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HOLOCENE EVOLUTION OF A WAVE-DOMINATED BARRIER-LAGOON SYSTEM IN RIO DE JANEIRO, BRAZIL

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ABSTRACT. In a wave-dominated coast, most of the Jacarepaguá coastal plain is occupied by buildings. During a new construction in this region at Barra da Tijuca, the subsurface area was excavated, exposing its quartzose sand nature, with a high mollusk shell concentration and in situ echinoderms at –10 m depth. The possibility to access this area encouraged us to investigate the evolution of the coastal plain. A 7.84-m-long core was recovered by percussion drilling. Stratigraphic, grain size, and geochemical analysis were undertaken. Three carbonate samples were dated by radiocarbon accelerator mass spectrometry (^{14}C AMS). The revised sea-level variation curve revealed that the last postglacial marine transgression reached the present mean sea-level at 7945–7500 cal BP. The sandy deposit bottom was an ancient shoreface, with in situ echinoderms buried at 7770–7540 cal BP by the Pleistocene inner barrier reworking due to the last marine transgression. The Holocene outer barrier-lagoon and its flood tidal delta were formed from 5440–5070 cal BP. Mid-Holocene marine regression allowed the outer barrier progradation and the lagoon shallowing/infill. This paper confirms prior models proposed by other researchers for the Rio de Janeiro central coast and shows its similarity with the New South Wales coast, Australia.

KEYWORDS: Barra da Tijuca, coastal barriers, Jacarepaguá coastal plain, paleoenvironmental reconstruction, relative sea-level variations.

INTRODUCTION

Geological heritage, relative sea-level variations, and climatic changes determine topography, coastal orientation, sediment production and availability, and accommodation space, as well as wind, wave, and coastal currents (Murray-Wallace and Woodroffe 2014; Khan et al. 2015). The balance among these factors establishes the evolution of coastal systems. In densely urbanized coastal areas, human interventions interfere with the landscape evolution by altering the sedimentation conditions from the source to the depositional environments. In beach systems, permanent buildings and engineering works prevent the natural mobility of the sediments, which intensifies erosion, making it difficult to understand the past evolution and the current coastal processes.

The area of this study is situated at Barra da Tijuca, a highly urbanized location at the eastern end of Jacarepaguá coastal plain, in the city of Rio de Janeiro, southeastern Brazil (Figure 1). The coastal plain of Jacarepaguá has approximately 140 km^2, a coastline of 20 km, and exhibits a lagoon complex composed of Jacarepaguá, Tijuca, Camorim, and Marapendi lagoons (Figure 1). The studied site was a building construction site approximately 700 m from the

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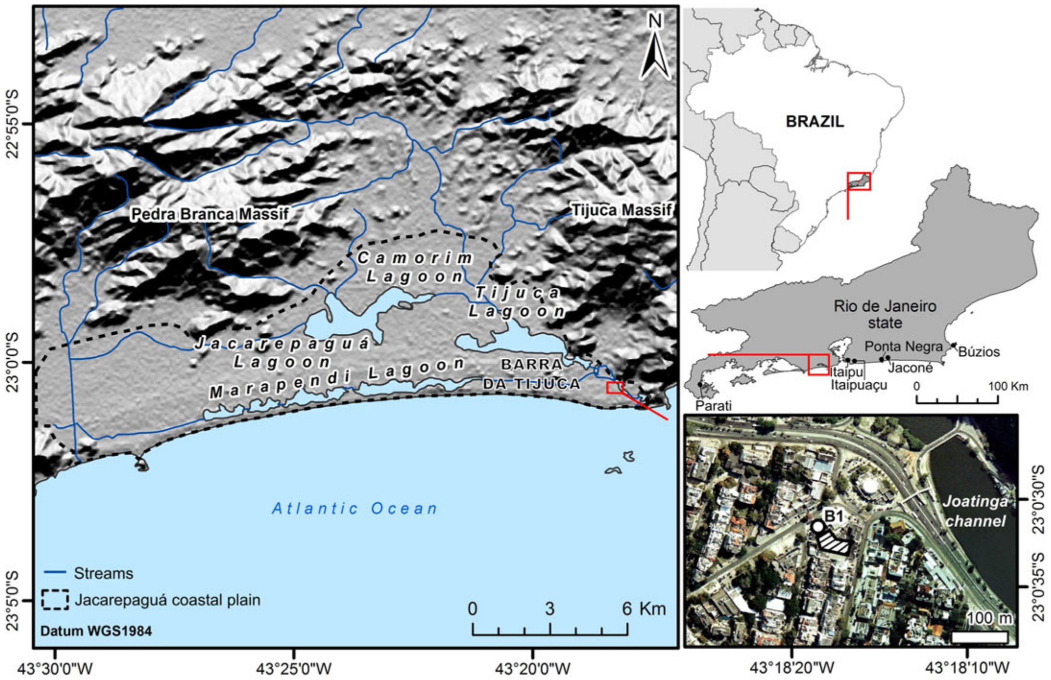

Figure 1 Jacarepaguá coastal plain, with the location of the study site (at Barra da Tijuca), indicated in the insert, at right-hand below, by the circle B1 (drilling) and the hatched polygon (excavated area for the construction of the commercial building). Hillshade terrain from SRTM/USGS/TOPODATA (Valeriano 2008). Ortho-photo from IBGE (the Brazilian Institute of Geography and Statistics).

current coastline and 200 m from the Joatinga channel, which connects the Tijuca lagoon with the sea.

By acknowledging prior studies developed in the region and at the Australian coast, the objective of the present work is to contribute to the knowledge of the evolution of the wave-dominated barrier-lagoon systems associated with the relative sea-level variations. Analyses were performed on sediment samples collected after a percussion drilling in the area next to the construction site.

Previous geotechnical studies for the construction indicated that the groundwater level was approximately 2.7 m below the surface. To permit excavation to a 10-m depth for foundation construction, it was essential to build an underground containment wall around the entire area of 2500 m^2 and drain it using hydraulic pumps before executing the excavation. This prevented the analysis of stratigraphy in profile, but traces of a 30-cm-thick muddy sediment horizon remained in place attached to the wall, at –6.3 m. Moreover, at the bottom of the excavation (at –10 m), a sandy-quartz deposit was exposed with a great abundance of in situ mollusk shells and echinoderm specimens of “sand dollars”. It was possible to recover a 7.84-m-long sediment core by percussion drilling. Three samples were dated by ^{14}C AMS. The core stratigraphy was analyzed for organic matter content (OM), calcium carbonate content ($CaCO_3$), and the physical characteristics of the sediment. Mollusk shells and echinoderm skeletons collected were also taxonomically identified.

BACKGROUND

Continental rifting and normal faulting (from Jurassic to Paleogene) controlled the development of Rio de Janeiro bedrock into a mountain range, coastal massifs and semi-grabens, all parallel to the coastline (Zalán and Oliveira 2005). This tectonic process was responsible for the settlement of the WSW-ENE regional drainage system that does not flow into the study area, but a few kilometers to the interior. According to Dias and Kjerfve (2009), the Jacarepaguá coastal plain is part of the geomorphologic unit classified as "the low-lying Fluminense sedimentary plain", characterized by the presence of several coastal lagoons. The river discharge and sediment input directly from the lagoons to the ocean are relatively low.

In the wave-dominated, microtidal Rio de Janeiro central coast, double transgressive barriers separate lagoons from the Atlantic Ocean (Dias and Kjerfve 2009). According to Turcq et al. (1999), the source of sand that formed the barriers, during the Upper Pleistocene and Holocene, was the shallow and low gradient continental shelf (maximum 0.2º, according to Reis et al. 2013; Dias et al. 2019). In the Jacarepaguá coastal plain, the inner barrier, which isolates the lagoons of Camorim, Jacarepaguá, and Tijuca, is 17.5 km long, 950 m wide to the west and 150 m wide to the east, 9.5 m high to the west, 11.5 m to the center and 8.5 m to the east. The outer barrier, which isolates the lagoon of Marapendi, is 18 km long, 300 m wide to the west, 20 m wide to the east, and its height varies from 4.5 to 6.5 m (Dias and Kjerfve 2009).

Roncarati and Neves (1976) presented a seminal model of the evolution of the Jacarepaguá coastal plain based on stratigraphy and geomorphology and assumed that the double transgressive barriers developed during the Holocene. They followed the hypothesis of Lamego (1945), based on Gilbert (1885), and argued that the lagoons would have been isolated by sand spits that migrated longitudinally at the coast by longshore currents transport, forming elongated barriers. Muehe and Correa (1989) opposed this model and agreed with Hoyt (1967), Schwartz (1971), Field and Duane (1976), stating that the prevalence of frontal waves leads to only moderate longshore currents, and the formation of lagoons on the back-barrier might be predominantly a consequence of landward beach migration caused by marine transgression.

Maia et al. (1984) suggested that the double barriers are transgressive features. However, based on radiocarbon (^{14}C) dating of surface lagoon samples and the oscillating Holocene relative sea-level curve developed by Martin et al. (1979), they proposed that the inner barrier formed between 7000 and 5100 BP and the outer barrier between 3800 and 3500 BP. These sea-level oscillations were later refuted by Angulo and Lessa (1997), Angulo et al. (2006), and Angulo et al. (2016), showing that from 4400 BP the sea-level was lowered to the present mean sea-level (PMSL) without the significant oscillations showed by Martin et al. (1979).

The model proposed by Turcq et al. (1999) is considered, in the present research, the most applicable to the current concepts and scientific knowledge, regarding the relative variations of sea-level during the Holocene for the southeastern Brazilian coast. Turcq et al. (1999) recognized that the inner barrier formed in the Upper Pleistocene as a result of the penultimate transgression of around 123,000 BP (based on analogy analysis of Th/U dating of corals found underlying a beach terrace at the eastern Brazilian coast by Martin et al. 1982). After carrying out ^{14}C dating, Turcq et al. (1999) showed that the outer barrier-lagoon system began to form in the Mid-Holocene, as a result of the most recent post-glacial marine transgression (PMT), between 7000 and 5000 BP. In the same direction, relied on diatoms analysis and ^{14}C dating from Itaipu and Ponta Negra lagoons, less than 70 km east of Barra da Tijuca (see Figure 1), Ireland (1987) had already concluded that the inner barrier-lagoon systems were formed in the Pleistocene and the outer was formed after about 7150 BP. These allowed the development of semi-enclosed coastal lagoons, connected to the sea through a single channel (Joatinga channel, at Barra da Tijuca), typical wave-dominated environments.

Muehe and Lins-de-Barros (2016) pointed out that during the penultimate transgression, the climate was similar to the current one and the sea-level reached between approximately +7 and +8 m (above PMSL), at the Rio de Janeiro state coast. According to Angulo et al. (2006), Muehe and Lins-de-Barros (2016), and Angulo et al. (2016), the most recent PMT surpassed the PMSL on the coast of Rio de Janeiro state ca. 7000 BP and reached the elevation between +3 to +4 m, within 5800 and 5000 BP. In the last 4400 cal BP the relative sea-level has dropped smoothly to the PMSL (Angulo et al. 2016).

The sea-level variation in the Rio de Janeiro coast during the Upper Pleistocene and Mid-Holocene is similar to the observed at the eastern and northeastern Australian coast, also on a relatively tectonically stable continental margin (Sloss et al. 2018). The geomorphological evolution of double transgressive barriers separated by lagoons is similarly described by Roy and Thom (1981) on the northern coast of New South Wales (NSW), Australia. The wave-dominated transgressive double barriers cut by the Joatinga channel also correspond to the barrier estuary described by Sloss et al. (2005) at Lake Illawarra (NSW), even though in that case the Pleistocene inner barrier was not preserved.

MATERIALS AND METHODS

Percussion drilling was performed in the area outside the building excavation at the coordinates 43°18′18.4"W/23°0′31.7"S (see Figure 1, insert), using a Rammkernsonden sampler (RKS). The position of the borehole and the terrain altimetry were obtained using a GNSS receiver (TechGeo GTR-G2), set to WGS 1984 datum. The altitude data were post-processed and corrected concerning the PMSL with the GTR Processor software and data from the Brazilian Network for Continuous Monitoring of GNSS (RBMC), provided by IBGE (Brazilian Institute of Geography and Statistics). The RBMC supports the Brazilian Geodetic System and defines the geodetic height at different locations considering a geoid model (MAPGEO2015), referenced to the Brazilian Vertical Datum (Imbituba) to determine the local PMSL (Fortes et al. 2009; IBGE 2010).

The recovered sections were photographed and visually described in the field before being sub-sampled. At the Laboratory of Sedimentology of Universidade Federal Fluminense, the steps for the analysis of the samples were: (i) lyophilization; (ii) quantification of OM by loss-on-ignition at 410°C for 16 hr, according to Schumacher (2002); (iii) quantification of $CaCO_3$ by weight difference after dissolution in hydrochloric acid (10% HCl), according to Gross (1971); (iv) grain size analysis and morphometry of sand samples with CAMSIZER particle analyzer (Retsch Technology) and mud samples with Mastersizer 2000 Hydro G (Malvern Instruments).

The CAMSIZER analyzer is convenient to characterize dry, free-flowing materials, by simultaneously measuring particle size and shape using dynamic image analysis. It optically measures grain sizes ranging from 20 µm (very coarse silt) to 30 mm (coarse gravel) using two CCD (charge-coupled device) cameras with 30 fps (60 images/s) and 1.3 Mpixel each, and a LED strobe light source. The Mastersizer 2000 Hydro G measures particles in suspension by laser diffraction, from clay (< 2 µm) to coarse sand (1 mm).

The distribution of grain size and sorting were obtained through the software Gradistat 8.0 (Blott and Pye 2001), which bases its statistics on Folk and Ward (1957). Sphericity and roundness of the sandy samples and the sandy fraction contained in the finer sediment samples measured by CAMSIZER (based on Krumbein 1941) were evaluated according to the standards published in Blott and Pye (2008).

Calcareous shells of mollusks were manually removed from the drilling sampler using sterilized tweezers and along with samples collected from the excavation site were taxonomically identified to support paleoenvironmental reconstruction. The scientific nomenclature has been updated according to the definitions of the WoRMS Editorial Board (2018). The shells and animal remains were photographed, and three samples were picked for dating by ^{14}C AMS. The material was prepared at the Radiocarbon Laboratory of Universidade Federal Fluminense (LAC-UFF) (Macario et al. 2013) and sent for measurement by accelerator mass spectrometry (AMS) to CAIS (Center for Applied Isotope Studies), University of Georgia, USA (Cherkinsky et al. 2010). For dating, the most intact samples were chosen to reflect the death of the organism in situ, ensuring that there was no considerable reworking. The sub-sampling procedure and pre-treatment were performed according to Macario et al. (2014). Sample preparation started with separation of ca. 30 mg of carbonate from individual shells and followed acid etching with 0.1M HCl until removal of 50% in mass. Samples were converted to carbon dioxide by acid hydrolysis by injecting 85% H_3PO_4 in evacuated vials. Gas samples were purified using cryogenic traps to remove water (dry ice/ethanol mixture) and segregate pure carbon dioxide, using liquid nitrogen. After being transferred and frozen into Pyrex tubes, these were individually torch sealed and heated in a muffle oven at 550°C. Graphite was formed over iron powder using the Zn/TiH_2 method (Xu et al. 2007; Macario et al. 2017).

The calibration of results was done using OxCal v4.3.1 (Bronk Ramsey 2017), with the Marine13 curve (Reimer et al. 2013), and taking into account the closest available local reservoir offset $\Delta R = 32 \pm 44$ ^{14}C yr (Alves et al. 2015), and 2 σ of error (95.4% reliability). Results are presented as calibrated age intervals. Previous published ^{14}C ages have also been analyzed (Ireland 1987; Mansur et al. 2011; Silva et al. 2014; Angulo et al. 2016; Jesus et al. 2017). For the discussion, all ^{14}C ages consulted in the literature had the calibration updated, except when the conventional ages were not published in the source.

RESULTS

The terrain altitude concerning the PMSL was measured at +1.953 m (±1.4 cm). A 7.84-m-long sediment core was recovered, but some intervals were lost during drilling (Figure 2). The quartzose sediment of the bottom of the excavation site (at –9 m) presented moderately well-sorted gravelly coarse sand with unimodal distribution, rounded grains, and high sphericity. The sediment taken from the base of the core, from –7.84 m up to –7.2 m, showed the predominance of moderately sorted fine sand, with unimodal distribution, sub-rounded to rounded, and high sphericity (Figure 2).

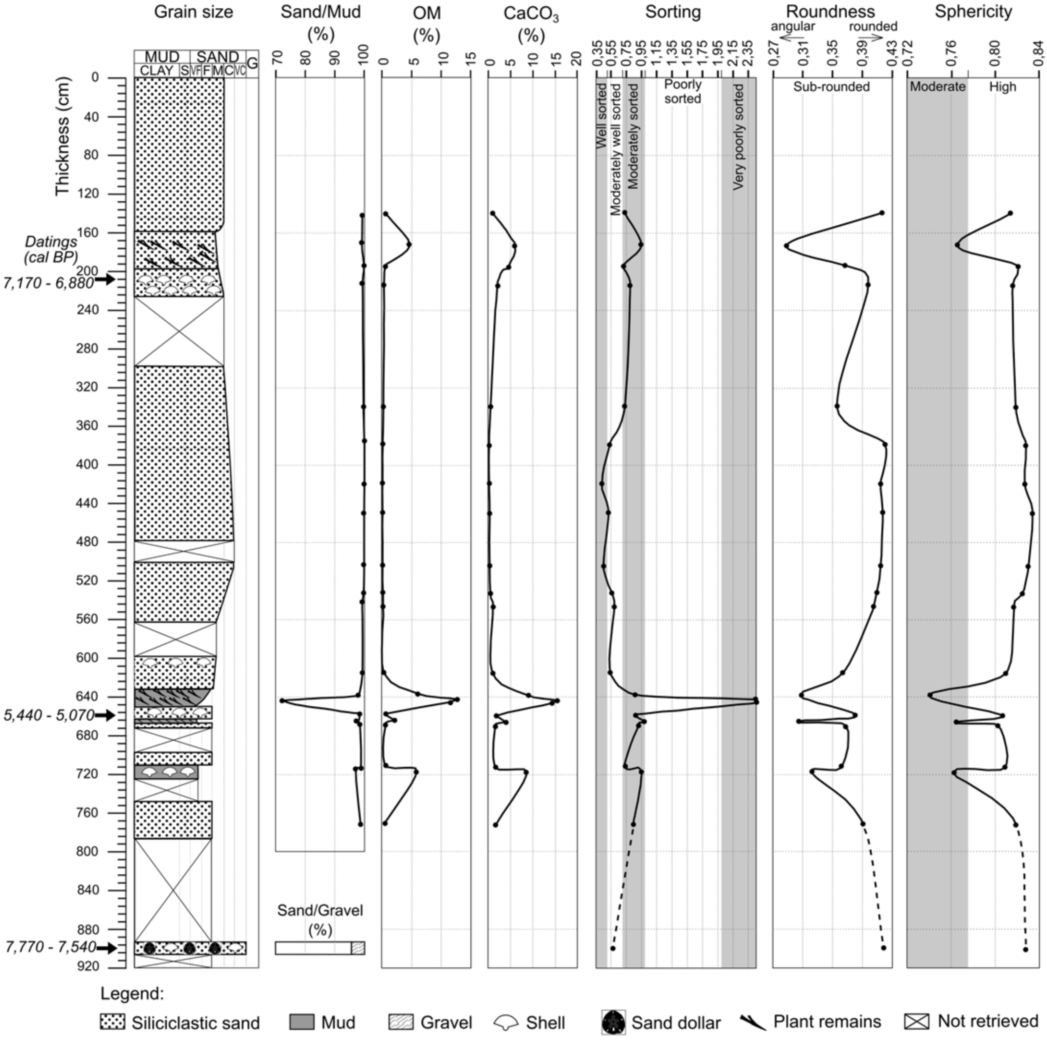

Figure 2 Profile of the core collected, with grain size distribution, organic matter (OM) and calcium carbonate ($CaCO_3$) contents, sorting, and shape parameters of sand fraction. On the left, the ^{14}C ages obtained are shown in the positions indicated by arrows (see Table 1). The data of the base at –9 m correspond to the sample collected at the bottom of the excavation site.

Two muddy layers were observed from –7.2 to –6.3 m interspersed with narrow fine sand intervals. The lower mud layer, at –7.2 m, is moderately sorted and contains shell fragments, while the upper mud layer, at –6.3 m, is very poorly sorted and contains plant traces. The lower layer has a smaller proportion of fine sediments in relation to sand and smaller content of OM and $CaCO_3$ (Figure 2). At –7.2 m, the muddy fraction is divided, on average, into 2.5% of silt and 0.5% of clay. At –6.3 m, this ratio is 26.3% of silt and 1.4% of clay. The sand roundness of the two layers does not differ considerably, being sub-rounded to angular. Even though both layers present moderate sand grain sphericity, the upper layer presents notable less spherical grains.

Table 1 ^{14}C ages of three samples from the study area. The first two were picked from the core and the third was obtained from an organism in living position (echinoderm) taken from the bottom of the excavation.

LAC-UFF lab code	CAIS lab code	Level relative to terrain (m)	Orthometric Altitude (m)	Sample	Conventional age (BP)	Calibrated age (cal BP)
170146	30431	–2.1	–0.15	*A. flexuosa*	6552 ± 28	7170–6880
170147	30432	–6.6	–4.65	*A. flexuosa*	4969 ± 29	5440–5070
170148	30433	–9	–7.05	*E. emarginata*	7205 ± 28	7770–7540

Above –6.3 m to the core top (at –1.4 m), the grain size becomes medium to coarse sand, with unimodal distribution. Between –6 and –3 m, the sandy layers presented the lowest OM and $CaCO_3$ content and the absence of stratification, plant traces, and shell fragments. Within this range, sands are coarser between –5.2 and –4.7 m, varying from medium to coarse. Between –6.15 and –3.8 m, the sands are well sorted, sub-rounded to rounded, and with high sphericity (Figure 2). From –1.2 m to the surface, a landfill and debris layer was present.

A fragment of bivalve shell from a sandy sample at –6.6 m was dated at 4969 ± 29 BP (5440–5070 cal BP). Another shell sample from –2.1 m was dated at 6552 ± 28 BP (7170–6880 cal BP), indicating an age inversion (Figure 2 and Table 1). In some sectors untouched by backhoes at the base of the excavation, there were concentrations of echinoderms *Encope emarginata* (sand dollars) in living position (Figure 3). Nine specimens of *Encope emarginata* were collected between –10 and –9 m. A skeleton sample collected at –9 m was dated at 7205 ± 28 BP (7770–7540 cal BP) (Table 1). Regarding the inconsistency of age inversion, it is considered that the dating of the echinoderm is reliable, due to the grouped skeletons found in living position. The same is attributed to the bivalve sample at –6.6 m due to the lateral continuity observed between the sediment core and the excavation site. The age obtained from the sample at –2.1 m is the only doubtful result.

In the excavation site, many well-preserved shells indicated that there was no intense reworking of the sediments, although articulated pairs of bivalve shells in living position were not found. Muddy sediments left traces of a dark grey layer adhered to the surface of the retaining wall at 6.3 m deep (Figure 4a), the same depth as the mud layers identified at the core. The abundance of mollusk shells was remarkable, predominantly between –10 and –9 m (Figures 4b and 4c). Twenty-two taxa of Bivalvia and Gastropoda classes (Table 2 and Figure 5) were identified, distinctive of the marine environment, basically of the beach, but with rocky shore contributors (gastropods).

DISCUSSION

Correlations with Holocene Paleo Sea-Levels on the Coast of Rio de Janeiro State

The benthic community of *Encope emarginata* found in living position between –9 and –10 m represents an indication of a pre-existing marine surface. Considering the ^{14}C age of 7770–7540 cal BP, it is necessary to infer the vertical position of these organisms to the paleo sea-level and consequently verify the correspondent paleoenvironment. For that, the Holocene sea-level oscillation on the coast of Rio de Janeiro state is described below, as retrieved from recently published literature.

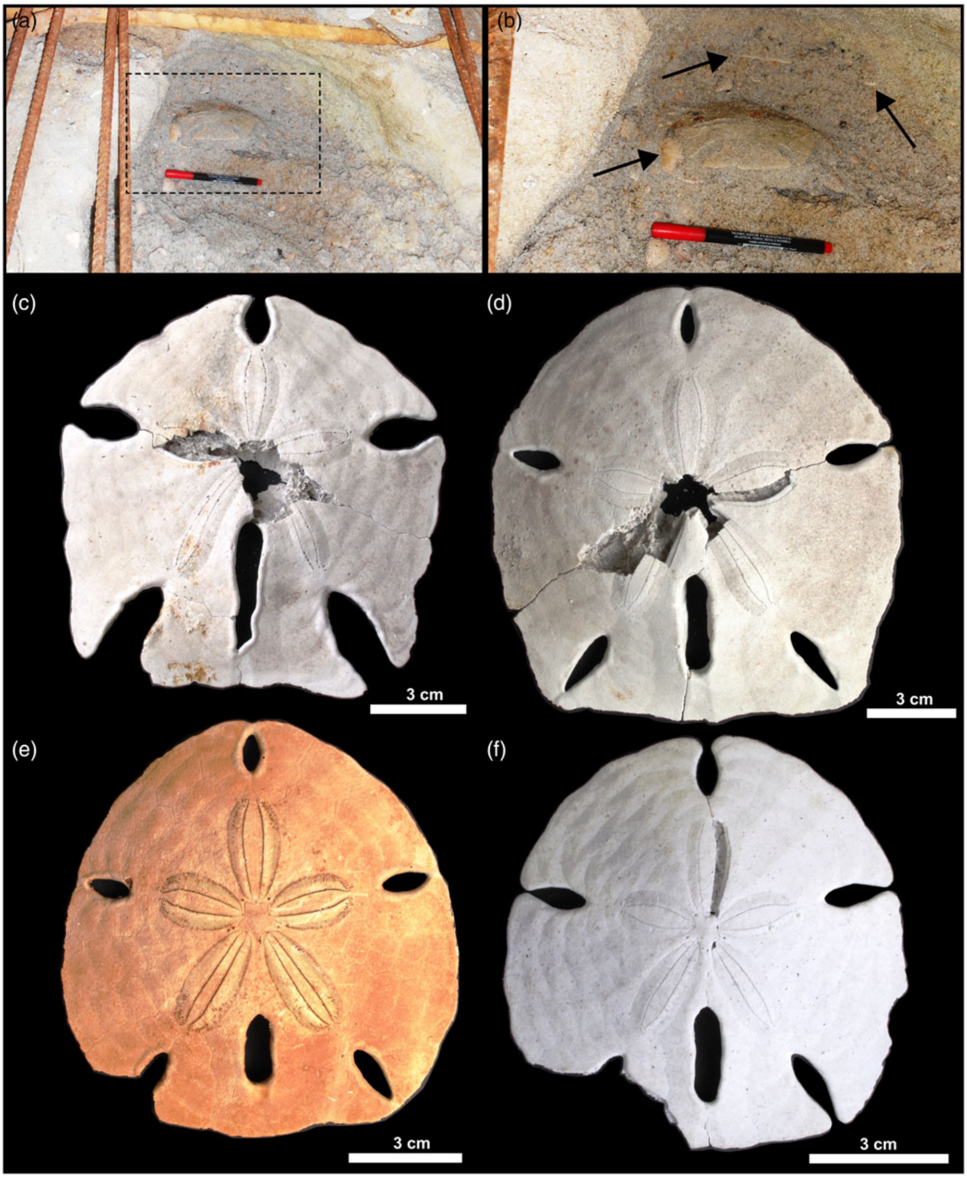

Figure 3 (a) and (b): Skeletons of *Encope emarginata* found in situ in living position; (c), (d), (e), and (f): Some of the specimens collected.

To establish when the relative sea-level during the last post-glacial marine transgression (PMT) crossed the present mean sea-level (PMSL) on the coast of Rio de Janeiro state, Angulo et al. (2016) considered the ^{14}C ages published by Mansur et al. (2011) in Jaconé, an area located only 70 km to the east of the study area (Figure 1). The ages presented were 9190 ± 30 BP and 7410 ± 30 BP, the first relative to shell samples and the second relative to carbonate cement of a mapped beach rock in the region. These ages were reported as calibrated respectively as 8198–7827 cal BP and 6008–5786 cal BP, but even though these calibrations

Figure 4 (a) Quartzose sand intercalated by a dark muddy layer (indicated by red arrows) that left traces in place on the surface of the retaining wall, at 6.3 m depth underground. (b) and (c) Shells found on the excavation site between –10 and –9 m. Photographs kindly provided by engineer Roberto Almeida.

were expressed in cal BP, the values correspond in fact to AD/BC years. In the present study, after recalculating the calibrations, the results found were 10,134–9874 cal BP and 7945–7795 cal BP.

Regarding the beach rocks as indicators of paleo sea-levels, Angulo et al. (2016) pointed out that the shells that compose them may be older than the rock formation and thus the dating can indicate only a maximum age. For this reason, the dating of the carbonate cement obtained by Mansur et al. (2011) is more reliable to compute the age of the beach rock formation itself and therefore designate a more consistent paleo sea-level. So here we used the recalibrated carbonate cement age in our sea-level curve (Figure 6).

Angulo et al. (2016) emphasized that the reconstruction of paleo sea-levels for the coast of Rio de Janeiro state using vermetids and barnacles (*Tetraclita stalactifera*) from the southern coast (from Parati to Búzios; see location in Figure 1) is compatible with the geophysical model of glacial isostatic adjustment proposed by Milne et al. (2005) for the same region. Angulo et al. (2016) gathered data of several authors (Delibrias and Laborel 1969; Laborel 1969; Martin and Suguio 1978; Martin et al. 1979; Martin et al. 1979/80; Martin and Suguio 1989; Martin et al. 1997; Angulo et al. 2006), with ages ranging from about 4700 cal BP to the present, showing a

Table 2 List of taxonomic identification of shells (see Figure 5).

Number in Figure 6	Scientific nomenclature
1	*Anadara notabilis*
2	*Anomalocardia flexuosa*
3	*Bulla occidentalis*
4	*Cerithium atratum*
5	*Codakia* sp
6	*Monoplex parthenopeus*
7	*Divalinga quadrisulcata*
8	*Donax hanleyanus*
9	Unidentified gastropod
10	*Iphigenia brasiliensis*
11	*Phacoides pectinatus*
12	Lucinidae (family)
13	*Natica livida*
14	*Neritina virginea*
15	*Ostrea* sp.
16	Ostreidae
17	*Pitar* sp.
18	*Stramonita brasiliensis*
19	*Tagelus plebeius*
20	*Tellina* sp.
21	*Dallocardia muricata*
22	*Venus* spp. (family Veneridae)

decline in relative sea-level in this period from +3.0 ± 1.0 m to the PMSL. These data were also used by Milne et al. (2005) to validate their models with the peat samples dated by Ireland (1987).

Using the same approach, a data compilation of Ireland (1987), Mansur et al. (2011) and Angulo et al. (2016) were superimposed on the models of Milne et al. (2005) (Figure 6). Other data obtained in the literature were added, such as:

(i) Silva et al. (2014), related to the formation of Itaipuaçu beach rock (see location in Figure 1), with ^{14}C age of 8110 ± 30 BP (8682–8400 cal BP), placing the beach position at the time between –5 and –7 m depth (below PMSL);

(ii) Jesus et al. (2017), with seven samples of vermetids collected in the region of Búzios between +0.243 ± 0.5 m and +1.622 ± 1.0 m, dated from 1397 ± 81 BP (1137–752 cal BP) to 3139 ± 64 BP (3097–2753 cal BP), indicating higher past sea-levels.

The ^{14}C-dated beach rocks and vermetids are indicative of paleo-shoreline positions and are used here to reconstruct sea-level variation. Figure 6 shows that the age of the Jaconé beach rock carbonate cement (Mansur et al. 2011) conforms to the geophysical modelling of Milne et al. (2005), while the shells age of the same beach rock departs considerably from the model. The age of the Itaipuaçu beach rock (Silva et al. 2014), although it was obtained from the dating of a shell sample, is also consistent with the curve of Milne et al. (2005).

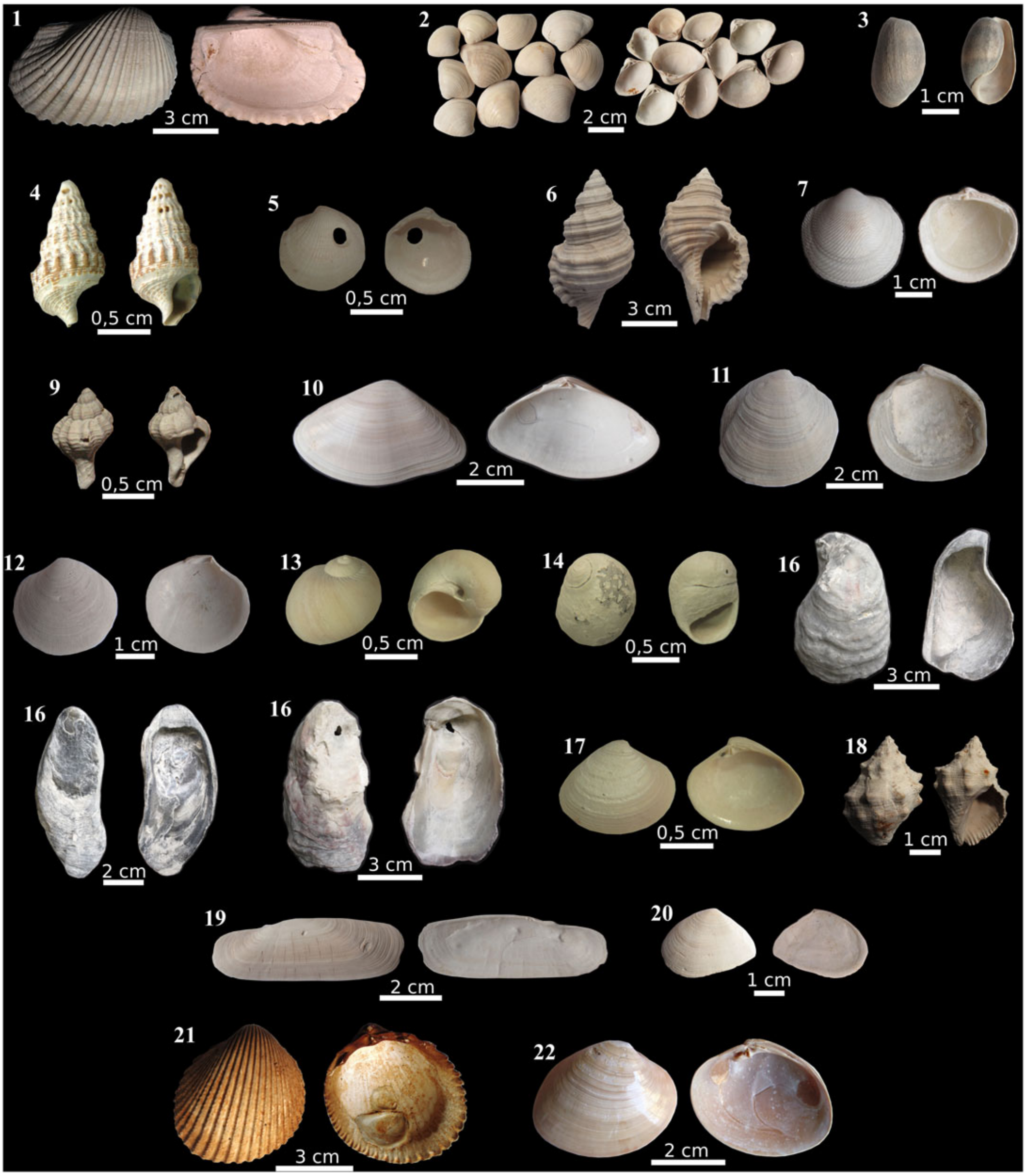

Figure 5 Photographs of mollusk shells collected (identified in Table 2). The photographs of the bivalves show the external and internal faces of the same valve.

The relative sea-level variation at the end of the most recent PMT on the coast of Rio de Janeiro state is well delineated, with a good correlation with the geophysical models of Milne et al. (2005) and the paleo level indicators used here. Thus, we argue that the age of Jaconé beach rock cement (Mansur et al. 2011) and the model by Milne et al. (2005) represent the best parameters to infer the interval in which, during the last PMT, the relative sea-level crossed the PMSL on the coast of Rio de Janeiro state: between 7945 cal BP and approximately 7500 cal BP.

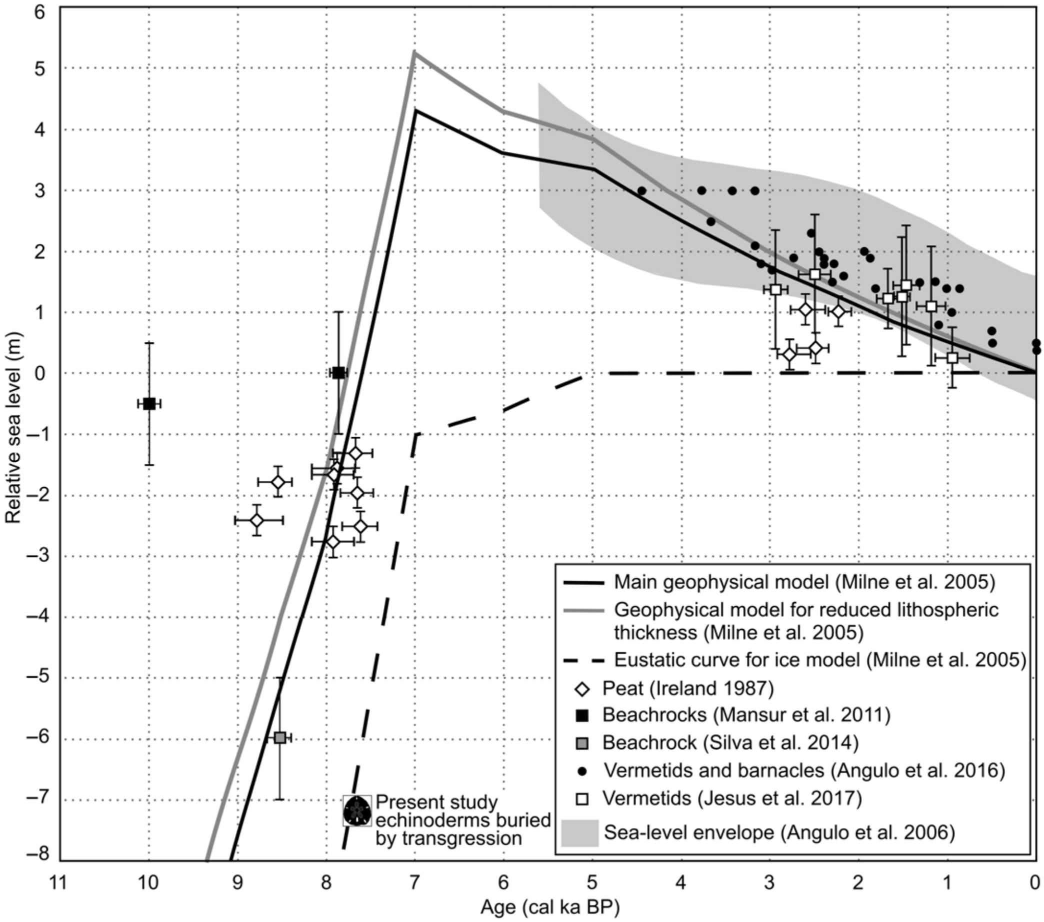

Figure 6 Revised variation curves of relative sea-level and paleo sea-level indicators exclusively for the coast of Rio de Janeiro state in the last 10,000 cal BP, compiled from Ireland (1987), Milne et al. (2005), Mansur et al. (2011), Silva et al. (2014), Angulo et al. (2016), and Jesus et al. (2017). Present study echinoderms (sand dollars) buried by transgression must have lived under a water depth of about 7–8 m.

Correlating the calibrated age of the echinoderms (7770–7540 cal BP) with the curve shown in Figure 6, it is reasonable to state that the relative paleo sea-level was at that time equal to or very close to PMSL (0 m). The sand dollars are positioned between approximately –7 and –8 m below PMSL, which means they must have lived under a water depth of about 7–8 m, consistent with the environment where they are found today, from the intertidal to the subtidal zone, on sandy substrate. Therefore, it is interpreted that during a fast Holocene marine transgression, the sand dollars colonized the substrate on a shoreface environment. Roncarati and Neves (1976) recognized a correlated subsurface deposit in the center of the coastal plain between –9 and –11 m, levels compatible with the drilling and excavation analyzed in this research.

Interpretations of Stratigraphy Observed

Based on the model of Turcq et al. (1999), it is interpreted that at the end of the most recent PMT (Figure 7c), when the relative sea-level exceeded the current level (PMSL), the Pleistocene inner barrier was partially reworked, leading to deposition of sand on the ancient shoreface. It is estimated that this stage promoted the burial of the echinoderms (Figures 3 and 6) and accumulation of almost 1.8 m thick of fine sand rich in shells of bivalves and gastropods (Figure 2). The occurrence of bivalves, mainly *Anomalocardia flexuosa* and *Anadara notabilis*, is indicative of the establishment of transgressive estuarine sand flats, analogously to the observations by Sloss et al. (2005) in Lake Illawarra (NSW, Australia) regarding the occurrence of *Anadara trapezia* and *Ostrea angasi*.

According to Turcq et al. (1999), after the drowning of the Pleistocene coastal plain, during the Holocene transgression, the outer barrier and the paleo-lagoon of Marapendi developed (Figure 7d). In this period, the marine dynamics ceased to act in isolation in the studied area, and the estuarine/lagoon dynamics began to prevail. The first indication of this phase in the analyzed core is the muddy-sand layer at –7.2 m. The increase of OM and $CaCO_3$ content is consistent with an environment subject to lower hydrodynamic energy, but with a connection to the sea. The reduced sorting and the less rounded sand grains with moderate sphericity indicate decreased reworking, determining the characteristics of a lagoonal/estuary environment, where the sea waves do not act directly on the sediments. The ^{14}C age of 5440–5070 cal BP, obtained from a sample collected at –6.6 m, demonstrates that the outer barrier-lagoon system began to form before this age, corroborating with the model of Turcq et al. (1999) and with data from Ireland (1987), less than 70 km east of the study area.

The stabilization of the relative sea-level after the Holocene maximum transgression around 6000 cal BP led to the isolation of the outer lagoon system through the build-up of the Holocene barrier (Figure 7d) (in agreement with Turcq et al. 1999), followed by the sea-level regression that accelerated the infill/shallowing of the outer lagoon (Figure 7e). The distinction among the muddy layers identified in the core reveals the evolution of the lagoonal environment. The muddy layer at –6.3 m presents OM and $CaCO_3$ content about two times higher than the muddy layer bellow, has vegetal remains and is almost ten times muddier (see Figure 5), which may represent the transition between estuarine conditions and infill/isolation of the Marapendi lagoon around core B1/excavation site.

Between –7.2 and –6.3 m, the muddy sediments interlayered with lagoonal sands reflect a typical process of a flood tidal delta, as characterized by Dalrymple et al. (1992) and Dalrymple and Choi (2007). The flood tidal deposit is then buried by the build-up of the Holocene barrier. Between –6.3 and –6 m, the fine sand layer with shell fragments suggests the last stage of sedimentation before complete isolation of the paleo-lagoon of Marapendi. Thus, the estuarine-lagoon phase is recorded in at least 1.2 m thick on the core (see Figure 5).

According to Turcq et al. (1999), a marine regression began around 5200 cal BP. Maia et al. (1984) presented ^{14}C ages of samples from paleo-lagoonal beaches that revealed the reduction of the size of the Jacarepaguá and Marapendi lagoons during regression (see Figures 7e and 7f). In the present research, the regressive build-up of the Holocene barrier is interpreted as promoting sandy sedimentation between –6 and –2.3 m on the studied area, which became medium and coarse sand, well-sorted, and without calcareous bioclasts (see Figure 5). From –2.3 m anomalies are observed in all parameters analyzed and are probably related to human intervention, which also resulted in the ^{14}C age inversion from the sample collected at –2.1 m (7170–6880 cal BP).

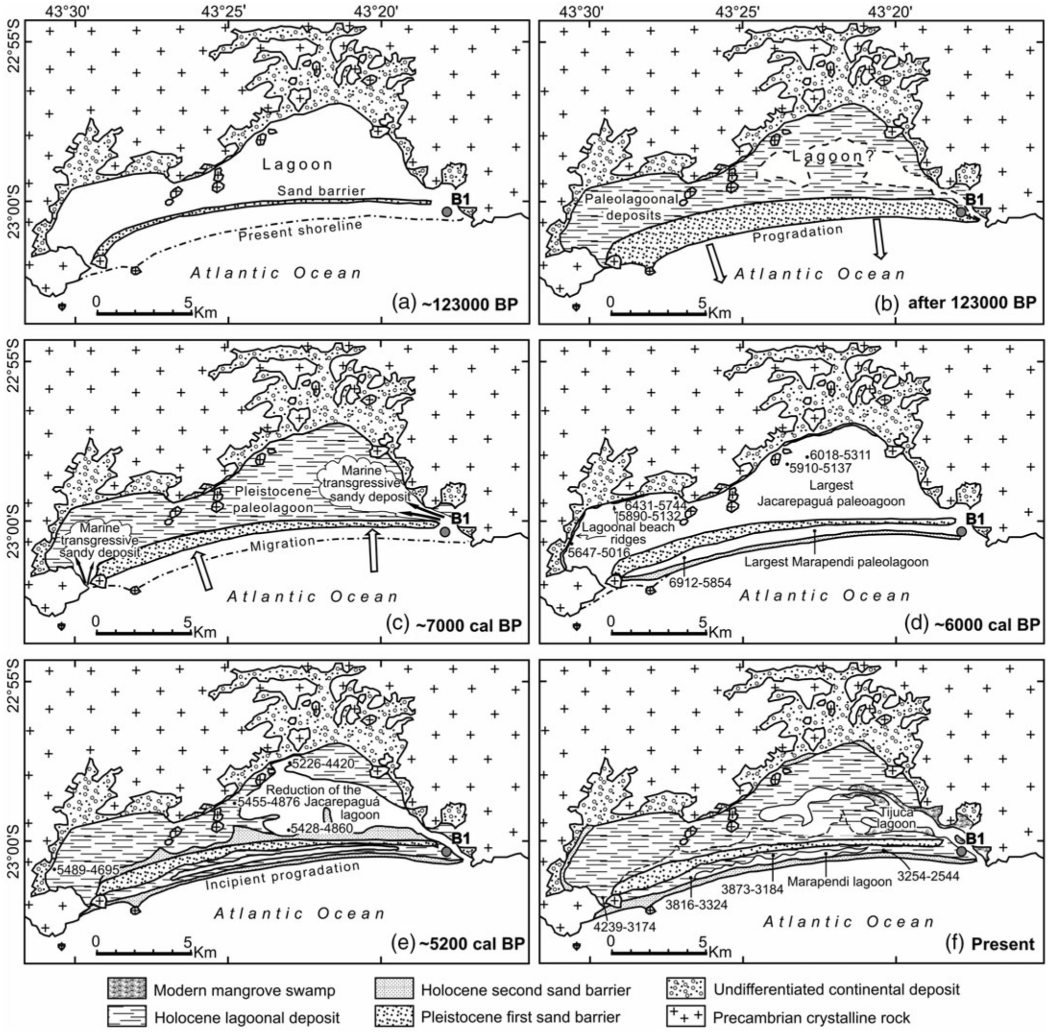

Figure 7 Evolutionary model of Jacarepaguá coastal plain as proposed by Turcq et al. (1999), with the ages of phases (c), (d), and (e) calibrated and adjusted to the literature updates (see Figure 6 and corresponding text). The location of the survey site of the present study (B1) is superimposed on the model. ^{14}C ages published by Maia et al. (1984) are presented calibrated (2 σ) on age range BP, at (d), (e), and (f). Source: modified after Turcq et al. (1999).

CONCLUSIONS

Marine transgressions and regressions developed barrier-lagoon systems along the central coast of Rio de Janeiro since Late Pleistocene on a tectonically stable continental margin. The low gradient continental shelf acted as the main sediment source due to the low fluvial sediment input on this wave-dominated coast. Based on the revised sea-level curve, the postglacial marine transgression (PMT) crossed the present mean sea-level between 7945 and 7500 cal BP on the region increasing the accommodation space.

In the studied area, at Barra da Tijuca (Jacarepaguá coastal plain), the PMT allowed the sedimentary deposition of a shoreface paleoenvironment between 7 and 8 m water column evidenced by the presence of a marine paleo-surface colonized by *Encope emarginata*. These echinoderms lived in front of the inner Pleistocene coastal barrier where they were buried due to the sub-aqueous rework of the barrier at 7770–7540 cal BP.

The PMT developed the outer Holocene barrier and back-barrier lagoonal deposits of the Marapendi lagoon since at least 5440–5070 cal BP, and the deposition of flood tidal delta sediments. The incipient base-level lowering enhanced the lagoon shallowing and infill, followed by relative sea-level stability that allowed the regressive widening/progradation of the Holocene barrier.

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REFERENCES

Alves E, Macario K, Souza R, Pimenta A, Douka K, Oliveira F, Chanca I, Angulo R. 2015. Radiocarbon reservoir corrections on the Brazilian coast from pre-bomb marine shells. Quaternary Geochronology 29:30–35. doi: 10.1016/j.quageo.2015.05.006.

Angulo RJ, Lessa GC. 1997. The Brazilian sea-level curves: a critical review with emphasis on the curves from Paranaguá and Cananéia regions. Marine Geology 140:141–166.

Angulo RJ, Lessa GC, Souza MC. 2006. A critical review of mid to late Holocene sea-level fluctuations on the eastern Brazilian coastline. Quaternary Science Reviews 25:486–506.

Angulo RJ, Giannini PCF, De Souza MC, Lessa GC. 2016. Holocene paleo-sea-level changes along the coast of Rio de Janeiro, southern Brazil: Comment on Castro et al. (2014). Anais da Academia Brasileira de Ciencias 88(4):2105–2111.

Blott SJ, Pye K. 2001. Gradistat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf. Process. Landforms 26:1237–1248.

Blott SJ, Pye K. 2008. Particle shape: a review and new methods of characterization and classification. Sedimentology 55:31–63.

Bronk Ramsey C. 2017. Methods for summarizing radiocarbon datasets. Radiocarbon 59(2): 1809–1833.

Cherkinsky A, Culp RA, Dvoracek DK, Noakes JE. 2010. Status of the AMS facility at the University of Georgia. Nuclear Instruments and Methods in Physics Research B 268(7–8): 867–870.

Dalrymple RW, Zaitlin BA, Boyd R. 1992. Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology 62(6):1130–1146.

Dalrymple RW, Choi K. 2007. Morphologic and facies trends through the fluvial-marine transition in tide-dominated depositional systems: a schematic framework for environmental and sequence-stratigraphic interpretation. Earth-Science Reviews 81(3–4):135–174.

Delibrias G, Laborel J. 1969. Recent variations of the sea-level along the Brazilian coast. Quaternaria 14:45–49.

Dias GTM, Kjerfve B. 2009. Barrier and Beach Systems of Rio de Janeiro Coast. In: Dillenburg SR, Hesp PA, editors. Geology and geomorphology of Holocene coastal barriers of Brazil. Heidelberg/Berlin: Springer. p. 225–252.

Dias GTM, Dias MS, Ternes CF. 2019. Plataforma Continental do Rio de Janeiro. In: Dias MS, Bastos AC, Vital H, orgs. Plataforma Continental Brasileira. Série I: Estados do Rio de Janeiro, Santa Catarina e Rio Grande do Sul. 1ª Edição, Rio de Janeiro, P2GM Projetos e Produções. p. 7–55.

Field ME, Duane DB. 1976. Post-Pleistocene history of the United States inner continental shelf: Significance to origin of barrier islands. Geological Society of America Bulletin 87(5): 691–702.

Folk RL, Ward WC. 1957. Brazos River Bar: a study in the significance of grain size parameters. Journal of Sedimentary Petrology 27:3–26.

Fortes LP, Costa SMA, Abreu MA, Silva AL, Júnior NJM, Monico JG, Santos MC, Tétreault P. 2009 Latest Enhancements in the Brazilian Active Control Network. In: Sideris MG, editor. Observing our changing Earth. International Association of Geodesy Symposia. Vol. 133. Heidelberg/Berlin: Springer. p. 65–70.

Gilbert GK. 1885. The topographic features of lake shores. U.S. Geological Survey Report 5:69–123.

Gross MG. 1971. Carbon determination. In: Carver RE, editor. Procedures in sedimentary. New York: Wiley-Interscience. p. 573–596.

Hoyt JH. 1967. Barrier islands formation. Geological Society of America Bulletin 78:1125–1135.

IBGE. 2010. Instruções técnicas para Controle Geodésico de Estações Maregráficas – CGEM e sua vinculação vertical ao Sistema Geodésico Brasileiro – SGB. Manuais técnicos em geociências 11. Ministério do Planejamento, Orçamento e Gestão. Instituto Brasileiro de Geografia e Estatística – IBGE. Diretoria de Geociências. Coordenação de Geodésia. 38 p.

Ireland S. 1987. The Holocene sedimentary history of the coastal lagoons of Rio de Janeiro state, Brazil. In: Tooley MJ, Shennan I, editors. Sea-level changes. Oxford: Basil Blackwell. The Institute of British Geographers. Special Publications Series 20. p. 25–66.

Jesus PB, Dias FF, Muniz RA, Macario KCD, Seoane CS, Quattrociocchi DGS, Cassab RCT, Aguilera O, Souza RCCL, Alves EQ, et al. 2017. Holocene paleo-sea-level in southeastern Brazil: an approach based on vermetids shells. Journal of Sedimentary Environments 2(1):35–48.

Khan NS, Ashe E, Shaw TA, Vacchi M, Walker J, Peltier WR, Kopp RE, Horton BP. 2015. Holocene Relative Sea-Level Changes from Near-, Intermediate-, and FarField Locations. Curr. Clim. Chang. Reports 1:247–262. doi: 10.1007/s40641-015-0029z.

Krumbein WC. 1941. Measurement and geological significance of shape and roundness of sedimentary particles. Journal of Sedimentary Petrology 11:64–72.

Laborel J. 1969. Les pouplements de madréporaires des côtes tropicales du Brésil. Annales de l'Universtité D'Abidjan. Serie E-II Fascicule 3. Ecologie. 261 p.

Lamego AR. 1945. Ciclo evolutivo das lagunas fluminenses. Rio de Janeiro: Departamento Nacional da Produção Mineral/Divisão de Geologia e Mineralogia. Bol 118. 48 p.

Macario KD, Gomes PRS, Anjos RM, Carvalho C, Linares R, Alves EQ, Oliveira FM, Castro MD, Chanca IS, Silveira MFM, et al. 2013. The Brazilian AMS radiocarbon laboratory (LAC-UFF) and the intercomparison of results with CENA and UGAMS. Radiocarbon 55(2):325–330.

Macario KD, Oliveira FM, Moreira VN, Alves EQ, Carvalho C, Jou RM, Oliveira MI, Pereira BB, Hammerschlag I, Netto B, et al. 2017. Optimization of the amount of zinc in the graphitization reaction for radiocarbon AMS measurements at LAC-UFF. Radiocarbon 59(3):885–891. doi: 10.1017/RDC.2016.42.

Macario KD, Souza RCCL, Trindade DC, Decco J, Lima TA, Aguilera OA, Alves EQ, Oliveira FM, Chanca IS, Carvalho C, Anjos RM, Pamplona FC, Silva EP. 2014. Chronological model of a Brazilian Holocene shellmound (Sambaqui da Tarioba, Rio de Janeiro, Brazil). Radiocarbon 56(2):489–499.

Maia MCAC, Martin L, Flexor JM, Azevedo AEG. 1984. Evolução Holocênica da Planície Costeira de Jacarepaguá (RJ). Rio de Janeiro: Anais do XXXIII Congresso Brasileiro de Geologia. p. 105–118.

Mansur KL, Ramos RRC, Godoy JMO, Nascimento VMR. 2011. Beachrock de Jaconé, Maricá e Saquarema - RJ: importância para a história da ciência e para o conhecimento geológico. Revista Brasileira de Geociencias 41(2):290–333.

Martin L, Bittencourt ACSP, Vilas-Boas GS. 1982. Primeira ocorrência de corais pleistocênicos da costa brasileira - datação do máximo da penúltima transgressão. Ciências da Terra, SBG 3:16–17.

Martin L, Suguio K. 1978. Excursion route along the coastline between the town of Cananéia (state of São Paulo) and Guaratiba outlet (state of Rio de Janeiro). In: International Symposium on Coastal Evolution. Special Publication 2:1–98.

Martin L, Suguio K. 1989. Excursion route along the Brazilian coast between Santos (SP) and Campos (RJ) (North of State of Rio de Janeiro). In: International Symposium on Global Changes in South America during the Quaternary. Special Publication 2:1–136.

Martin L, Suguio K, Dominguez JML, Flexor JM. 1997. Geologia do Quaternário costeiro do litoral norte do Rio de Janeiro e do Espírito Santo. Belo Horizonte: CPRM. 112 p. 2 maps.

Martin L, Suguio K, Flexor JM. 1979. Le Quaternaire marin du littoral brésilien entre Cananéia (SP) et Barra de Guaratiba (RJ). In: Suguio K, Fairchild TR, Martin L, Flexor JM, editors. Proceedings of the "1978 International Symposium on Coastal Evolution in the Quaternary". São Paulo (SP), Brazil. p. 296–331.

Martin L, Suguio K, Flexor JM, Bittencourt ACSP, Vilas-Boas GS. 1979/1980. Le quaternaire marin brésilien (littoral pauliste, sud fluminense et bahianais). Cahiers ORSTOM. Série Géologie 11:95–124.

Milne GA, Long AJ, Basset SE. 2005. Modeling Holocene relative sea-level observations from the Caribbean and South America. Quaternary Science Reviews 24:1183–1202.

Muehe D, Corrêa CHT. 1989. Dinâmica de praia e transporte de sedimentos na restinga de Maçambaba RJ. Revista Brasileira de Geociências 19(3):387–392.

Muehe D, Lins-de-Barros FM. 2016. The Beaches of Rio de Janeiro. In: Short AD, Klein AHF, editors. Brazilian Beach Systems. Springer. Coastal Research Library 17. p. 363–396. doi: 10.1007/978-3-319-30394-9_14.

Murray-Wallace CV, Woodroffe CD. 2014. Quaternary sea-level changes: a global perspective. 1st ed. Cambridge: Cambridge University Press. 484 p. doi: 10.1017/CBO9781139024440.

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, et al. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal AP. Radiocarbon 55(4): 1869–1887. doi: 10.2458/azu_js_rc.55.16947.

Reis AT, Maia RMC, Silva CG, Rabineau M, Guerra JV, Gorini C, Ayres A, Arantes-Oliveira R, Benabdellouahed M, Simões I, Tardin R. 2013. Origin of step-like and lobate seafloor features along the continental shelf off Rio de Janeiro State, Santos basin-Brazil. Geomorphology 203:25–45.

Roncarati H, Neves LE. 1976. Projeto Jacarepaguá. Estudo geológico preliminar dos sedimentos recentes superficiais da Baixada de Jacarepaguá, Município do Rio de Janeiro - RJ. PETROBRÁS. CENPES. DEXPRO. 89 p.

Roy PS, Thom BG. 1981. Late Quaternary marine deposition in New South Wales and southern Queensland—an evolutionary model. Journal of the Geological Society of Australia 28:417–489.

Schumacher BA. 2002. Methods for the determination of total organic carbon (TOC) in soils and sediments. Las Vegas: U.S. Environmental Protection Agency/Ecological Risk Assessment Support Center Office of Research and Development. 25 p.

Schwartz ML. 1971. The multiple causality of Barrier Islands. The Journal of Geology 79(1): 91–94.

Silva ALC, Silva MAM, Souza RS, Pinto MLV. 2014. The role of beachrocks on the evolution of the Holocene barrier systems in Rio de Janeiro, southeastern Brazil. In: Green AN, Cooper JAG, editors. Proceedings 13th International Coastal Symposium (Durban, South Africa). Journal of Coastal Research, special issue 70:170–175. ISSN 0749-0208.

Sloss CR, Jones BG, Murray-Wallace CV. 2005. Holocene sea-level change and the evolution of a barrier estuary: a case study, Lake Illawarra, NSW, Australia. Journal of Coastal Research 21:943–959.

Sloss CR, Nothdurft L, Hue Q, O'Connor SG, Moss PT, Rosendahl D, Petherick LM, Nanson RA, McKenzie LL, Sternes A, Jacobsen GE, Ulm S. 2018. Sea-level change and coastal landscape evolution in the southern Gulf of Carpentaria, Australia. The Holocene 28(9):1411–1430.

Turcq B, Martin L, Flexor J-M, Suguio K, Tasayaco-Ortega L. 1999. Origin and evolution of the quaternary coastal plain between Guaratiba and Cabo Frio, State of Rio de Janeiro, Brasil. In: Knoppers B, Bidone ED, Abrão JJ, editors. Environmental Geochemistry of Coastal Lagoon systems of Rio de Janeiro, Brazil. Série Geoquímica Ambiental 6:25–46.

Valeriano MM. 2008. Topodata: guia para utilização de dados geomorfológicos locais. Relatório INPE-15318-RPQ/818. São José dos Campos: Instituto Nacional de Pesquisas Espaciais. 75 p.

WoRMS Editorial Board. 2018. World Register of Marine Species. Available at http://www.marinespecies.org. Accessed on 09-17-2018. doi:10.14284/170.

Xu X, Trumbore SE, Zheng S, Southon JR, McDuffee KE, Luttgen M, Liu JC. 2007. Modifying a sealed tube zinc reduction method for preparation of AMS graphite targets: reducing background and attaining high precision. Nuclear Instruments and Methods in Physics Research B 259(1):320–329.

Zalán PV, Oliveira JAB. 2005. Origem e evolução estrutural do Sistema de Riftes Cenozóicos do Sudeste do Brasil. Boletim de Geociências da Petrobras 13(2):269–300.