and Martin (1979). Bezerra et al. (1998) identified three sedimentary facies in beachrock in order to increase the precision of the sea level indicator in a mesotidal regime: (a) sandstone with tabular to medium scale trough cross-beddings that correspond to the upper shoreface zone; (b) conglomerates and sandstones with swash cross-bedding (stratifications and set boundaries at low angles that formed parallel to changing slope of beachface and dip generally seaward) that would have been deposited in the lower foreshore zone; and (c) massive conglomerates composed of pebbles and boulders mostly derived from the adjacent sea cliffs that would have been formed within the foreshore zone. However, difficulties such as the use of death assemblages during the interpretation of these ages indicate that beachrock ages should be compared with ages obtained from other indicators (Bezerra et al., 1998). A detailed description of beachrock as sea level indicator was presented by Hopley (1986).

On the coastlines of the states of Pernambuco and Paraíba, beachrock units form linear features that are roughly parallel to the present-day beaches. These units range from a few meters to kilometers long and 40 m wide. These beachrock units are either submerged in the present shoreface or outcrop for part of the day in the present foreshore.

The age of the beachrock units in the study area were measured through the death assemblage of mollusk thanatocoenosis. These correspond to samples PB-2, PE8A, PE15A, PE26, SER, BV1, whose ages range from 2,850 ± 60 to 6,920 ± 100 cal yr BP (Table 1).This species is commonly found in the modern beaches of the study area as *Anomalocardia brasiliana*, *Anadara ovalis*, *Glycymeris undata*, *Tivela mactroides*, *Chione subrostrada*, *Macoma constrieta*, *Divaricella quadrisuleata*, and *Corbula caribaea* (Martin et al., 1979; Muniz and Oliveira, 1974).

Vermetid as a past relative sea level indicator

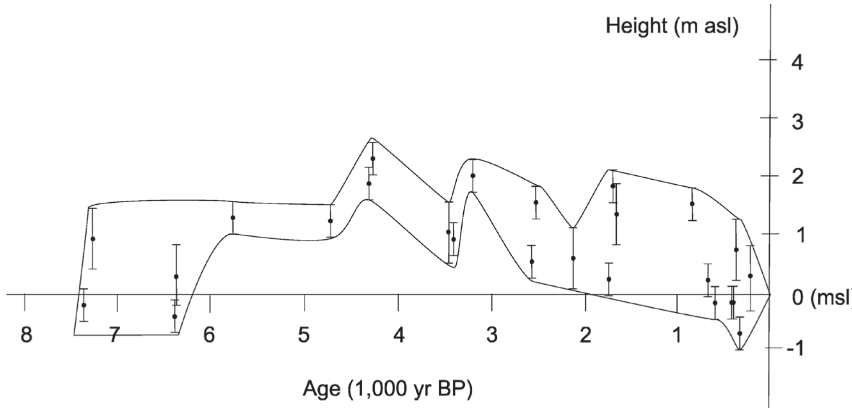
According to Laborel (1986), the vermetid gastropod is a stenohaline colonial and sessile animal, which occurs in tropical to subtropical open oceanic waters. It is found, for example, along the coasts of southern Italy and Sicily, as well as the coasts of the Middle East and Northern Africa. This vermetid has been observed in many areas along the Atlantic coast, including the coasts of Western Africa and Brazil. The shapes and sizes of the vermetid indicators are variable and depend on the substrate nature, as well as tides and surfs. Vermetid formations fossilize easily when raised above their normal growth level and are protected from rainfall, humic acids, and soils. However, when submerged in seawater, vermetid preservation is poor due to biological erosion.

Height measurements of vermetid remains should be made, when possible, in relation to the summit of the living vermetids on the present shore in the same area (Laborel, 1986). In tideless seas, and especially when the encrustations depend on erosional features, such as notches or marine platforms, this measurement represents an almost perfect past RSL indicator with errors as small as ± 0.1 m. However, in the mesotidal regime of the Pernambuco and Paraíba littoral zones, we adopted an error of ± 0.5 m — following Laborel (1979, 1986) —, which was observed at the walls of a granite at Gaibu beach in the south of Recife in our study area.

Table 1. Radiocarbon ages of the past relative sea level change proxy records from the Barra de Sagi (state of Paraíba) to São José da Coroa Grande (state of Pernambuco).

Sample	Laboratory number Beta	Sample height	RSL indicator/rock	$^{13}C/^{12}C$ ratio (‰)	^{14}C age (yr BP)	^{14}C calibrated age 2σ (yr BP)
PB2	190322	-0.08 ± 0.5	dab/br	-1.5	6,010 ± 50	6,530 – 6,300
PB3A	190323	0.72 ± 10	blp/pd	-2.1	580 ± 70	360
PB4	190324	0.72 ± 0.5	vm/br	+ 1.50	1,300 ± 50	940 – 730
PB13A	190325	0.6 ± 1.0	vm/bf	+1.9	2,460 ± 50	2,270 – 1,980
PB13B	190326	1.82 ± 1.0	wd/s	-26.8	1,770 ± 60	1,8440 – 1,540
PE1A	190327	1.06 ± 1.0	blp/pd	-3.1	3,580 ± 50	3,580 – 3,360
PE2A	190328	0.94 ± 0.5	vm/gr	+1.4	3,530 ± 50	3,530 – 3,320
PE2B	190329	1.87 ± 0.5	vm/gr	+1.6	4,240 ± 50	4,440 – 4,210
PE2C	190330	2.01 ± 0.5	vm/gr	+1.3	3,370 ± 70	3,380 – 3,040
PE5A	190331	-0.15 ± 0.5	vm/gr	+0.8	800 ± 50	510 – 320
PE5B	190332	1.55 ± 0.5	vm/gr	+1.1	2,820 ± 50	2,710 – 2,360
PE6	190333	2.3 ± 0.5	vm/gr	+1.5	4,210 ± 70	4,490 – 4,090
PE7B	190334	-0.65 ± 0.5	vm/gr	+1.9	660 ± 50	420 – 240
PE8A	190335	-0.15 ± 0.5	dab/br	-1.6	6,920 ± 100	7,580 – 7,250
PE8B	190336	-0.15 ± 0.5	vm/br	+2.0	760 ± 50	490 – 290
PE12	190337	1.25 ± 0.5	vm/vr	+2.5	4,640 ± 60	4,750 – 4,740 and 7,990 – 4,780
PE14A	190338	0.25 ± 0.5	vm/br	+1.7	2,160 ± 50	1,860 – 1,620
PE15A	190339	0.55 ± 0.5	dab/br	+1.6	2,850 ± 60	2,740 – 2,400
PE15B	190340	-0.25 ± 0.5	vm/br	+3.1	1,110 ± 50	740 – 610
PE18B	190342	1.35 ± 0.5	vm/br	+1.7	2,080 ± 60	1,810 – 1,520
PE21B	190344	0.15 ± 0.5	vm/br	+2.1	1,030 ± 50	670 – 520
PE26	190345	0.95 ± 1.0	dab/br	-0.3	6,780 ± 60	7,420 – 7,200
PE28	190346	0.3 ± 1.0	coral	-0.8	390 ± 50	420 – 340
SER	C1103	0.4 ± 1.0	dab/br	-0.5	6,120 ± 80	6,741 – 6,365
BV1	219202	1.24 ± 0.5	dab/br	+0.7	5,540 ± 40	5,900 – 5,710

dab: death assemblage of bivalve shells; br: beachrock; blp: bivalve shell in living position; pd: peat deposit; vm: vermetid; bf: Barreiras Formation; wd: wood fragment; s: sand; gr: granite; vr: volcanic rock; RSL: relative sea level.



asl: above sea level; msl: mean sea level.

Figure 2. Curve of relative sea level change for the states of Pernambuco and Paraíba. We assume the age error as the intercept medium at 2 σ.

Paleomangroves as a past relative sea level indicator

Mangrove swamps are formed in the vicinity of fluvial mouths in the coastal zones of tropical climates. The relationship between paleomangrove deposits and RSL change was determined by Schaeffer-Novelli et al. (1990), who proposed a complex interplay among type, size, and frequency of occurrence of available mangrove landforms as a function of the particular mix of fluvial, tidal, and wave energies in a region. Mangroves in the study area fall in the segment V proposed by these authors, where mangroves develop in protected areas in association with many estuaries and some coastal lagoons due to high wave energy of the coast.

In the study area, the mangrove phytophysiognomy is characterized by the presence of halophilous plants of the genus *Avicennia*, *Laguncularia*, and *Rhizophora*, as well as equally halophilous grasses, such as *Spartina*. This ecosystem also provides shelter for plentiful fauna, including several species of crustaceans, mollusks, and fish. We collected two samples of mollusk shells in living positions (PB3A and PE1A) from peat deposits in a paleomangrove.

LAGOA OLHOS D'ÁGUA SEDIMENT CORE

We drilled a core in the Lagoa Olhos d'Água (state of Pernambuco) in order to study the diatomological and palynological contents of the sediments. This lagoon represents a small connection to the open sea and is close to a nearby wave-built terrace. This small lake represents a residual feature of a lagoon that existed during the positive Holocene sea level fluctuation, but is presently almost isolated from the open ocean.

Microorganisms as past relative sea level indicators

Microorganisms represented by foraminifera, diatom, and ostracode have been proposed as RSL indicators (Scott and Medioli, 1986). Some of these indicators, such as the diatoms from the Tokyo Bay estuary (Kanto Coastal Plain) in Japan, have been used as RSL indicators to reconstruct the paleoenvironment of the earlier Jomon Period (Japanese Prehistory) (Kosugi et al., 1989).

A few studies have used microorganisms to reconstruct the RSL change along the littoral zone of Brazil. A study by Medeanic et al. (2009) used palynomorphs and diatoms to characterize the Holocene marine transgression in the coastal area of southern Brazil. More recently, Medeiros (2010), Santos (2010), and Vilela (2010) carried out an integrated study that analyzed palynomorphs and siliceous microorganisms (*i.e.*, silicoflagellates, marine sponge spicules, and diatom frustules) in core sediments from a littoral zone in southern Brazil. They described a 5.79 m long sediment core with a basal age of 9,400 cal yr BP. The site was previously described as a paleolagoonal deposit by Suguio (2004). The results of these studies in southeastern Brazil are in agreement with a RSL culmination stage at about 5,100 Cal yr BP, followed by a brief drop phase at about 4,000 cal yr BP, a new rise in RSL, and finally a gradual decrease towards the present day, as already proposed by Suguio et al. (1985).

The basic prerequisite that allows for a profitable employment of microorganisms as RSL indicators is that they are contained within sediments deposited in estuarine brackishwater such as in lagoonal environments. Therefore, their restricted and variable communication channel with the open sea could have been completely interrupted or very well established, according to RSL drop and rise, respectively. As a consequence, the microorganism species that lived within the paleolagoonal environment could have been changed alternatively from freshwater to blackish-water. Careful analyses of such records can become more efficient for RSL reconstructions than surface proxy records (*i.e.*, beachrocks and gastropode vermetid encrustations), particularly for mesotidal to macrotidal regimes, such as the one in northeastern Brazil.

Lithology and chronology of the Olhos d'Água Lagoon core

The 2.66 m long sediment core from the Lagoa Olhos d'Água is composed of the following sediments from bottom to top: clayey medium sand (2.66 – 2.33 m), organic brownish clay with plant fragments (2.33 – 1.81 m), peat with shell debris (1.81 – 1.71 m), black clay with scattered plant fragments (1.71 – 1.54 m), grayish green clay with disperse shell debris (1.54 – 0.84 m), grayish green clay (0.84 – 0.65 m), grayish green clay with shell debris (0.65 – 0.64 m), grayish green clay (0.64 – 0.28 m), grayish green clay with debris (0.28 – 0.25 m), grayish green clay (0.25 – 0.15 m), and organic clay with plant fragments (0.15 – 0.0 m) (Figure 3). The radiocarbon dates of this core are presented in Table 2.

Microbiological relative sea level indicators in the Lagoa Olhos d'Água sediments

We used diatoms as sea level indicators. Diatoms are excellent indicators of former sea levels in Quaternary studies worldwide (Horton and Sawai, 2010) and its use in association with pollen and spore grains have been employed by Castro et al. (2013) to determine Quaternary sea level changes in Amazonian coast and by Amaral et al. (2012) for southern Brazil whereas pollen, as the principal proxy, in studies of alternating sea level fluctuations are reported by Haberle (1997) in the Amazon and by Behling et al. (2000) in northeastern Brazil. A more complete use of various microfossils, including pollen, spores, foraminifera and algal remains in reconstitution of paleoenvironments under the context of sea level change, is given by Jaramillo et al. (2010). These studies exemplify the generalized use of such microfossils as reliable proxies for the evaluation of past changes in former sea levels in Quaternary and Cenozoic studies.

The marine palynomorphs of the studied sediments are composed of dinoflagellate cysts and chitinous foraminiferan carapaces, whereas the continental palynomorphs

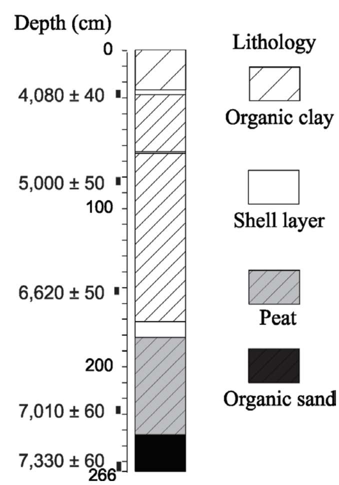


Figure 3. Sediments and ages of core from the Olhos d'Água Lagoon.

Table 2. Radiocarbon ages of sediments from Olhos d'Água Lagoon.

Sample	Laboratory number Beta	Dated sediment	Borehole interval (m)	$^{13}C/^{12}C$ ratio (‰)	Conventional age (yr BP)	^{14}C calibrated age 2σ (yr BP)
LAGOA 3MC 87.5-94.5CM	190321	Organic clay	2.60 – 2.66	-26.5	7,330 ± 60	8,300 – 8,260; 8,210 – 8,000
LAGOA 3MC 54-59CM	190320	Gray organic clay	2.25 – 2.30	-26.6	7,010 ± 60	7,950 – 7,700
LAGOA 2MC 65-70CM	190319	Black organic clay	1.49 – 1.54	-24.9	6,620 ± 50	7,580 – 7,430
LAGOA 1MC 80-84.5CM	190318	Gray organic clay	0.80 – 0.84	-23.5	5,000 ± 50	5,900 – 5,610
LAGOA 1MC 25-30CM	190317	Gray organic clay	0.25 – 0.30	-23.8	4,080 ± 40	4,810 – 4,760; 4,700 – 4,670; 4,650 – 4,440

are represented by *Polypodium* (fern spore), pollen grains belonging to *Poaceae* (mainly terrestrial herbs), *Cyperaceae* (mainly aquatics), *Arecaceae* (palms), *Ilex* (arboreal), *Tapirira* (arboreal), *Melastomataceae* and *Combretaceae* (arboreal, possible of mangrove affinity) and *Rizophora* (mangrove tree). In general, all samples were poor in pollen, with their lowest concentrations, while marine diatoms were abundant. On the other hand, when the diatom frustules were abundant throughout the core, they were represented by a total of 93 taxa, of which 50 were predominantly marine, 39 were of freshwater, and only 4 were typical of brackish waters (Figures 4 and 5).

Concentration values of biological indicators (*i.e.*, palynomorph and diatom categories) of the Olhos d'Água sediment core were grouped into five zones (Figure 4). Zone 1 is comprised of peat-like sediments that were deposited from 8,210 – 7,770 cal yr BP. This zone exhibits a predominance of arboreal pollen taxa in its lower part (ca. 1,500 grains/cm^3). This frequency gradually decreases towards the end of the zone. There is a significant contribution of pollen grains belonging to freshwater aquatic and terrestrial herbs, synchronously with a high concentration of arboreal pollen stand. During the decreasing phase of the arboreal pollen contribution, *Rhizophora* pollen and chitinous foraminiferan carapaces gradually increase in the sediments.

Zone 2 differs from Zone 1 in its fluctuating low concentration of pollen grains associated with an increasing number of microscopic chitinous foraminiferan caparaces, the return of aquatic and terrestrial herbs, and a slight decrease in *Rhizophora* pollen concentration. Zone 2 (ca. 7,770 – 7,430 cal yr BP) indicates the onset of marine diatom deposition in the Lagoa Olhos d'Água at ca. 7,650 cal. yr BP (Figure 4).

Zone 3 (7,580 – 7,430 cal yr BP to 5,049 cal yr BP) is distinguished from Zone 2 by the disappearance of all pollen categories and an increase in the concentration and percentage of marine microfossils, especially diatoms and chitinous foraminiferans. In this zone, arboreal and terrestrial herbpollen reach their lowest levels, whereas marine diatom frustules attain their highest concentration at 5,990 – 5,610 cal yr BP (Figure 4).

Zone 4 (ca 5,049 to 4,650 – 4,440 cal yr BP) marks the decline of marine diatoms, which started to decrease at the end of Zone 3. The boundary between Zones 3 and 4 is marked by a general decrease in the concentration of all palynomorphs (Figure 4).

In Zone 5 (4,650 – 4,440 to present), all palynomorph categories, which were previously found in low concentrations, reappear with significant importance (*e.g.*, *Rhizophora* and chitirous foraminifera carapaces), and attain their highest values in the entire sediment sequence. A trend towards a marine diatom maximum concentration is attained at the end of this zone at 4,650 – 4,440 cal yr BP. This zone differs from the previous zones in the significant increase in freshwater diatoms, as well as in the arboreal, herb, and *Rhizophora* pollen, and the complete absence of marine diatom frustules. The absence of radiocarbon dating at the top of the core and the low sedimentation rate of this zone make the topmost age unclear (Figure 4).

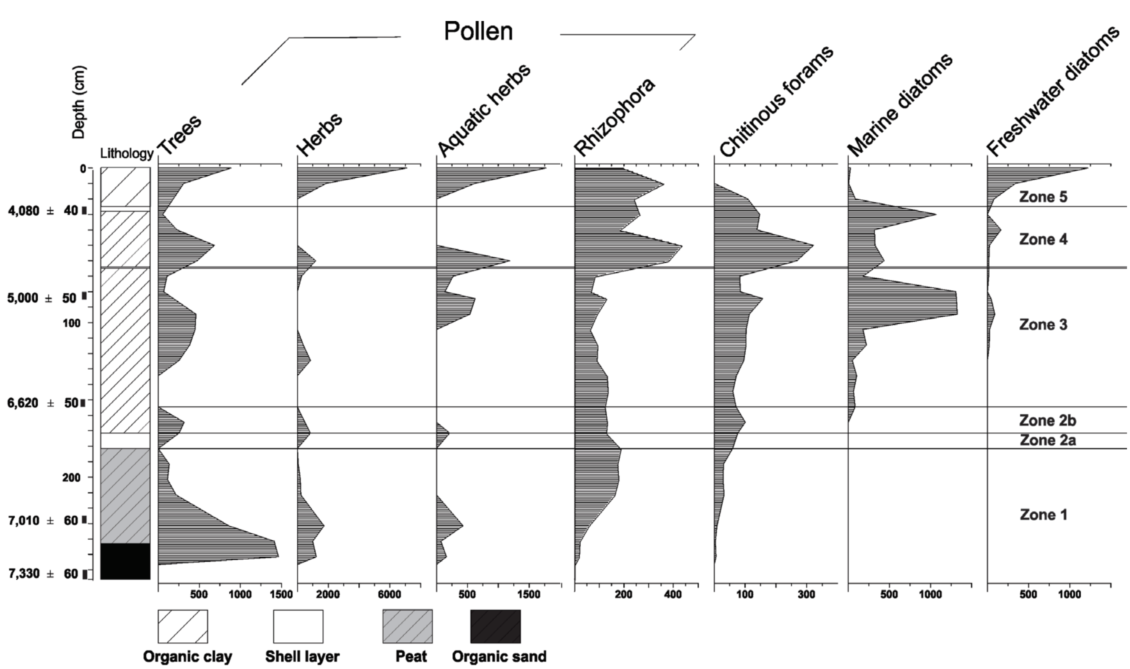


Figure 4. Microorganism concentration in the Olhos d'Água core.

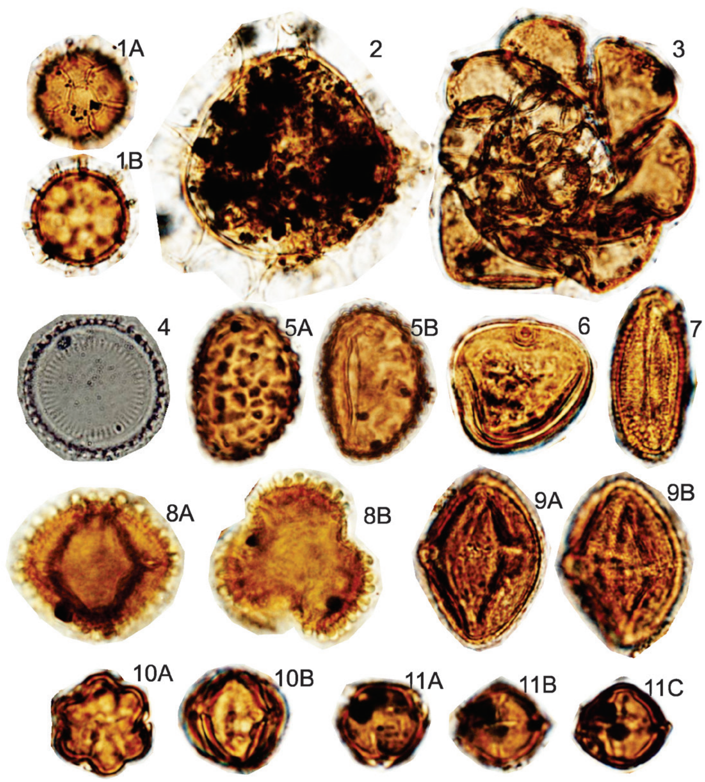


Figure 5. (1A and 1B; 2) Diniflagellate; (3) Foraminifera; (4) Diatom; (5A and 5B) Pollen/spor – Polypodiaceae; (6) Poaceae (Gramineae); (7) Arecaceae (Palmae); (8A and 8B) Aquifoliaceae; (9A and 9B) Anacardiaceae; (10A and 10B) Melastomataceae/Combretaceae; (11A, 11B, and 11C) Rhizophoraceae.

DISCUSSION

The first RSL change curves based on three types of proxy records (*i.e.*, geological-geomorphological, biological, and prehistorical) for a coast less than 100 km long was presented for the state of São Paulo by Martin and Suguio (1975), Martin et al. (1986), Suguio et al. (1980, 1985). Our use of sea level indicators is mainly based on two studies, as follows. First, the study by Martin et al. (1986) recognized the existence of at least three kinds of sea level indicators along the Brazilian coast: geological-geomorphological, biological, and prehistorical. This study also established the basic criteria for using these sea level indicators. Second, the study by Scott and Medioli (1986) listed and characterized in detail 16 RSL change proxy records, 6 of which were geological-geomorphological, 9 were biological, and 1 was prehistoric (shell-middens). Among the past RSL surface proxy records used here, there are some geological and/or geomorphological records (*i.e.*, beachrocks, paleomangrove deposits, and wave-built terraces), but the diatoms and palynomorphs in the drilled core, as well as the vermetid gastropods, bivalve, and other mollusk shells collected from outcrops, are of biological nature.

As previously reported by Dominguez et al. (1990), the Pernambuco coast in the southern part of the study area was subjected to a RSL rise in the Holocene, which was mainly caused, among other factors, by the global warming in the hypsithermal age, also referred to in Suguio (2001). The consequent wave-built terrace was formed by a transition followed by a regression, which supplied an indicator of RSL as dated by the sample PB18B (Table 1). The age of only about 1,770 ± 60 cal yr BP obtained here corresponds to the late regressive phase, and the RSL attained after a previous culmination stage was about 3 m above the present level. The envelope curve for the states of Pernambuco and Paraíba presented here is also well correlated with the envelope curves for the same time interval as previously obtained by Bezerra et al. (2003).

Data from the lagoon core also point to sea level oscillations. The palynomorph concentration diagram (Figure 4) obtained from the Lagoa Olhos d'Água sediment core suggests that a series of RSL changes occurred in the study area during the Holocene. From ca. 8,200 – 7,700 cal yr BP, this site was dominated by a tropical forest with adjoining mangrove swamps, as explained by the lowered RSL, which was rapidly rising. This conclusion is also suggested by the decrease in the arboreal plant and the synchronous increase in mangrove forest pollen as represented by *Rhizophora* and foraminiferan carapaces.

It is likely that the presence of certain marine microscopic subfossils of Zone 1 reflected some marine influence, even in brackish water, as also suggested by the bivalve mollusk shell remains within Zone 2. On the other hand, the lack of marine diatoms within Zone 1 can be explained by the considerable distance (at least a few kilometers) from the coastline, which prevented a marine diatom frustules contribution even during sea storms. Noticeable forest retreat favored a substantial expansion of the local mangrove at the end of Zone 1, which is supported not only by palynomorph evidence, but also by the gradual increase in frequency of the foraminiferan carapaces.

The almost mirror-like image of the increasing foraminiferan carapaces and the decreasing *Rhizophora* pollen frequencies (Figure 4) suggest an enhanced RSL rise, which culminated in the deposition of abundant marine diatom frustules at about 5,900 – 5,610 cal yr BP. This approximately coincides with the Holocene RSL culmination stage in other areas along the Brazilian coast. During this phase, the RSL was at least 2 m above the current level at this site.

Since the onset of the marine diatom deposition within the sediments, the continuous and gradual decrease of the *Rhizophora* pollen is counteracted by the approaching forest vegetation until ca. 5,600 cal yr BP, when the marine diatom frequency reaches its maximum and arboreal plant pollen exhibits low values. This can be easily explained by the probable removal by tides, which can wash them out with the rhythmic changes in the water levels. Based on the marine diatom frequencies, a second significant and rapid RSL rise is identified at ca. 4,600 – 4,400 cal yr BP at the transition from Zone 4 to 5, followed by a sudden decline, in agreement with the Salvador (Bahia state) curve (Suguio et al., 1985).

Freshwater diatom frustules dominate the sediments from 4,650 – 4,440 cal yr BP, suggesting a receding coastline that was gradually covered by forest vegetation and mangroves. The complete absence of marine diatoms in the sediments deposited after ca. 4,000 cal yr BP, as represented by Zone 5, is also in agreement with the tendency estimated by the Salvador curve. The last zone indicates that the present conditions, with a complete absence of marine sediments, are dominated by tropical forest vegetation with a marginal mangrove.

The envelope RSL change curve observed in this study area attained the current level, for the first time between ca. 7,600 – 7,500 cal yr BP, whose culmination stage of about 3 m above the present one was reached between 4,000 – 5,000 cal yr BP. The RSL drop after the culmination stage until the current level occurred gradually and was probably interrupted by some fluctuations, mainly indicated by the oscillations in frequencies of microscopic marine and freshwater organisms, here identified within a paleolagoonal sediment core. Nevertheless, the results of the surface (beachrock and vermetid encrustations) and subsurface (microscopic biological remains) proxy records do not perfectly correlate with one another. However, their results are perfectly complementary, and an adequate combination of the two is necessary to gain a better idea about the local RSL change during the Holocene.

CONCLUSION

This study presents 25 uplifted proxy records collected along the coastal area and diatomological and palynological analysis of a drilling core from a lake along in the states of Pernambuco and Paraíba. The RSL curve obtained from sea level indicators along the coast indicates that sea level reached the current level at ~7,400 cal yr BP. A sea level culmination of ~ 3 m above sea level was attained between 4,000 – 5,000 cal yr BP. Sea level dropped until the present after that culmination, with possible phases of slight oscillations. These oscillations are consistent with microscopic marine and freshwater organisms in the sediment core of the Olhos d'Água Lagoon (southeastern Recife, Pernambuco state). However, the data of the beachrock and vermetid encrustations do not perfectly correlate with data from subsurface (microscopic biological remains) proxy records.

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