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ARTICLE

Sedimentary architecture and depositional evolution of the Quaternary coastal plain of Maricá, Rio de Janeiro, Brazil

Arquitetura sedimentar e evolução deposicional no Quaternário da planície costeira de Maricá, Rio de Janeiro, Brasil

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ABSTRACT: The coastal geomorphology of Maricá (Rio de Janeiro state) is characterized by a large lagoon and by two sandy barriers that confine a series of small isolated chain-like lagoons. Data collected from ground-penetrating radar and boreholes from the central coastal plain of Maricá provided information on the sedimentary architecture and evolution of this area in the Quaternary. Six lithological units were identified comprising three depositional sequences limited by erosional surfaces, related to barrier–lagoon systems that migrated onshore, offshore, and longshore, giving rise to a sedimentary deposit 25 m thick or more. The data reveal a retrograding barrier overlying a basal mud unit which rests in unconformity upon Precambrian basement, thus characterizing an important Pleistocene transgression. A second Pleistocene barrier of 45,000 cal years BP migrated over a lagoonal mud unit (48,000–45,000 cal years BP) reaching over the previous barrier. A progradational phase followed due to a fall of sea level. A long interval of erosion of the barrier created an unconformity that represents the Pleistocene–Holocene boundary. A beachrock in nearby Itaipuaçu, 100 m offshore from the present-day beach, dated as 8,500 cal years BP marks the onset of Holocene sedimentation due to gradually rising sea level, which continued until at about 5,000 years ago. This promoted the retrogradation of the barrier–lagoon system. A brief episode of progradation is observed as a series of paleobeach scarps. Today's rising sea level is causing the retrogradation of the barrier.

KEYWORDS: Quaternary; barrier–lagoon systems; ground-penetrating radar; sea-level change; radiocarbon ages; southeast Brazil.

RESUMO: *A geomorfologia costeira de Maricá (estado do Rio de Janeiro) é caracterizada por uma imponente lagoa e por duas barreiras arenosas que confinam uma série de pequenas lagunas isoladas e colmatadas. Dados de georadar (GPR) e sondagens realizadas na área provém informações sobre sua arquitetura sedimentar e evolução no Quaternário. Os resultados indicam a existência de seis unidades litológicas compondo três sequências deposicionais limitadas por superfícies erosivas, relacionadas a sistemas barreira-laguna que migraram para o continente, para o mar e lateralmente, formando um depósito sedimentar de 25 metros ou mais de espessura. Há evidências de uma barreira retrogradante sobre uma unidade lamosa basal, que se formou sobre uma superfície erosiva representada pelo topo do embasamento Pré-Cambriano, apontando uma importante transgressão no Pleistoceno. Uma segunda barreira, formada há cerca de 45.000 anos cal A.P., migrou sobre uma unidade lamosa lagunar (48.000–45.000 anos cal A.P.) alcançando a barreira anterior. A seguir, uma fase de progradação ocorre em resposta a um rebaixamento do nível do mar. Um longo período de erosão da barreira resulta em uma discordância representando o limite entre Pleistoceno e Holoceno. O arenito de praia em Itaipuaçu, submerso a cerca de 100 metros da linha de praia atual, datado em 8.500 anos cal A.P., marca o início da sedimentação holocênica devido ao aumento gradual do nível do mar até 5.000 anos atrás. Este evento promoveu a retrogradação do sistema barreira-laguna. Um breve episódio de progradação é observado através de uma série de paleoescarpas de tempestades. Atualmente, uma elevação do nível do mar tem causado a retrogradação da barreira.*

PALAVRAS-CHAVE: *Quaternário; sistemas barreira-laguna; georadar; mudanças do nível do mar; idades do radiocarbono; sudeste do Brasil.*

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INTRODUCTION

Understanding the evolution of the barrier–lagoon systems is important for coastal planning and management projects so crucial for rapidly developing areas. The complex interaction between different coastal processes, such as coastal dynamics and sea-level changes, can be better understood as consequence of them. Barriers are the sites of some of the world's most beautiful beaches. They may represent some of the most expensive real estate in many countries due to their development by the resort industry and because many people wish to live next to the sea. They form due to the combined action of wind, waves, and longshore currents, whereby these strips of land are but a few to several meters above sea level and they protect the mainland from the forces of the sea, particularly storms. Barriers are prominent depositional features of many coasts, and similar sandstone bodies are represented in the stratigraphic record and may become important reservoirs for water, gas, and oil. The external geometry, distribution, nature of facies, and associations are variables in this setting and depend on sediment supply, relative sea-level changes, and other aspects of the history of individual examples. A useful approach is to identify major facies, determine their lateral distribution and relationships, and use available information on local and regional settings for interpretation (McCubbin 1982; Davis Jr. & Fitzgerald 2004; Clifton 2006).

The well-established models proposed by Kraft and Chrzastowski (1985) to explain the evolution of barrier–lagoon systems are here applied for the understanding of Maricá coastal plain (Rio de Janeiro, Brazil) (Fig. 1). These models represent starting points for understanding ancient coastal records, the geochronological evolution of a coast, correlation of coastal records, and regressive and transgressive sea-level events. Records formed by coastal progradation are better understood and many examples have been recognized compared to records formed by retrogradation of a shoreline due to a transgressive event. The low preservation potential of these regressive sand bodies, formed during sea-level rise, makes the understanding of such events and geological records more complex (Friedmam & Sanders 1978; McCubbin 1982; Kraft & Chrzastowski 1985; Davis & Fitzgerald 2004; Clifton 2006). Such is the case for the Maricá coastal plain, where measurements have indicated a landward migration of the barrier of about 15 m for the past 30 years (Lins-de-Barros 2005; Silva *et al.* 2008b).

Ground-penetrating radar (GPR) provides high-resolution images of the shallow stratigraphy with much more detail and continuity than previous methods. The application of GPR became a common practice in many parts of the world from the 1970s onwards (Neal 2004) and in Brazil mainly during the last decade. In this work, GPR has been used to map the almost unknown sedimentary deposits and architecture of the Quaternary barrier–lagoon systems. Boreholes were fundamental in identifying the sedimentary units and sequences as well as in providing samples for radiocarbon dates.

The APA Maricá, part of Rio de Janeiro coast (Fig. 1), is an environmental protection area and, thus, is relatively well preserved as compared to extensively urbanized coastal areas of Rio de Janeiro state. Nevertheless, illegal sand mining has been destroying the local vegetation and landscape, and there is an increasing population concentration in nearby areas mainly due to the construction of an oil refinery not far away. Despite this, the well-preserved barriers are suitable for the GPR working.

This article provides information about the sedimentary architecture and the stages of evolution of the Maricá coastal plain (Rio de Janeiro, Brazil) in the Quaternary (Fig. 1). It is based on a research accomplished by integrating data from GPR and boreholes in addition to sediment analysis and radiocarbon dates.

STUDY AREA

The study area corresponds to APA Maricá, located in the central coastal plain near the town of Maricá (Fig. 1). The area is about 8 km long and 1 km wide in average, extending from the Costa and São Bento channels to an intermittent breaching on the barrier (near Barra de Maricá) towards the east. The study area is limited by the Maricá lagoon to the north and the Atlantic Ocean to the south (Fig. 1). This is a wave-dominated coast with predominant more intense S–SW stormy waves during winter months (Muehe 1979; Silva *et al.* 2008a; Pardal 2009). The predominant longshore currents are to the west in response to the southeast waves. However, the occasional wave incidence from more than one direction (SE and SW) contributes to the generation of currents to the east as well (Silva *et al.* 2008a). Maximum spring tidal fluctuation is 1.5 m (Navy Hydrograph Directory). The wind climate is strongly influenced by the South Atlantic subtropical anticyclone. The prevailing wind directions are from the east and northeast quadrants (Amarante *et al.* 2002). Occasionally, winds of greater intensity come from the south and southwest associated with polar masses (CPTEC-INPE).

The coastal plain morphology is characterized by the large Maricá lagoon and by two barriers that confine a small plain containing a chain-like series of isolated swampy and nearly dry lagoons (Figs. 1 and 2). The inner barrier

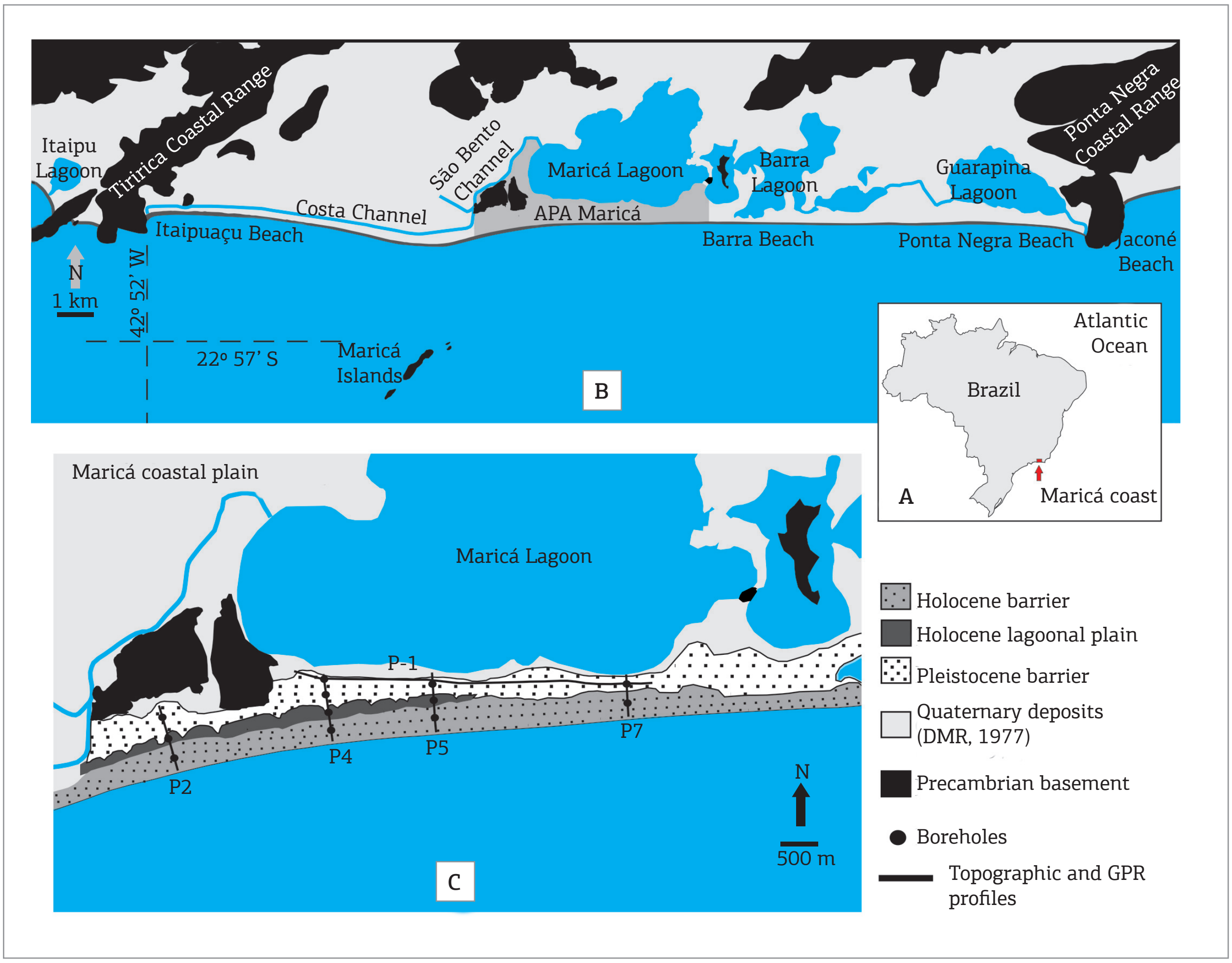

Figure 1. (A) Location of the study area in Rio de Janeiro, southeast Brazil. (B) Main geomorphological features of the Maricá: area in grey, designated APA Maricá, is the study site; Costa and São Bento channels are the limits to the west, Maricá Lagoon to the north, and a beach in the Holocene barrier, near Barra Lagoon, to the east. (C) Barrier–lagoon system with topographic and GPR profiles and borehole locations (other profiles obtained during survey are indicated but will not be discussed in this article). Barrier–lagoon system ages based on Ireland (1987), Turcq *et al.* (1999), Pereira *et al.* (2003), and Silva (2011).

(Pleistocene), 5–9 m above contemporary mean sea level, presents gentle, undulating relief, whereas the outer barrier (Holocene) is 5–7 m above sea level and, at many places, is levelled out as a consequence of sand mining. Few dunes are still preserved in the Holocene barrier and reach 12 m of height. The distance between the crest of the two barriers is 300 m. The lagoonal plain is about 150 m wide and 1.5 m above sea level. It gradually disappears towards the easternmost limit of the study area where the two barriers meet (Fig. 2). The coastal ranges of Tiririca and Ponta Negra (Fig. 1) are made up of Precambrian granites, gneisses, and pegmatites cut by Mesozoic mafic dykes. Weathering of these rocks supply medium—coarse, quartz-rich sand to this coastal plain.

The mechanisms responsible for the evolution of the Rio de Janeiro coast during the Quaternary, as well as its stratigraphy and depositional sequences, are poorly known. One of the first hypotheses, based on the surface morphology, proposed the formation of a spit enclosing large embayments giving rise to barrier–lagoon systems for the coast of Rio de Janeiro as a whole (Lamego 1940, 1945) and specifically to the Jacarepaguá coastal plain, about 50 km from the study area (Roncarati & Neves 1976). Sea-level fluctuations began to be considered later as the most important process for evolution of the Rio de Janeiro coast, with submergence of the low-lying areas and formation of barriers as a mechanism for straightening the coastline (Perrin 1984; Coe Neto *et al.* 1986; Ireland 1987; Muehe & Corrêa 1989; Turcq *et al.* 1999; Pereira *et al.* 2003). In addition to sea-level fluctuations as a cause of changing coastline, coastal dynamics due to longshore currents generated by waves oblique to the shoreline has been proposed as a mechanism influencing the evolution of Rio de Janeiro barrier–lagoon systems

Figure 2. (A and B) Geomorphology of Maricá coastal plain: Maricá Lagoon to the north, two barriers (Pleistocene and Holocene) and the lagoonal plain in between. Approximately 800 m wide from beach to lagoon margin (photos by Guichard, D. 2009).

(Perrin 1984). Perrin also proposed that an important transgressive event at around 120,000 years BP formed a large embayment in the Maricá area, followed by a regression of the sea, which caused the progradation of the coastline and exposure of the continental shelf (Perrin 1984). Paleontological evidence from Maricá and Niterói lagoonal sediments indicate that the outer barrier started to form at around 7,150 years BP during a sea level rise that lasted until about 5,000 years BP (Ireland 1987). Similar behavior has been observed elsewhere in Brazil (Martin *et al.* 1993, 2003). Sediment analysis of the Brejo do Espinho and Vermelha lagoons, which occupy the depression between the two barriers, in nearby areas, indicate the ages between 5,100 and 7,000 years BP, pointing out that the barrier–lagoon system was indeed formed during the Holocene transgression. Lagoonal deposits identified by GPR and drilling dated as 6,000 years BP are present under the outer barrier, thus corroborating the retrograding character of the outer barrier during the Holocene (Pereira *et al.* 2003), as proposed before by Ireland (1987) and Turcq *et al.* (1999).

In this article, evidence is presented on the sedimentary architecture and depositional sequences of the Quaternary coastal plain of Maricá which will provide a better understanding of the processes responsible for its evolution.

MATERIALS AND METHODS

The various geomorphological environments of the Maricá coastal plain were characterized by a topographic survey. A total of five profiles were obtained, one parallel and four perpendicular to the coastline, from the beach to the Maricá lagoonal margin (Fig. 1C). For this task, conventional topographic equipment was used because of the difficulty of moving along the dense bush and marsh areas. Mean sea level was deduced from the topographic profiles: the starting point for the perpendicular profiles was mean sea level, always at times of calm sea and same tidal regime (quarter moon). Topographic profiles were georeferenced with a Garmin GPS 12 XL equipment, and navigation system used was a WGS 84. GPR data were collected along the same lines.

GPR data of approximately 7 km area were collected using an SIR-2000 system (Geophysical Survey Systems Inc.) with a 200 MHz antenna. This system recorded reflection data up to 25 m below surface. The basic parameters used in the data acquisition of GPR include sampling window 400 nanoseg, spacing of 10 cm between shot points, 512 samples per trace, frequency limits between 100 and 450 MHz, transmit antenna with 100 W of radiated power, 16-bit and survey-wheel record method. Velocities were adopted as of 0.10 m/ns previously determined from CMP (common mid-point) surveys in nearby areas (Pereira *et al.* 2003). This is the medium velocity calculated from other CMP surveys in lagoonal muds and undersaturated and saturated sands below the water table (Neal & Roberts 2000 in Neal 2004). Data processing was conducted using RADAN 6.6 (Radar Data Analysis) software and included application of gains and filters, deconvolution, topographic correction, and migration.

Basic principles of seismic stratigraphy have been applied for interpretation of the radargrams. The main reflection patterns considered for this work are dip, shape, continuity, intensity, and reflector relationships (Neal 2004).

Five GPR profiles were acquired, four perpendicular (Figs. 3 to 6) and one parallel to the coastline (Fig. 7). Profiles perpendicular to the coastline show better resolution in areas of the lagoonal plain and inner barrier (Figs. 3 to 6); the proximity to the saltwater causes reduction of the radar resolution due to signal attenuation, thus decreasing the quality of the Holocene barrier images (Fig. 4A). The parallel profile (Fig. 7) shows good resolution except towards the east on the back of the inner barrier, where the road has been paved with a thick layer of mud. For this reason, only the west part of profile 1 is presented in this article.

Twelve boreholes were made, using either percussion or mechanical borers and reaching a maximum depth of 27 m. Sediments were collected during drilling and, depending upon their homogeneity, sampling was carried out at intervals of every meter or centimeter in order to characterize changes. The drilling company hired for this research used PVC tubes of different diameters varying from 150 mm (for the first few meters) to 40 mm (for greater depth) in order to avoid closure of the boreholes and mixing of the sediments. Approximately 300 sediment samples were collected and described during drillings, and 1-m-long cores were also described and sampled. A total of 160 samples representing the main units were selected for grain-size and organic matter concentration analyses. Still in the field, the samples were selected for ^{14}C analysis and immediately placed in a freezer. Five samples containing shells and organic matter were sent to the Center for Applied Isotope Studies at the University of Georgia (USA) for radiocarbon dating by the accelerator mass spectrometry (AMS) method. Age calibrations were performed using OxiCal4 software (https://c14.arch.ox.ac uk). Organic matter samples were calibrated with SHCal13 curve and shells samples were calibrated with Marine13 curve (Reimer *et al.* 2013; Hogg *et al.* 2013; Bronk Ramsey *et al.* 2009). For mud-sized particles, grain size analyses were carried out in a laser diffraction machine (Malvern Mastersizer 2000). For sand and gravel, screen analyses were carried out. All sediments were classified according to the Wentworth scale (1922, in Pettijohn 1975). Organic matter concentration in muddy sediments was obtained by calcination in a muffle at 480 °C, and in coarse sediments, by hydrogen peroxide.

DATA PRESENTATION

GPR profiles perpendicular to the coastline present many similarities in geometry and patterns of reflection

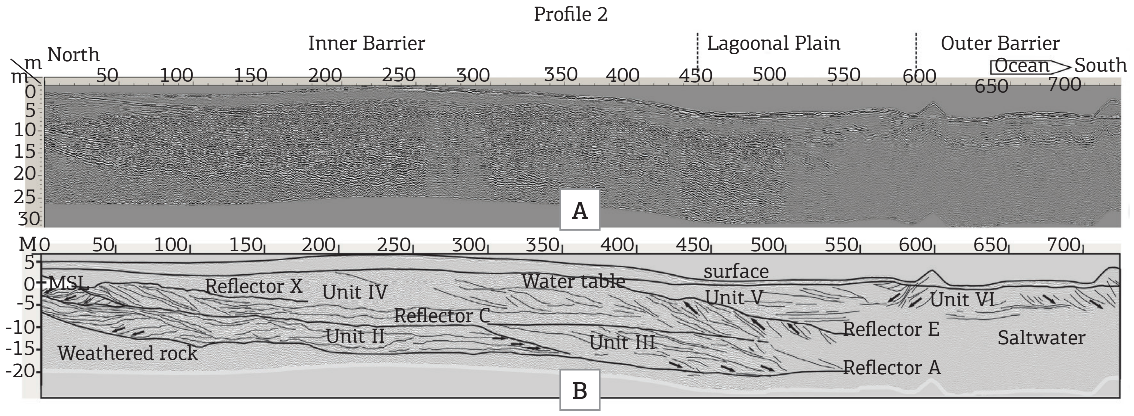

Figure 3. (A) GPR Profile 2 collected perpendicularly to the shoreline. (B) Interpretation of the GPR transects. The arrows indicate the main patterns of termination and reflections observed.

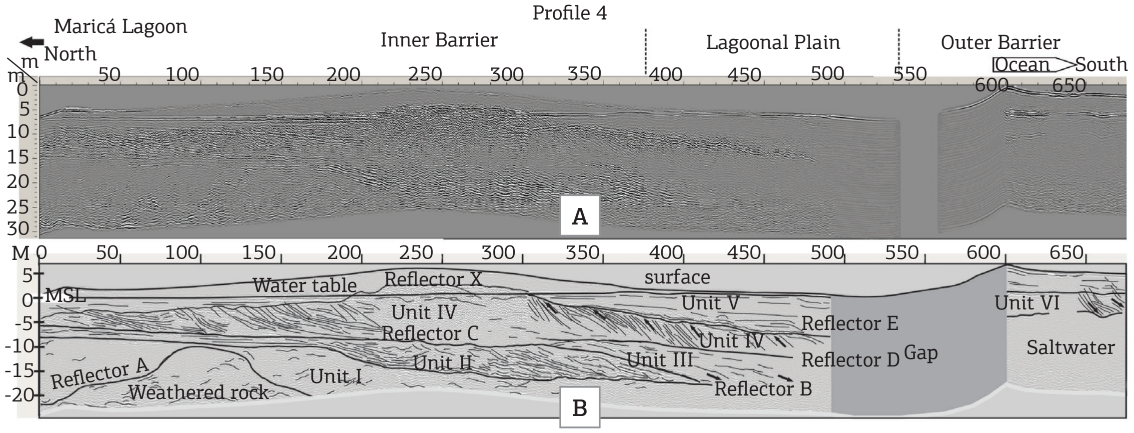

Figure 4. (A) GPR Profile 4 collected perpendicularly to the shoreline. (B) Interpretation of the GPR transects. The arrows indicate the main patterns of termination and reflections observed.

(Figs. 3 to 6) and thus allow mapping of the main depositional units and sedimentary architecture. Also, coastal sequences can be identified, and the stratification patterns indicate moments of retrogradation and progradation of the barrier–lagoon systems during the Quaternary. Furthermore, parallel profiles (Figs. 7 and 8) enable the recognition of channels and the lateral migration of the barrier as a whole (as a spit) through mapping of the inclined stratification along the trend of the coastline. The integration of GPR data and boreholes allowed us to recognize six lithological units forming this 27-m-thick coastal deposit, made up mainly by sand and mud layers with subordinate amounts of gravel (Figs. 9 to 11).

The surface of basement rock (very weathered Precambrian gneiss) at about 20–27 m depth was identified as the basal boundary of the coastal sedimentary architecture (Fig. 9A). The basement surface comprises a low-amplitude, discontinuous interval reflection with a general dip towards the sea and corresponds to Reflector A (Figs. 3 to 6). This reflector decreases in amplitude in the area of the Holocene outer barrier. The basement is a reflection-free unit regarded as typical of basement (Neal 2004; Switzer *et al.* 2006).

Above Reflector A, there occurs a 5-m-thick mud layer, Unit I (Figs. 4 to 6, 9B, and 10), that presents very few reflectors and low reflectance. The top of Unit I is limited by

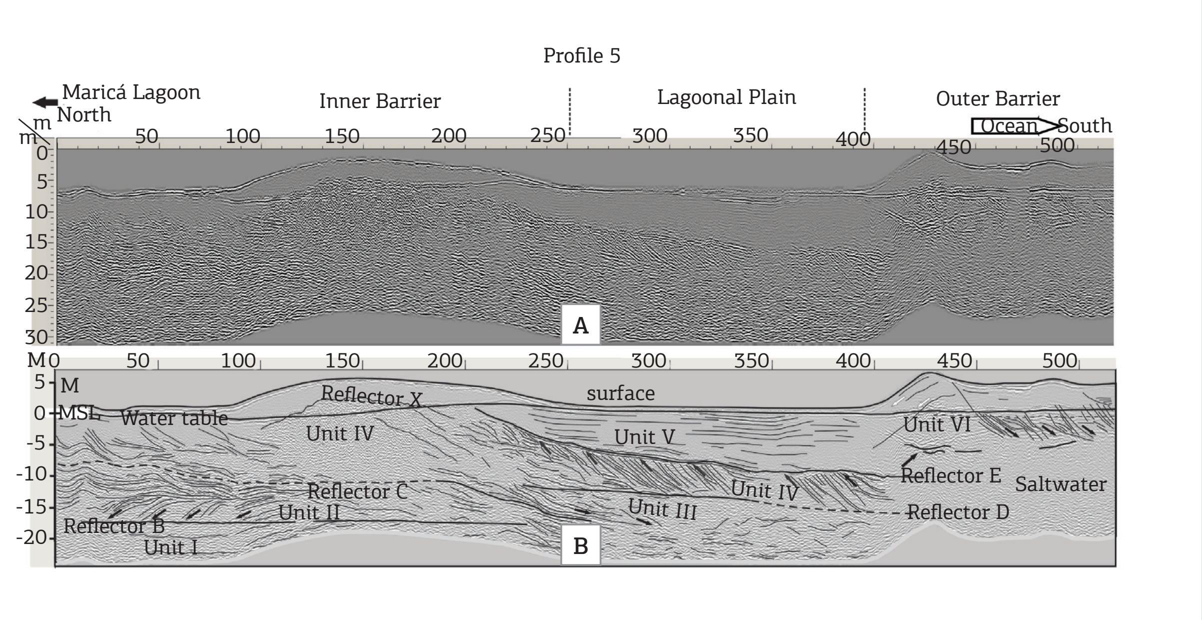

Figure 5. (A) GPR Profile 5 collected perpendicularly to the shoreline. (B) Interpretation of the GPR transects. The arrows indicate the main patterns of termination and reflections observed.

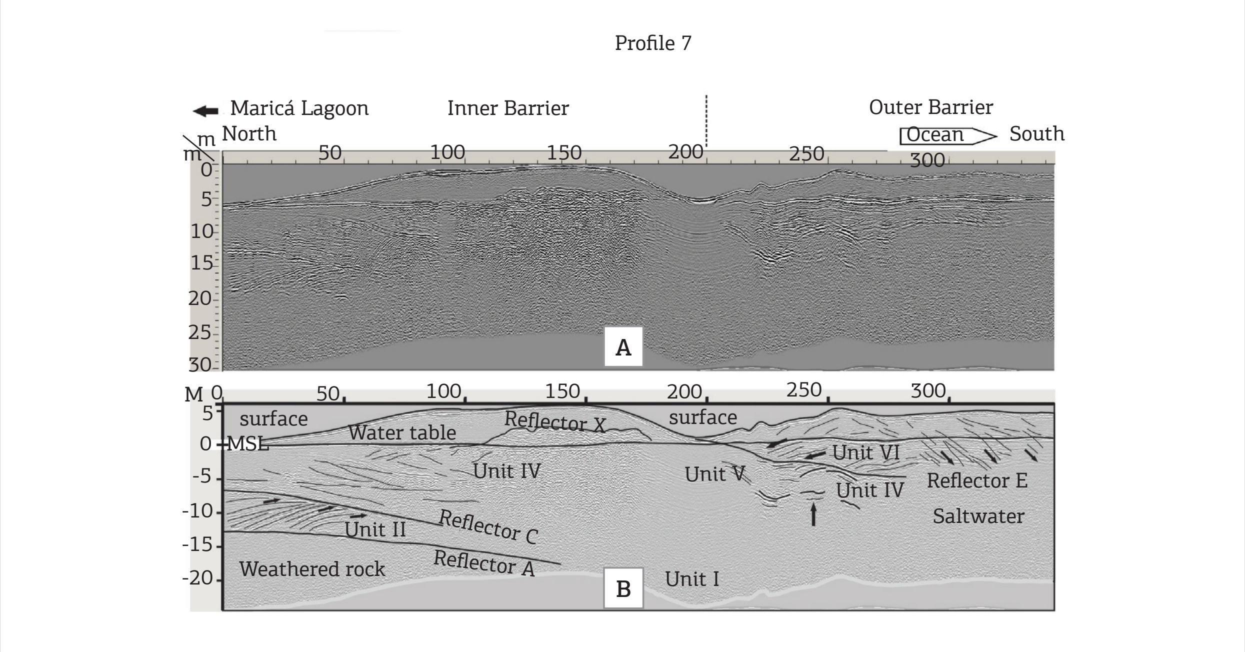

Figure 6. (A) GPR Profile 7 collected perpendicularly to the shoreline. (B) Interpretation of the GPR transects. The arrows indicate the main patterns of termination and reflections observed.

Reflector B, a horizontal to slightly seawardly inclined reflector, that extends 250 m to the south (Figs. 4 to 6). Reflector B is interpreted as an erosional surface formed during a low-sea-level event. On the western side of the study area, this paleosurface is cut by three channels (Figs. 7 and 8, parallel profile). These channels, located at about 10–15 m depth in the profiles, are similar in size, about 6 m deep and 20 m wide (channels A and B, Fig. 7) and 100 m wide (channel C, Fig. 7). The stratification of the channel fill dips mostly to the east, but also to the west, suggestive of a predominant and progressive lateral migration of these channels to the east (Figs. 7 and 8).

Unit II occurs above Reflector B, between 17 and 21 m depth, in the area of the Pleistocene inner barrier (Figs. 3 to 6). This unit, composed of white sand (Fig. 10), displays a variety of reflection patterns: sets of plane-parallel

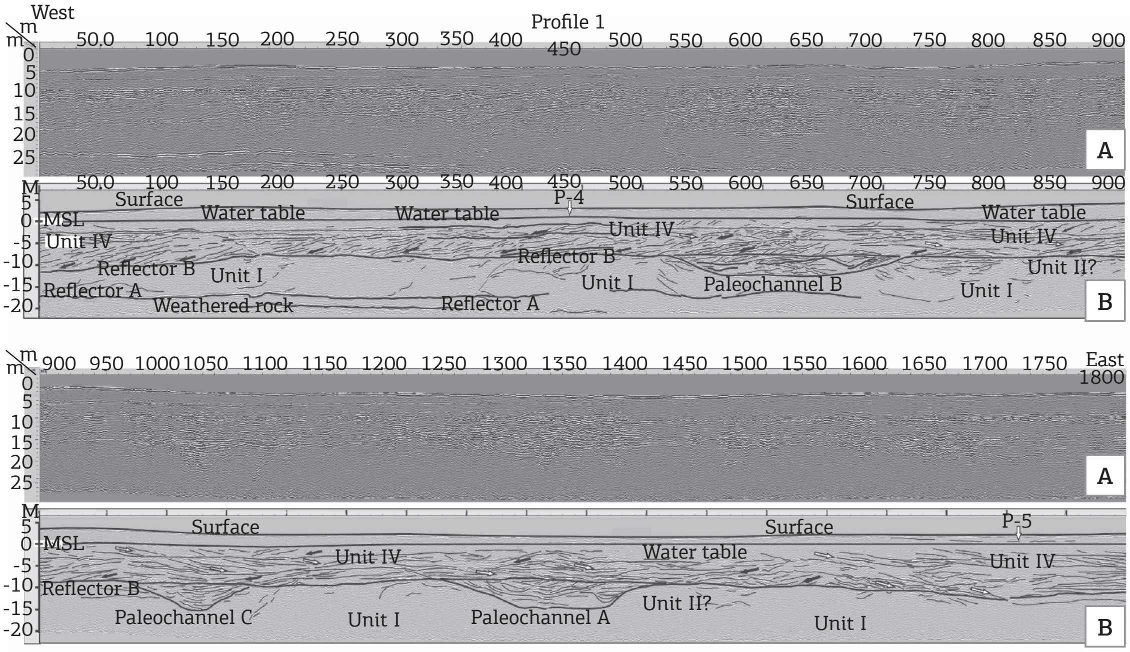

Figure 7. (A) GPR Profile 1 acquired parallel to the shoreline. (B) Interpretation of GPR transect. The arrows indicate the main patterns of termination and reflections observed. P-4 and P-5 show the points of intersection between the perpendicular and parallel profiles.

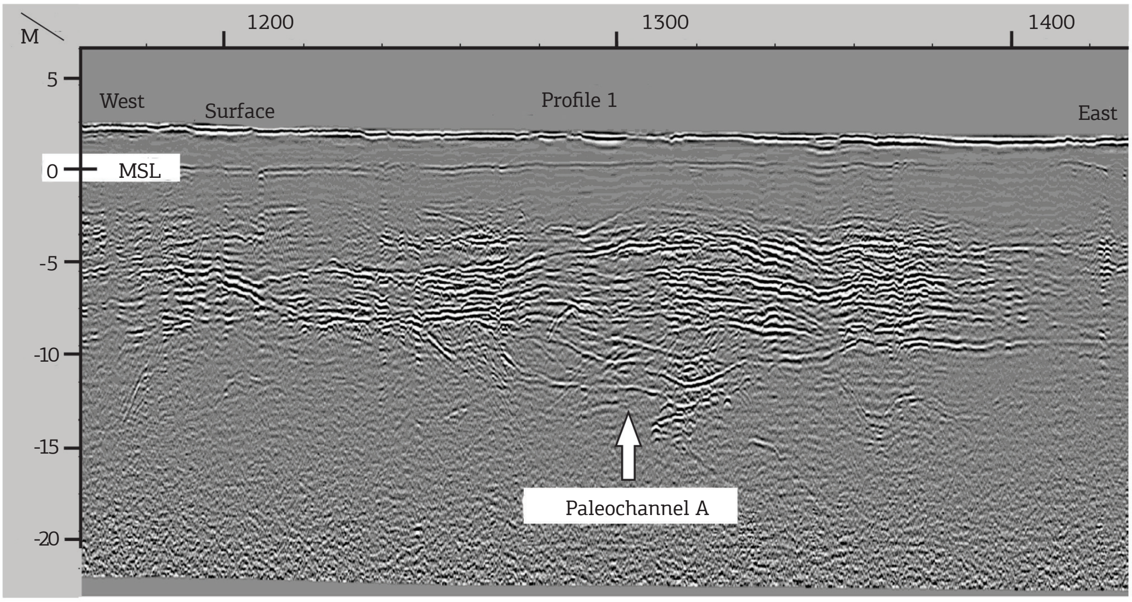

Figure 8. Paleochannel A, about 200 m wide and 6 m thick, in GPR Profile 1.

horizontal strata, sets of strata dipping 20°–25° towards the sea, and groups of strata dipping 18°–22° towards the continent (downlaps), thus indicating the occurrence of a former episode of barrier retrogradation. Unit II is limited

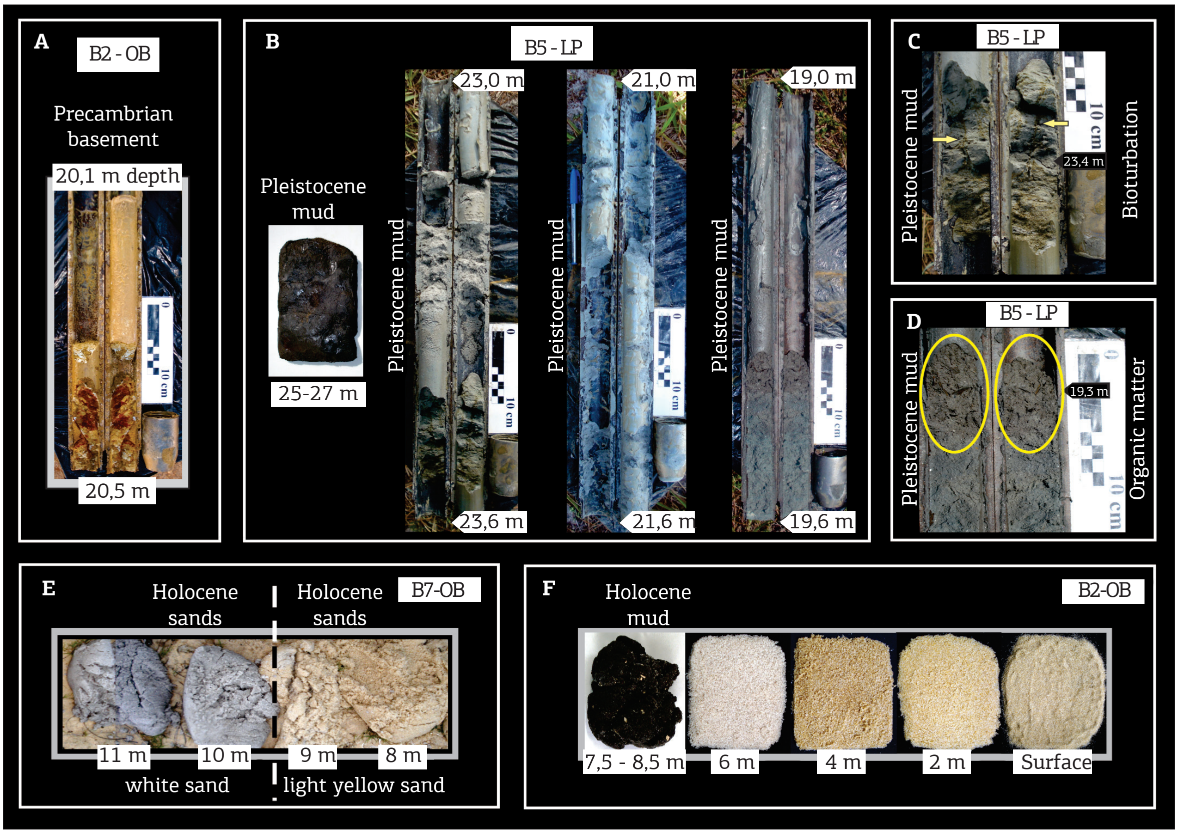

Figure 9. (A–F) Sediment samples collected with percussion or mechanical borers allowed the recognition of a 27-m-thick coastal deposit, composed mainly of sand and mud layers.

by Reflector C, which can be followed for about 400 m to the lagoonal plain between the barriers (Figs. 3 to 6). There, stratification within Unit II appears truncated, indicating the erosive nature of the event that gave rise to this prominent surface (Reflector C). Thus, Unit II must have been more widespread than observed now, corresponding to an earlier barrier–lagoon system in a more northern position.

Unit III, a 5- to 8-m-thick mud layer, occurs mainly below the lagoonal plain area (Figs. 3, 4, 5, and 10). The mud is bioturbated (Fig. 9C) with intercalated sandy layers (or sandy mud layers). Dating of shells and organic matter (Fig. 9D) indicated ages of approximately 47,567, 46,842, and 45,627 cal years BP (Tab. 1). Unit III presents stratification dipping 10°–12° seaward near the margin, but these strata are not seen under the Holocene barrier. The lenticular geometry of this mud deposit is very suggestive of a paleolagoon. Reflector D would correspond to the surface of this filled-up lagoon.

Unit IV, a 15- to 22-m-thick layer, formed by medium-to-coarse white sand, lies directly over Reflector C or between Reflectors D and E (Figs. 3 to 6, 9E, and 10). The most striking feature of Unit IV is a set of plane-parallel strata dipping 24°–26° toward the continent (downlap), about 5 m beneath the surface in the inner barrier area, denoting a previous phase of retrogradation of this barrier. A second and more abundant set of strata dips steeply 30°–45° seaward, indicating a later phase of progradation of this barrier. Radiocarbon dating revealed ages of approximately 45,125 cal years BP for this unit (Tab. 1). Parallel Profile 1 (Fig. 7) shows inclined strata within Unit IV; the inclination is both to the west (seen at about 7–12 m under the surface) and to the east (depths 4–7 m) (Fig. 7). This stratification pattern may indicate the result of longshore drift and lateral migration of the barrier, in this case, predominantly to the west. An eastward component probably existed, as seen in the cross-stratification within the paleochannels (Fig. 7). Reflector X, which appears in Profiles 4, 5, and 7 (Figs. 4 to 6), represents a transitional contact between a layer of dark-brown coarse sand rich in organic matter and a layer of white coarse sand, confirmed by drilling.

Reflector E is a prominent surface topping Unit IV (Figs. 3 to 6). This surface dips locally 11° seaward and is concave-up changing to flat in the direction of the Holocene barrier and

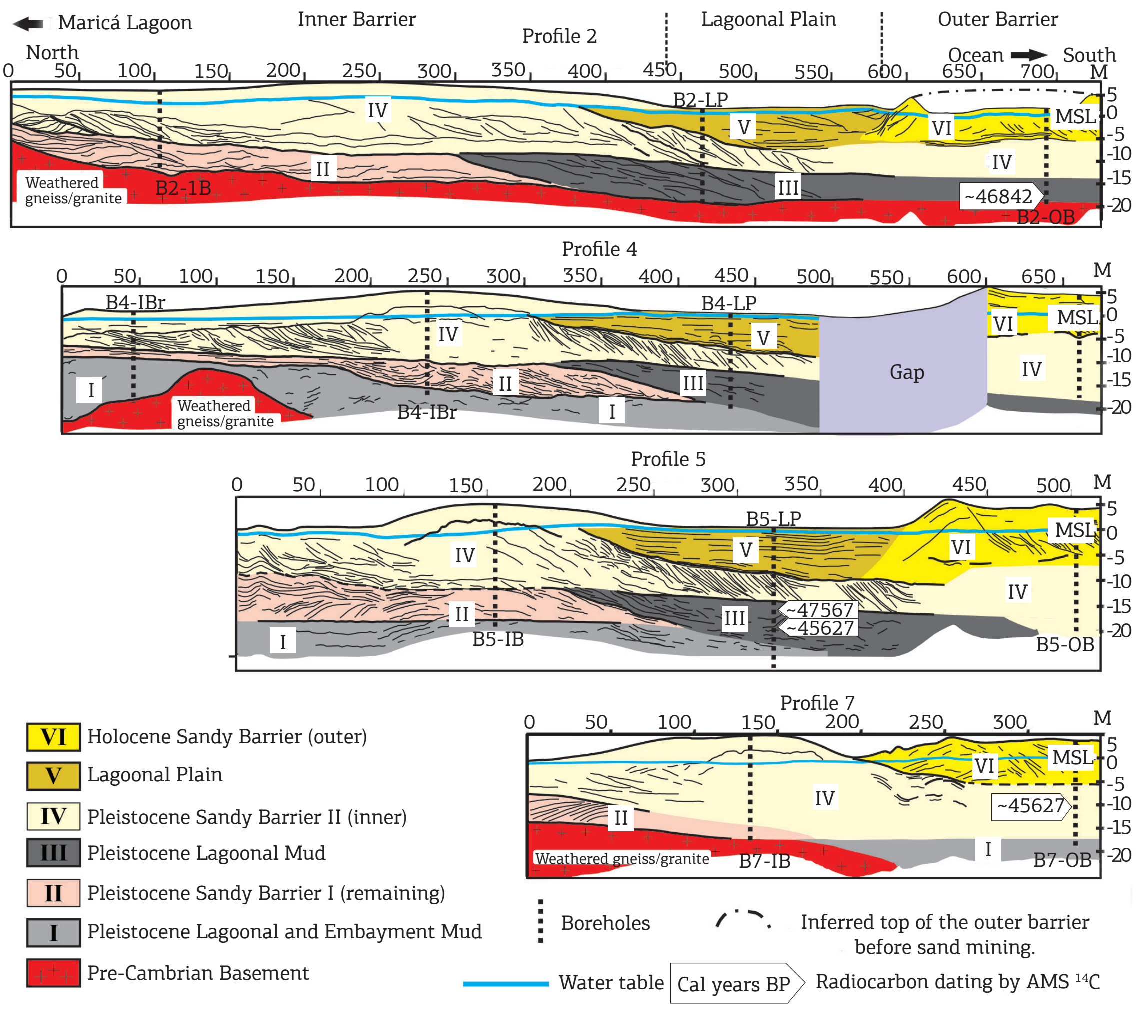

Figure 10. Depositional model of the Maricá coastal plain: GPR profiles made perpendicularly to the coastline, integrating geological drilling data and the results of radiocarbon dating (^{14}C).

extending for 500 m. It corresponds to an important erosional interval during which part of Unit IV was eroded. It is also the unconformable contact between the Pleistocene and Holocene barriers.

Resting upon the erosive surface E, the Holocene Sequence represented by Units V and VI is up to 10-m thick (Figs. 3 to 6, 9F, and 10). Unit V is located well under the paleolagoon plain and is formed by plane parallel to almost horizontal stratification. Unit VI, formed by medium-to-coarse light yellow sand, is characterized by strata showing dips of 45° towards the continent and is commonly present underneath the area of present-day dunes; another group of strata dipping 20°–45° seaward resembles today's strata forming stormy beach scarps (Figs. 3 to 6, and 9E).

DISCUSSION

The Quaternary stratigraphy of the Maricá coastal plain consists of three sedimentary sequences: Pleistocene Sequence I (PSI), Pleistocene Sequence II (PSII), and the Holocene Sequence (HS) (Fig. 11). These sequences are limited by discontinuities, designated as Surfaces A, B, C, and E, representing the partial erosion of the various barrier–lagoon systems during the time interval in question (Figs. 11 and 12).

Sedimentation began with deposition of Unit I, interpreted as lagoonal/embayment muds resting on top of eroded basement (Surface A) (Figs. 11, 12A and B). A marine transgression at about 120,000 years BP proposed for the

Table 1. AMS radiocarbon data of the beachrock and borehole samples

Laboratory number[a]	Sample ID	Depth (m)	Site	Location	Lithology	Material	Conventional age ^{14}C years BP	Calibrated years BP (2 sigma)[b]	Medium age (cal. years BP)
5232	A8AP05	-5[#]	Itaipuaçu beach	22º58'16.2"S 043º00'34.1"W	Beachrock	Biv. Shell	8,110	8,674-8,447	8,560
5233	S2CE18	-18*	Profile 2	22º58'07.6"S 042º53'38.7"W	Muddy sediment	Biv. Shell	43,300	49,374-44,311	46,842
5234	S5PL15	-15*	Profile 5	22º57'45.3"S 042º51'44.6"W	Muddy sediment	Shell	46,240	Before 50,000-45,135	47,567 or more
5235	S5PL19	-19*	Profile 5	22º57'45.3"S 042º51'44.6"W	Muddy sediment	Organic matter	40,280	49,781-41,473	45,627
5236	S7CE14	-14*	Profile 7	22º57'45.4"S 042º50'25.1"W	Sandy sediment	Organic matter	40,880	47,844-42,406	45,125

[a]Center for Applied Isotope Studies (CAIS), University of Georgia, USA.
[b]95.4% reliable.
[#]Below modern mean sea level.
*Below coastal plain surface.
BP: before present;
Biv: Bivalve; cal: calibrated.

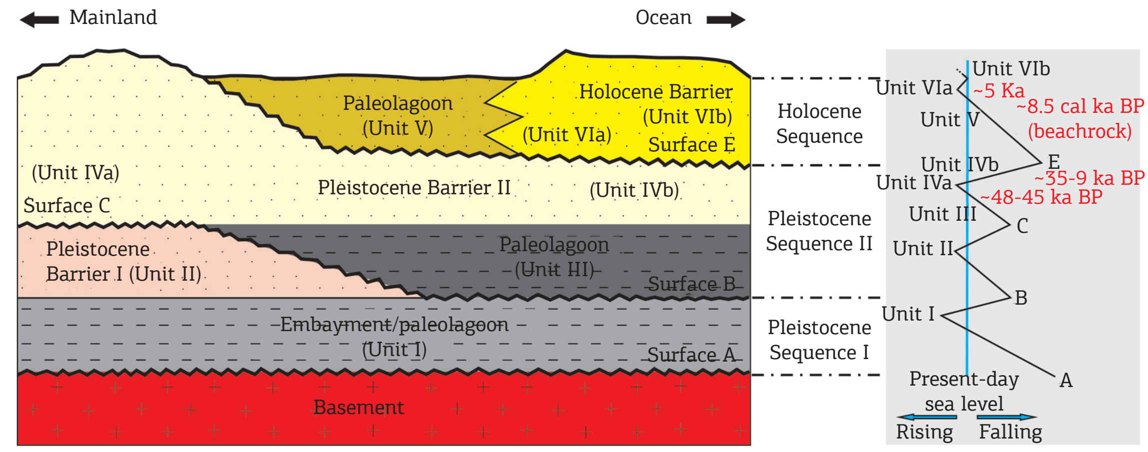

Figure 11. Lithologic units and depositional sequences that form the coastal sedimentary deposit of Maricá: Pleistocene Coastal Sequence I, Pleistocene Coastal Sequence II, and Holocene Coastal Sequence.

coast of Rio de Janeiro as a whole (Perrin 1984) and the mud deposited during this phase of maximum inundation were the starting point for the coastal sedimentation history of the studied area, previously interpreted to be related to a large lagoon or an embayment (Lamego 1940, 1945; Perrin 1984). This transgression has also been recognized along the southern coastal plain of Brazil where a barrier–lagoon system known as Barrier Island System III is believed to have formed around 123,000 years BP (Villwock *et al.* 1986; Tomazelli & Villwock 1996; Tomazelli *et al.* 2000). A subsequent erosional phase is represented by Surface B (Figs. 11 and 12C).

Prominent stratification dipping towards the continent, above Surface B (Fig. 12D), indicates retrogradation of a barrier that reached maximum inland position in the study area (Pleistocene Barrier I, Fig. 11). Three channels are seen in the PBI (Fig. 7), and the sedimentary architecture of the channels points to their migration mainly eastward. Consequently, during this time interval, the barrier grew as a spit. We assume that PBI was formed during a high sea level, which caused the retrogradation of the barrier and at the same time longshore currents promoted growth of a spit to the east. Units I and II form Pleistocene Sequence I, limited by erosional surfaces A and C (Fig. 11).

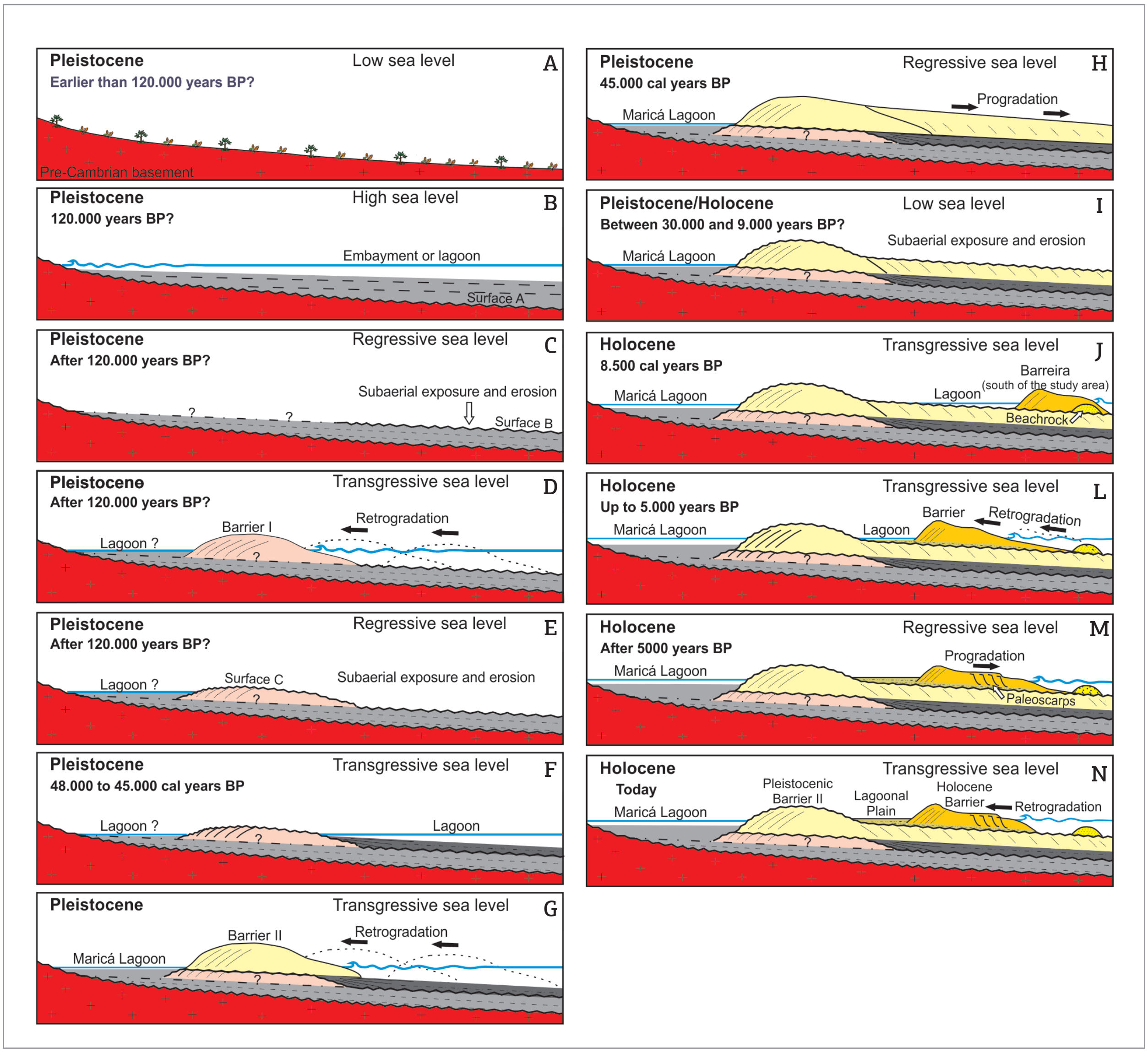

Figure 12. (A–N) Model showing the various stages that mark the evolution of the Maricá coastal plain.

A lenticular bioturbated mud deposit, rich in shells and organic matter, and dated at 47,567–45,627 cal years BP (Tab. 1),indicates formation of a late Pleistocene lagoon following the previous barrier–lagoon system (Figs. 11 and 12F) that was intensively eroded (surface C) leaving a remnant of the previous PBI Figs. 11 and 12E). Similarly, dating of muddy sediments from the Itaipu lagoon (Fig. 1) yielded ages between 42,500 and 35,000 years BP (Ireland 1987).

With the continuous rise of the sea, the barrier retrograded (Unit IVa) to a more northern position, giving rise to Pleistocene Barrier II (PBII), as clearly indicated by strata dipping to the north (Figs. 11 and 12G). This is, in fact, the inner barrier that outcrops today along the northern limit of the study area (Figs. 1 and 2). In subsurface, under the Holocene system, stratification dips towards the sea (IVb). The relationship between Units III and IV (Fig. 11) point to a regressive sequence, called Pleistocene Sequence II (Fig. 11). However, at about 45,125 cal years BP (Tab. 1), the PBII presented progradational behavior, as seen by the downlaps in the GPR radargrams (Figs. 3 to 5). GPR parallel profile (Fig. 7) shows that strata in the barrier, at this time, dipped both westward and eastward (although less to the east). This is an indication of longshore currents causing lateral migration of the barrier system, predominantly to the west apparently. This pattern of drifting sand is similar to today's dynamics which result from the oblique incidence of southeast waves (Silva *et al.* 2008a). There is evidence that the mechanism for the evolution of the barrier system is a combination of multiple causes, as proposed by Schwartz (1971).

An important erosional phase of the barrier system followed as sea level continued to fall (Surface E) (Figs. 11 and 12I). Sea-level curves for southern Brazil point to a fall of 120 m, which exposed the continental shelf (Correa 1996 cited by Suguio *et al.* 2005). If we consider the ages of 46–40,000 years BP (Tab. 1) for the sediments described here and 42,500–35,000 years BP (Ireland 1987) for the Itaipu lagoon muds as representing the last episode of sedimentation, we see that the erosional interval lasted from about 35,000 to about 8,560 cal years BP (Tab. 1), when Holocene sedimentation recommenced in the study area. Surface E is the unconformable contact between the Pleistocene sequences and the Holocene sequence. On the surface, the Pleistocene sands can be easily distinguished by their bright white color as opposed to the yellowish Holocenic sands.

The ages of the sediments found for the Pleistocene Sequence II point to a position of the sea level at 48–45,000 cal years BP (Tab. 1) closer to the present-day level. This is very different from those observed on the global eustatic sea level curve chart for this time interval: at about 40,000 years BP sea level was 50 m below today's level – MIS3 isotope stage (Lambeck & Chappell 2001; Waelbroeck *et al.* 2002; Peltier & Fairbanks 2006). Such contradiction needs to be better understood. The three samples dated for this work characterize very well this time interval for the study area and need to be taken into account. In São Paulo, at the São Sebastião Canal, about 280 km west of the Maricá coast, dating of muddy marine deposits, now in a very coastal setting, also indicates a higher than expected sea level at about 40,000 years BP (Klein & Mahiques 2003; Klein 2005; Mahiques *et al.* 2010). This problem, which may be either methodological or geological, will be addressed as future research continues to enhance and clarify Brazilian sea-level behavior during the Quaternary.

A 8,560 cal years BP (Tab. 1) beachrock is the first evidence of Holocene sedimentation in the area. This beachrock forms a 3-km long submarine outcrop at a depth of about 5 m and approximately 100 m from the beach at nearby Itaipuaçú (Figs. 1 and 2). It marks the base of the Holocene Sequence, overlying surface E (Figs. 11 and 12J). Similarly, in Jaconé beach (Fig. 1), a beachrock has been found and dated as 8,198–7,827 cal years BP (Mansur *et al.* 2011).

The Holocene Sequence is a transgressive (Fig. 11) and formed by two depositional units (V and VI), which are related to a barrier–lagoon system moving mostly inland (Unit Via: Figs. 11 and 12L), but also exhibiting a brief phase of progradation (Unit VIb: Figs. 11 and 12M). In nearby Itaipuaçu (Fig. 1), at the same stratigraphic level that of plane-parallel, very continuous strata are seen in GPR images, lagoonal peats indicated an age of 6,040–5,900 years BP (Pereira *et al.* 2003) (Fig. 12 L), suggesting the existence of a lagoon associated with the barrier where the beachrock was formed.

A continuous trend of rising sea level promoted retrogradation of the barrier, which reached a maximum at about 5,000 years BP, when sea level was about 3–5 m above present mean sea level (Angulo & Lessa 1997; Angulo *et al.* 1999; Lessa & Angulo 1998; Angulo *et al.* 2006; Martin *et al.* 1993, 1998, 2003). This is corroborated by a set of strata dipping towards the continent and resulted in the infilling of the lagoonal depression between the two barriers, giving rise to the geomorphological feature seen today as a paleolagoon plain (Figs. 1 and 2).

Later, the barrier prograded, as shown by groups of reflectors deep down in the sand deposit, resembling present-day beach scarps (Figs. 3, 4, 5, and 6) and indicative of former beach positions (Fig. 12M). Retrogradation followed by progradation in the Holocene is also observed in different parts of the Brazilian coast (Villwock *et al.* 1986; Tomazelli & Villwock 1996; Tomazelli *et al.* 2000).

Today, the barrier is again retreating and overwash deposits are commonly seen along the barrier system (Figs. 12N and 2B). Lins-de-Barros (2005) and Silva *et al.* (2008b) showed that the barrier has retrograded about 15 m in the past 30 years.

CONCLUSIONS

The geological evolution of the Maricá coastal plain during the Quaternary was strongly controlled by relative changes in sea level. Transgressions and regressions of the sea were responsible for deposition and erosion of lithological units as the barrier–lagoon systems formed and migrated throughout the study area.

Six lithological units were identified, forming three depositional sequences limited by erosional surfaces: Pleistocene Sequence I, Pleistocene Sequence II, and the Holocene Sequence containing the present-day barrier system.

A model for the evolution of the Maricá coastal plain includes the following main episodes of sedimentation and erosion:

- Over Precambrian basement, a 25-m-thick or so deposit of mostly sand and mud is found.
- Unit I occurs at the base of the Pleistocene Sequence I and probably represents deposition of mud in a large lagoon or embayment formed during a major marine transgression at about 120,000 years BP (Perrin 1984). This mud deposit was partially eroded during a retreat of the sea giving rise to Surface B. On top of this surface, sandy Unit II represents the first barrier in the study area and

points to a phase of intense retrogradation. These two unities compose Pleistocene Sequence I. The existence of the Maricá Lagoon can be envisaged at this point.

- Erosion of the barrier due to low sea level formed Surface C, leaving only a remnant of the previous barrier. Erosive Surface C, together with part of Surface B, forms the upper limit of Pleistocene Sequence I.
- At about 47,000 cal years BP, Unit III was deposited as lagoonal muds. This is highly suggestive of a barrier located farther south, part of another barrier–lagoon system. Rising sea level caused retrogradation of such a barrier, leaving sandy Unit IV. This unit is seen today as the inner barrier at the northern limit of the study area. The Maricá Lagoon was definitely present at this point in time. Later, a lowering of sea level caused progradation of the barrier, which reached a new position at about 45,000 cal years BP. These two units (Units III and IV) make up Pleistocene Sequence II. With the continuous fall of sea level, the area underwent erosion, from at least 35,000 to about 9,000 years BP, which resulted in the important erosional Surface E, marking both the upper limit of PSII as well as the limit between the Pleistocene and the Holocene.
- Holocene sedimentation started with formation of beachrock at 8,560 cal years BP, that represents an old barrier positioned about 100 m south of today's beach. This barrier may have been associated with a paleolagoon (Unit V) at about 6,000 years BP (Pereira *et al.* 2003). Continuous rise of sea level during most of the Holocene, with a maximum at about 5,000 years BP (Angulo & Lessa 1997; Angulo *et al.* 1999; Lessa & Angulo 1998; Angulo *et al.* 2006; Martin *et al.* 1993, 1998, 2003), promoted the retrogradation which formed Unit VIa whose sands filled up the lagoon and gave rise to today's lagoonal plain. These two units compose the Holocene Sequence overlying Surface E. A brief episode of falling sea level allowed the barrier to prograde (Unit VIb). Today, as sea level is rising once again, the barrier has retrograded 15 m in the past 30 years (Lins-de-Barros 2005; Silva *et al.* 2008b).

Understanding the evolutionary history of the Maricá coastal plain is important for better management and preservation of this coastal area in the face of global climate changes and sea-level rise. Moreover, our results and the model proposed here provide a modern analogue for oil and gas reservoirs associated with barrier–lagoon systems.

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