Chapter 8
Beaches of Rio Grande do Norte

Helenice Vital, Iracema Miranda da Silveira, Werner Farkatt Tabosa, Zuleide Maria Carvalho Lima, Francisco Pinheiro Lima-Filho, Flavo Elano Soares de Souza, Marcelo dos Santos Chaves, Felipe M. Pimenta, and Moab Praxedes Gomes

Abstract The Rio Grande do Norte coast extends 410 km, and consists of sandy beaches (72 %), active sea cliffs carved into Cenozoic sediments of the Barreiras and Tibau formations (26 %), and transgressive dune fields and beachrock. It comprises two different sectors: the northern (equatorial) coast trends east for 244 km, while the eastern (oriental) coast trends south for 166 km. The eastern sector is characterized by wave-dominated and some tide-modified beaches that are mainly reflective to intermediate states. In contrast, the northern sector has resulted in tide-modified and tide-dominated beaches that range from reflective (the dominant state) to intermediate. In general the Refletive + Low tide terrace (R + LTT) is present along the entire coast for most of the year, while wave-dominated Longshore bar and trough (LBT), Rhythmic bar and beach (RBB), Transverse bar and rip (TBR), Low tide terrace (LTT) and reflective (R) occur along the eastern sector, and tide-dominated Beach + tidal sand flats (B + TSF) occurs along parts of the northern sector. R + rock flats and coral reef flats are present in both sectors, where bedrock and beachrock reefs are prevalent. Beachrock reefs are very common along the Rio Grande do Norte shore, occurring in both the offshore and onshore zones. Beach morphodynamics is modified due the presence of the beachrocks. Sea level variability is dominated by tides (up 98 % of the energy spectra). The sea level subtidal

H. Vital (✉) • W.F. Tabosa • F. Pinheiro Lima-Filho • M.P. Gomes
Departamento de Geologia/Programa de Pós-Graduação em Geodinâmica e Geofísica, Centro de Ciências Exatas e da Terra Universidade Federal do Rio Grande do Norte-UFRN Campus Universitário, 1639 Lagoa Nova, Natal, RN 59072-970, Brazil
e-mail: helenicevital2004@yahoo.com.br; werner@geologia.ufrn.br; pinheiro@geologia.ufrn.br; gomesmp@geologia.ufrn.br

I.M. da Silveira
Museu Câmara Cascudo Universidade Federal do Rio Grande do Norte- UFRN, Av Hermes da Fonseca, 1398 Tirol, Natal, RN 59020-650, Brazil
e-mail: iracema_miranda@hotmail.com

Z.M.C. Lima • M.d.S. Chaves
Departamento de Geografia/Programa de Pós-Graduação em Geografia, Centro de Ciências Humanas Letras e Artes Universidade Federal do Rio Grande do Norte-UFRN/Campus Universitário, 1596 Lagoa Nova, Natal, RN 59072-970, Brazil
e-mail: zuleide@ufrnet.br; mschaves2007@gmail.com

A.D. Short, A.H. da F. Klein (eds.), *Brazilian Beach Systems*, Coastal Research Library 17, DOI 10.1007/978-3-319-30394-9_8

component is well correlated with the winds, but demonstrate very low amplitudes. Longshore currents are wind modulated, while cross-shore currents are primarily modulated by tides and secondarily by winds. Erosional hotspots and, both natural and anthropogenic hazards, are present along the Rio Grande do Norte coast.

8.1 Introduction

The Rio Grande do Norte coast lies between 04°49′53″ and 06°29′18″ S. It extends for 410 km, and consists of sandy beaches (72 %), active sea cliffs carved into Cenozoic sediments of the Barreiras and Tibau formations (26 %), and transgressive dune fields and beachrock. Owing to its location on the northeast "corner" of Brazil, Rio Grande do Norte comprises two different sectors: the northern (equatorial) coast trends east for 244 km, while the eastern (oriental) coast trends south for 166 km (Fig. 8.1). Along the semi-arid northern coast, tide-modified to tide-dominated beaches dominate, together with extensive ebb tidal deltas, active dune fields, barrier islands, and spits. Along the humid tropical eastern coast, wave-dominated to tide-modified beaches dominate, with active sea cliffs carved into tablelands alternating with vegetated dune-barrier sections. Beaches with rock flats and fringing reefs occur in both sectors. According to the Instituto Brasileiro de Geografia e Estatística (IBGE 2013), there were an estimated 3,408,510 million people residing in Rio Grande do Norte in 2014, with 1,456,065 (43 %) residing near the coast, which represents a coastal population density of ~220 inhabitants km^2.

8.1.1 Geology

Rio Grande do Norte is located in the eastern part of the northeastern South American Platform (i.e. Borborema Province). This province was defined by Almeida et al. (1977) as a complex mosaic-like folded region where major Neoproterozoic tectonic, thermal, and magmatic events were associated with the Brasiliano Cycle. The area contains three main groups of rocks (Fig. 8.2): (1) Precambrian units (3.45 Ba to 542 Ma); (2) Cretaceous units of the

F.E.S. de Souza
Centro de Tecnologia, Colégio Agrícola de Jundiaí, Universidade Federal do Rio Grande do Norte, UFRN RN 160 Km 03 Distrito de Jundiaí, Escola Agrícola de Jundiaí, Macaiba, RN 59280-000, Brazil
e-mail: flavogeo@ig.com.br

F.M. Pimenta
Departamento de Geociências, Centro de Filosofia e Ciências Humanas, Universidade Federal de Santa Catarina, UFSC/Campus Universitário, Trindade, Florianópolis, SC 88040-900, Brazil
e-mail: felipe.pimenta@ufsc.br

Fig. 8.1 Location of Rio Grande do Norte, Brazil, including the northern and eastern coastal sectors

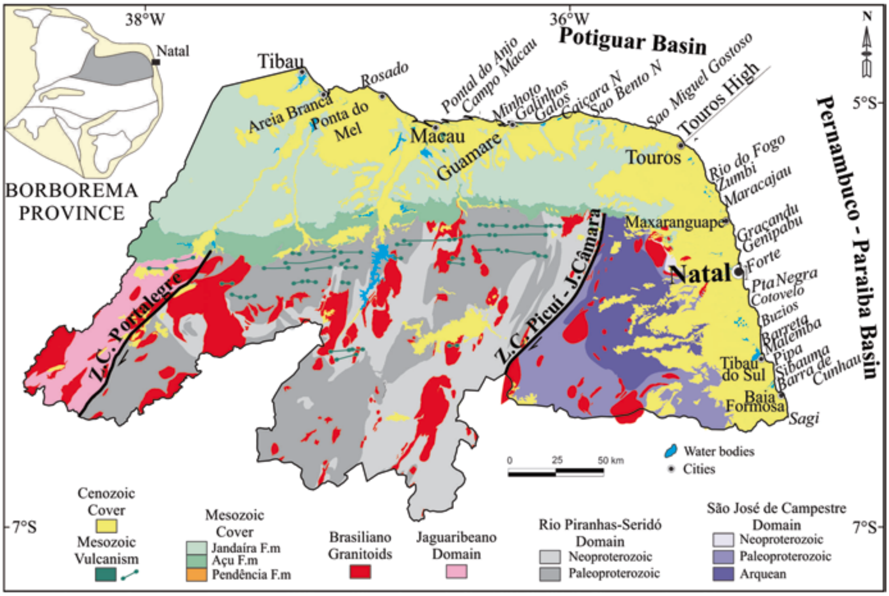

Fig. 8.2 Geological map of Rio Grande do Norte, Brazil (Modified from Medeiros et al. 2010). Beaches cited on the text are also showed

Pernambuco-Paraiba and Potiguar basins (145 to 65 Ma), and associated volcanic deposits; (3) Cenozoic sedimentary cover (65 Ma to present).

The northern and eastern Rio Grande do Norte coastal sectors are located in the Potiguar and Pernambuco-Paraíba basins, respectively. These basins, which are separated by the Touros high (Fig. 8.2), developed during the Upper Cretaceous post-rift phase of the Atlantic Ocean formation. The Potiguar Basin includes an offshore segment with an area of ~27,000 km^2, and an onshore segment covering 22,000 km^2; the latter being related to failed rift basins (Milani and Thomaz Filho 2000). The basin underwent a complex evolution, merging elements from both the Equatorial and the Southern Atlantic tectonic zones. The Pernambuco-Paraíba Basin represents the northernmost segment of the Occidental, the extensional margin of the South American continent. It lies mainly offshore and has a total area of ~35,000 km^2, of which just ~9000 km^2 are located on land. This region was the last to experience rifting owing to the nature and high rigidity of the Precambrian basement cratonic rocks (Matos 1998).

Milani and Thomaz Filho (2000) reported that tectonic events have occurred in the Potiguar Basin since the Oligocene. East-west compression along pre-existing northeast–southwest trending faults makes this one the most seismically actives regions of Brazil. Instrument and historical data also support the theory that both the Pernambuco-Paraíba and Potiguar basins are located in one of the most seismically active intraplate areas of South America (e.g. Ferreira et al. 1998, 2008).

Both basins contain well-exposed Cenozoic sandy-clayey sediments of the Barreiras Formation, which were deposited by fluvial and marine systems. The age of the Barreiras Formation has long been a source of debate, with proposed dates extending from the Miocene to the Pliocene (Salim et al. 1975; Suguio et al. 1986). Lima (2008) dated weathering profiles and found ages of 12–7 Ma. Rossetti et al. (2013) related the deposition of the Barreiras Formation to a transgressive episode during the early/middle Miocene. The Barreiras Formation is overlain by Quaternary deposits related to Pleistocene and Holocene. The most important Quaternary coastal deposits along the Rio Grande do Norte coast include dune fields, barrier island-spits, tidal channels with small tidal deltas, beachrock, and lagoonal /tidal sediments (Vital 2009).

The adjacent continental shelf represents a modern, highly dynamic mixed carbonate-siliciclastic system characterized by reduced width and shallow depths, as compared with other parts of the Brazilian shelf. It has an average width of 40 km, and the shelf-break lying at a depth of 60–70 m (Vital et al. 2010; Gomes et al. 2014; Vital 2014). The shelf is subject to the full strength of the westerly South Equatorial current, along with high winds and moderate–high tides and waves.

8.1.2 *Climate*

The Rio Grande do Norte climate varies from tropical dry–semi-arid (Köppen type Bs) on the northern coast, to tropical humid (Köppen type Af) on the eastern coast (Nimmer 1989), and is subjected to the movement and location of the Inter Tropical

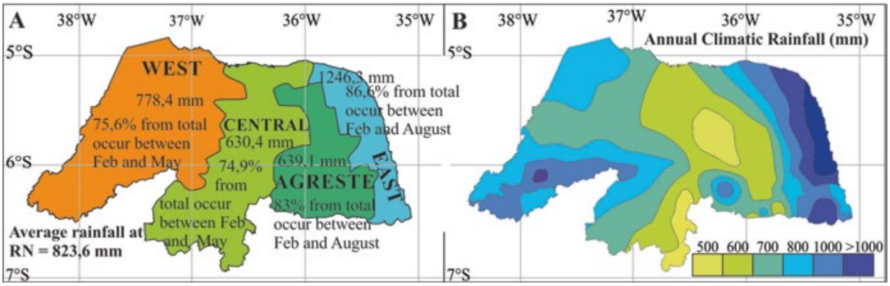

Fig. 8.3 Pluviometry in the sub-regions of Rio Grande do Norte, Brazil: (**a**) mean rainfall (mm) and the main rainfall seasons in the West, Central, Agreste, and East regions; (**b**) annual precipitation (mm) across Rio Grande do Norte (Figure after Pinheiro et al. 2010). Feb = February

Convergence Zone (ITCZ). Isohyets are generally parallel to the coast, with annual precipitation decreasing rapidly toward the interior and to the west (Fig. 8.3).

The Rio Grande do Norte coast has three precipitation zones: the West and Central regions of the northern coast, and the East region of the eastern coast (Fig. 8.3). On the northern coast, precipitation is between 600 and 800 mm $year^{-1}$ (or lower), while the eastern coast experiences up to 1600 mm $year^{-1}$ (Pinheiro et al. 2010). Maximum precipitation occurs during the austral spring and is strongly linked to the maximum zonal intensity of the trade winds. Higher precipitations and reduced wind speeds are associated with the ITCZ.

The dry period extends from June to January, while the rainy period extends from February to May. The mean annual air temperature is ~27 °C, with minimum temperatures (~25 °C) occurring at the end of winter (July) and maximum temperatures (~29 °C) experienced in February.

Though El Nino events are popularly believed to be associated with droughts in northeast Brazil (Kane 2001), approximately 40 % are likely to be ineffective. This is because conditions in the Atlantic may be favorable for droughts in northeast Brazil in some years, while excess rain occurs in other years. In the latter case, the effects of excess rain are due to Atlantic conditions that may reduce or even obliterate the drought effects of El Nino.

8.1.3 Drainage

The two most important hydrographic basins in the Rio Grande do Norte, the Piranhas-Açu and Apodi-Mossoró, have their mouths located on the northern coast, where they are subject to anthropogenic impacts from the oil and salt industries, shrimp farms, and tourism (Fig. 8.4). Similar to other rivers in semi-arid northeastern Brazil, they have an intermittent flow. The Piranhas-Açu River is the largest source of freshwater in this region, and has the largest hydrographic basin. It is dammed by the Armando Ribeiro Gonçalves Dam, and has a total maximum discharge of 1750 $m^3\ s^{-1}$ during ebb tides and 324 $m^3\ s^{-1}$ during flood tides (Rocha and Vital 2009). The east coast has a greater number of basins, although they are smaller

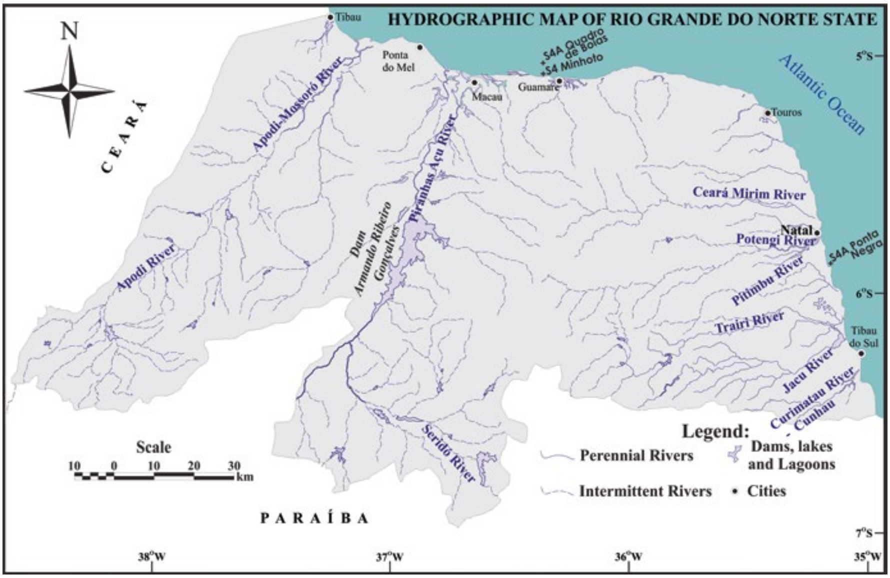

Fig. 8.4 Hydrographic network of Rio Grande do Norte, Brazil. S4 and S4A current meter are also located adjacent to Ponta Negra and Minhoto beaches

in size (e.g. the basins of the Ceará-Mirim, Potengi, Trairi, Jacu, and Curimataú rivers), which contribute to the reduced fluvial discharge and sediment deposition in the region (Fig. 8.4).

8.1.4 Tides, Currents, and Waves

The Rio Grande do Norte coast has a semi-diurnal meso-tidal regime with low amplitude subtidal variability. Sea level records for the northern shelf (Minhoto Beach, Guamaré) in June 2003, and for the eastern shelf (Ponta Negra Beach, Natal) in March of 2014, illustrate the dominant semidiurnal character of sea level variability (Fig. 8.5), with spring tide range varying from 2.5 to 3.0 m and neap-tides from 1.5 to 2.0 m. Wind forcing is relatively strong, but the associated sea level variability is very low amplitude. Tides constitute ~98 % of the sea level energy spectra (Ribeiro 2014). Currents along Minhoto Beach have a dominant semidiurnal signal with low velocities (~10 cm s^{-1}) and a residual component towards the northwest (i.e., Vnorth > 0, Veast < 0). For Ponta Negra Beach, tidal current amplitudes are larger (~20 cm s^{-1}), but the influence of wind in the along-shelf circulation dominates and residual currents flow north.

Relatively little is known about the Rio Grande do Norte wave climate, as compared with southern Brazil, and the knowledge we do have is based on modeling and occasional short-term observations. Pianca et al. (2010) provided the first assessment

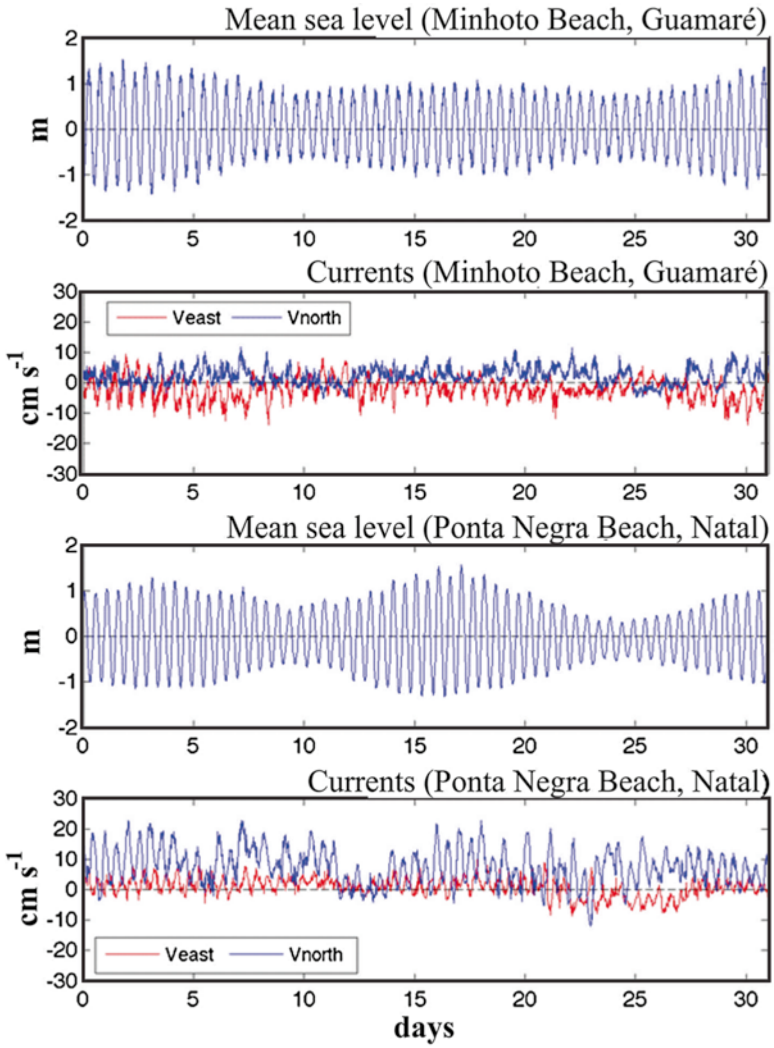

Fig. 8.5 Time series (days) of sea level (m) and coastal currents (cm s^{-1}) along Minhoto Beach, Guamaré, and along Ponta Negra Beach, Natal. Minhoto Beach records represent the northern shelf and cover the period 1 June to 17 July 2004. Ponta Negra Beach measurements represent the eastern shelf and cover the period 14 March to 15 April 2014. Mean sea level was computed from pressure gauge measurements. The eastern and northern current components are denoted as Veast (*red line*) and Vnorth (*blue line*), respectively (Modified from Araujo et al. 2004 and Ribeiro 2014)

of the wave climate for Brazilian waters using an 11-year time series (Jan 1997–Dec 2007) of the National Oceanic and Atmospheric Administration (NOAA) Wave Watch 3 (NWW3) model reanalysis. We used their results for two grid locations on the eastern (9 °S 33.75 °W) and northeastern (3 °S 37.5 °W) regions to represent the Rio Grande do Norte wave climate and to allow correlation with in situ measurements of the Rio Grande do Norte inner shelf.

Table 8.1 Rio Grande do Norte northern sector wave statistics

Variable*	Spring (SON)	Summer (DJF)	Fall (MAM)	Winter (JJA)
$\mathbf{D_p}$	E (57.5 %)	N (36.5 %)	NE (52.7 %)	SE (72.6 %)
$\mathbf{H_s}$	1–2 m (37.9 %)	1–2 m (21.3 %)	1–2 m (43.4 %)	2–3 m (51.6 %)
$\mathbf{T_p}$	6–8 s (46.1 %)	8–10 s (11.7 %)	6–8 s (36.9 %)	6–8 s (59.3 %)
$\mathbf{H_s}^{\mathbf{max}}$	3.2 m from SE	3.1 m from N	2.8 m NE	3.4 m from SE
$\mathbf{T_p}^{\mathbf{max}}$	21 s from N	18 s from N	16 s from N	16 s from N

Modified from Pianca et al. (2010)

*D_p spectral peak direction of the most energetic components of the wave spectra, H_s mean significant wave height (trough to crest), T_p peak period of the most energetic components of the wave spectra; max superscript = maximum observed values in 11-year time series, *N, S, E, W* north, south, east, and west, respectively. Percentages indicate the level of occurrence

Northern Sector Pianca et al. (2010) reported that the dominant wave directions (D_p) in the northern Rio Grande do Norte are from the east and north during the spring and summer, and from northeast and southeast during the fall and winter, with heights (H_s) that vary from 1 to 2 m between spring and fall, and 2–3 m during the winter (Table 8.1). The peak periods for the most energetic components of the wave spectra (T_p) are 6–8 s for all seasons, except during the summer when values are between 8 and 10 s. The highest waves (H_s^{max}) are typically between 3.1 and 3.4 m, and the longest peak periods vary between 16 and 21 s (T_p^{max}).

In situ measurements along the northern coast, close to Guamaré (Araujo et al. 2004), indicate mean H_s of 2.0 m and periods of 7.0 s for November 2003 (representing the summer dry period), and a less intense wave-field (mean height of ~1.8 m and a period of 8.3 s) from May to June 2004 (winter or rainy period). These seasonal differences in currents and waves were attributed to remote forcing and the position of the ITCZ. Stronger southeast trade winds induce more intense coastal currents and waves fields, while weaker currents and smaller and less frequent waves are observed during the winter (rainy period), when the southeast trade winds are weaker.

Eastern Sector Pianca et al. (2010) reported that for the eastern Rio Grande do Norte coast, dominant wave directions are from the east during the spring, summer, and fall, with height ranging between 1 and 2 m with periods of 6–8 s (Table 8.2). During the winter, the dominant direction is southeast. The highest waves are observed from the southeast and generally have heights of 2–3 m, with a maximum wave height of 4.3 m. The longest periods vary from 16 s in the fall to 21 s in spring.

More recently, Almeida et al. (2015) evaluated the Ponta Negra Beach wave climate by investigating propagation of deep-water spectral wave scenarios under low and high tides. The eastern sector exhibited small variability in wave direction, with the predominant direction east-southeast (75 %) in all seasons, followed by waves

Table 8.2 Rio Grande do Norte eastern sector wave statistics

Variable*	Spring (SON)	Summer (DJF)	Fall (MAM)	Winter (JJA)
$\mathbf{D_p}$	E (60.1 %)	E (50.2 %)	E (42.1 %)	SE (52.2 %)
$\mathbf{H_s}$	1–2 m (47.6 %)	1–2 m (44.6 %)	1–2 m (25.4 %)	2–3 m (35.5 %)
$\mathbf{T_p}$	6–8 s (53.8 %)	6–8 s (43 %)	6–8 s (33.2 %)	8–10 s (25 %)
$\mathbf{H_s^{max}}$	3.8 m from SE	2.6 m from N	4 m from SE	4.3 m from SE
$\mathbf{T_p^{max}}$	21 s from N	19 s from N	16 s from S	17 s from S

Modified from Pianca et al. (2010)

*D_p spectral peak direction of the most energetic components of the wave spectra, H_s mean significant wave height (trough to crest), T_p peak period of the most energetic components of the wave spectra; max superscript = maximum observed values in 11-year time series, *N, S, E, W* north, south, east, and west, respectively. Percentages indicate the level of occurrence

from the east (20 %), southeast (3 %), and east-northeast (2 %). Significant mean wave heights varied between 0.5 and 2.8 m, and waves were below 1.6 m in 75 % of sea states. Waves higher than 2.6 m had a return period of approximately 10 years. Peak period values ranged from 4 to 20 s, and were below 8 s in 75 % of sea states. Waves with periods of greater than 18 s showed a return period of more than 10 years. The analysis of the joint distribution of mean wave height to peak wave period, and mean wave height to direction, showed that the most frequent waves are those between 1.3 and 1.7 m in height, have a period of ~8 s, and are from a 110 ° (east-southeast) direction.

8.1.5 Coastal Sediments

The Rio Grande do Norte coast is located along the sediment-starved coast of northeastern Brazil (Dominguez 2009). The rivers of the study area are small and do not contribute a significant amount of bedload sediment to the coast. Moreover, rivers with the highest discharge (e.g. the Piranhas-Açu and Apodi-Mossoró rivers) are dammed, and reservoirs prevent sediments from reaching the ocean. As a result, the river waters that discharge into the ocean do not form large sediment plumes. Loss of sediments towards the land by dune field and spit-barrier island formation, tectonic setting, and longshore sediment removal and transport also contribute toward this negative sediment budget (Vital 2006; Vital et al. 2006).

The beaches are dominated by siliciclastic sands, with muddy sediments (mainly coarse silt) restricted to river mouths. Beach sediments are mainly moderately sorted fine–medium grained quartz. Carbonate sediments are observed only when biodetrical gravel is present (e.g. Lima et al. 2006; Chaves et al. 2006; Vital 2009). Heavy minerals, which are normally associated with high-energy periods, are found in the form of ilmenite, zircon and rutile, and are derived from rivers mouths and Barreiras Formation outcrops (Vital and Guedes 2000).

8.1.6 Coastal Provinces and Geomorphology

Most of the present-day relief along the Rio Grande do Norte coast resulted from the deformation and erosion of preexisting topography and it is characterized by coastal plains, coastal tableland, fault-controlled valleys, beachrock, and coastal dune fields (mainly barchans and barchanoids). The Touros platform, representing a structural high from the Potiguar Basin, separates the eastern and northern sectors.

Along the northern coast, dunes are mostly barchans and barchanoids. Barrier islands and sandy spit systems are restricted to the northern sector, between Ponta do Mel and Ponta dos Tres Irmãos, where cliffs from the Barreiras Formation are not found. Of the 244 km of the northern coastline, which represents 59 % of the Rio Grande do Norte coast, 194 km (80 %) is sandy beaches, 10 km (4 %) is muddy beaches, and 40 km (16 %) is active cliffs.

The eastern coast has a length of 166 km, representing 41 % of the Rio Grande do Norte coast, of which 101 km (61 %) is composed of sandy beaches, and 65 km (39 %) is composed of active cliffs of the Barreiras Formation, together with extensive parabolic or blowout dune fields controlled by vegetation. The dominant morphological signature in the eastern sector is a horst-graben structure along the margin, which has driven the erosion associated with waves refraction patterns, and explains the differential erosion on Barreiras Formation rocks. The horst-graben structure controls the morphology of the coastal tablelands (e.g. Bezerra et al. 2001), with these beaches variably referred to as zeta curved bays (e.g. Carter 1988), headland embayed beaches, structurally controlled beaches (Short and Masselink 1999), or headland bay beaches (Klein 2004).

8.2 Rio Grande do Norte Beach Systems

The Rio Grande do Norte coast is exposed to easterly and southeasterly waves and meso-tides, which has resulted in a predominantly tide-modified coast and beaches on the open shore (Fig. 8.6). Rio Grande do Norte hosts 100 beach systems along its open coast, which are tide-modified to tide-dominated along the northern sector, and tide-modified to wave-dominated along the eastern sector. Reflective and rock or coral reef flats are present in both sectors.

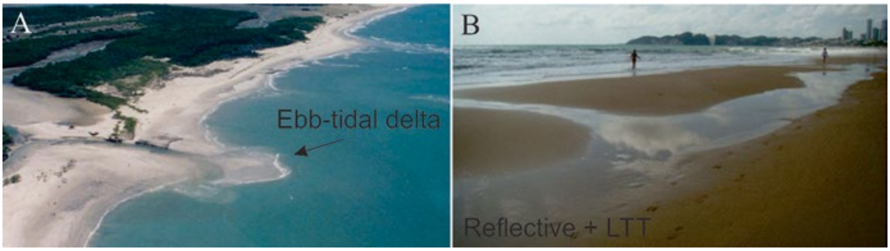

Fig. 8.6 Tide-modified beaches along the coast of Rio Grande do Norte, Brazil: (**a**) Diogo Lopes Beach, northern Sector; (**b**) Ponta Negra Beach, eastern Sector (Photos courtesy of H.Vital)

8.2.1 Coastal Processes and Parameters

The Rio Grande do Norte region experiences high-energy, coastal and shelf parallel currents driven by combined flows related to oceanic, tidal, and wave processes. Since strong winds are almost constant, water masses are well mixed with no stratification.

The breaker wave height during spring high tides, acquired monthly from different beaches along the Rio Grande do Norte coast, indicate that wave heights are greater along the eastern sector. Along the northern sector, waves have a maximum height of 0.8 m during the summer, and 0.7 m during the rainy (winter) season (Tabosa et al. 2001; Silveira et al. 2006; Lima et al. 2006; Chaves et al. 2006), with a medium wave period of 7.5 s. In the eastern sector, waves have a maximum height of 1.85 m during the summer, and a maximum height of 0.85 m during the rainy (winter) season (Chaves 2000; Souza 2004; Frazão 2003).

8.2.2 Beach Types and States

Rio Grande do Norte beaches range from wave-dominated to tide-modified and tide-dominated, with beach type controlled by the relative tidal range (RTR):

$$RTR = TR / H_b$$

where TR is the spring tide range (m) and H_b is the breaker wave height (m). Rio Grande do Norte beaches have RTR values ranging from 1 to 35 (Fig. 8.7). Those with RTR < 3 are wave-dominated, those with RTR of 3–10 are tide-modified, and those with RTR > 10 are tide-dominated. The dimensionless fall velocity Ω, can be expressed as:

$$\Omega = H_b / W_s T$$

where W_S is the sediment fall velocity (cm s^{-1}) and T is the wave period (s). Reflective beaches tend to occur when $\Omega < 1$, intermediate rip-dominated beaches

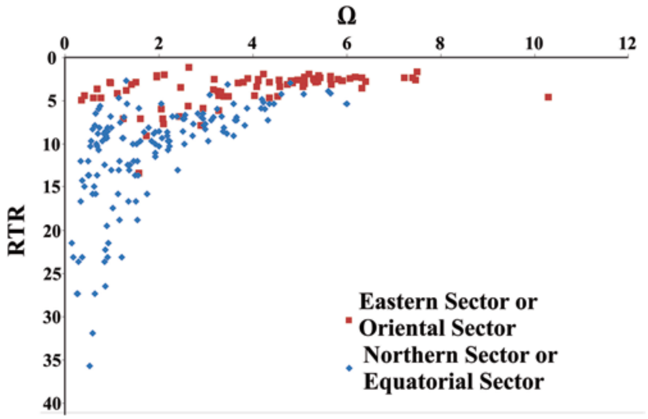

Fig. 8.7 Relationship between Ω (dimensionless fall velocity) and relative tidal range (*RTR*) of beaches along the eastern (or oriental) sector (*red squares*) and northern (or equatorial) sector (*blue diamonds*) of the Rio Grande do Norte coastline, Brazil

occur when Ω ~2–5, and dissipative beaches occur when Ω>6. The Rio Grande do Norte coast contains the full range of beach states (Fig. 8.7), with the higher energy eastern sector characterized by wave-dominated and some tide-modified beaches (predominately in reflective and intermediate states), while the lower energy and higher tidal range northern sector is characterized by tide-modified and tide-dominated beach states, with beaches ranging from reflective to intermediate (with reflective state beaches dominant).

Tide-modified beaches are by far the dominant type along the Rio Grande do Norte coast. The Reflective + low tide terrace (+ rips) (R + LTT) and Reflective + low tide bars & rips (R + LTR) rips are the most frequent along the northern and eastern coastlines, respectively. Wave-dominated beaches (RTR < 3) occur only along the eastern coast, where each of the six wave-dominated state types have been observed, although they are very few in number. Despite Ω>6, most waves are lower than 1 m and the dissipative beaches state is the most scarce, while the Longshore bar & trough (LBT) state is the most frequent among the wave-dominated beaches. The beaches on the eastern sector have fine–medium sand, which coarsens where cliffs are present.

The northern sector contains both tide-modified and the only tide-dominated beaches, which occur where waves are very low and the tide is higher than 3 m (e.g. Galinhos, Pontal do Anjo). Sediments range from fine to coarse sand, and are moderately to poorly sorted.

8.2.3 Spatial Variations in Beach State

Spatial variations in beach state (Fig. 8.7) are primarily driven by changes in the breaker wave height, which is controlled by regional orientation (e.g. northern and eastern sectors) and bedrock, which influences wave attenuation and breaker wave height. Although the mean wave height on the inner shelf is 2.0 m, breaker waves are considerably lower owing to attenuation across the shelf and around headlands. Furthermore, TR is between 2.3 and 2.7 m on the eastern sector, but increases to 3 m on the northern sector. Along both coasts, sediments are predominately fine–medium sand, coarsening due to carbonate shells on the northern sector, and near cliffs of the Barreiras Formation along the eastern sector.

The higher waves and lower tides of the eastern sector combine with sediments to maintain both wave-dominated (in most exposed locations) and tide-modified beaches. Dissipative beaches are favored in exposed areas of finer sand, while reflective beaches are favored in areas of coarser sand. Along the northern sector, the lower waves and higher tides have favored the formation of tide-modified beaches and, in the areas with the lowest waves, tide-dominated beaches.

In general the R+LTT is present along the whole coast for most of the year, while wave-dominated LBT, Rhythmic bar & beach (RBB), Transverse bar & rip (TBR), LTT, and R occur along the eastern sector, and tide-dominated Beach+tidal sand flats (B+TSF) occurs along parts of the northern sector. Reflective+rock flats (R+RF) or Reflective+coral reef flats (R+CF) are also present in both sectors, where bedrock and beachrock reefs are prevalent.

8.2.4 Temporal Variations in Beach State

Temporal variations in the states of the Rio Grande do Norte beaches occur as a result of the lower summer and higher winter waves (Fig. 8.8a). On the eastern sector the Ω is highest during winter when waves are higher (Table 8.2), with lowest values accompanying the lower summer waves. Likewise along the northern sector the lower summer waves lead to higher RTR (more tide-dominated) compared to winter (Table 8.1). This results in some beaches shifting to higher energy states, and possibly from tide-modified to wave-dominated states between summer and winter.

Figure 8.8b plots the response of three beaches during the lunar tidal cycle. The beaches range from wave-dominated (Campo Macau in winter) to tide-modified (Pontal do Anjo-Macau in summer; Fig. 8.9), to tide-dominated (Galinhos in summer). Beach profiles were measured during the four phases of the moon. Moreover, the Galinhos Beach topographical profile was measured five times during the full moon phase, at intervals of 1 h between each profile, beginning 2 h before the low tide (for details see Lima et al. 2006 and Chaves et al. 2006). The data set

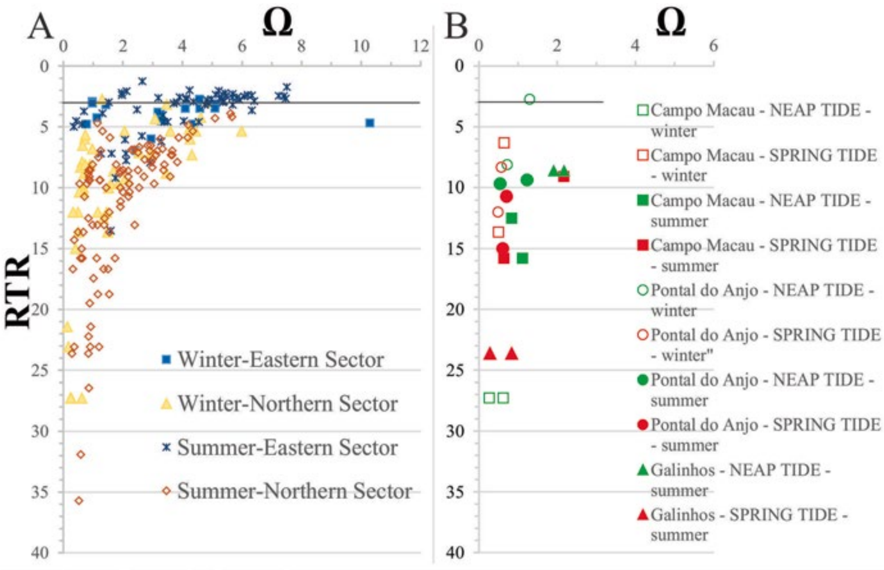

Fig. 8.8 Temporal relationship between Ω (dimensionless fall velocity) and relative tidal range (*RTR*) of beaches along the Rio Grande do Norte coastline, Brazil: (**a**) seasonal variations, with data sorted by winter and summer for the eastern (*blue squares* and *blue* x, respectively) and northern (*yellow triangles* and *brown diamonds*, respectively) sectors; (**b**) variations with the lunar cycle, with data sorted by neap tides (*green colors*) and spring tides (*red colors*), winter and summer seasons at Campo Macau Beach (*squares*), Pontal do Anjo Beach (*circles*), and Galinhos Beach (summer only; *triangles*)

Fig. 8.9 Pontal do Anjo Beach (Northern sector, Rio Grande do Norte coastline, Brazil) during a spring low-tide: (**a**) summer of 2001; (**b**) winter (rainy season) of 2002

collected across a lunar cycle showed that deposition is highest during spring tides accompanying the full moon. The changes observed during the tidal cycle also showed that modification of the beach profile begins soon after the slack tide, when the tide begins to flood.

8.2.5 Beach-Dune Interactions

Along almost the entire Rio Grande do Norte coast, regardless of the presence of cliffs, significant aeolian sedimentation records show that past climatic and geological conditions were more favorable than at present to the accumulation of aeolian deposits.

Extensive coastal dune deposits are present along the Natal coast (eastern sector), just landward of the beach, and are termed the Barrier Dune System (Melo 1995). This barrier dune system is very important to Natal City because it hosts part of the aquifer supplying water to the city, as well as regulating groundwater distribution and the supply of water to coastal lakes (Medeiros et al. 2001). The predominant aeolian transport direction is from southeast to northwest. Where active dunes occur they are usually the reworking older inactive dunes, generally in the form of blowout. Most inactive dunes are vegetated parabolics that no longer have an active sediment source.

The northern sector has few cliffs, some with elevations of less than 5 m, which were generated by the erosion of aeolianite rocks, beachrock, and the Tibau and Barreiras formations. There are occasional dune blowouts, and more frequent active dune fields (e.g. the Zumbi and Rosado dune fields). Where there are active cliffs along the eastern sector, and in the region of Pipa, the cliff top dunes which cover coastal tablelands probably predate the erosion of the cliffs.

Coastal sediment supply and aeolian transport from beaches to the mainland are not yet fully understood along the Rio Grande do Norte coast. Both could be associated with lower relative sea level that may have exposed the shelf to wind action, although this is unlikely. It is more likely that they are related to transgressive and higher relative sea level, which allowed for the erosion of the cliffs and deposition of more sediments on the beaches; thus, generating a surplus sediment budget. Conclusively identifying the correct process requires systematic dating of the various dune fields, using a well-designed chronostratigraphic framework for correlation with the changing sea level curve.

The dunes of the Rio Grande do Norte coast are classified as recent (Holocene) dunes and paleodunes (Pleistocene), according their stability, the age of stabilization, and to morphological, sedimentological and biological criteria (Barreto et al. 2004; Angelim et al. 2006). Regardless of classification or age, the dune fields have a maximum thickness of 50 m, with the sand color white or yellow/red. In some dunes the yellowish/reddish color be attributed to pedogenetic processes, and these are considered “paleodunes”; however, these colors are also found in active dunes, resulting from the erosion of red rocks of Barreiras Formation that are rich in iron oxide cement (e.g. the Rosado dune field). Therefore, color cannot be used as a reliable criterion for characterizing “paleodunes”.

One of the most important differences between the eastern and northern sectors relates to the wind transport pattern. Along the eastern sector, the direction of migration is consistently southeast-northwest, ranging from N31 °W near Paraiba Border to N64 °W at Touros. In the northern sector, at least two dominant wind transport directions are evident: southeast-northwest and northeast-southwest. In both sectors, wind transport from southeast to northwest is associated with the southeasterly trade winds, which are most active during the winter (rainy) season. Along the northeastern coast during the summer, the Atlantic Equatorial Mass provides the dominant northeast winds.

Costa Neto (2009) monitored the direction and speed of winds along the northern sector and found that between October and April, the velocities of winds from the northeast and east-northeast range between 20 and 30 km h^{-1}, but exceed 30 km h^{-1} in 5–15 % of the observations. February has the highest percentage (~15 %) of high wind speeds, while in December only 10 % of the observed wine speeds are greater than 30 km h^{-1}. The differences in the dune migration direction between the eastern and northern sectors can be attributed to the orientation of the shoreline, and to the action of the Atlantic Equatorial Mass, which has a dominant wind direction of northeast and east-northeast in the eastern sector; although, southeast winds also present significant speed values for at least 2 months a year (during the drought period). Therefore, the eastern sector has a more effective capacity for wind transport. The migration of dunes (active or inactive) is limited to ~20 km inland. However, some dunes are contained close to the shoreline owing to interception by water bodies, in particular perennial rivers of different sizes.

An integrated view of the geological framework of the Rio Grande do Norte coastal region can be seen in Ground Penetrating Radar (GPR) records (Fig. 8.10). In GPR radargrams we can interpret saline wedges and stratigraphic stacking of sedimentary packages, which emphasizes recent beach deposits (indistinct foreshore and backshore) of ~2.5 m in maximum thickness. The sandy rocks of Tertiary Barreiras Formation are interpreted as fluvial (Araujo et al. 2006) and serve as a substrate for younger sedimentary deposits, including the Potengi Formation of unknown age, which is up to 10 m thick, and Quaternary sediments of active dunes, where two generations of dunes can be identified (Fig. 8.10a). A radargram showing a northwest–southeast profile ~60 m in length and 6 m depth (Fig. 8.10b), shows foredune and sand sheets deposits. In the frontal dunes, two 2nd order surfaces are observed, recording three main stages of dune migration at Malemba Beach. Figure 8.10c shows wind-driven sedimentary packages along an 820 m section of Buzios Beach (collected with a GPR antenna of 50 MHz) that are limited by 2nd and 3rd order surfaces and by a complex arrangement of layers. To ensure that ages have geological significance, dating of these deposits will rely on the development of a chronostratigraphic framework to accurately define sampling sites.

8.2.6 Beach-Beachrock Interactions

Beachrock reefs are common along the Rio Grande do Norte shore, occurring in both the offshore and onshore zones (Fig. 8.11). Owing to high ocean temperatures, beachrock can form in a few decades, cementing the intertidal beach sands. This cementation may lead to substantial modification of Holocene coastal processes and

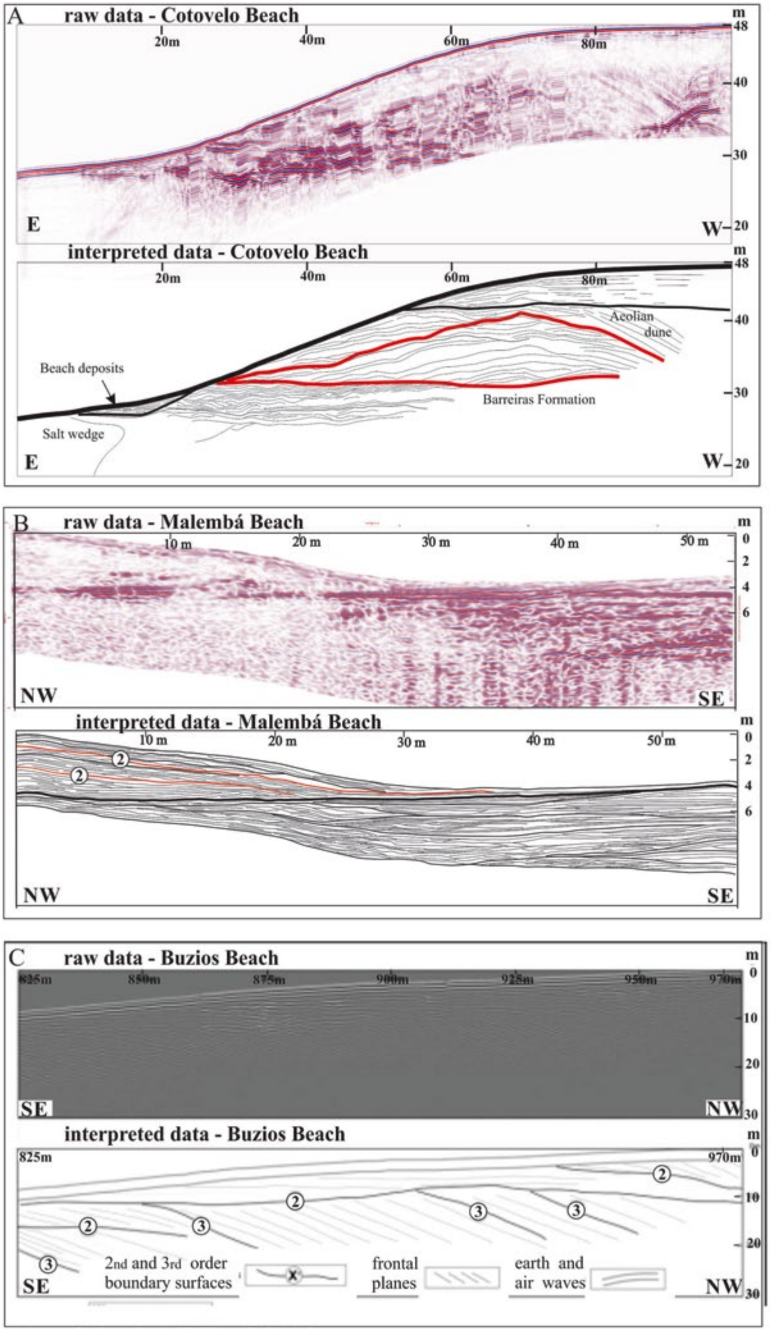

Fig. 8.10 Ground Penetrating Radar (*GPR*) radargrams of dunes along the Rio Grande do Norte coastline, Brazil. In each sub-plot, the top plot shows raw data and the bottom plot shows the interpreted cross-section: (**a**) Cotovelo Beach, including a salt wedge, beach deposits and two generations of dunes; (**b**) Malemba Beach, including a foredune with two 2nd order surfaces, and sand sheets deposits; (**c**) Buzios Beach, including 2nd and 3rd order surfaces, and a complex arrangement of layers observed in dunes

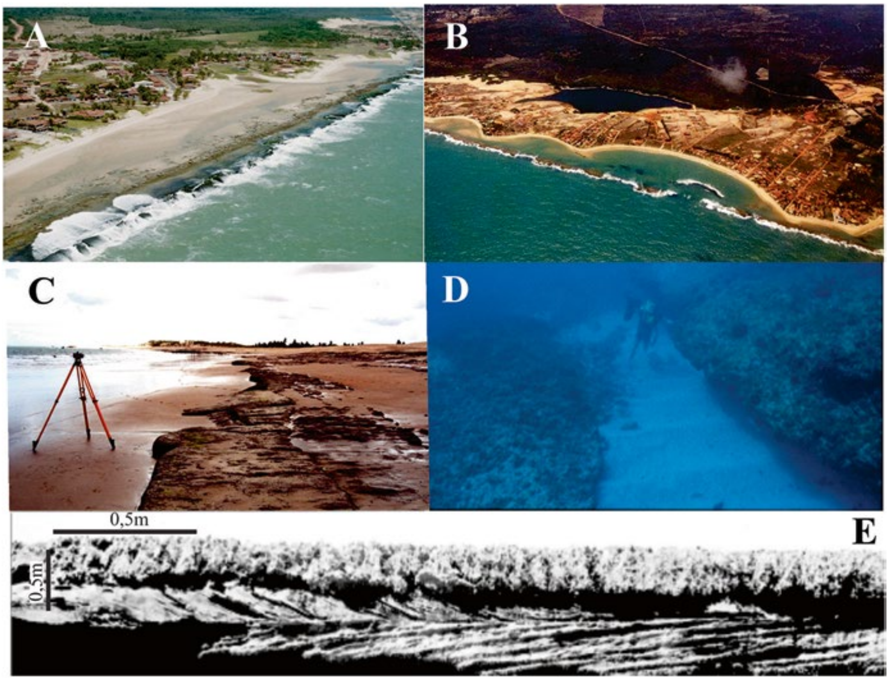

Fig. 8.11 Beachrock along the Rio Grande do Norte coastline, Brazil: (**a**) Graçandu Beach at low-tide; (**b**) Barreta Beach at high-tide; (**c**) Galos Beach; (**d**) submerged beachrock at 25 m depth, Urca do Minhoto; (**e**) sedimentary structures observed in the beachrock of Praia do Forte Beach; (Photos courtesy of H. Vital (**a**, **c**, **e**), L.H.O. Caldas (**b**), and A. Schimanski (**d**)

subsequent Holocene beach and barrier formation (Vousdoukas et al. 2007; Cabral Neto et al. 2014). Reefs are better developed on the eastern coast because of their continuity (e.g. the Barreta, Forte, and Graçandu beaches), but are also present on the northern coast (e.g. the Galinhos and Ponta do Mel beaches). Submerged beachrock reefs are also reported along the littoral region at different depths (Vianna et al. 1991; Testa and Bosence 1998, 1999; Vital 2006, 2009; Vital et al. 2008a; Santos et al. 2007; Cabral Neto et al. 2014). The most continuous structure is situated along the 20–25 m depth isobaths, but small structures are also found along the 10 and 40 m isobaths. Elevations reach 2.5–5 m above the sea floor, and the widths vary between 500 and 1000 m.

Beachrock laminations are oriented sub-horizontally and dip gently seaward (<10°). They are composed of siliciclastic (70–75 %) and bioclastic components (30–25 %), with quartz the main mineral (up to 68 %), followed by feldspar and heavy minerals. Bioclastic components can reach up to 30 % and are mainly red algae and bivalves. Beachrock composition is usually similar to modern sands of the adjacent beaches (Branner 1904; Oliveira et al. 1990; Vieira et al. 2007; Cabral Neto et al. 2014), and are characterized by swash-cross stratification in the foreshore zone (top) and trough-cross stratification in the shoreface zone (base).

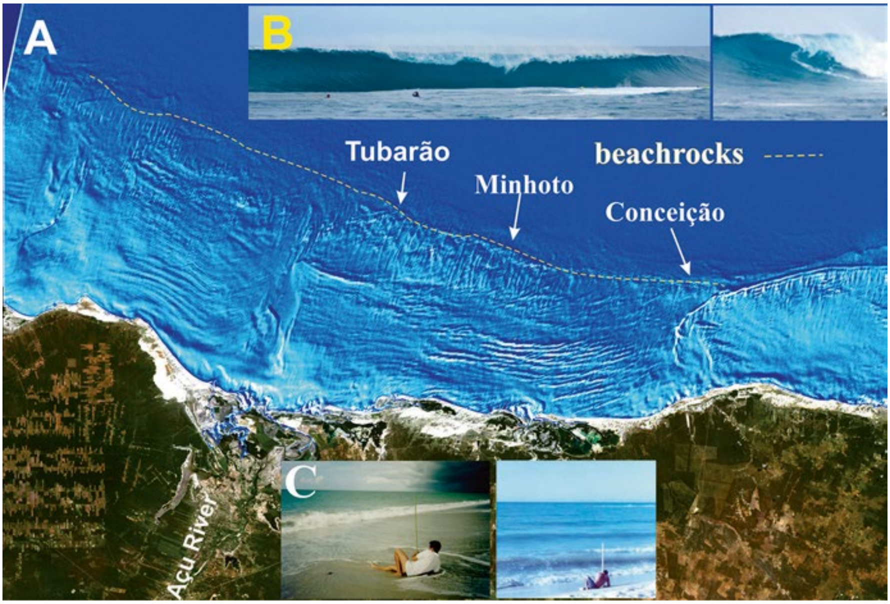

Fig. 8.12 Wave height vs. submerged beachrock along the northern sector of the Rio Grande do Norte coastline, Brazil: (**a**) Landsat 7 Enhanced Thematic Mapper plus (ETM+) image of the Brazilian tropical northeast shelf (Northern sector), running adjacent to Rio Grande do Norte and showing the almost continuous submerged beachrock (*yellow dashed line*) and different seabed features. Land is shown in *yellow–white colors*, and the shallow subaqueous shelf is shown in *blue colors* (Image modified from Gomes and Vital 2010); (**b**) offshore waves (Image courtesy of C. Bandeira); (**c**) break zone waves

Relict submerged beachrock reefs on the Rio Grande do Norte shelf (Figs. 8.11d and 8.12) are aligned parallel to the present-day coast at 20–25 m depth, and can be tracked from at least Natal to Areia Branca. The submerged beachrock lines modify beach morphodynamics by reducing and redistributing the wave energy impacting on the coastline. As a result, offshore waves on the border of the medium and outer shelf (25 m depth) are higher (2–5 m) than on the inner shelf (2 m) and breaker zone (Fig. 8.12 b, c).

8.2.7 Beach-Barrier Islands

Spit-barrier island systems on the Rio Grande do Norte northern coast range from barrier spits (e.g. Galinhos, Diogo Lopes) to barrier islands (e.g. Ponta do Tubarão, Amaro). They are composed of sandy sediments and often capped by dunes. The evolution of these barrier systems has been cyclic (Xavier Neto et al. 2001; Lima et al. 2001, 2002; Silveira et al. 2006; Silva et al. 2011) indicating an ancient system of barrier islands that has developed into the current spits, and spits that have recently detached to form barrier islands (Vital et al. 2008b, 2011; Rocha et al. 2009). Studies of modern coastal environments and sediments in this area (e.g. Vital et al. 2003a) show that barrier spits and barrier islands occur only along the east-west northern coast, confined between two important fault systems: the Carnaubais and Afonso Bezerra systems (Fig. 8.13). However, in the past, barrier islands were abundant along the entire northern coast (e.g. Caldas et al. 2006; Vital 2009; Vital et al. 2013).

The prograding nature of this coastal plain was first presented in the Silva (1991) model, in which lagoons, tidal flats, and fluvial sediments were deposited behind a barrier spit, while tidal inlet, tidal flat, and small secondary spit sediments were deposited seaward of the barrier spit. A restricted microfaunal assemblage occurred behind the barrier spit, while an open marine fauna occurred in front of the spit. The environments seaward of the barrier spit represented a tidal inlet sub-facies of the ebb-tidal delta facies preserved in the subsurface, with the ebb-tidal delta complexes attached to the mainland and promoting shoreline progradation.

8.2.8 Longshore Transport and Beach Stability/Erosion

Coastal current observations are scarce for the Rio Grande do Norte coast. The longest measurements were obtained for the eastern sector (Ponta Negra Beach, Natal), between October 2013 and April 2014. A S4A current meter was moored at 10 m depth and positioned 1.5 m from the bottom, returning more than 212 days of sea level and current observations (Ribeiro 2014). For the northeastern sector, measurements have been collected offshore of Guamaré City by the Quadro de Boias station, an S4A current meter moored at 20 m depth and positioned 10 m from the bottom, during November 2003; and nearshore, off Minhoto Beach, using an S4 current meter moored at 4 m and positioned 2 m from the bottom, during November 2003 and May–June 2004 (Vital et al. 2008a).

The Ponta Negra observations demonstrate that inner shelf currents mainly flow north, with low directional variability during the observed seasons (Fig. 8.14a). Stronger currents (>0.20 m s^{-1}) occur during summer and fall. Longshore currents mainly flow north, but ocassionally reverse to the south. Trajectories computed for virtual drifters illustrate northward residual currents, parallel to the coastline and with trajectories that range from 150 to 320 km in different seasons[1] (Fig. 8.14b). Coastal currents change direction owing to tides in the cross-shelf direction, which steer the flow towards and against the coast. The sea level subtidal component is well correlated to winds, but demonstrate very low amplitudes. Spectral analyses indicate that alongshore currents have more energy in the meteorological (~15 %) and low frequency (>50 %) bands, while cross-shore currents are dominated by semi-diurnal (>28 %) tides (Fig. 8.14c).

[1] Virtual trajectories are found by integrating the velocity field in time and further assuming a horizontally uniform flow.

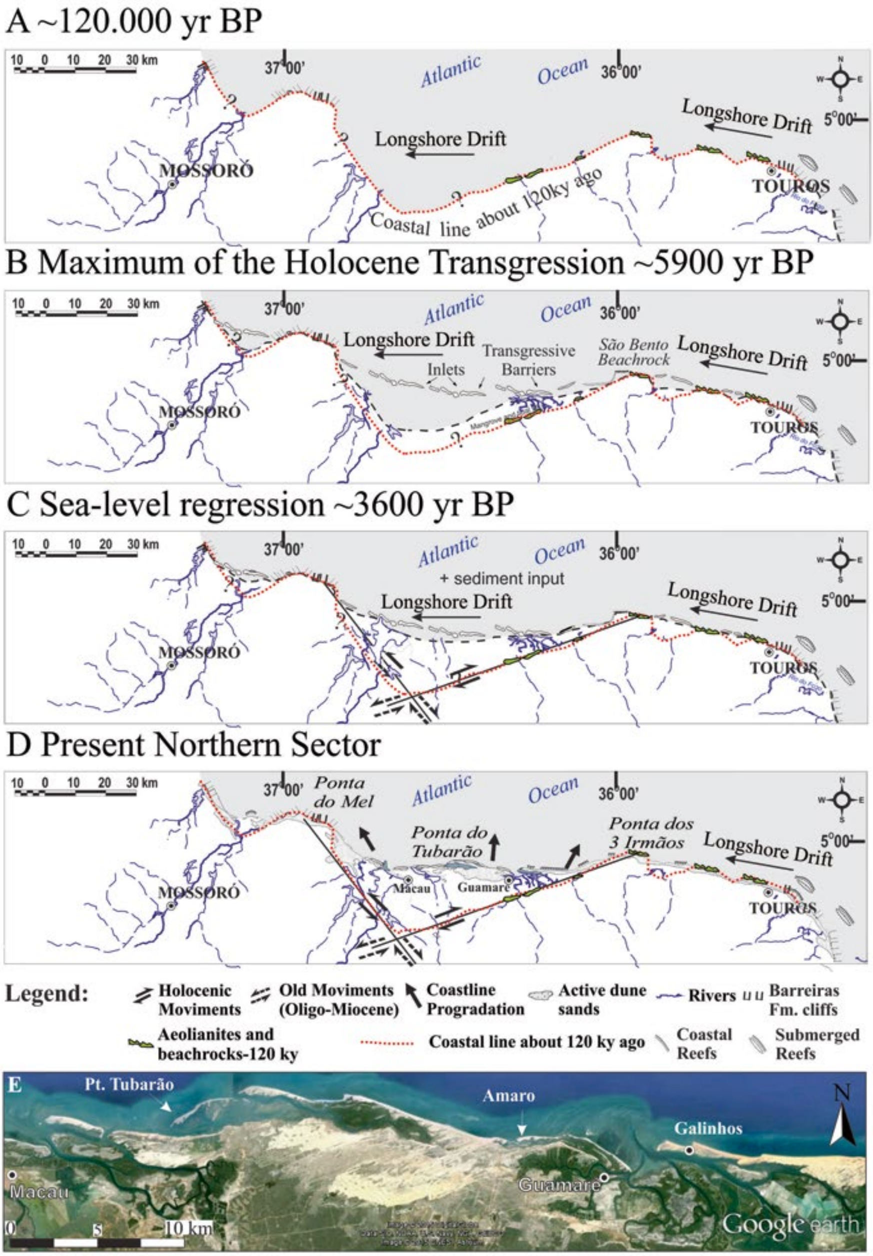

Fig. 8.13 Evolutionary model for the coastal barriers of the northern Rio Grande do Norte State coastline, Brazil (based on Silva 1991, Fonseca 1996 and Caldas 2002): (**a**) Shoreline at ~120 ka before present (BP); (**b**) shoreline at ~5.9 ka BP; (**c**) shoreline at ~3.6 ka BP; (**d**) present-day shoreline (Modified from Vital 2009 and Vital et al. 2013); (**e**) Google Earth view of the barrier-spit system (image©2015 DigitalGlobe, image date 03/24/2014)

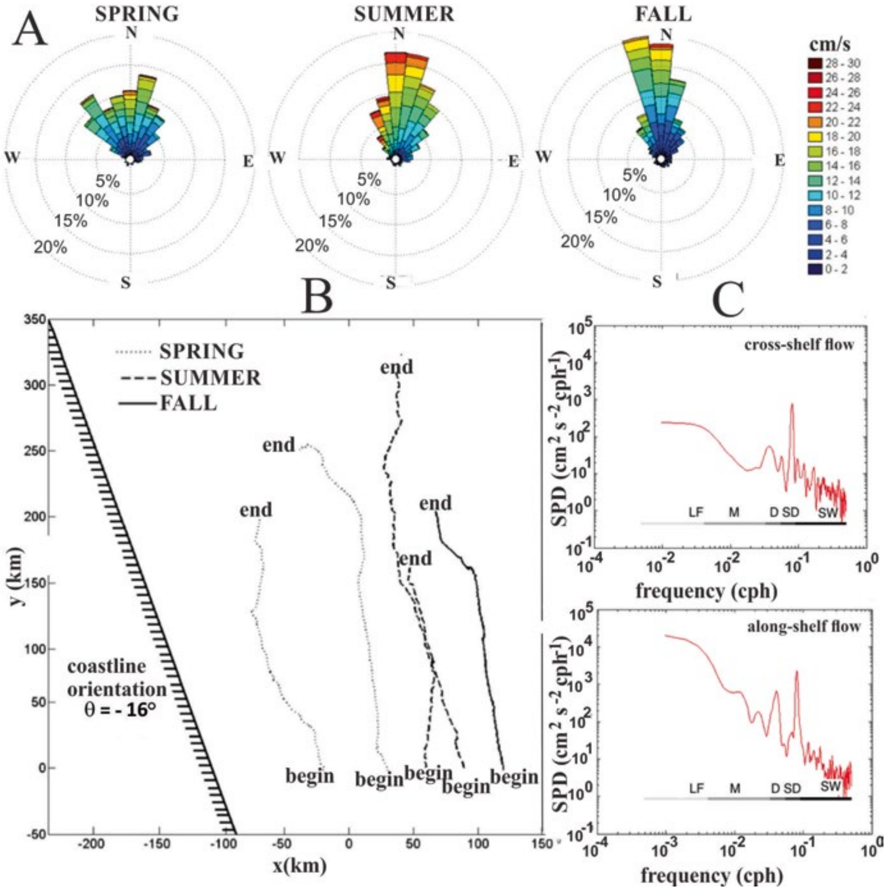

Fig. 8.14 Coastal currents for the eastern sector (Ponta Negra Beach, Natal), modified from Ribeiro (2014). For location see Fig. 8.4. (**a**) Direction and speed distributions for inner shelf currents for the summer, spring and fall. The bars follow the oceanographic convention and point towards the direction that the current flows. The bar color indicates the current speed, while the radius indicate the percentage of occurrence. (**b**) Trajectories for virtual drifters computed from inner-shelf currents records. A *straight line* illustrates the average orientation of the coastline, while trajectories are shown in kilometers. (**c**) Spectral density estimates (*SPD*) for Ponta Negra cross- and alongshelf currents during the fall. Note that the semi-diurnal band (*SD*) is dominant for the across-shelf flow, while meteorological (*M*) and lower frequency (*LF*) bands dominate the alongshelf flow. Other symbols represent the diurnal (*D*) and shallow water (*SW*) components

Along the northern sector, longshore currents flow towards the west-northwest (oblique to the coast) with a maximum of 97 cm s^{-1} during rising tides, and towards the north (perpendicular to oblique to the coast) with a maximum of 50 cm s^{-1} during falling tides. These are by far the dominant contributors to net sediment transport along the coast of Rio Grande do Norte. Owing to the obliquity of the strongest winds, alongshore wind-driven currents increase sediment transport rates, while the relatively small tidal currents (~5–60 cm s^{-1}) have only a small transport capacity.

On the northern coast, the impact of the currents on sedimentation processes is clear. Extensive west-trending spits generated by nearshore currents occur parallel to the coast (e.g. Silveira et al. 2006; Lima et al. 2006), while smaller perpendicular spits (Silva et al. 2011; Vital 2009) are generated by tidal currents. Nearshore current measurements show tidal currents up to 130 cm s^{-1}, flowing southwest, west, and northwest during flood tides, and north-northeast during ebb tides (Vital et al. 2011). The predominance of the ebb-tide is indicated by the higher values of the average currents (30–70 cm s^{-1}) when compared with the flood-tide (20–60 cm s^{-1}). The calculated longshore sediment transport is between 100 and 110 m^3 d^{-1} (Chaves et al. 2006; Vital et al. 2006).

The seven most common indicators of coastal erosional along the Rio Grande do Norte coast are (e.g. Vital et al. 2003b, 2006; Vital 2006): (1) general and progressive landward shoreline displacement (retrogradation) during the last six decades; (2) severe erosion of the Tertiary Barreiras Formation, as well as erosion of Quaternary aeolian and/or marine deposits along the coastline; (3) destruction and burial of mangroves adjacent to the beach; (4) subaerial exposure of peat bogs from ancient lagoonal or mangrove deposits on foreshore and upper shoreface surfaces; (5) persistent destruction of engineering works; (6) concentrated heavy minerals in foreshore zones; and (7) the development of beach embayments.

Furthermore, the most important factors and causes of coastal erosion along the Rio Grande do Norte coast are related to (e.g. Vital et al. 2003b, 2006; Vital 2006): (1) coastal circulation dynamics: beachrock along both the northern and eastern sectors, which are aligned parallel and intermittent to the beach, change wave energy and cause accentuated erosion and beach embayments. Where beachrock reefs are continuous, they protect extensive stretches of coast; in contrast, accentuated erosion take place where in lee of gaps in the beachrock (Fig. 8.11b). When beaches are eroded, the beachrock remain as natural breakwaters to modify wave energy, and thereby control the shape of the retreating shoreline; (2) Holocene evolution of the coastal plain: sedimentation during the Holocene has mainly been controlled by variations in sea level, longshore currents, and the advance of active dunes along the coast (Caldas et al. 2006). Intensive erosion along some stretches of the coast can be related to intense longshore drift (northerly along the eastern sector, and westerly along the northern sector) associated with a negative sediment budget and sediment loss towards the land during dune field and spit-barrier island formation; (3) naturally insufficient sediment supply: long-term trends of coastal erosion in northeastern Brazil relate to an insufficient sediment supply (Dominguez and Bittencourt 1996). The rivers in the study area are small and do not contribute significant sediments. Moreover, the largest rivers (e.g. the Açu and Mossoro-Apodi rivers) are dammed, which prevents sediments from reaching the ocean. The relationships between the small size of drainage basins, low intra-basinal relief, and low precipitation values in Rio Grande do Norte have resulted in the small sediment volume from the hinterland to the shelf (the so-called sediment-starved coast: Dominguez 2009); (4) construction of hard interface structures: hard structures prevent the further erosion of beaches or impede the motion of sand along beaches. Inappropriate structures can exacerbate the situation and harm adjacent beaches. Along the Rio Grande do Norte coast, groin fields were constructed on different beaches (e.g. Caiçara do Norte, Macau, Touros), likely because they are traditionally used to prevent erosion on shorelines with significant alongshore transport. However, these structures were built without sufficient background-knowledge of the most important aspects and mechanism impacting on coastal erosion; and (5) tectonic factors: along the northern sector, erosional areas are likely linked to large-scale bottom morphology, while along on the eastern sector, large-scale coastal morphology is the driving force. These differences are mainly due to divergent longshore drift and the negative sediment budget.

8.3 Beach Hazards and Safety

The Rio Grande do Norte beaches contain both natural and anthropogenic hazards. Natural hazards include strong rip and longshore currents, breaking waves, and variable topography associated with beachrock reefs and headlands. Anthropogenic hazards are mainly related to intense exploitation of beaches by tourism, shrimps farms, and the energy industry (wind, oil, and gas exploration). We currently possess a relatively poor understanding of how geological hazards (e.g., storms, active tectonics) impact on the coast and coastal shelf.

Most hazards reported from the eastern coast relate to rip currents (e.g. Buzios Beach), with the majority of accidents occurring when the number of people swimming increases (particularly summer tourists) and when places are not well signed. This is highlighted by preventive work guidance and education, including the placement of road signs at urban beaches with a higher incidence of drowning, which was intensified following the 2014 Fédération Internationale de Football Association (FIFA) World Cup. Because of this, since the beginning of 2015, beaches where flags or plates were placed, or where lifeguards are present, have not registered any fatal drownings.

Along the northern coast, hazards are mainly related to the higher tidal range and to the presence of tidal inlets (especially between the Galinhos and Porto do Mangue beaches) with their strong tidal, nearshore, and oceanic currents. Anthropogenic hazards relate to shrimps farms, the oil industry, and wind-energy projects in extremely fragile and dynamic environments where seabed erosion, strong currents, and sediment transport dominate.

8.4 Summary and Conclusions

The Rio Grande do Norte coast is dominated by sandy beaches backed by cliffs of the Tertiary Barreiras Formation, dune fields, barrier island-spits, and tidal channels. It is exposed to easterly and southeasterly waves and meso-tides that have resulted in a predominantly tide-modified coast and beaches on the open shore. The coast comprises two sectors: the northern, (equatorial) coast trends eastward for 244 km, and the eastern (oriental) coast trends southward for 166 km. The higher energy eastern sector is characterized by wave-dominated and some tide-modified beaches that are mainly reflective to intermediate states. In contrast, the lower energy and higher tidal range of the northern sector has resulted in tide-modified and tide-dominated beaches that range from reflective (the dominant state) to intermediate. In general the R + LTT is present along the entire coast for most of the year, while wave-dominated LBT, RBB, TBR, LTT and R occur along the eastern sector, and tide-dominated B + TSF occurs along parts of the northern sector. R + rock flats and coral reef flats are present in both sectors, where bedrock and beachrock reefs are prevalent.

Beachrock reefs are very common along the Rio Grande do Norte shore, occurring in both the offshore and onshore zones. The reefs modify beach morphodynamics by reducing and redistributing the wave energy impacting the coastline. Longshore currents are mainly towards the north along the eastern sector, and to the west along the northern sector. Sea level variability is dominated by tides (up 98 % of the energy spectra). The sea level subtidal component is well correlated with the winds, but demonstrate very low amplitudes. Spectral analyses indicate that longshore currents have more energy in the meteorological and low frequency bands, while cross-shore currents are dominated by semi-diurnal tides. Longshore currents are wind modulated, while cross-shore currents are primarily modulated by tides and secondarily by winds.

Different indicators of coastal erosion are observed along the Rio Grande do Norte coast. Areas of erosion along the northern sector are likely linked to large-scale bottom morphology, but along the eastern sector erosion is related to large-scale coastal morphology. Natural hazards along the coast are associated with strong rip and longshore currents, breaking waves, and variable topography associated with beachrock reefs and headlands. Anthropogenic hazards mainly relate to intense exploitation of Rio Grande do Norte beaches by tourism, shrimps farms, and the energy industry (wind, oil, and gas exploration).

This chapter has presented a brief overview of our existing knowledge regarding the beaches of Rio Grande do Norte. Systematic morphodynamic studies along all beaches in the region are necessary for a more accurate and complete picture of this remote corner of Brazil.

Acknowledgements The authors express their thanks to the editors (AD Short and AHF Klein) for their invitation to write this chapter and for their helpful comments on the initial version. We also thank the Navy of Brazil (SECIRM / SSN-3) with the support of boats and ships.This work was funded by CNPq (PQ 303481/2009-9, Universal 486451/2012-7), CAPES (Ciências do Mar 207/2010), FINEP/PETROBRAS (PRH-ANP22, PLAT N-NE). This is a contribution from GT 1.1 & GT 2.1 to INCT AmbTropic (CNPq/FAPESB/CAPES).

References

Almeida FFM, Hasuy Y, Brito Neves BB, Fuck RA (1977) Provincias Estruturais Brasileiras. Annals of the 7 Simpósio de Geologia do Nordeste, Campina Grande, October 1977, p 363–391

Almeida LR, Amaro VE, Marcelino AMT et al (2015) Avaliação do Clima de Ondas da Praia de Ponta Negra (Rio Grande do Norte-Brasil) através do Uso do SMC-Brasil e sua contribuição à gestão costeira. Geostão Costeira Integrada http://www.aprh.pt/rgci/pdf/rgci-532_Almeida.pdf,| DOI:10.5894/rgci532

Angelim LAA, Medeiros VC, Nesi JR (2006) Geologia e recursos minerais do estado do Rio Grande do Norte. Escala 1:500.000. Texto explicativo dos mapas geológico e de recursos minerais do estado do Rio Grande do Norte. CPRM, Recife, p 119

Araujo M, Vital H, Amaro VE, Silva MA (2004) Caracterização das Forçantes Hidrodinâmicas – Correntes, Ondas e Marés – na Região Costeira de Guamaré-Rio Grande do Norte. In: Proceedings of the III workshop PETRORISCO, Belém, September 2004 (CD-ROOM)

Araujo VD, Perez YAR, Lima RO et al (2006) Fácies e Sistemas Deposicionais da Formação Barreiras na Região da Barreira do Inferno, Litoral Oriental do Rio Grande do Norte. Geologia USP. Série Científica 6:43–49

Barreto AMF, Bezerra FHR, Tatumi SH et al (2004) Geologia e Geomorfologia do Quaternário costeiro do Estado do Rio Grande do Norte. Rev Instit Geoc – USP. Série Científica 4:1–12

Bezerra FHR, Amaro VE, Vita-Vinzi C et al (2001) Pliocene-quaternary fault control of sedimentation and coastal plain morphology in NE Brazil. J S Am Earth Sci 14:61–75

Branner JC (1904) The stone reefs of Brazil, their geological and geographical relations with a chapter of the coral reefs. Mus Comp Zool Bull, Harvard Coll, Cambridge 44:275

Cabral Neto I, Cordoba VC, Vital H (2014) Beachrocks do Rio Grande do Norte, Brasil, vol 1, 1st edn. EDUFRN, Natal, p 156

Caldas LHO (2002) Late quaternary coastal evolution of the Northern Rio Grande do Norte coast, NE Brazil. PhD thesis, Christian Albrechts University, Kiel

Caldas LHO, Stattegger K, Vital H (2006) Holocene sea-level history: evidence from coa stal sediments of the northern Rio Grande do Norte coast, NE Brazil. Mar Geol 228:39–53

Carter RW (1988) Coastal environments: an introduction to the physical, ecological and cultural systems of coastlines. Academic, London, p 617

Chaves MS (2000) Sedimentologia, Morfologia Praial eVulnerabilidade Costeira entre as Praias da Redinha e Genipabú Natal/Rio Grande do Norte. MSc dissertation, Universidade Federal de Pernambuco

Chaves MS, Vital H, Silveira IM (2006) Beach morphodynamics of the serra oil field (NE, Brazil). J Coast Res 39:594–597

Costa Neto LX (2009) Caracterização Geológica, Geomorfológica e Oceanográfica do Sistema Pisa Sal, Galinhos-Rio Grande do Norte. PhD thesis, Universidade Federal do Rio Grande do Norte

Dominguez JML (2009) The coastal zone of Brazil. In: Dillenburg SR, Hesp PA (eds) Geology and geomorphology of holocene coastal barriers of Brazil. Springer, Berlin, pp 17–51

Dominguez JML, Bittencourt ACSP (1996) Regional assessment of long-term trends of coastal erosion in Northeastern Brazil. An Acad Bras Cienc 68:355–372
Ferreira JM, Oliveira RT, Takeya MK et al (1998) Superposition of local and regional stresses in northeast Brazil: evidence from focal mechanisms around the Potiguar marginal basin. Geophys J Int 134:341–355
Ferreira JM, Bezerra FHR, Sousa MOL et al (2008) The role of Precambrian mylonitic belts and present-day stress field in the coseismic reactivation of the Pernambuco lineament, Brazil. Tectonophysics 456:111–126
Frazão EP (2003) Caracterização hidrodinâmica e morfo-sedimentar do estuário Potengi e áreas adjacentes: subsídios Pará controles e recuperação ambiental no caso de derrames de hidrocarboneto. MSc dissertation, Universidade Federal do Rio Grande do Norte
Gomes MP, Vital H (2010) Revisão da compartimentação geomorfológica da Plataforma Continental Norte do Rio Grande do Norte, Brasil. Braz J Geol 40(3):321–329
Gomes MP, Vital H, Bezerra FHR et al (2014) The interplay between structural inheritance and morphology in the equatorial continental shelf of Brazil. Mar Geol 355:150–161
IBGE (2013) Atlas do Censo Demográfico 2010. http://www.cidades.ibge.gov.br/
Kane RP (2001) Limited effectiveness of El Niños in causing droughts in NE Brazil and the prominent role of Atlantic parameters. Braz J Geophys 19:231–236
Klein AHF (2004) Morphodynamics of headland-bay beaches: examples from the coast of Santa Catarina State, Brazil. Universidade do Algarve, Faro, p 218
Lima MG (2008) A História do Intemperismo na Província Borborema Oriental, Nordeste do Brasil: implicações Paleoclimáticas e Tectônicas. PhD thesis, Universidade Federal do Rio Grande do Norte
Lima ZMC, Alves AL, Amaro VE (2001) Coastline evolution of the Galinhos Spit (NE Brazil) using air photography and landsat TM images. Pesq em Geoc 28:497–507
Lima ZMC, Vital H, Xavier P et al (2002) Sand spits from NE Brazil: high resolution Quaternary analogous for reservoir model. AAPG ACE 2002, Extended Abstract
Lima ZMC, Vital H, Tabosa WF (2006) Morphodynamic variability of the Galinhos Spit, northeastern Brazil. J Coast Res 39:598–601
Matos RMD (1998) The transversal zone: a key feature between NE Brazil and W Africa. In: Proceedings of the Rio'98 AAPG international conference and exibition. Rio de Janeiro, Brazil, p 426–427
Medeiros WE, Nascimento da Silva CC, Jardim SAF et al (2001) Integração de dados estruturais, de sensores remotos e de geofísica na prospecção hidrogeológica em terrenos cristalinos: estudo de casos no Estado do Rio Grande do Norte., Nordeste do Brasil. Simp Hidrogeologia do NE 1:445–454
Medeiros VC, Nascimento MAL, Sousa DC (2010) Geodiversidade do Estado do Rio Grande do Norte: 2.Geologia. In: Pfaltzgraff PAS, Torres FAM (eds) Geodiversidade do Estado do Rio Grande do Norte, 1st edn. CPRM, Recife, pp 15–38
Melo JG (1995) Impacto do desenvolvimento urbano nas águas subterrâneas de Natal/Rio Grande do Norte. PhD thesis, Universidade de São Paulo
Milani EJ, Thomaz Filho A (2000) Sedimentary basins of South America. In Cordani UG, Milani EJ, Thomaz Filho A, Campos DA (eds) Tectonic evolution of South America. 31 international geological congress, p 389–449
Nimmer E (1989) Climatologia do Brasil. IBGE, Rio de Janeiro
Oliveira MIM, Bagnoli E, Farias CC, et al. (1990) Considerações sobre a geometria, petrografia, sedimentologia, diagênese e idade dos "beachrocks" do Rio Grande do Norte. 36 Congresso Brasileiro de Geologia, Natal, v 2, p 621–634
Pianca C, Mazzini PLF, Siegle E (2010) Brazilian offshore wave climate based on NWW3 reanalyis. Braz J Oceanogr 58(1):53–70

Pinheiro JU, Bristot G, Lucena LRF (2010) Clima do Estado do Rio Grande do Norte. In: Pfaltzgraff PAS, Torres FAM (eds) Geodiversidade do Estado do Rio Grande do Norte, 1st edn. CPRM, Recife, pp 93–98

Ribeiro F (2014) Caracterização das Correntes da Plataforma Continental Interna da Praia de Ponta Negra. Trabalho de Cocnlcusão do Curso de Oceanografia. Universidade Federal de Santa Catarina

Rocha AKR, Vital H (2009). High resolution geophysical investigations of the Açu estuary, Northeastern Brazilian Cost. In: Amorosi A (ed) 27th IAS meeting of sedimentologists, medimond international proceedings, Monduzzi Editore, p 91–97

Rocha GR, Vital H, Rocha AKR (2009) Coastal erosion monitoring of the Arrombado tidal inlet, Macau-Rio Grande do Norte (NE Brazil). In: Amorosi A (ed) 27th IAS meeting of sedimentologists. Amorosi A (ed) Medimond international proceedings, Monduzzi Editore, p 65–71

Rossetti DF, Bezerra FHR, Dominguez JM (2013) Late oligocene-miocene transgressions along the equatorial and eastern margins of Brazil. Earth-Sci Rev 123:87–112

Salim J, Souza CS, Muniz GCB et al (1975) Novos subsídios Pará a elucidação do episódio Barreiras no Rio Grande do Norte. 7 Simpósio de Geologia do Nordeste, Fortaleza, p 149–158

Santos CLA, Vital H, Amaro VE et al (2007) Mapeamento de Recifes Submersos na Costa do Rio Grande do Norte. Rev Bras Geof 25(1):27–36

Short AD, Masselink G (1999) Embayed and structurally controlled beaches. In: Short AD (ed) Handbook of beach and shoreface morphodynamics. Wiley, New York, pp 230–249

Silva CG (1991) Holocene stratigraphy and evolution of the Açu River Delta, Rio Grande do Norte State, Northeastern Brazil. PhD thesis, Duke University

Silva AGA, Vital H, Silveira IM (2011) Presidio's barrier island migration and adjacent coastal erosion, through satellite images analysis. In: Wang P, Rosati JD, Roberts TM (eds) Coastal sediments 2011, vol 2, 1st edn. World Scientific Publishing Co. Pte. Ltd, Danvers, pp 1190–1202

Silveira IM, Vital H, Amaro VE, Chaves MS (2006) The evolutionary study of environmetal conditions of the coastal area of the municipal district of Guamaré – RN. J Coast Res 39:237–241

Souza FES (2004) Evoluçao morodinamica da região de influencia estuarina do rio Curimatau/ RN. PhD thesis, Universidade Federal do Rio Grande do Norte

Suguio K, Bidegain JC, Mörner N-A (1986) Dados preliminaries sobre as idades paleomagnéticas do Grupo Barreiras e da Formação São Paulo. Rev Bras Geoc 6:171–175

Tabosa WF, Lima ZMC, Vital H et al (2001) Monitoramento Costeiro das Praias de São Bento do Norte e Caiçara do Norte – NE Brasil. Pesq em Geoc 28:383–392

Testa V, Bosence DWJ (1998) Carbonate-siliciclastic sedimentation on high-energy, ocean-facing, tropical ramp, NE Brazil. In: Wright VP, Burchette TP (eds) Carbonate ramps, Geol Soc London SP 149:55–71

Testa V, Bosence DWJ (1999) Physical and biological controls on the formation of carbonate and siliciclastic bedforms on the north-east Brazilian Shelf. Sedimentology 46:279–301

Vianna ML, Solewicz R, Cabral A, Testa V (1991) Sandstream on the northeast Brazilian Shelf. Cont Shelf Res 2:509–524

Vieira MM, Ros LF, Bezerra FHR (2007) Lithofaciology and palaenvironmental analysis of holocene beachrocks in northeastern brazil. J Coast Res 23:1535–1548

Vital H (2006) Erosão e Progradação no Litoral do Rio Grande do Norte. In: Muehe D (ed) Erosão e progradação do litoral brasileiro. Ministério do Meio Ambiente, Brasilia, pp 159–176

Vital H (2009) The mesotidal barrier of Rio Grande do Norte. In: Dillenburg SR, Hesp PA (eds) Geology and geomorphology of holocene coastal barriers of Brazil. Springer-Verlag Berlin Heildelberg. Lecture notes in Earth Sciences 107:289–324

Vital H (2014) The north and northeast Brazilian tropical shelves. In: Chiocci FL, Chivas AR (eds) Continental shelves of the world: their evolution during the last glacio-eustatic cycle, vol 41. Geol Soc Mem, London, pp 35–46

Vital H, Guedes IMG (2000) Heavy minerals of the inner continental shelf offshore the Açu River's delta. NE Brazil. Rev Bras Geosc, Rio de Janeiro 30(3):453–455

Vital H, Lima ZMC, Silveira IM et al (2003a) Barrier-spit system from the Northern Rio Grande do Norte State Coast, NE Brazil: a tectonic control? In: Proceedings of the 3th Latin-American congress on sedimentology, p 113–115

Vital H, Stattegger K, Tabosa WF et al (2003b) Why does erosion occur on the Northeast of Brazil. J Coast Res SI 35:525–529

Vital H, Amaro VE, Silveira IM (2006) Coastal erosion on the Rio Grande do Norte State (Northeastern Brazil): causes and factors versus effects and associated processes. J Coast Res SI 39:1307–1310

Vital H, Stattegger K, Amaro VE et al (2008a) Inner continental shelf off Northern Rio Grande do Norte, NE Brazil: a modern high-energy siliciclastic-carbonate platform. In: Hampson G, Dalrymple R (eds) Recent advances in shoreline–shelf Stratigraphy. SEPM SP 90:175–188

Vital H, Santos Neto F, Plácido Jr JS (2008b) Morphodynamic of a tropical tidal inlet: case study on the Rio Grande do Norte Coast, NE Brazil. Revista de Gestão Costeira Integrada 8:113–123

Vital H, Gomes MP, Tabosa WF et al (2010) Characterization of the Brazilian continental shelf adjacent to Rio Grande do Norte State, NE Brazil. Braz J Oceanogr 58(SI 1):43–54

Vital H, Rocha GR, Placido JS Jr (2011) Morphodynamics of Arrombado tidal inlet, Macau-Rio Grande do Norte (NE Brazil). In: Wang P, Rosati JT, Roberts TF (eds) Coastal sediments '11, vol 1. World Scientific, New Jersey, pp 327–338

Vital H, Tabosa WF, Souza ZS et al (2013) Carta Geológica Folha Jandaíra SB.24-X-D-III. Relatório Tecnico + 1 mapa, color. Escala 1:100.000. CPRM-Serviço Geológico do Brasil. Programa de Geologia do Brasil

Vousdoukas MI, Velegrakis AF, Plomaritis TA (2007) Beachrock occurrence, characteristics, formation mechanisms and impacts. Earth-Sci Rev 85:23–46

Xavier Neto P, Lima ZMC, Andrade PRO et al (2001) GPR images of the Galinhos Península, NE Brazil: the register of a geologic evolution from paleochannel to a sand spit? In: Proceedings of the Ist symposium GPR in sediments. Geol Soc and UCL, London 324