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Holocene Coastal Evolution and Facies Model of the Bragança Macrotidal Flat on the Amazon Mangrove Coast, Northern Brazil

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ABSTRACT

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The Bragança coastal plain is a large back-barrier, macrotidal flat located in Northern Brazil. The plain is part of the largest mangrove system in the world, with approximately 8,900 km^2. Data derived from surface sediment samples, vibra- and percussion-cores, radiocarbon dating, and pollen analysis, allowed for a detailed stratigraphic interpretation along a 25 km long cross-normal profile and the reconstruction of paleo-environmental changes in the mangrove plain. On the basis of lithology, sedimentary structures, texture, color, elevation and bounding surfaces, ten sedimentary facies were identified. Coastal evolution during the last 5100 ^{14}C yr B.P. has been apparently modulated by small scale subsidence events, with the onset of three phases of barrier development. Old mangrove deposits have apparently been deposited around the barriers with ages from 5115 ^{14}C yr BP to 3412 ^{14}C yr BP. After 2100 14C yr B.P., with the development of the last barrier island, about 20 km of mangrove progradation occurred inside the estuary.

INTRODUCTION

The ending of the eustatic sea-level rise around 6000 yr ^{14}C B.P. has left local, relative sea-level trends governed by isostatic and/or tectonic adjustments worldwide. While the high and mid-latitude coastal regions in the northern hemisphere underwent different trends depending on their position in relation to the thawed ice masses, the equatorial region and the southern hemisphere in general went initially through a phase of submersion followed by an emersion cycle (ANGULO *et al.*, 1999; RAMSAY and COOPER, 2002) that might have already ended. Hence, prograded coastal plains are ordinary features along most of the southern hemisphere shorelines, and especially along wave-dominated coasts. Along the Brazilian coast (from Sergipe to Rio Grande do Sul), coastal progradation and the establishment of regressive sedimentary sequences occurred under a condition of excess sediment supply and concomitant sea-level fall (DOMINGUEZ *et al.,* 1992; ANGULO and LESSA, 1997; LESSA *et al.*, 2000).

In the macrotidal coast of northern Brazil (a 480 km long coastline west of the 46º longitude), however, Holocene subsidence (SOUZA FILHO, 2000) has influenced the development of a jagged coast with numerous bays and estuaries that harbor the largest mangrove system in the world. Although contrary to the generally accepted idea that macrotidal settings (tidal range > 4 m) are not conducive to barrier formation (DAVIS and HAYES 1984), estuaries in this macrotidal coast are barred by sand bars in a truly transgressive fashion (MASSELINK and LESSA, 1995; SOUZA FILHO and EL ROBRINI, 2000). Preliminary investigations of the sedimentary facies architecture in a sector of this coastal plain suggested that coastal evolution occurred with sea level close to the current one at least in the last 5000 years (SOUZA FILHO and EL-ROBRINI, 1998; VITAL and STTATTEGUER, 2000; BEHLING *et al*., 2001). Recent palinologic analysis of deep-core samples taken by the international "Mangrove Dynamic and Management MADAM" project, has provided a chance to investigate the complete Holocene sedimentary record of the coastal plain and to incorporate paleo-environmental data into the analysis of the sedimentary facies. The purpose of this paper is to provide a detailed stratigraphic interpretation of the Holocene sediment succession in sector of the coastal plain and to propose a model for the evolution of this setting in the last 6000 years.

DATA SOURCES AND METHODS

The study area is the Bragança coastal plain, which encompasses a 25 km wide mangrove flat and 2 major estuaries: the Caeté and the Taperaçu rivers. A total of fifteen cores (Figure 1) were utilized in this study. The vibracores (BVC) #1 to #9, as well as the percussion cores (PC) #7, #8 and #9, all 6 m in length, were obtained from previous studies (SOUZA FILHO and EL ROBRINI, 1998; BEHLING *et al.*, 2001). The remaining three vibracores were taken with a "Rammkernsonde" (RKS) that reached 19 m below ground level. Ground elevation at the core sites were determined with topographic surveys aided by tidal levels. The RKS cores were described, photographed and sampled for grain size analysis and radiocarbon dating when still in the field. In the laboratory, 107 sediment samples were grain sized and 14 samples were radiocarbon dated.

Standard pollen analyses were performed in 0.5 cm^3 samples taken from muddy layers throughout the RKS cores. Amongst of the 81 sediment samples, only 24 had a minimum of 300 pollen grains necessary to be validated by statistical analysis. Five 1 cm thick slabs of organic-rich mud were taken for radiocarbon dating by the accelerator mass spectrometry (AMS) method in the Laboratory for Age Determination and Isotopic Research of Kiel University. The samples were collected from RKS #1, RKS #2 and RKS #3 at elevations -4.0 and -7.8 m, -4.0 and -4.59 m, and 5.51 m, respectively.

RESULTS

Fossil pollens

Among the 81 samples counted, 42 different pollen types were recognized. Mangrove-related pollens, produced by *Rhizophora, Avicennia* and *Laguncularia*, accounted for 88% of the total. Pollen grains, produced by herbs such as *Poaceae*

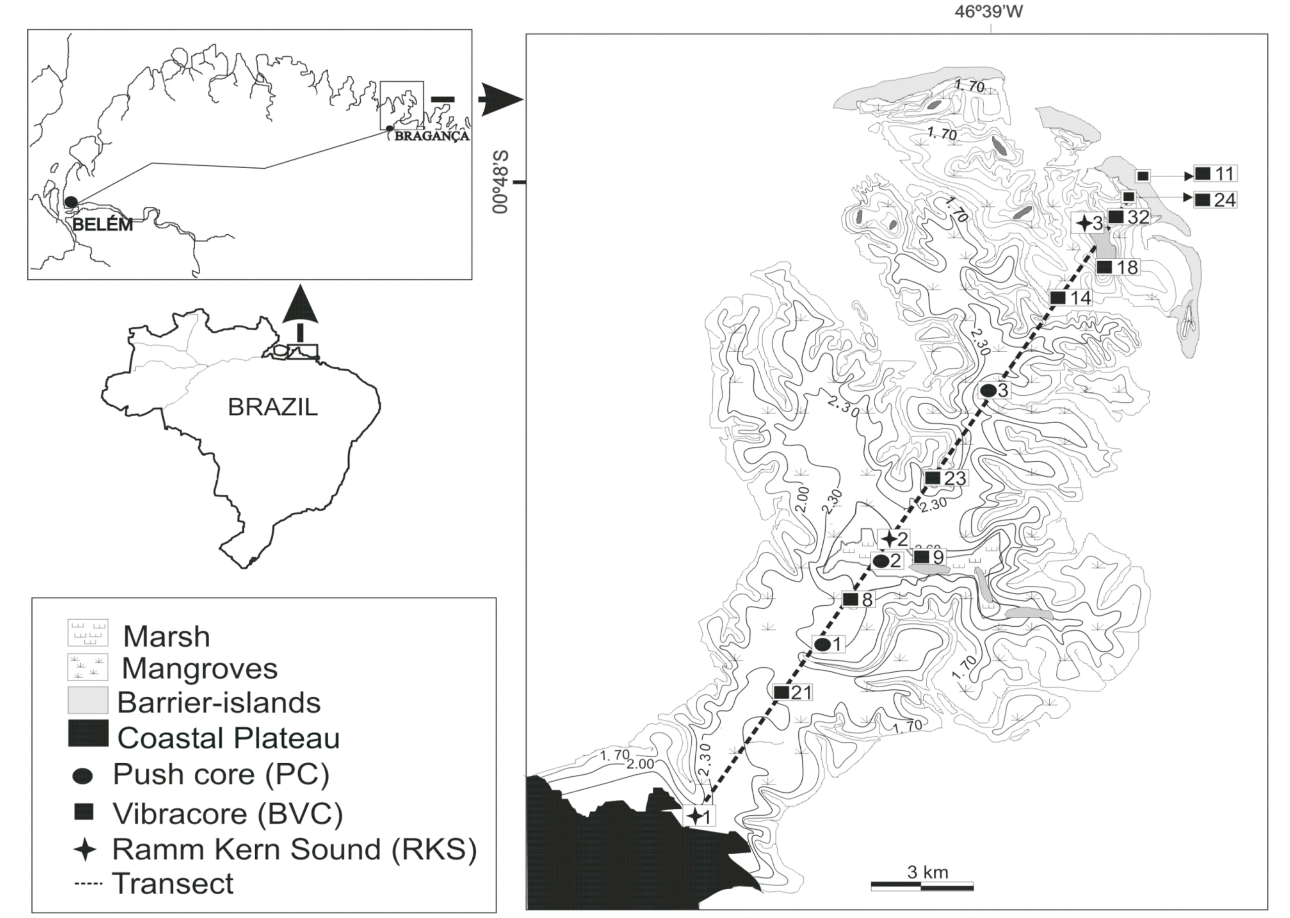

Figure 1. Location of the study area and its associated topography (reduced to mean sea level in mete) r and coastal environments. Also, location of the morphostratigraphic transect with the coring sites and corer type.

Cyperaceae, Acanthaceae, Amaranthaceae-chenopodiaceae, Alternanthera, Asteraceae-Asterioideae, Asteraceae-Cichorioideae, Borreria and *Spermacoceae*, accounted for 6% of the total.

A statistically significant number of mangrove pollen grains in RKS #1 were only found at elevations 0.5 m, -0.85 m and -17.9 m, with *Rhizophora* grains representing 90-97%, *Avicennia* grains representing 1-6%, and *Laguncularia* grains representing 0-0.3%. In RSK #2 only the -1.09 m to -1.45 m elevation interval presented sound evidence of mangrove colonization with 85-91%, 2-7%, and 0-0.2% of *Rhizophora, Avicennia, and Laguncularia*, respectively. A significant quantity of *Cyperaceae* (62%) and Poaceae pollen (10%) was identified at -1.6 m. The mangrove pollens at this level accounted for 19% of the total pollen grains identified. In RKS #3, a significant number of mangrove pollen grains were only observed between +2m and -1m where 5 layers were sampled.

Radiocarbon Dates

The two samples from RSK #1, collected at - 4.01 m and -7.8 m, were dated at 1441 ± 28 and 37,110 ± 310 yr B.P. ^{14}C, respectively. The samples from core RKS-2 were dated at 2820 ± 30 (-4.0 m elevation) and at 3412 ± 31 ^{14}C yr BP (-4.59 m elevation). Finally, the sample from core RKS #3, -5.51 m elevation, was dated at 756 ± 30 ^{14}C yr BP.

Eight other radiocarbon dates used in this paper were published by Behling et al. (2001), and their location, age (^{14}C) and elevation are listed as: PC #1, -15 ± 41 yr B.P., -1.4 m; PC #1, 1830 ± 23 yr B.P., -3.4 m; PC #1, 2088 ± 39 yr B.P., -6.4 m; PC #2, 373 ± 25 yr B.P., -1.5 m; PC #2, 1018 ± 26 yr B.P., -2.1 m; PC #2, 5115 ± 35 yr B.P., -2.55 m; PC #3 at -482 ± 23 yr B.P., -1.1 m; PC #3, 1265 ± 25 yr B.P., -2 m; PC #3, 1437 ± 35 yr B.P., -2.59 m.

Sedimentary facies

On the basis of lithology, sedimentary structures, texture, color, elevation and contact, 10 sedimentary facies, overlaying the Miocene substrates, were identified in the coastal plain (Figure 2). Two sedimentary facies were interpreted as Miocene in age, one was interpreted as Pleistocene, and the remaining ones were interpreted as Holocene. The substrates for the Quaternary sedimentation include the Miocene carbonates of the Pirabas Formation (ROSSETTI, 2001) at the base of the RKS #3 (Figure 2) and the Tertary siliciclastic sands and muds of Barreiras Formation (ROSSETTI, 2001) at the bottom of core RKS #1. From the oldest to the youngest, the facies are:

(1) Pre-Holocene fluvial channel: poorly-sorted, very coarse quartz sand to gravel and light gray in color. This facies appears to fill in the paleo-valley incised into the Miocene substrate (Figure 2). The lithological similarity and physical continuity of these deposits with present fluvial deposits strongly suggest that theses sands and gravels were deposited in a fluvial environment landward of the bayline. It was found in core RKS #1.

(2) Transgressive-mud facies: composition of this facies is characterized by more than 70 % of fine sediments (<0.062 mm), with a small percentage of very fine quartz sand and shell fragments. The transgressive-mud facies rests on the substrate (RKS #2 and #3) and is overlaid by the subtidal sand-flat and intertidal sandshoal facies.

(3) Tidal meanders facies: is comprised of tidal deposits marked by laminations of white, fine quartz sand and gray-greenish mud, mostly bioturbed and with root fragments. This facies overlies the Pre-Holocene fluvial channel facies in abrupt contact, and underlies the subtidal sand-flat facies.

It was found in core RKS #1 between 15.8 and 17.6 m elevation.

(4) Aeolian sand facies: this facies is composed predominantly of light-gray, fine-quartz sand beds, mostly bioturbed and

intercalated with fine-mud beds that were radiocarbon dated (UtC-8737) at 37110 ± 310 ^{14}C yr B.P. Parallel sand laminations (highlighted by organic matter) are the most frequent sedimentary structures. The contact between dune and interdune subfacies and underlying tidal meandering facies is abrupt and marked by a discordance, while the contact with the overlying intertidal shoal facies is likely to be erosive, defined by gravel coarse sands. According to KOCH *et al.* (2003), analyses of inorganic compounds in sediment suggest fluvial deposition due to high concentration of organic carbon (~8%) and biomarker distributions which rather resembled herbal species. However, based on stratigraphic analysis this deposit can be associated to fresh water lakes in the interdune zones. Dune subfacies is represented by vegetated foredunes characterized by massive, and tabular cross-bedded, rooted and burrowed, well-sorted very fine quartz sands with few shell fragments. Dune sands often appear weathered, with oxidation best developed landward. The thickness of this facies varies between 0.5 to 7.0 m and it is deposited over mangrove mud facies. The contact between bthis facies and mangrove mud is abrupt and define a ravinement surface.

(5) Subtidal sand-flat facies: is comprised of rounded and well-sorted fine quartz sands with shell fragments. The sediments are light-gray in color with greenish tone due to different degrees of mud content. Characteristic sedimentary structures are bioturbation, which lends a mottled structure, cross-bedding and flaser. The contact between this facies and the underlying transgressive mud facies is abrupt, whereas the contact with the overlying old barrier-dune-beach facies is marked by an erosion surface where medium to coarse sand, rich in shell fragments, accumulates. The presence of marine organism associated with sedimentary structures is a strong indication that this facies was subjected to marine processes, but it was still influenced by tidal process.

(6) Intertidal sand shoal facies: is comprised of a very fine, well-sorted, rounded, white to very light-gray quartz sands, showing bioturbation, sparse concentration of shell fragments, and pieces of mangrove wood. The main sedimentary structures are flaser bedding and small scale cross-stratification associated to ripple marks. This facies can be subdivided in an upper and lower section based on the sedimentary structures. While the lower section is mostly characterized by a profusion of flaser beddings, cross-stratification and a more significant amount of shells and shell fragments are most common in the upper section. The lower and upper contacts of this facies are commonly gradational, overlying upper-flow regime sand flats, transgressive muds and subtidal sandbars facies, and underlying old beach-ridges and mudflats and recent mangroves. This facies represents the thickest sedimentary unit, forming a wedge that thickens seaward from 6 m (RKS #1) to 10 m (RKS #2) (Figure 2).

(7) Barrier-island facies: is comprised of a fine, well-sorted, rounded, white and brownish quartz sands (response to oxidization processes) with sparse shell fragments. It is generally composed of three subfacies, which are beach, dune and washover facies. Three generations of barrier-islands were recognized in the plain, as follows:

-Oldest barrier-island: a beach subfacies was recognized from parallel lamination and bioturbation, while an aeolian dune subfacies could be distinguished by climbing laminations and its preserved morphology. This barrier is restricted to RKS #3 (from +1.4 to -4.60 m in elevation) and BVC #9 (from +1.4 to -2.1 m in elevation), outcropping along the Bragança-Ajuruteua road 12 km landward from the present shoreline. It overlies the intertidal shoal facies and is underlain by mangrove mud facies. The contact between the barrier and mangrove facies was radiocarbon dated (UtC-8737) at 5115 ^{14}C yr B.P. (BEHLING *et al.,* 2001).

-Second oldest barrier-island: is restricted to RKS #2 (from surface to 1.8 m in elevation). This barrier overlies mangrove mud facies radiocarbon dated (KIA-13961) at 2820 ± 30 ^{14}C yr B.P. Its lower contact is abrupt, chopping animal burrows filled with fine sands. This facies can be subdivided in three sub-facies: i) dune facies, with the original morphology still preserved, composed of very fine, white sand with large tabular cross-stratification; ii) beach facies, characterized by oxidized brownish fine sands with massive and mottled structures ascribed to bioturbation; and iii) washover facies, distinguished by foreset stratification dipping 23º landward. This barrier has been found outcropping at least 2.5 km landward in relation to present shoreline.

-Most recent barrier-island: given its pristine condition, it was possible to differentiated five sub-facies: i) vegetated and mobile coastal dunes with climbing and tabular cross-stratification; ii) high intertidal zone with a thin to medium set of inclined plane-parallel laminae defined by quartz and heavy minerals sands intercalated; iii) mid-intertidal zone with plane-parallel sedimentary structures; iv) low intertidal zone where it is possible to observe shallow alongshore channels with low angle cross-stratification, and v) subtidal zone composed of mixed sand-mud sediments densely bioturbed by burrows of *Callichirus* sp. and others crustaceans. Characteristic elevations of this unit were +7 (in the dunes), +2.8 (in the beach scarp) and 2.7 (in the bottom of BVC #11). The presence of a barrier island with a transgressive morphology, with dunes migrating over mangrove forests and active washover fans, and above all, drowned dune deposits in the intertidal zone (Figure 2), are considered evidence of an ongoing transgressive episode (SOUZA FILHO and EL-ROBRINI, 1998). This facies is underlain by mangrove mud facies with an abrupt contact interpreted as a wave-ravinement surface (BVC #11).

(8) Mudflat facies: is composed of soft, dark gray and organic-rich mud, with mean grain size commonly about 4.005 Phi. Lenticular beddings are common. This unit is restricted to RKS #1 from 0.45 to 3.00 m in elevation, where mangrove pollens were not found. This unit is interpreted as a progradational mudflat that overly the intertidal sand shoal facies whose contact is marked by abrupt lithological change from very fine sand to mud.

(9) Mangrove mud facies: a soft, dark gray, highly organic mud, found at the top of most of the cores (Figure 2). The maximum elevation of this facies is about +2.4 m above the mean sea-level, and the minimum elevation is around -4.5m. Its thickness increase seaward, from 2 m to 5-6 m. The mangrove mud is overlaying mudflat, intertidal sand shoal and old dune-beach ridge facies, and is interpreted as a progradational unit, with radiocarbon ages younger than 2088 ^{14}C yr B.P. This facies is observed in the surface of all cores, except in the BVC #8, RKS#2 and RKS#3.

(10) Marsh mud facies: composed of hard, dark gray and organic mud, whose interstitial pore water presents salinity about 19. The top of this facies is marked by mud cracks and salt accumulation during the dry season, defining a sub-aerial exposure surface. The contact between marsh mud facies and the underlying mangrove mud facies is defined by significant decrease in *Rhizophora* pollens and increase of *Avicennia* and Cyperaceae pollens in direction to the top. This contact was radiocarbon dated (UtC-8724) at 373 ^{14}C yr B.P. (BEHLING *et al*., 2001). The unit is distributed over the highest areas of the plain (+2,6 m above the mean sea-level) densely covered by grassland. Based on polled record, this is 0.5 m in thick in RKS #3. This unit is interpreted as formed within a supratidal salt marsh.

INTERPRETATIONS AND DISCUSSION

The base of the Quaternary sedimentation is represented by the Pre-Holocene fluvial sand and gravel facies deposited in a fluvial channel section carved in the Tertiary deposits (Figure 2). The incised valley would be older than the fluvial deposits, which may rest on a sequence limit and harbor an initial inundation surface. This initial inundation surface may also be represented by the contact between the transgressive mud facies and the Miocene substrate (Facies 4, RKS #2 and RKS #3). The deposition of this facies followed the inundation of the coastal lowlands with fringing marsh and mangrove muds. Similar

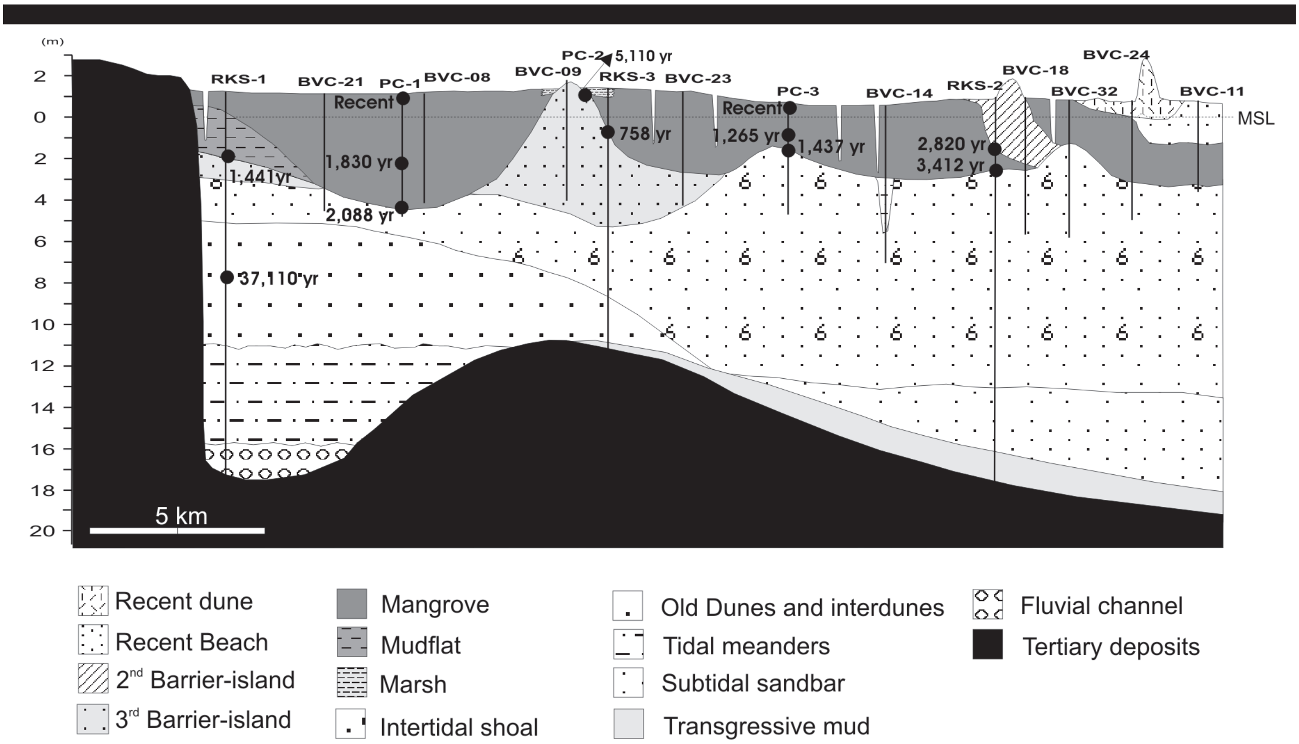

Figure 2. Cross-normal morphostratigraphic profile along the Bragança coastal plain, between the coastal plateau and the shoreline with the most recent barrier-island.

deposit would apparently be the over-consolidated mud identified by TORRES (1997) in Amazon River mouth, in the bottom of a 17 m deep channel. The transgressive mud facies thins landward as it onlaps the Miocene substrate. The absence of this facies landward, draping over the fluvial channel facies, could be related to non-deposition or erosion caused by a more intense tidal ravinement in a narrower incised valley, with stronger tidal current velocities and possibly a thinner deposit due to smaller accommodation space. This process was mentioned by LESSA *et al.* (1998) to explain the absence of transgressive mud facies in the landward half of Paranaguá Bay, Southern Brazil.

Erosion of the transgressive mud facies closer to the coastal cliffs might be ascribed to the establishment of tidal meanders, which laid down the tidal meandering facies over the fluvial sand and gravel facies. The contact between these facies may also represent the tidal ravinement surface. The presence of subtidal sand-flat and intertidal sandshoals deposited over transgressive mud facies indicates that a shallow intertidal sand sheet has continuously transgressed over an estuarine environment as the sea level rose. These facies (5 and 6 and 7) comprised the upper portion of the estuarine transgressive deposit. According to MASSELINK and LESSA (1995), bed aggradation allows a gradual transition from subtidal sandbar into intertidal shoal. The presence of flaser bedding and wood fragments indicates that mangroves or muddy tidal flat existed close by.

According to DALRYMPLE *et al*. (1992), estuaries in a mixed energy (tide plus wave) coast may be associated with short barrier islands. Besides the present barrier-island, at least two others can be observed in the coastal plain overlying intertidal shoals and underlying old mangrove mud. The older barrier-island (5115 ^{14}C yr B.P.) is associated with to Holocene transgression maximum of 5100 ^{14}C yr B.P., when the coastline was situated some 12 km landward from the present one (Figure 2). Given the low elevation of this facies, a 1-2 m subsidence must have occurred to explain its position close to present mean sea level.

In accordance to BEHLING (2002), there is a general decrease of the pollen content in the mangrove deposits of the State of Para between 5600 and 3600 ^{14}C yr B.P., suggesting a fall of sea level and a decrease of the forested area. This may also be the reason for the apparent inexistence of mangrove deposits between 5100 yr. B.P. and 2800 ^{14}C yr B.P. in the study site. The mangrove deposition around this latter date may have occurred as a response to a new transgressive cycle that was also conducive to the development of a second generation of barrier island, which rolled over back-barrier sediments.

In the last 2000 years there was a fast mangrove progradation internal to the estuary, from paleo-cliffs all the way to the 2nd oldest barrier. It is initially suggested that such progradation may have occurred in a more sheltered environment that came about with the development of a larger barrier island(s).

Another regressive-transgressive cycle, perhaps with a smaller magnitude, has apparently occurred more recently as suggested by the presence the 3rd generation of barrier island that is presently burying back-barrier deposits. Transgression is evidently an ongoing process, as indicated by washover fans and especially drowned (within the intertidal level) sedimentary structures characteristic of aeolian sand dunes.

CONCLUSIONS

The Bragança coastal plain evolved from a riverine environment into an intertidal muddy area accompanying the last eustatic sea level rise. Deposition of the marine/estuarine facies has occurred in association with three generations of barrier islands, developed in a truly transgressive fashion, triggered apparently by at least two small subsidence episodes in the last 3000 years. The absence of mangrove deposits with ages between 5100 and 2800 ^{14}C yr B.P., as well as general decrease of mangrove pollen in the whole region, suggests that a sea level fall preceded at least the development of the second barrier-island generation. In the last 2100 years, a more stable sea level was conducive to the most significant progradation phase, when mangrove swamps prograded more than 20 km. A new transgressive event is apparently occurring, and makes the Bragança coastal plain a classic study case of barrier island development on a macrotidal setting.

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