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Determination of controls on Holocene barrier progradation through application of OSL dating: The Ilha Comprida Barrier example, Southeastern Brazil

C.C.F. Guedes [a,*], P.C.F. Giannini [a], A.O. Sawakuchi [a], R. DeWitt [b,1], D.R. Nascimento Jr. [a], V.A.P. Aguiar [a], M.G. Rossi [a]

[a] Departamento de Geologia Sedimentar e Ambiental (Instituto de Geociências da Universidade de São Paulo), Rua do Lago 562, São Paulo-SP 05508-080, Brazil
[b] Radiation Dosimetry Laboratory, Department of Physics, Oklahoma State University, 1110 South Innovation Way Drive, Stillwater, OK 74074, USA

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ABSTRACT

Barrier development during the Holocene is studied using the example of the Ilha Comprida, Southeastern Brazil. Aerial photos, facies analysis, and optically stimulated luminescence dating are used to define the barrier emergence and evolution. Optically stimulated luminescence ages and facies successions indicate that the Ilha Comprida probably began as a Holocene transgressive barrier island 6000 years ago, just before the last relative sea-level maximum. Since then the barrier has prograded through the addition of curved beach ridges. Based on beach ridge alignments, six units of growth are identified with two growth directions, transverse and longitudinal. Rates of progradation with transverse growth vary from 0.13 to 4.6 m/year. Rates of longitudinal growth to NE range from 5.2 to 30 m/year. Variation in coastal progradation rates and sediment retention during the last 6000 years is compared with climate, physiography and relative sea-level changes. The physiography, represented by pre-Cenozoic hills, is the major control on sediment retention and alternation between longitudinal and transverse growth. Climate variations, such as the Little Ice Age event, apparently control the formation of ridges types: beach ridges, foredunes, and blowouts. These results allow the use of the Ilha Comprida Barrier as an example to analyze the major controls on barriers progradation.

1. Introduction

Successions of ridges (strandplains) formed by progradation of wave-dominated coastal systems are common features on Quaternary coastal plains. “Beach ridge” has been used as a generic term (Otvos, 2000), including coastal aeolian and wave deposits, or as a specific term (Hesp et al., 2005) referring to wave deposited ridges usually formed during high wave conditions and/or elevated water level. Foredunes are distinguished from beach ridges and consist of wind transported sands trapped by vegetation on the backshore (Hesp et al., 2005). The study of the morphology and truncation pattern of beach and foredune ridges successions allows paleogeographic scenarios of coastal evolution to be defined (Tanner, 1995; Otvos, 2000; Murray-Wallace et al., 2002; Goodwin et al., 2006; Nielsen et al., 2006; Rink and López, 2010). Recent developments of optically stimulated luminescence (OSL) dating methods (Duller, 1995; Murray and Wintle, 2000; Wintle and Murray, 2006) provide a precise timescale for models of paleogeographical evolution in coastal settings. Based on OSL dating, some studies have demonstrated that the morphology of beach and foredune ridges as well as coastal progradation are sensitive to Holocene climate changes on millennial to centennial timescales (Goodwin et al., 2006; Brooke et al., 2008; Sawakuchi et al., 2008; Nott et al., 2009; Timmons et al., 2010).

Holocene sandy barriers are common landforms along most populated subtropical to tropical coastal regions of the Earth. The evolution of Holocene regressive barriers has been intensely studied during recent years due to the high sensitivity of these coastal settings to autogenous sedimentary dynamics, climate and sea-level changes. However, few studies have focused on the evolution of regressive barriers on the eastern coast of South America. The Southeastern Brazilian coast stands out due to its specific characteristics, which include wet climate without dry season, well developed rainforest and coastline segmented by rivers with permanent flow and hills of igneous and metamorphic rocks. The present knowledge about the geology and geomorphology of Holocene regressive barriers from the Brazilian coast has been summarized recently by Dillenburg and Hesp (2009), but detailed chronologies of the depositional history of these barriers are still scarce. In this context, the Ilha Comprida Barrier is one of the most studied Holocene barriers on the Brazilian coast (Geobrás, 1966; Suguio and Martin, 1978; Nascimento et al., 2008; Sawakuchi et al., 2008; Giannini et al., 2009; Guedes et al., 2011). Giannini et al. (2009) provided a detailed characterization of the

* Corresponding author. Tel.: +55 11 3091 4128; fax: +55 11 3091 4129.
E-mail addresses: ccfguedes@yahoo.com.br (C.C.F. Guedes), pcgianni@usp.br (P.C.F. Giannini), andreos@usp.br (A.O. Sawakuchi), regina.kalchgruber@okstate.edu (R. DeWitt), danieljr@usp.br (D.R. Nascimento), vitor_ap_aguiar@hotmail.com (V.A.P. Aguiar), mgros_ma@yahoo.com.br (M.G. Rossi).
[1] Tel.: +1 405 744 1013; fax: +1 405 744 1112.

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barrier geology and geomorphology. The chronology of the aeolian dunes present at the seaward portion of the Ilha Comprida Barrier and their relation with Late Holocene climate changes were analyzed by Sawakuchi et al. (2008). Nevertheless, the chronology of the barrier evolution still has not been determined. In this work, OSL dating of quartz grains is used to establish a detailed chronology of the development of the Ilha Comprida Barrier and to calculate coastal progradation rates during the last 6000 years. The variation of barrier progradation rates is compared with climate, physiographic and relative sea-level (RSL) changes. The results of this comparison permit us to use the Ilha Comprida Barrier evolution to analyze the major controls on progradation of barriers and strandplains. Understanding the evolution of barriers from different climate, sea level and physiographic contexts is necessary for the development of general models of coastal depositional systems.

2. Regional setting

2.1. The Ilha Comprida Barrier

The Ilha Comprida Barrier is located in the southern coast of São Paulo State, in the southeast Brazil (Fig. 1). It is a coastal sand barrier formed by multiple coastal-parallel beach and foredune ridges. According to the Roy et al. (1994) classification, it can be considered as a prograded barrier. However, it also can be classified as a barrier island in a geomorphic sense (Reinson, 1992) because it is separated from the mainland by the Cananéia–Iguape estuary–lagoon system.

Evolutionary models for the Ilha Comprida Barrier were proposed by Geobrás (1966), Martin and Suguio (1978), and Giannini et al. (2009) based on the geometry of beach ridge alignments. The control exerted on the barrier growth both by the Icapara inlet dynamics and the physiography, in particular, by the hill near Iguape, was highlighted by Geobrás (1966) and Giannini et al. (2009). Otherwise, Martin and Suguio (1978) linked different beach ridge generations to RSL variations in the Quaternary over the physiographic control. The initial formation of the barrier was associated both with a Holocene capture of drainage (Geobrás, 1966) and with a previous Pleistocene barrier (Martin and Suguio, 1978). This Pleistocene phase has been dismissed by Holocene radiocarbon ages (Angulo et al., 2009; Giannini et al., 2009), but the Ilha Comprida emergence is still unclear.

2.2. Physiographic setting

The Brazilian southeast coast is characterized by the Serra do Mar escarpment, which is closer to the coastline in the north and lies further back in the south. This recess on the southern coast coincides with the development of extensive coastal plains, such as the Cananéia–Iguape plain, which comprises the Ilha Comprida Barrier. The Cananéia–Iguape coastal plain occupies an approximately triangular area along the coast, about 130 km long (between Cardoso Island and the Itatins granulitic terrain, at Peruíbe) and 40 km at its widest (the distance from its apex, at Registro, to the coastline of Ilha Comprida). This geomorphological feature corresponds to an amphitheater formed by fluvial erosion of the Serra do Mar hills by the tributaries of the lower Ribeira de Iguape drainage basin (Almeida and Carneiro, 1998), and/or by fault slopes (Souza et al., 1996; Zalan and Oliveira, 2005).

The limits of the amphitheater show orientation coincident with directions of major regional structural lineaments (NW, WNW, and NE), generated or reactivated since the Mesozoic Era (Giannini et al., 2009). The presence of crystalline basement tilted blocks dipping to the NW, detected by geophysical methods under the Cananéia–Iguape coastal plain, allowed Souza et al. (1996) to infer the presence of a Cenozoic hemigraben related to the Serra do Mar rift system.

In this context, some pre-Cenozoic basement that outcrops near Ilha Comprida could have influenced the barrier growth by changes in the ancient Icapara inlet dynamics. Some of them are the hills near Pedrinhas and Iguape and the Pedra do Tombo, a submerged outcrop in the Mar Pequeno Lagoon (Fig. 1).

2.3. Climate, tides, waves, winds and relative sea-level curves

The dominant climate in the Ilha Comprida region is the Cfa type (wet subtropical with a warm summer) according to the Köppen classification. The annual average temperature is 20.7 °C, with average relative air humidity higher than 80% and absence of a well defined dry season (Lepsch et al., 1990). The coast is under a microtidal regime (Davies, 1964) with an average tidal range varying between 1.2 m in the spring tide and 0.25 m in the neap tide (Mesquita and Harari, 1983). Two swell wave systems operate in the region: one from E and NE associated with trade winds and another from S and SE related to cold fronts (Tessler, 1988). The two wave systems are responsible for alongshore transport systems with opposite directions but predominant transport to NE. Grain-size trends and heavy-minerals distribution in recent sediments (Barcelos, 1975; Tessler, 1982, 1988; Souza, 1997; Tanaka et al., 2005; Nascimento, 2006; Nascimento et al., 2008; Giannini et al., 2009; Guedes et al., 2011) as well as in older deposits of the Ilha Comprida Barrier (Tessler, 1988; Giannini et al., 2009; Guedes et al., 2011) have been interpreted in terms of this alongshore transport.

Previous studies about Late Quaternary RSL changes on the Brazilian coast were performed by Martin and Suguio (1975, 1976, 1978), Martin et al. (1979, 1979/80), Suguio and Martin (1978), Suguio et al. (1976, 1980) and Angulo et al. (1999). Angulo and Lessa (1997) and Angulo et al. (2006) carried out an extensive revision of the Holocene RSL changes on the Brazilian coast. Vermetid shell data compiled and reinterpreted by Angulo et al. (2006) indicate a maximum RSL of 2 to 3.5 m above the present level between 7000 and 5000 years cal BP followed by smooth relative sea-level fall until the present. This pattern agrees with the global eustatic curve predicted by the model of Milne et al. (2005).

3. Methods

3.1. Aerial photos analysis

Beach and foredune ridge orientation was mapped using two different aerial photo mosaics, from the years 1962 and 2000, at scales 1:25,000 and 1:35,000 respectively. This map was elaborated in three steps: 1. definition of alignment directions by the identification of height contrasts considered independent of vegetal cover; 2. delineation of successive ridge truncations between the alignment directions previously traced; 3. identification of evolutionary phases, based on the sets or bundles of concordant ridge alignments. This method allowed the separation of six different units of barrier growth.

3.2. Sediment accumulation estimates

Estimates of sediment accumulation over time were based on the ratio between the area and the time period of each growth phase. The area of each growth unit was calculated through GIS software using georeferenced Landsat images and aerial photos. In each case, the area value adopted corresponds to the island area during that time span, excluding the paleolagoon area. The absence of dunes and foredunes morphology, as well as changes on topography, in almost all the barrier surface allow us to consider the area of each growth unit a good approximation of sediment volume of the unit. The time span of each phase was obtained by OSL ages and the respective rates of sediment accumulation were expressed in 10^3 m^2/year.

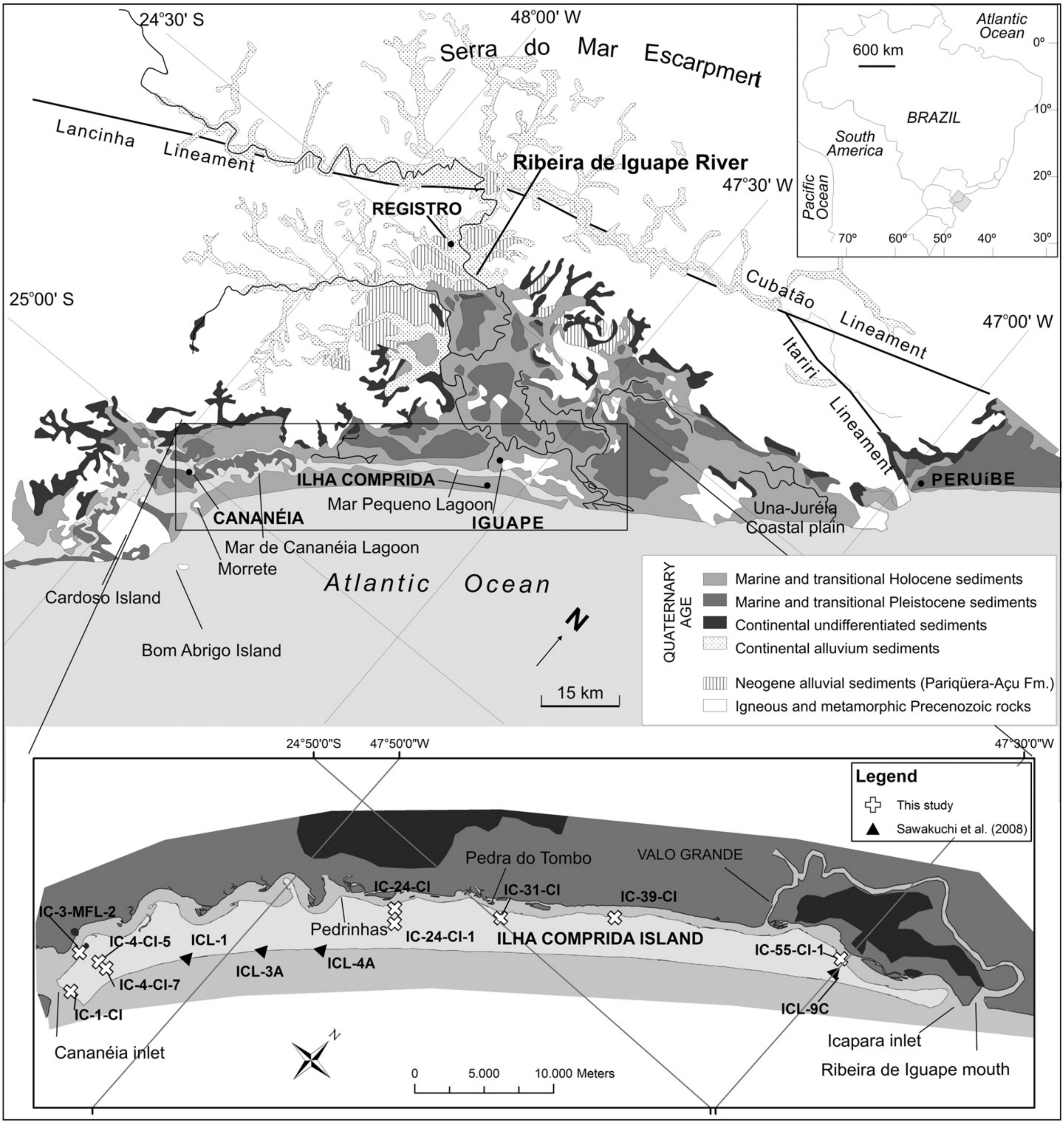


Fig. 1. The Cananéia–Iguape lagoonal system and the Ilha Comprida Barrier: location and geological map, modified from IPT (1981). The bottom map shows the OSL sample locations.

3.3. Facies analysis

Facies analysis was based on sedimentary structures, grain size and pedogenic features observed in outcrops from cliffs along the inner margin of Ilha Comprida Barrier and in trenches or pits. The distinction between aeolian and subaqueous facies was based on their sedimentary characteristics and morphologic aspects (beach ridges, foredunes, blowouts, parabolic and barchanoid dunes) in the field and/or aerial photos. 317 measurements of dip direction were taken on cross stratifications to estimate paleoflux directions.

3.4. OSL dating

Nine sediment samples were collected in pits and outcrops within areas previously separated by aerial photo interpretation (Fig. 1). The upper pedogenic horizons (spodossol O, A and E) were avoided to prevent the possible effect of weathering on the determination of equivalent radiation doses and dose-rates.

The equivalent doses were determined with quartz aliquots using a single aliquot regeneration-dose (SAR) protocol (Murray and Wintle, 2000; Wintle and Murray, 2006). The preparation of quartz aliquots was performed under red light and consisted of: separation of 120-150 μm sand grains through wet sieving; treatment with H_2O_2 27%, HCl 3.75%, HF 48–51% for 40 min, in order to remove organic carbon, $CaCO_3$ and feldspars, respectively; density separation with lithium polytungstate solution (at densities of 2.75 g/cm^3 and 2.62 g/cm^3). The OSL measurements were carried out with an automated Risø DA-15 TL/OSL system in the Radiation Dosimetry Laboratory at Oklahoma State University (Stillwater). The built-in ^{90}Sr/^{90}Y beta sources give dose rates of 99.6 ± 4.1 mGy/s. Optical stimulation was carried out with blue LEDs (470 nm), delivering 31 mW/cm^2 to the sample. The heating rate used was 5 °C/s. The equivalent dose of each sample was calculated as the weighted mean of 20 to 24 quartz aliquots.

The concentrations of ^{40}K, ^{238}U and ^{232}Th used for dose-rate estimation were determined by gamma-spectrometry with a high resolution HPGe detector inside a 15 cm lead shield. Concentrations were obtained by comparison with standard samples of isotopes. Beta and gamma dose-rates were calculated using the conversion factors given by Adamiec and Aitken (1998). The contribution of cosmic radiation to the dose rate was calculated as described by Barbouti and Rastin (1983) and Prescott and Stephan (1982).

4. Results

4.1. Beach ridge and dune ridge characteristics

In Ilha Comprida, beach and foredunes ridges can be identified through changes in vegetation types and density. However, the contrast in vegetation characteristics is not persistent along a ridge. Therefore, it was not possible to define the number of ridges, but only the ridge directions. Two main types of contrasts in vegetation were observed: between dense and sparse arboreal vegetation, and between sparse arboreal vegetation and grass vegetation. The first type is found in old stabilized beach ridges from inner portions of the island (inner unit sensu Sawakuchi et al., 2008), while the second is predominantly observed near the shoreline (middle and outer unit sensu Sawakuchi et al., 2008). The ridges near the beach are mainly foredune ridges, as observed during fieldwork (Fig. 2). For ridges located on the inner part of the island it is not possible to find out the origin (if foredune ridge or beach ridge) due to the high density of vegetation. Indeed, the presence of aeolian deposits in the inner part of the island was not confirmed in the field. Thus, coastal morphodynamic conditions may have been different in the past for the island.

In recent times, the ongoing process of formation of curved ridge alignments is clearly observed at the northeastern end of the island. This same pattern of ridge geometry can also be observed in ancient ridges almost along the entire island (Fig. 3). The first curved ridge is located 3.5 km NE from the Frade Spit (Fig. 4). These curved ridges occur in the inner portion of the island, near the lagoon or paleolagoon areas, and occupy almost the entire width of the barrier near the northeastern end. This pattern indicates how the barrier grows through transverse and longitudinal accretion, as described by Guedes (2003) and Giannini et al. (2003, 2009) and it is similar to the Icapara Inlet morphology.

The directions of ridge alignments are variable. Thus, older beach ridges can be truncated by younger ones or by the present shoreline in places under wave erosion. Based on the observed truncations of ridge alignments, different units of barrier evolution were distinguished. Where it was impossible to map ridges that limit evolutionary units continuously along the entire island, the frontier between units was traced in a direction parallel to the adjacent visible ridges, except where there was evidence of truncation between ridges. As a result, the barrier was divided into six units of growth (Fig. 5).

Unit 1 is located in the inner west of the island. It has few visible beach ridges due to its dense vegetation. According to Suguio and Martin (1978), it would correspond to a Pleistocene area. However, its Holocene age was subsequently determined by radiocarbon dating (5308–4877 cal yr BP) of an in situ wood trunk (Giannini et al., 2009). Units 2 and 3 are characterized by a combined transverse and longitudinal barrier growth. Transverse growth is virtually absent in unit 4, which shows truncated ridges. Unit 5 is strongly influenced by the presence of the hills near Iguape, which blocked the longitudinal barrier growth with the formation of about one third of the present total width of the island. In the remaining unit 6, the evolution of the barrier is characterized by the end of the hill blockade and the return of conditions of high longitudinal barrier growth.

On a 300 to 1000 m wide section on the shoreside portion of the barrier, several wind deposited features can be observed, such as incipient foredunes, established foredunes, blowouts, parabolic and barchans dunes. Through analysis of aerial photos, a relatively tall (up to 9 m) and laterally continuous ridge of stabilized dunes was observed, which limits the occurrence of wind deposited features. Belonging to unit 5, this ridge also marks the beginning of the last evolutionary unit (6), and recesses up to 1000 m from the present coastline close to the region of maximum narrowing of the island, in the northeast end. Towards the SW direction, this wind generated ridge gradually converges on the coastline up to the mid-southwest portion of the barrier, where it is under present wave erosion. In this region, this ridge is capped by active blowouts, with advance of wind features onto the older and inner beach ridges. Finally a small active trangressive dunefield, 2 km long and 400 m wide migrating to NW, is observed in the maximum narrowing area of the barrier. In aerial photographs, barchans and parabolic dunes are observed on this dunefield.

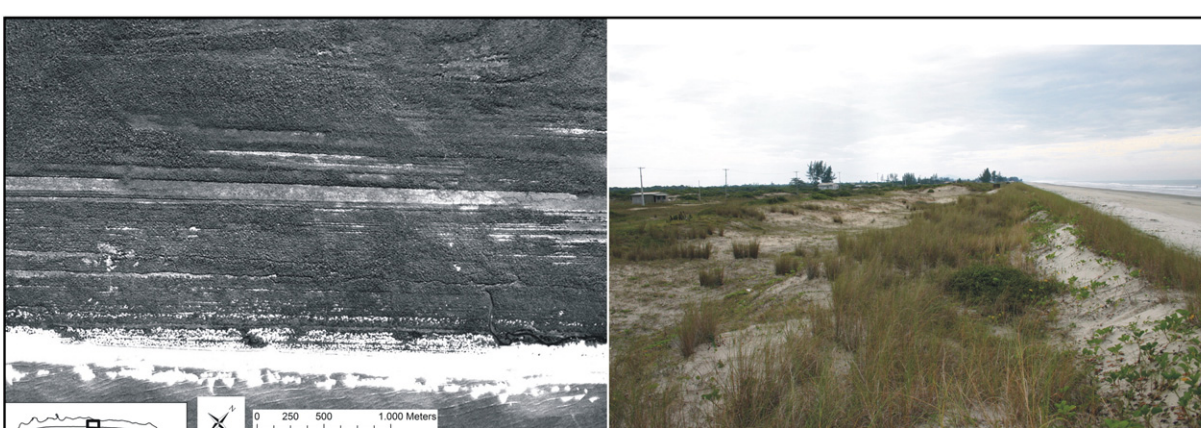


Fig. 2. Foredune ridges as seen near the shoreline. Left from 1962 aerial photos and right in the field.

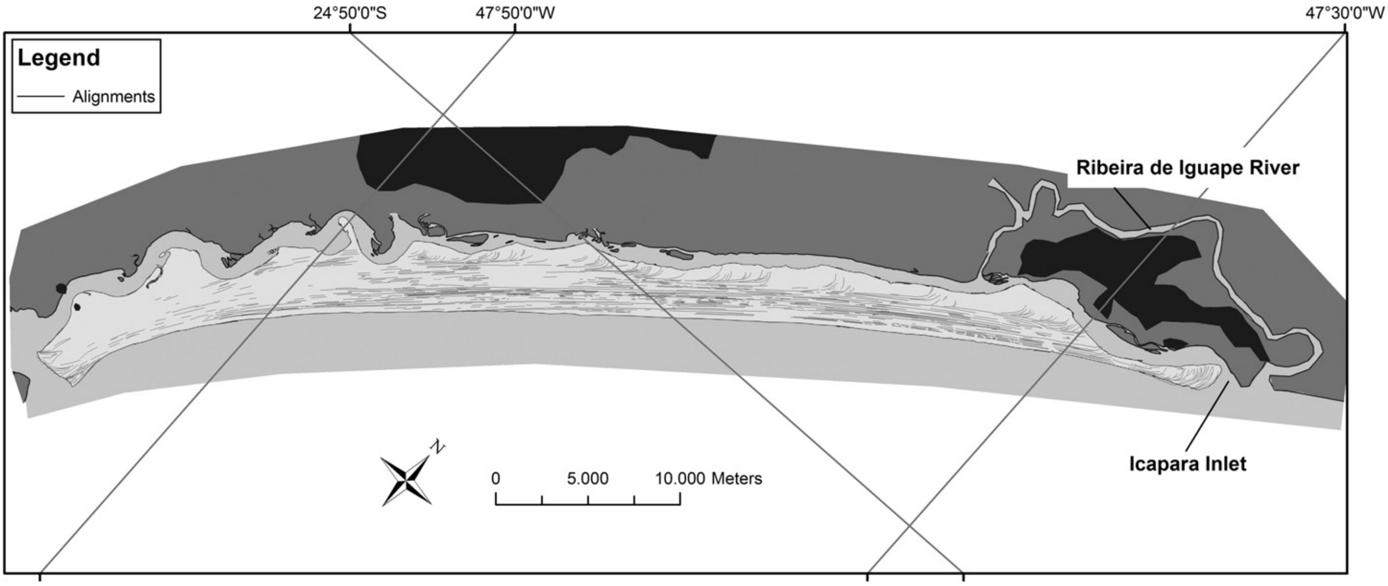


Fig. 3. Map of beach ridge alignments in the Ilha Comprida Barrier.

Foredunes occur mainly as ridges, but also as terraces or ramps, with average height of 1.3 m and a maximum height of 3.5 m. The prevalence of incipient foredune ramps in the mid-southwest (Fig. 6) is remarkable, where the beach morphodynamics change from dissipative to intermediate-dissipative, and wave generated cliffs are frequent. In other parts of the island, ridges and terrace incipient foredunes and ridges of established foredunes occur under dissipative beach morphodynamics (Nascimento et al., 2008; Sawakuchi et al., 2008; Giannini et al., 2009).

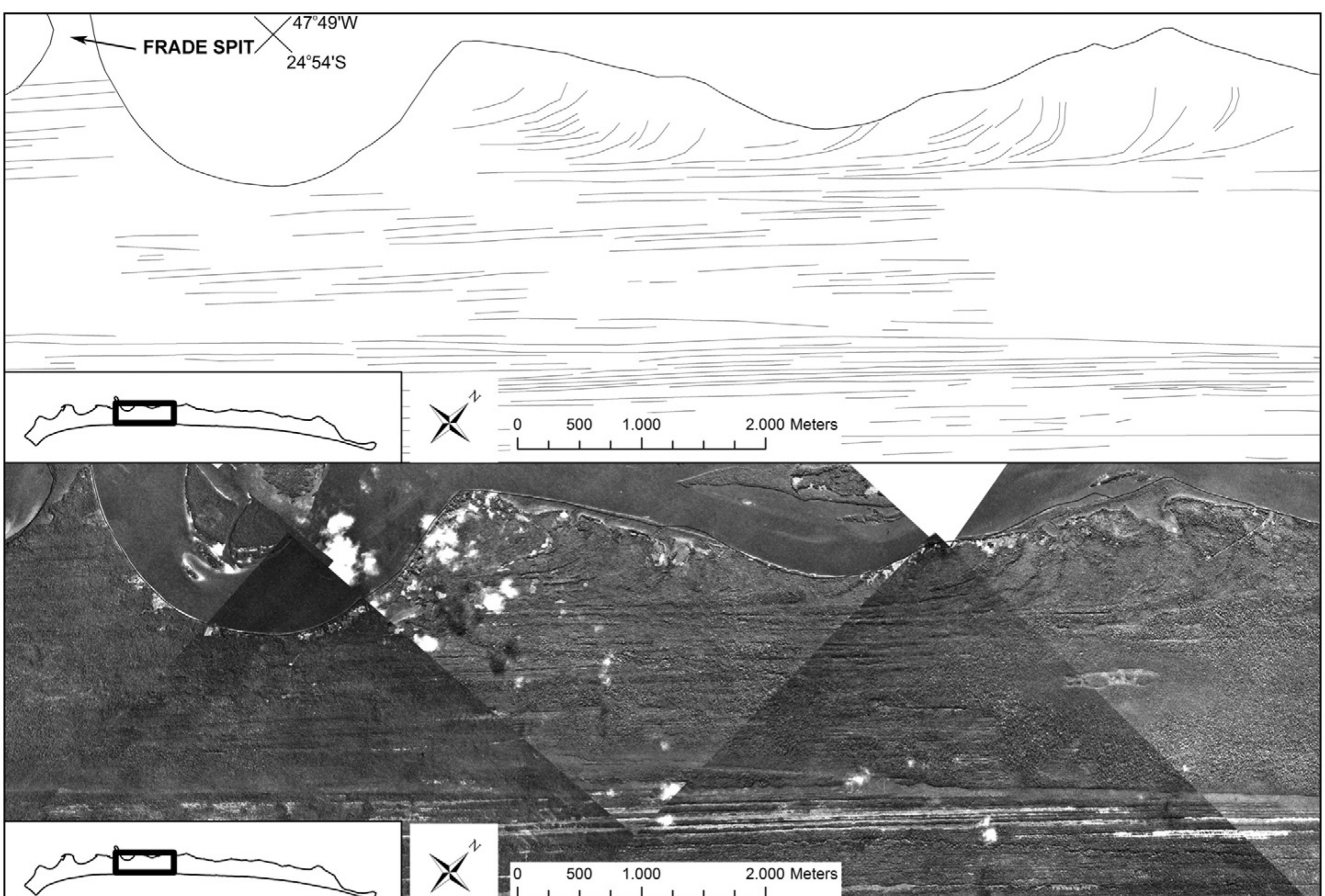


Fig. 4. Curved beach ridges in the inner mid-southwest portion of the barrier. The oldest curved beach ridge is located about 3.5 km to the NE from the Frade Spit.

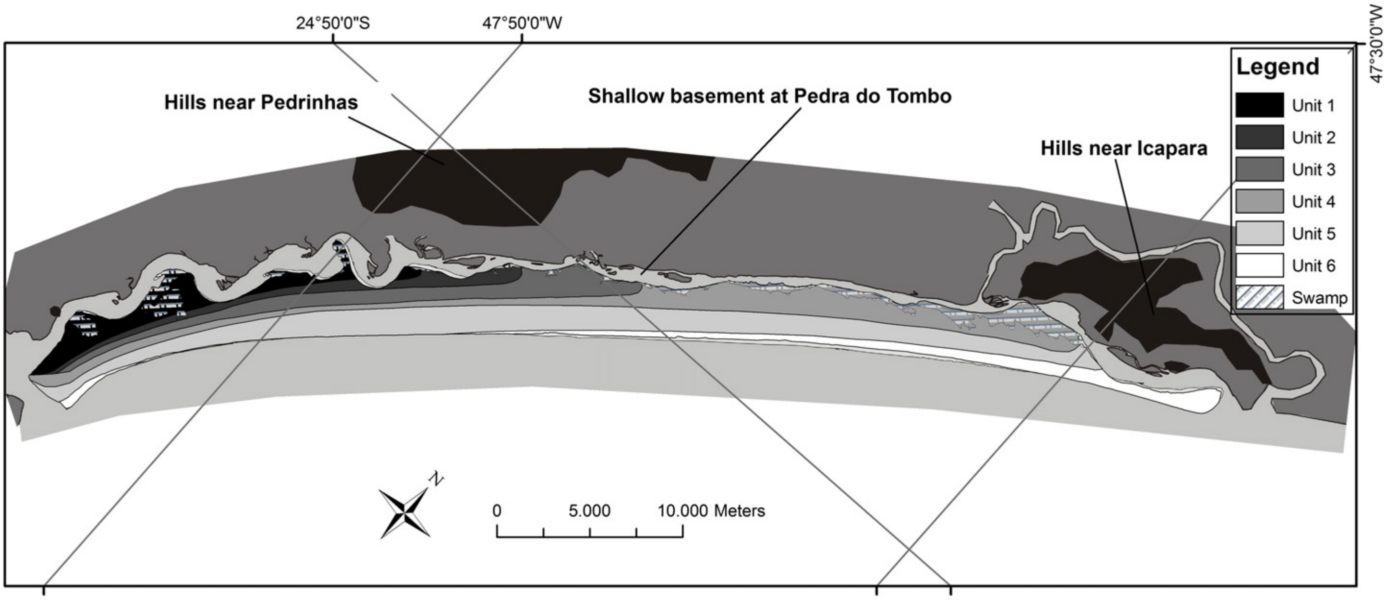


Fig. 5. Map of growth units of the Ilha Comprida Barrier.

4.2. Depositional facies

Seven depositional facies were recognized, similar to those previously identified by Giannini et al. (2009). These facies are defined as: sand with plan-parallel lamination (Sp), sand with plan-parallel lamination and abundant icnofossils (Spi), sand with cyclic cross-stratification and abundant icnofossils (Scci), sand with hummocky cross stratification (Sh), mud with woody trunks (Mt), massive sand (Sm) and sand with cross stratification (Sc).

Facies Sp (Fig. 7) is the most common in cliffs and pits. It corresponds to fine and very fine sands with plan-parallel lamination, sometimes bioturbated (Spi), by widespread warty burrows (*Ophiomorpha*) characteristic of the arthropoda *Callichirus major* and conic excavations (Fig. 7). Facies Spi can be related to low tide swash, while the facies Sp would record the same process occurring at higher tide conditions and in a more inland position. The most common facies succession pattern is progradational with Sp over Spi, except at IC-3-MFL-2 where the occurrence of Spi over Sp suggests retrogradation.

The facies Scci (points IC-11-FML and IC-17-FML) is less common and consists of fine sands with cross-stratification and abundant *Ophiomorpha* burrows (Fig. 7). It has an apparent dip to NE, with cyclic variation of thickness and distinctness, sometimes seeming as tidal

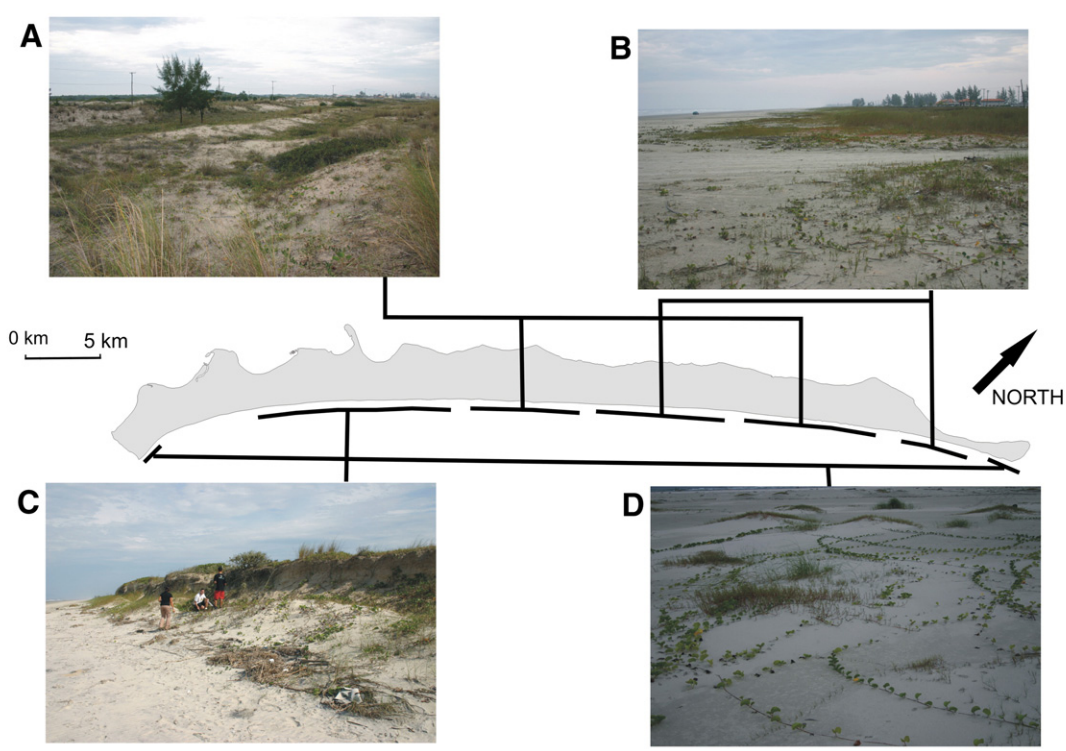


Fig. 6. Distribution of the most common morphologic types of foredunes along the Ilha Comprida Barrier: A: Ridges; B: Terraces; C: Ramp; D: Nebkhas.

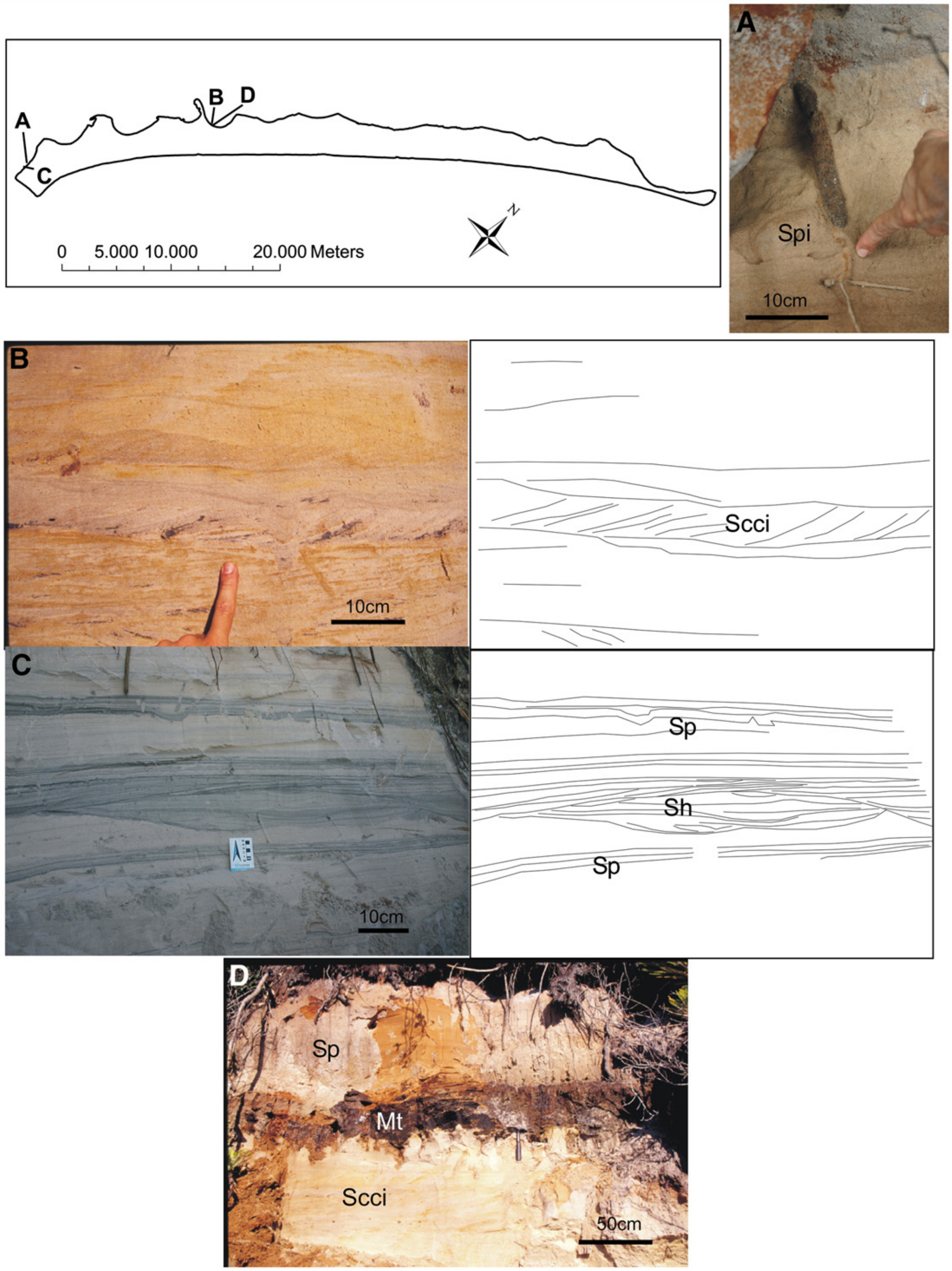


Fig. 7. Facies Spi with warty burrows (*Ophiomorpha*) characteristic of the arthropoda *Callichirus sp*, at site IC-2-FML-1 (A). Facies Scci at site IC-11-FML (B). Note the mud clasts. Facies Sh at site IC-3-FML-4 (C). Note the occurrence of levels with high concentration of heavy minerals, and erosive base between beds of the facies Sp. Facies Mt (D) at site IC-17-FML-1 between facies Scci and SP.

bundles. The facies Scci also stand outs due to the presence of tabular mud clasts up to 2 cm wide. This facies can be interpreted as a product of sand wave migration under the influence of tidal currents (Giannini et al., 2009). The bedforms corresponding to this facies can be related to tidal currents semi-confined at the paleo-inlet in the northeast end of the island.

Facies Sh was described at site IC-3-FML-4 in the extreme southwest of the lagoonal margin of the island (Fig. 7), where it intercalates with swash deposits (facies Sp). It occurs as an approximately tabular fine sand bed 45 cm thick and at least 20 m long. This facies is characterized by a high concentration of heavy minerals and by symmetric undulated stratification, with concave–convex truncations. Locally, the stratifications present deformation structures indicative of liquefaction and/or fluidization processes. The geometry and dimensions of the undulations, compatible with hummocky and swaley cross stratification (Duke, 1985; Yagashita et al., 1992), as well as the concentration of heavy minerals (Buynevich et al., 2004) are typical of high wave energy events.

Facies Mt occurs between facies Scci and Sp at outcrop IC-17-FML-1 (Fig. 7). It consists of a black mud bed, 35 cm thick, containing wood fragments of variable size, including a trunk 10 cm wide in vertical position (5308–4877 ^{14}C cal y BP, Giannini et al., 2009). This facies represents deposits of back-barrier swamp. The vertical succession found at outcrop IC-17-FML-1 where facies Sp lays over Mt is suggestive of a retrogradational stacking pattern.

Facies Sc and Sm (Fig. 8) are associated with aeolian features. Facies Sm occurs intercalated with the facies Sc or separating the facies Sp (below) from Sc. It consists of fine to medium sands, centimeters to decimeters thick, with high content of vegetal debris, which can be interpreted as a buried soil. The association formed by the intercalations of facies Sc and Sm is very common within the barrier and it is the most typical signature of the aeolian deposits in Ilha Comprida (Sawakuchi et al., 2008; Giannini et al., 2009). This facies association covers sediments of the facies Sp, indicating the onshore migration of aeolian dunes onto older beach ridges. The sets of cross stratification in facies Sc are up to 2 m thick. Measurements of dip directions of cross stratifications taken on the whole island indicate the predominance of dips to the NW (Fig. 9). This direction is coincident with the advance of parabolic dunes and blowout depositional lobes, observed in aerial photos and also in the field.

4.3. OSL dating

The dose rates of ionizing radiation (Table 1) ranged from 0.303 (IC-24-CI-1) to 0.716 mGy/year (IC-39-CI). These values are similar to previous data obtained for the Ilha Comprida Barrier sediments (Suguio et al., 1999, 2003; Sawakuchi et al., 2008; Giannini et al., 2009). The equivalent doses ranged from 695 (IC-1-CI) to 3898 mGy (IC-4-CI-5). The age distribution throughout the barrier (Fig. 10) is geologically consistent with the progradational growth pattern, indicated by geomorphological features. The obtained ages decrease to the northeast of the island and towards the present coastline. All ages obtained are within the Holocene period, and in agreement with the more accepted RSL curves for this region.

5. Discussion

5.1. Barrier growth rates

OSL ages allowed the calculation of rates of transverse and longitudinal barrier growth (progradation). Rates of longitudinal growth were calculated using the OSL ages obtained in the endings of curved ridges (Fig. 10). The rates of transverse growth range from 0.13 to 4.6 m/year (Fig. 10), values determined in the southernmost part and in the north end of the barrier, respectively. Longer time periods usually include a great number of erosional events, which result in a reduction of the sedimentation rates. The southernmost profile includes a higher number of mapped units (six) than the northernmost profile (two). So, the southern part of the barrier possibly comprises a more complex sedimentary history. Longitudinal growth rates range from 5.2 to 30 m/year, with higher values in recent periods, after the barrier has surpassed the hills near Iguape blockade (Fig. 10).

The progradation rates vary not only along but also across the barrier. This is the case in the central portion of the barrier (samples IC-24-CI and IC-24-CI-1), where the range in ages may be related to a

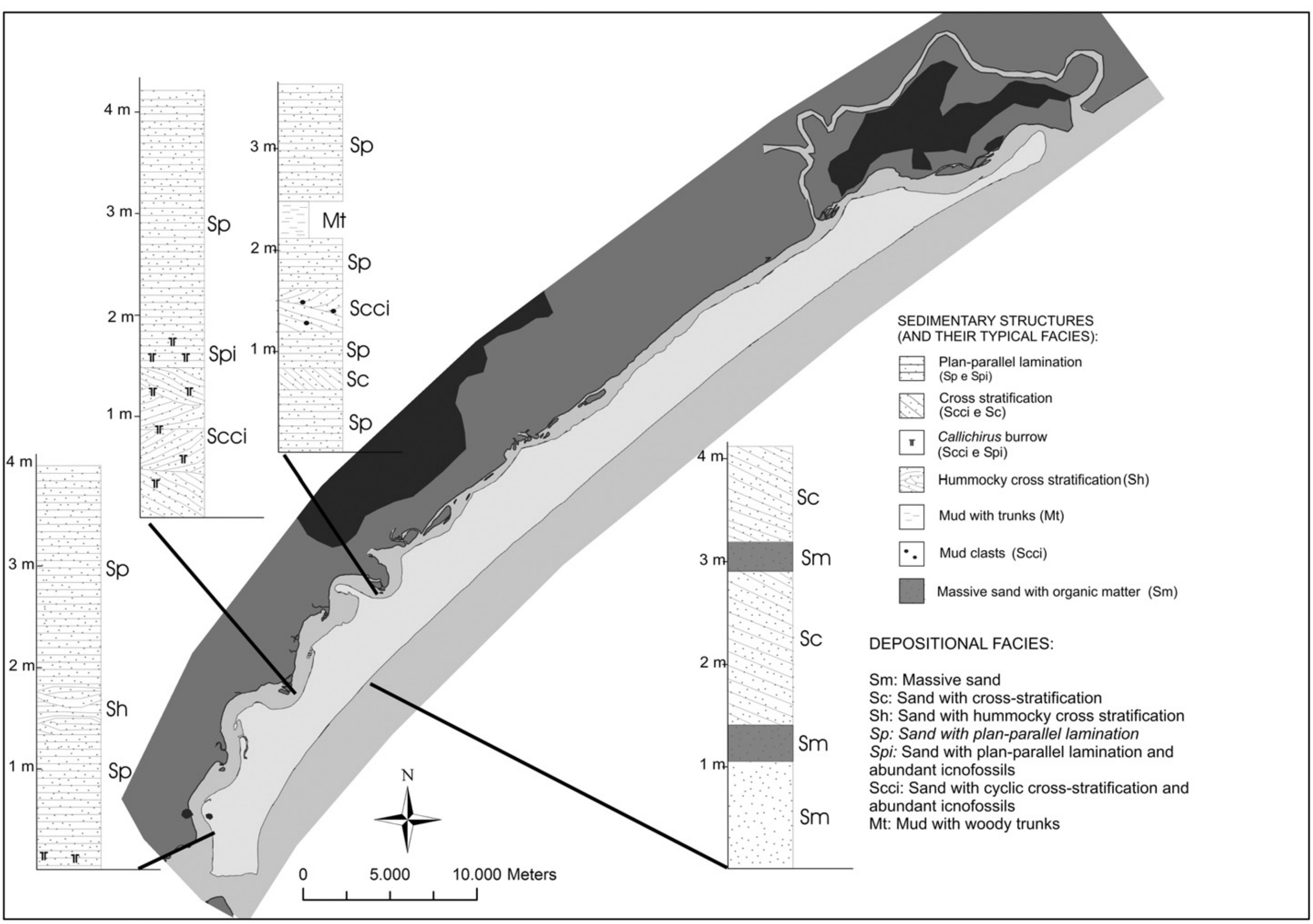


Fig. 8. Facies association described in the Ilha Comprida Barrier.

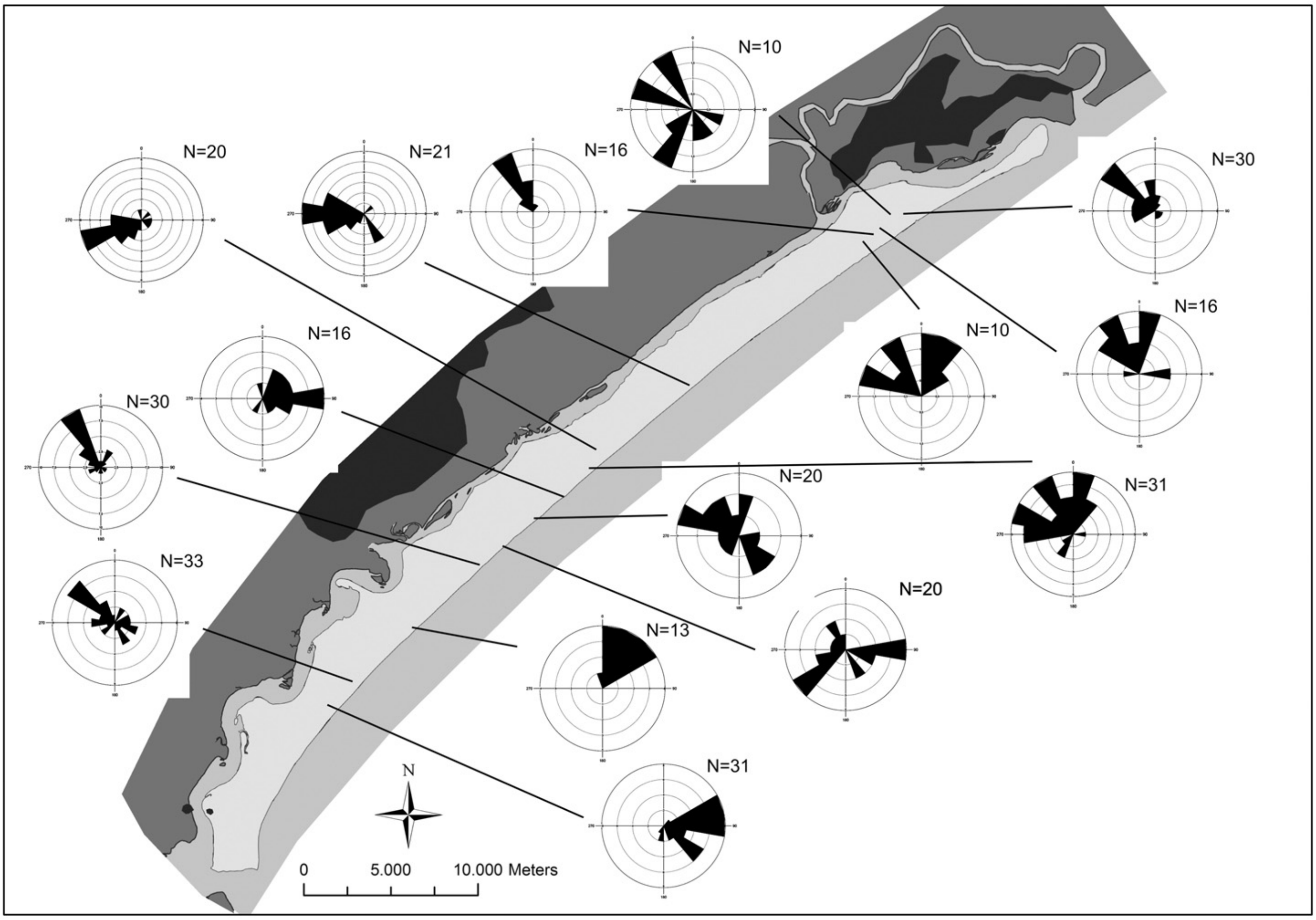


Fig. 9. Rose diagrams of dip directions of cross stratifications measured in facies Scp. Note the predominance of NW dip directions.

switching between the dominance of the longitudinal and the transverse growth component. The progradation rate of this profile, between 0.47 and 0.54 m/year (Fig. 10), is similar to the average rate determined for a millennial time scale. The outer stretch, between site IC-24-CI-1 and the present shoreline, has a very low progradation rate (0.31 to 0.37 m/year). Although the profile measures only 1800 m, it condenses 5450 years, which corresponds to the interval between units 4 and 6. In the beginning of this period (unit 4), the island had a strong longitudinal growth component. At the end of this period, the initial blockade exerted by the hills near Iguape triggered a transverse component of growth.

The units 5 and 6 are well represented in the northeast profile, where the chronology was based on samples IC-55-CI-1 and ICL-9C (Fig. 10). This profile presented the highest across shore rates of growth (0.84 to 0.98 m/year) within the profiles. However, this rate varies widely when the profile is divided in two parts: in the inner part (unit 5), between sampling sites IC-55-CI-1 and ICL-9C, the rate is 0.45 to 0.49 m/year; in the outer part (unit 6), between site ICL-9C and

Table 1
Equivalent radiation doses, concentration of natural radionuclides (K, U and Th), radiation dose-rates and OSL ages. CI: inner beach ridge; FML: cliff at the lagoon margin. Ages in years refer to 2008. *Samples from Sawakuchi et al. (2008).

Sample	Latitude	Longitude	Dose (mGy)	K (%)	Th (ppm)	U (ppm)	Total dose rate (mGy/year)	Gama dose rate (mGy/year)	Beta dose rate (mGy/year)	Cosmic dose rate (mGy/year)	Age (years)
IC-1-CI	25.05184 S	47.90022 W	695 ± 29	0.375	0.932	0.152	0.590 ± 0.039	0.136 ± 0.015	0.287 ± 0.035	0.1673 ± 0.0084	1179 ± 92
IC-24-CI	24.87235 S	47.76579 W	3385 ± 140	0.248	1.943	0.468	0.577 ± 0.034	0.171 ± 0.017	0.240 ± 0.029	0.1668 ± 0.0083	5866 ± 425
IC-24-CI-1	24.87982 S	47.75887 W	1650 ± 68	0.050	0.441	0.310	0.303 ± 0.024	0.060 ± 0.009	0.076 ± 0.021	0.1666 ± 0.0083	5451 ± 487
IC-31-CI	24.83169 S	47.70483 W	2475 ± 102	0.096	1.868	0.580	0.479 ± 0.034	0.156 ± 0.017	0.165 ± 0.028	0.1571 ± 0.0079	5169 ± 422
IC-39-CI	24.78242 S	47.64398 W	3406 ± 142	0.485	1.483	0.181	0.716 ± 0.052	0.182 ± 0.020	0.367 ± 0.047	0.1674 ± 0.0084	4755 ± 398
IC-3-FML-2	25.02917 S	47.91390 W	3617 ± 149	0.466	0.501	0.042	0.599 ± 0.043	0.127 ± 0.014	0.330 ± 0.040	0.1416 ± 0.0071	6041 ± 503
IC-4-CI-5	25.02534 S	47.89908 W	3898 ± 161	0.099	2.909	1.268	0.669 ± 0.041	0.254 ± 0.025	0.249 ± 0.032	0.1657 ± 0.0083	5831 ± 432
IC-4-CI-7	25.02555 S	47.89220 W	2032 ± 85	0.135	2.862	1.240	0.680 ± 0.041	0.252 ± 0.024	0.262 ± 0.032	0.1669 ± 0.0083	2986 ± 221
IC-55-CI-1	24.70537 S	47.50392 W	874 ± 36	0.181	1.049	0.310	0.443 ± 0.029	0.108 ± 0.012	0.166 ± 0.025	0.1691 ± 0.0085	1971 ± 154
ICL-1*	24.98432 S	47.85287 W	550 ± 35	0.148	1.435	0.651	0.547 ± 0.033	0.170 ± 0.019	0.218 ± 0.027	0.1588 ± 0.0079	1004 ± 88
ICL-3A*	24.94856 S	47.81607 W	804 ± 55	0.166	1.143	0.520	0.474 ± 0.030	0.145 ± 0.016	0.206 ± 0.025	0.1223 ± 0.0061	1697 ± 159
ICL-4A*	24.92272 S	47.78484 W	469 ± 26	0.101	1.112	0.488	0.395 ± 0.032	0.125 ± 0.014	0.155 ± 0.019	0.1145 ± 0.0057	1186 ± 98
ICL-9 C*	24.71339 S	47.50002 W	198 ± 15	0.331	2.686	1.151	0.892 ± 0.064	0.317 ± 0.037	0.429 ± 0.051	0.1604 ± 0.0080	222 ± 23

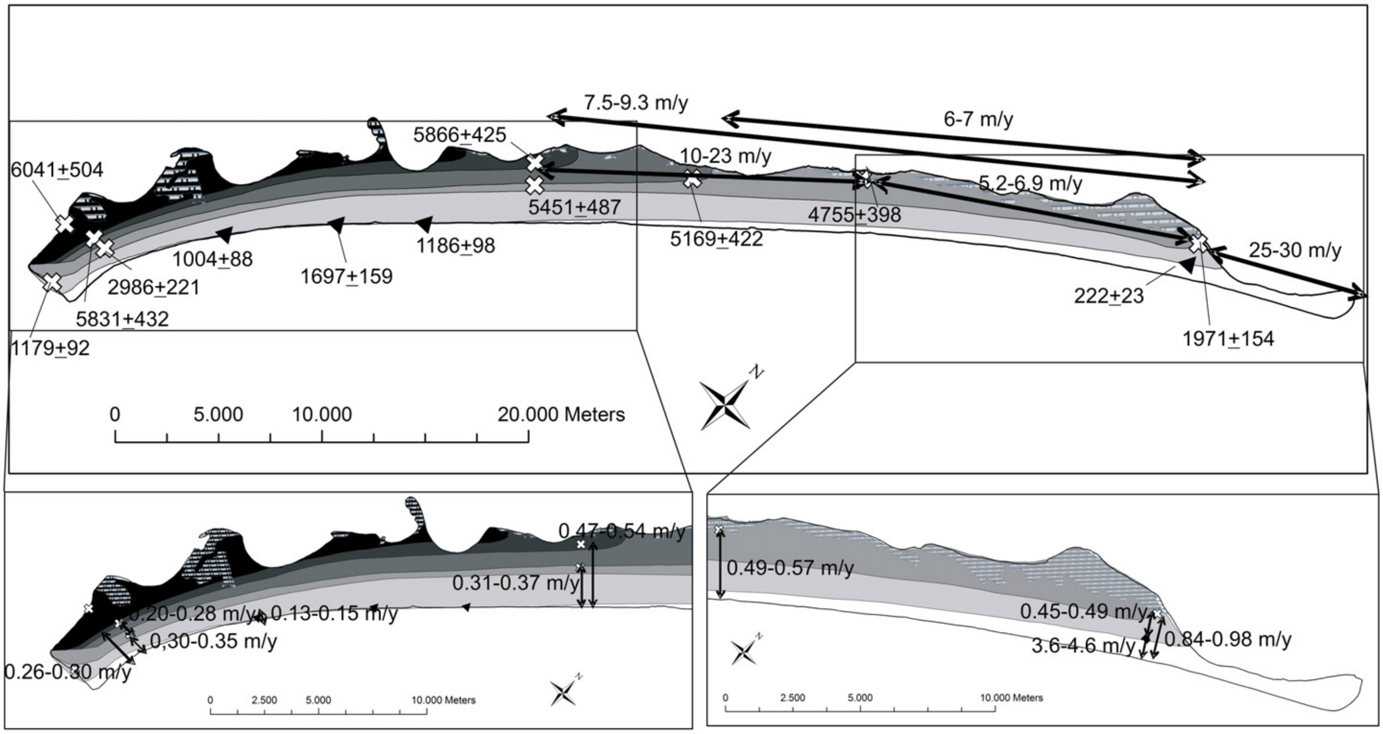


Fig. 10. The top map shows the OSL ages obtained for beach ridges of the growth units defined in the Ilha Comprida Barrier and the bottom map presents the longitudinal and transverse rates of barrier growth based on OSL ages. X: ages from this study. Triangle: ages from Sawakuchi et al. (2008).

the present shoreline, the rate is 3.8 to 4.6 m/year. This rate difference between the inner and the outer parts of the profile would be explained both by the paradox of sedimentation rate (Sadler, 1981; Korvin, 1992), which argues that longer periods of time comprise lower sedimentation rates, and by the beach ridge geometry. Unit 5 contains a longer period of time (1750 years) than unit 6 (200 years) and probably includes more events of erosional and/or stable shoreline as that supposedly occurred during the Little Ice Age (LIA) period (Sawakuchi et al., 2008). Furthermore, in unit 5 the barrier progradation has extended to the entire island while in unit 6 it was only from the center to the northeast corner, with increasing rate to this direction. If the sedimentary supply were considered constant, the sediment concentration in the northeast section of the island would increase the progradation rate at this site.

Despite the differences in regional climate, the range of progradation rates (millennial timescale) of the Ilha Comprida Barrier (0.13 to 0.98 m/year) is similar to that presented by Australian barriers (Roy et al., 1994; Murray-Wallace et al., 2002; Bristow and Pucillo, 2006; Goodwin et al., 2006; Brooke et al., 2008; Forsyth et al., 2010). According to Sawakuchi et al. (2008), this similarity results from analogous regional characteristics such as tectonic stability and Holocene relative sea level changes. Changes on progradation rates and ridges height in Australian barriers are associated to variations on accumulation space (Bristow and Pucillo, 2006) or climate, with a particular influence of cyclones activities (Brooke et al., 2008; Nott et al., 2009; Forsyth et al., 2010). However, in the Ilha Comprida example, changes on progradation rates are related to the barrier growth pattern, associated to the physiography, in a similar RSL falling context but different storminess context (rare cyclones).

The early phases (units 1 and 2) of the barrier are delimited by the samples IC-3-FML-2, IC-4-CI-5 and IC-24-CI, both with ages around 6000 years (Fig. 10). The samples IC-3-FML-2 and IC-4-CI-5, 1.5 km apart across the barrier, have very similar ages (6041 ± 503 and 5831 ± 432 years) with overlap in uncertainties of the age ranges. This demonstrates that either the region suffered intense progradation at this time (about 7 m/year) or developed simultaneously (in an instantaneous event). The last case could represent the formation of a transgressive barrier. This discrepancy with other calculated progradation rates, the lack or absence of beach ridges, and the occurrence of other equivalent ages in the region (Suguio et al., 1976; Angulo et al., 2009; Giannini et al., 2009), favors the hypothesis that this unit represents a barrier without a progradation character (Simms et al., 2006). The presence of a transgressive barrier in southern Brazil during the last Holocene RSL rise, preceding the establishment of a regressive barrier, was inferred by Lessa et al. (2000) in a similar regional context.

5.2. Changes in sediment accumulation

Changes in barrier area over time are related to the variation of sediment retention. Changes in sediment retention have been associated with climate variability (Goodwin et al., 2006; Brooke et al., 2008) and physiography (Goodwin et al., 2006). The sediment accumulation on the Ilha Comprida Barrier (in units of 10^3 m^2/year) varies over time (Fig. 11). Sediment accumulation started before the last RSL maximum when the sedimentary supply was greater than the generation of accommodation space. In the period from 5200 to 1900 years ago, the rates of transverse and longitudinal growth were relatively low and the retention of sediments was about three times lower than the overall average (26×10^3 m^2/year). In contrast, the periods from 6000 to 5200 years and 1970 to 200 years ago have rates that are about 50% above the overall average. These high sedimentary retention periods are linked to a physiographic control (Fig. 11), when obstacles like basement hills were reached, which forced the transverse growth of the barrier. Analogously, the period of low sediment retention is therefore associated with a higher sedimentary bypass, without physiographic obstacles.

Over the last 200 years (unit 6), the sediment accumulation rates have been three times higher than the overall average. This very high rate of sediment retention may be related to the short time interval

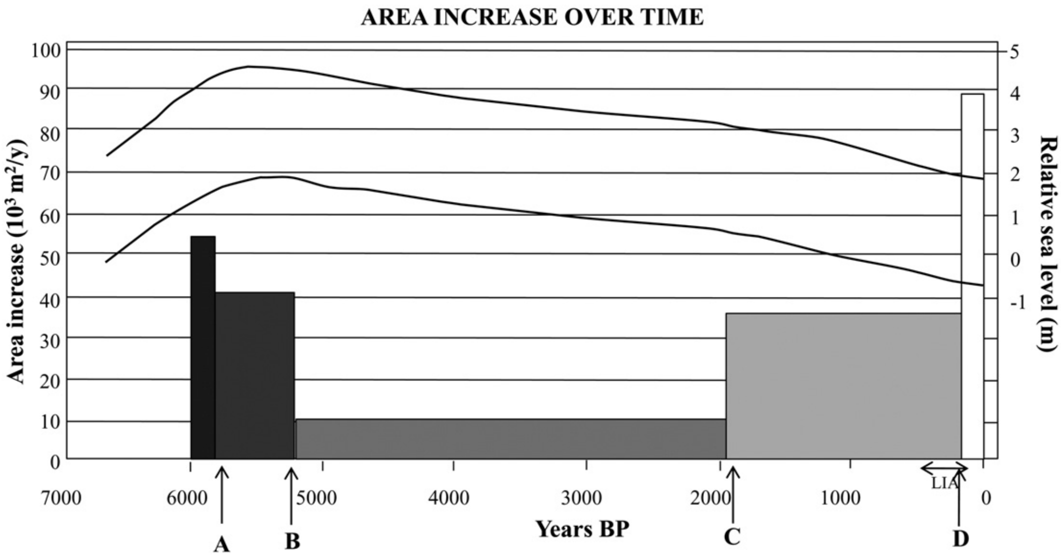


Fig. 11. Increase of area versus time. Continuous lines: envelope of RSL curve by Angulo et al., 2006. A: End of blockade by the hills near Pedrinhas at 5855 ± 425 y; B: End of blockade by Pedra do Tombo at 5169 ± 422 y; C: Start of blockade by the hills near Iguape at 1971 ± 154 y; D: End of blockade by the hills near Iguape (222 ± 23 y) and opening of the Valo Grande (1852 AD); LIA: interval of the Little Ice Age (1450–1850 AD).

comprised by this period, which implies a reduced number of erosional events as postulated by the paradox of the sedimentation rate. The anthropogenic influence as the deforestation in the Ribeira de Iguape River catchment and, mainly, the opening of the Valo Grande channel in the nineteenth century probably has major role in the unit 6 high rates. The Valo Grande channel favored the trapping of coastal sediments in the barrier system due to the intensification of the hydraulic jetty of the Icapara Inlet. However, records of recent local erosion are observed in the mid-southwest and in the northeast end of the barrier. Therefore, this last unit of very high sediment retention does not appear to be erosion and hiatus free, which would have diminished the rate of progradation. Thus, the growth rate increase is probably related to the Valo Grande opening.

5.3. Controls on longitudinal and transverse barrier growth

5.3.1. Physiography

Physiography is one of the most important boundary conditions to coastal evolution (Cowell et al., 2003) on a centennial to millennial timescale. Basement hills also work as an alongshore drift blockade, by increasing the sedimentary retention in updrift areas and decreasing it in downdrift regions, relative to the blockade. The physiographic control on sedimentary bypass is exemplified by Goodwin et al. (2006). Also, where physiographic controls seem to be constant over time, there are no significant changes on coastal progradation rates (Lessa et al., 2000; Murray-Wallace et al., 2002). The significance of the substrate slope on barrier formation and evolution was evaluated by Roy et al. (1994) through computer modeling. According to the authors transgressive sand barrier development occurs preferentially in substrates with slopes between 0.05° and 0.8° slopes.

Using the example of the Ilha Comprida Barrier, the physiography is the most important control on sediment retention on a millennial timescale (Fig. 11). The inner shelf slope of 0.05° favors barrier development (Roy et al., 1994). The units 2 and 3, which have an important transverse component of growth, but also some longitudinal growth, are apparently influenced by the hills near Pedrinhas and Pedra do Tombo, respectively (Fig. 11). At this turn, in unit 4,

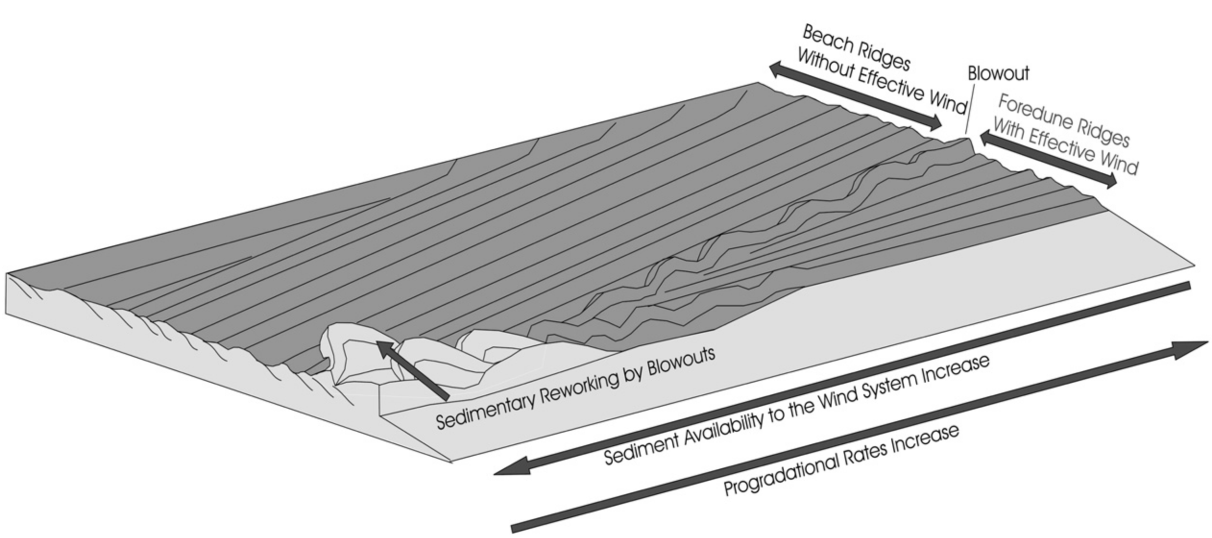
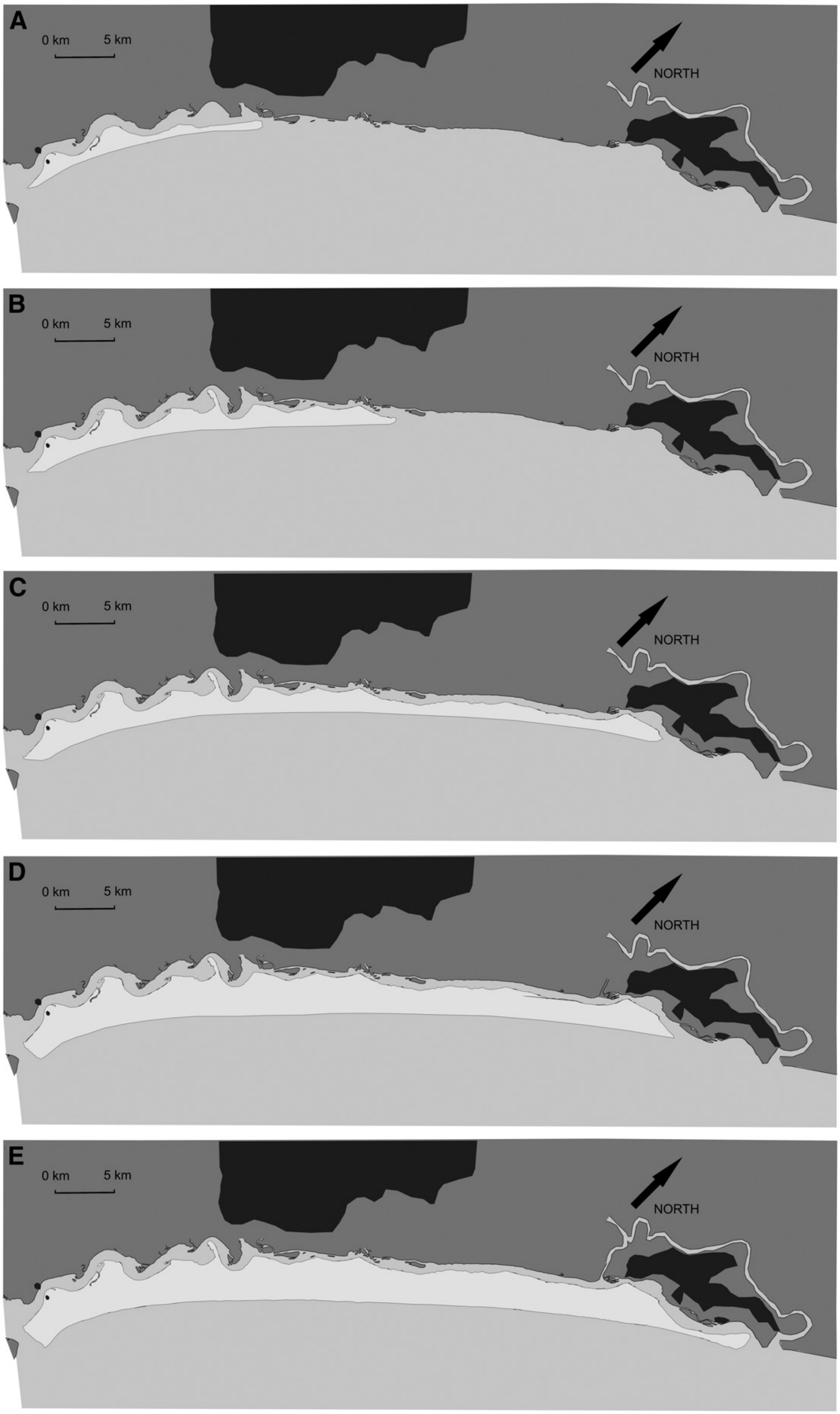


Fig. 12. Types of beach ridge formation scheme for the Ilha Comprida Barrier and intensity of active sedimentary processes.



A
0 km
5 km
NORTH
B
0 km
5 km
NORTH
C
0 km
5 km
NORTH
D
0 km
5 km
NORTH
E
0 km
5 km
NORTH

which does not have any obstacle to influence the paleo-inlet dynamics at Icapara, the sedimentary bypass increases, the transverse growth is much less important and the sediment retention is significantly smaller than the overall average. The blockade of the longitudinal barrier growth is well observed on unit 5 where the hills near Iguape promoted an intense transverse growth for nearly 1800 years. Consequently the physiographic control, by pre-Cenozoic basement outcrops, seems to be the major control on the sediment retention and the transverse/longitudinal growth component ratio. Thus, the Ilha Comprida Barrier model differs from others within the same regional context (Dominguez et al., 1992; Lessa et al., 2000) by the strong physiographic control, highly variable in a millennial timescale.

5.3.2. Inlet dynamics

At the northeast end of Ilha Comprida, the Icapara Inlet has a strongly dynamic behavior. In previous studies by Geobrás (1966), Tessler (1988), Nascimento et al. (2008), and Giannini et al. (2009) historic changes of the inlet were mapped using old maps and aerial photos since 1800 AD. According to Nascimento et al. (2008), the northeastwards littoral drift is the main shifting factor of the Icapara channel to NE, adding to a "meandering effect" of this channel because of its curvature. This effect is generated by interaction between tidal regime and fluvial sedimentary supply, through which the northward margin of the channel acts like an erosional levee, and the southward margin (Ilha Comprida), like a point bar. In this way, sand is removed in Iguape and deposited at the tip of Ilha Comprida (Geobrás, 1966; Tessler, 1988; Nascimento et al., 2008; Giannini et al., 2009). The average rate of growth towards NE, estimated from comparison of different bathymetric charts and aerial photos, is about 35 m/year between 1882 and 1965 (Geobras, 1966) and 27.5 m/year in the last two centuries (Nascimento et al., 2008). Higher rates after the opening of Valo Grande artificial channel at 1852 AD were inferred by Geobrás (1966) and Nascimento et al. (2008).

The opening of the Valo Grande channel (about 160 years ago) occurred at a similar time as the surpassing of the longitudinal blockade exerted by hills near Iguape on the barrier (about 200 years ago, not taking into account errors in the OSL age estimate). This fact raises the question of which effect causes the increased rates of longitudinal progradation in the last 200 years. However, longitudinal progradation rates calculated for the period before the Iguape blockade (7.5 to 9.3 m/year) differ substantially from the values after the end of this blockade (25 to 30 m/year) (Fig. 10). In the units formed before this blockade, it is also possible to observe changes in longitudinal growth rate, but these changes are relatively reduced, ranging from 10.2 to 22.8 m/year in the first period (IC-24-CI to IC-39-CI), and from 5.2 to 6.9 m/year at the end (IC-39-CI to IC-55-CI-1). Moreover, the barrier in these former periods/units also had obstacles to surpass (hills near Pedrinhas and Pedra do Tombo). Hence, it is more likely that the Valo Grande opening intensified the water discharge in the Icapara inlet and, consequently, increased the inlet dynamics and the hydraulic jetty.

5.3.3. Relative sea-level variations

Relative sea level variations are one of the most important controls of regional coastal evolution on a millennial timescale (Roy et al., 1994). In the Southern Hemisphere, e.g. on the Brazilian and Australian coasts, there is a predominance of Holocene coastal features, such as regressive barriers and strandplains on coastal morphology (Roy et al., 1994; Dillenburg and Hesp, 2009), under a RSL fall scenario (Belperio et al., 2002; Angulo et al., 2006). On the other hand, on coasts with rising RSL trend, such as the United States east coast (Horton et al., 2009), there is a dominance of transgressive barrier island morphology (Davies, 1994). The shift from barrier islands to strandplains in the east-northeastern coast of Brazil was attributed by Dominguez et al. (1992) to changes on RSL behavior, respectively from rising to falling RSL.

Although the previous Ilha Comprida evolution model (Martin and Suguio, 1978) was linked to pronounced negative oscillations in the late Holocene RSL trend (Suguio et al., 1980) a smooth decreasing RSL curve has now found wider acceptance to the last 5000 to 7000 years (Milne et al., 2005; Angulo et al., 2006). This smoother curve (Fig. 11) has two main implications to the barrier evolution. Firstly, the Ilha Comprida emergence is related to the deceleration of RSL rise before its last maximum, at which time there is generation of accommodation space lower than sedimentary supply. Secondly, the smooth RSL fall after this maximum contributes uniformly to the barrier progradation, remobilizing sediment from the inner shelf to the beach.

5.3.4. Climate and river input

Many studies recognize the climate control on beach ridge development (Dominguez et al., 1992; Dominguez and Bittencourt, 1994; Nott et al., 2009; Forsyth et al., 2010). Nott et al. (2009) associated the beach ridge formation in northeastern Australia to extreme tropical cyclone activity. Changes in the beach ridge orientation at Bahia State, northeastern Brazil, are attributed to climate control by Dominguez and Bittencourt (1994). Regional coastal erosion and alteration on barrier-island morphology from regressive to transgressive in North Carolina, USA, were related to an increase on storm frequency (Timmons et al., 2010). With regard to the Ilha Comprida Barrier, changes in the wind intensity would be associated with changes in ridge types (Sawakuchi et al., 2008). According to this model, the formation of beach ridges before the Little Ice Age period and of foredunes after this period, are related to changes in the wind effectiveness for sedimentary transport (Fig. 12). During the LIA, the Ilha Comprida experienced a generalized formation of NW oriented blowouts (Fig. 9), thought to be related to a higher frequency of cold fronts and strong winds from SE, with an erosional and/or stable shoreline (Sawakuchi et al., 2008). Today, the blowout formation is restricted to the mid-southwest portion of the barrier, which is under marine erosional conditions (Fig. 12).

In coastal barriers, changes in the average precipitation can promote alterations in the fluvial sedimentary input (Brooke et al., 2008) and its hydraulic jetty, and therefore, in the sediment retention. However, studies on Holocene climate variability (Cruz et al., 2009) did not record any changes in the amount of precipitation in the Ribeira de Iguape River catchment. Variations of sedimentary input for the Ilha Comprida by the Ribeira de Iguape River were studied by Guedes et al. (2011), based on heavy mineral analysis, which did not detect major modifications in the last 6000 years. Furthermore, fluvial sand supply to this region is thought to occur not directly, but instead, via the inner shelf storage (Guedes et al., 2011). This storage, at least in part, could be a relic of the Ribeira de Iguape River deposition during periods of forced regression, related to the Last Glacial Maximum. Therefore, the sedimentary fluvial contribution was apparently not climate sensitive in the Ilha Comprida example.

Differently from the Australian regressive barriers, where the cyclones seems to be the most important centennial to millennium timescale control on barrier progradation (Brooke et al., 2008; Nott et al., 2009; Forsyth et al., 2010), changes on progradation rates in the Ilha Comprida Barrier would be related to coastal physiography. The

Fig. 13. Evolution of Ilha Comprida from 6000 years ago until present. A: Transgressive barrier at 6000 years B.P. B: At 5000 years B.P. after a high progradation phase. C: At 1900 B.P., ending the phase with lower growth rate and starting the longitudinal component blockade by the hills near Iguape. D: At 200 years ago, after the end of blockade by the hills near Iguape. E: The recent situation resuming the ongoing longitudinal growth component.

climate apparently has a control on ridges types (Sawakuchi et al., 2008) with a subordinated influence on progradation rates.

5.4. Ilha Comprida Barrier evolution model

5.4.1. From 6000 to 1900 years BP

Two hypotheses have been proposed in previous studies for the barrier emergence: separation of part of the Holocene coastal plain through a drainage capture (Geobrás, 1966) and growth of a Holocene spit attached to a former Pleistocene barrier island (Suguio and Martin, 1978). However, OSL ages and facies stacking indicate that the Ilha Comprida began probably as a Holocene transgressive barrier island. Ages around 6000 years, obtained at unit 1, coincide with a period of probable RSL rising, immediately before the Holocene RSL maximum (Angulo et al., 2006). Evidence of transgressive stratigraphic stacking is suggested in the section IC-3-FML-2 and in outcrops described by Suguio et al. (1976), where marine sands are placed over paleolagoonal sediments. In these outcrops, wood trunks have been dated by Suguio et al. (1976) and reviewed by Angulo et al. (2009). Radiocarbon ages of 7659–6949 and 6050–5519 cal years BP, presented in Angulo et al. (2009) reinforce the idea of development of the Ilha Comprida as a transgressive barrier during the Holocene RSL rising.

After this initial transgressive phase (Fig. 13), the barrier progradated until present through two main components of growth, one in alongshore direction (to NE), and the other in a transverse direction (to SE). The beach/foredunes ridges morphology indicates that these two components of barrier growth have alternated in relative importance through time. From the initial transgressive phase until about 5000 years ago, the island had an accelerated phase of growth, both longitudinally and transversally, with the addition of beach ridges.

But from 5000 to about 1900 years ago, the Ilha Comprida Barrier experienced absence of transverse growth and a relatively low rate of longitudinal growth (5.2 to 6.9 m/year).

5.4.2. From 1900 years BP until the present

The period between 1900 and 200 years ago had increased transversal growth due to the blockade of the longitudinal growth by the hill near Iguape (Fig. 13).

Wave processes dominated the progradation of the Ilha Comprida Barrier until 550 years ago. The period between 550 and 200 years ago is marked by a shift in sandy ridges morphology, which is characterized by the development of foredune ridges and blowouts. The change in ridge morphology is attributed to the intensification of southern winds and storminess due to the enhancement of cold fronts activity during the Little Ice Age (Sawakuchi et al., 2008). This change in coastal dynamics would promote coastal erosion and coastline stability, favoring the development of blowouts alongshore.

Since the end of the LIA, the surpassing of the blockade exerted by hills near Iguape and the artificial opening of the Valo Grande channel in 1852 AD induced changes in the barrier growth rate and its transverse and longitudinal components. Moreover, the wind pattern apparently remained more intense after the LIA and foredune ridges replaced the beach ridges that characterized the earlier phases of barrier development. After surpassing the hills near Iguape, the rate of longitudinal barrier growth increased again to 25 to 30 m/year. This higher rate is probably due to the opening of the Valo Grande, which intensified the channel dynamics at the Icapara inlet and its effect of hydraulic discharge. The transverse growth component has been uneven across the island in this last phase with high rates of progradation at the ends of the island and erosion in the mid-southwest, where there is still blowout activity.

6. Conclusions

The combination of OSL dating and a detailed beach/foredune ridge mapping from the Ilha Comprida Barrier allow us to determine the sediment accumulation and progradation rates in the last 6000 years. Changes in progradation rates and sediment retention over time proved to be a good tool to analyze how the different controls influence the barrier development. Morphologic and chronological data added to stratigraphical evidences point out to the beginning of the island as a transgressive barrier. This hypothesis is compatible with the gentle slope of the inner shelf in the Ilha Comprida setting. The subsequent growth of this barrier by progradation is related to the last RSL maximum and the smooth fall since then. Changes in the Ilha Comprida barrier growth do not fit with the constant rate RSL fall, suggesting minor influence of RSL on progradation rates. The major control on sediment retention rates in the Ilha Comprida barrier remains associated to the physiography (pre-Cenozoic hills). This last aspect has acted as a centennial to millennium timescale control changing the sediment retention and the predominance of one or other of the two barrier growth components (longitudinal and transverse). Sand barrier, accumulated under the influence of physiographic traps, has behaved as an important sink of sediments remobilized from the inner shelf by the continuous RSL fall. The Icapara Inlet dynamics is influenced both by the physiography and, more recently, by anthropogenic changes. The hydraulic jetty is climate and anthropogenic sensitive and has a great influence on the sediment retention. Although climate changes do not alter the average precipitation on Ribeira de Iguape River catchment, therefore sediment retention by hydraulic jetty, the climate apparently has a role on ridges types by the wind effectiveness related to a higher frequency of cold fronts and strong winds from SE. Thus, Ilha Comprida Barrier is an example of barrier, developed in major part under a constant rate RSL fall scenario, where the strong control of the physiography surpasses the influence of the climate on the pattern of progradation.

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