Chapter 10
The Holocene Barriers of Maranhão, Piauí and Ceará States, Northeastern Brazil

Patrick A. Hesp, Luiz P. Maia and Vanda Claudino-Sales

10.1 Introduction

This chapter describes the coastal geomorphology and barrier types of three states, Maranhão, Piauí and Ceará. These states lie in the tropics, and extend from approximately 1° to 5°S. With a few exceptions, the barriers and coastal dunes have not yet been studied in terms of their sedimentology, stratigraphy, geomorphology and dynamics, and thus, this chapter attempts to provide a first brief overview of the coastal systems.

10.2 Geology

The coastal deposits of the three States have developed on the fringe of Pre-Cambrian deposits overlain by the Tertiary to Quaternary sandstones, mudstones and conglomerates (notably the Miocene to Pliocene Barreiras Formation) (Governo do Estado do Ceará 1997; Bezerra et al. 2001; Barreto et al. 2002). This formation has often been considered terrestrial in origin (e.g. Bigarella 1975), but portions of it at least have more recently been interpreted as marine (e.g. Rossetti 2001). The latter is typically a tabular surface ranging from 20 to 40 m high, and extending up to 50 km inland. The Holocene and Pleistocene barrier and coastal dune complexes are most extensive in Maranhão, and relatively less extensive in Piauí and Ceará, but still significantly large compared to many coasts in the world (Fig. 10.1).

The continental platform may be divided into two main sectors. The first one, with a general SE-NW orientation, extends from Rio Grande do Norte state border to Acaraú city (40º W); it has a steeper relative slope and a flat, smooth relief, due to the absence of palaeochannels and irregular morphologies. The sector extending from Acaraú to the border of Maranhão State (west) has a general E-W orientation and a lower relative slope, and displays structural forms and palaeochannels.

The Holocene sea level record has not been examined in these States, but in nearby Rio Grande do Norte State, one record indicates that sea level attained the present level around 6,700 cal yrs BP, reached +1.3 m above modern sea level at 5,900 cal yrs BP and thereafter fell to the present level (Caldas et al. 2006). Angulo et al. (2006) provide an excellent review of sea level data in Brazil.

10.3 Climate

The climate is controlled by the proximity to the equator, of the South Atlantic anticyclone and by the Intertropical Convergence Zone – ITCZ (e.g. Nimer 1979). This situation drives an important seasonal and interannual variation in the precipitation regime. The South Atlantic anticyclone operates almost uninterrupted throughout the year. Centered around 22° S, this high-pressure zone generates drought conditions for the northeast of Brazil, as well as the SE and E trade winds permanently established on the north flank of the anticyclone. For this reason, there is a relative absence of storms and frontal disturbances in these three States.

The Intertropical Convergence Zone (ITCZ) is the confluence area of the NE and SE trade winds, and its influence is mostly associated with its seasonal displacements in relation to the equator. It shifts to the south during the summer and autumn of the southern hemisphere and to the north during the austral winter, and exerts a significant control on the rainfall and aeolian regimes (Nimer 1979; McGregor and Nieuwolt 1998).

The annual average temperatures are high, of the order of 28–26.9°C (Bezerra 1998; Rossetti et al. 2007), with weak seasonal variations. The daily thermal variation is, however, considerable with average values of 7°C. This variation generates coastal sea breeze systems.

The convective activity associated with the ITCZ is responsible for abundant precipitation during the austral summer and autumn (Bezerra 1998; Wang et al. 2004) when virtually all the rainfall occurs (Fig. 10.2). The annual pluviometric totals vary from 2500–3000 mm yr^{-1} around the Maranhão border region (Rossetti et al. 2007), 2400 mm (Lençóis Maranhenses (Maranhão), 1716 mm (Acaraú (north coast, Ceará) 1386 mm (Fortaleza, central coast, Ceará), 850 mm (Icapuí, east coast, Ceará) and 644 mm (Monsenhor Tabosa lower east coast, Ceará) (Bezerra 1998; Governo do Estado do Ceará 1997). However, semi-arid conditions also occur and water deficits are considerable in the months of August to December when very little to virtually no rainfall occurs due to the displacements of the ITCZ and the strong interannual pluviometric variability (Maia et al. 1999) (Fig. 10.2). The months of water deficit also correspond to the months of greater wind speed.

The strong interannual variability is associated with the El Nino phenomenon. The presence of El Nino (positive ENSO) is thought to result in an earlier displacement of the ITCZ to the north, and droughts and higher wind speeds then occur in NE Brazil (Trenberth and Hoar 1997; Maia et al. 2005). The aeolian regimen is marked by the action of trade winds. The SE trade winds dominate especially during the second half of the year, and have an average speed of 8 ms^{-1} in Ceará (Claudino-Sales 1993; Maia 1998). The NE trade winds display lower velocities of the order of 3.5 ms^{-1}, and act in the first half of the year. Throughout the year, the penetration of trade winds from the East also occurs.

10.4 Littoral Dynamics

The wave climate is strongly seasonal, and directly associated with the behavior of the dominant winds. In general, from December to April, the NE trade winds generate swell waves with directions varying between 0º and 60º. During the rest of the year, the SE trade winds generate sea waves with directions between 60º and 120º (Maia 1998).

Annual average significant wave height in the Fortaleza region is 1 m, with a mean period of 5 s, and a dominance of easterly waves (Jimenez et al. 1999; Magalhães and Maia 2003). The largest wave heights occur during the second half of the year, with 85% of the distribution occurring in the interval 1.0–1.7 m. The peak period varies between 4 and 24 s, with approximately 60% varying between 5 and 10 s, 27% between 10 to 16 s and 1% between 17 and 19 s (Maia 1998). The interannual analysis shows that although this wave climate is common, certain anomalies exist, as, for example, the occasional occurrence of swell in August–October, associated with storms and hurricanes generated in the Caribbean region.

There is a net littoral drift from east to west and northwest. Due to the prevailing action of sea waves in all sectors (75%), the sediment transport in Ceará is intense (maximum of the order of 900,000 m^3 yr^{-1}). This phenomenon is constant throughout the year. The SE-NW (east) coast experiences the greatest erosion during the second half of the year when sea waves act, due to the strong angle (~45º) between the direction of incidence of the waves and the shoreline, generating as a consequence, a larger

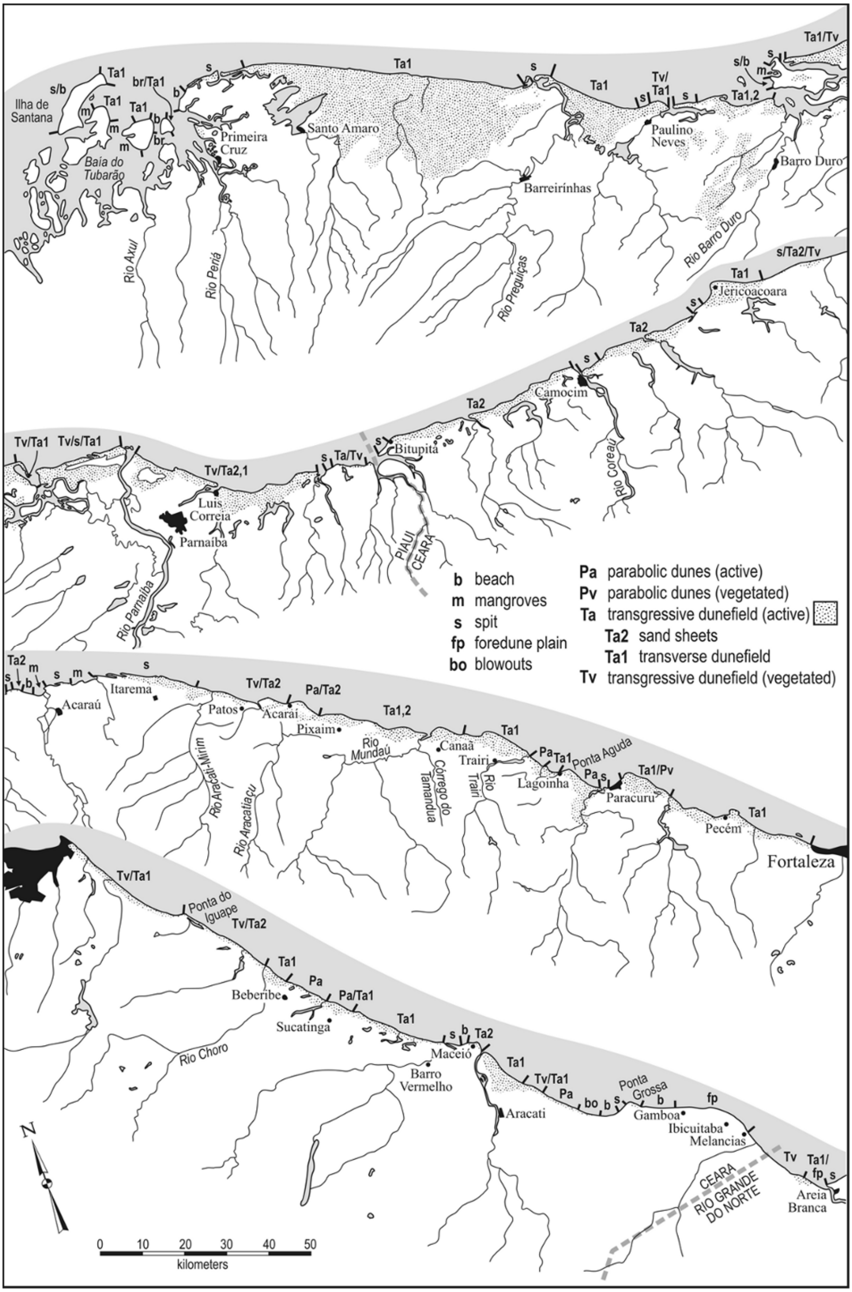

Fig. 10.1 Coastal geomorphology and landform classification of Maranhão, Piauí and Ceará

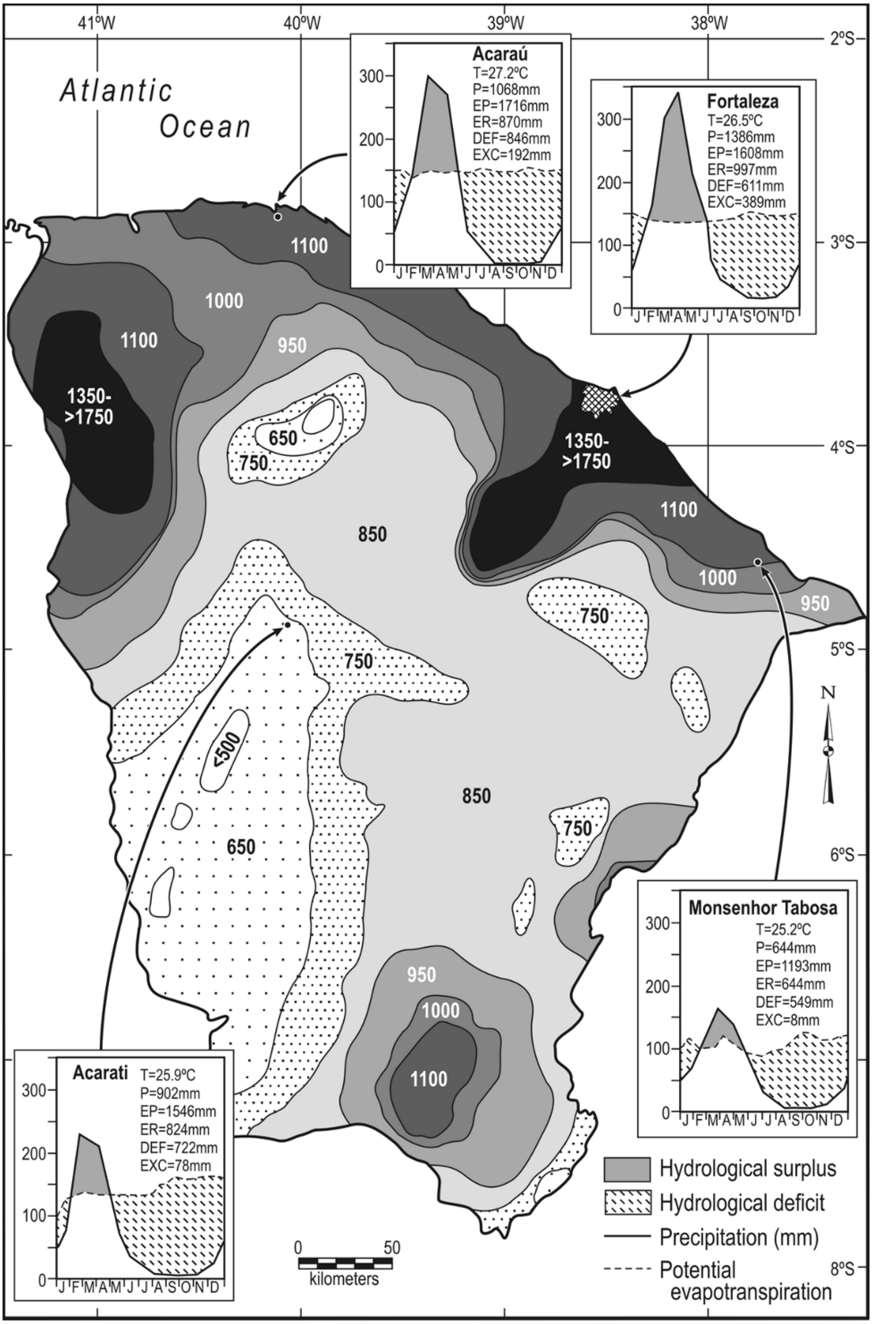

Fig. 10.2 Rainfall map of Ceará

sediment transport rate. On the northern facing coast, this behavior is locally interrupted in places by the presence of promontories, which allows the formation of attached barriers. Down drift of these natural structures, the occurrence of zetaform bays is common, and these are susceptible to erosion by swell waves.

The tide regime in the region ranges from mesotidal to macrotidal, with a semi-diurnal regularity. The neap and spring tide ranges at Itaqui Harbour in Maranhão State are 2.9 m and 6.5 m respectively. Neaps and springs are 1.1 m and 3.3 m respectively at Luis Correia Harbour in Piauí State. The average amplitudes registered at Pecém port and Mucuripe port, in the Fortaleza area (Ceará), for example, have oscillations between –0.2 and 3.2 m in relation to M.S.L.

10.5 Coastal Gemorphology and Barriers of Maranhão State

The western border of Maranhão lies at approximately 1° S, 46° W. In this chapter the coastal geomorphological mapping (Fig. 10.1) begins at ~2° 30'S, 43° 50' W due to space restrictions.

The system of highly irregular, digitate capes, islands and bays dominated by mangrove and funnel-shaped macrotidal estuaries and channel systems typical of the easternmost seaward portion of Pará State continues into Maranhão State. Sandy beaches, spits, foredunes, beach ridge plains (and cheniers or foredune plains?), and some active transgressive dunefields occur along this coast. Many of the islands display pseudo-anvil or 'trilobite' shapes with the beach and dune systems forming a convex form wrapped around the larger seaward margin of the islands (e.g. Ilha da Trauira, Raposa; Fig. 10.3; see Souza-Filho et al., Chap. 11, this volume). Most of these barriers are apparently prograded barriers with many displaying multiple phases of prograded ridges, spits and dunes interspersed with mangrove and channel deposits.

Further to the east, there are significant beaches and barriers extending along the Anil to Raposa NW coast of Ilha de São Luís (Fig. 10.3). The largest barriers on Ilha de São Luís are prograded barriers comprising both active and vegetated transgressive dunefields. The former range from a few hundred metres to nearly 2 km in width (measured along the NE to SW dune migration direction), while the vegetated dunefields are a maximum of 2 km wide. The prograded barrier active transgressive dunefields comprise up to four separate, discrete, active phases separated by narrow to moderately wide (~0.4 km) deflation plains dominated by multiple low, wavy, parallel gegenwalle ridges, and occasional NE-SW oriented transverse dune trailing ridges (Fig. 10.3). Gegenwalle ridges, (also termed vegetation marks by Maia et al. 2005), are formed on the upwind margin of individual and barchanoidal transverse dunes by vegetation growing along the dune base, and sometimes colonizing the lowermost dune slopes (Martinho et al. 2006). Transverse dune trailing ridges are formed by vegetation trapping the marginal sands along the sides of dunes and forming long, narrow, low ridges along the dune migration path (Hesp and Martinez 2008). The dunefields are migrating across both vegetated dunefields and into extensive mangrove and estuarine channel systems.

Fig. 10.3 Multiple phases of transgressive dunefields and mangrove systems on a prograding barrier at Raposa, Maranhão

Spits are very well developed along the northern coast of this state, particularly where the sediment supply is apparently high. Both moderate and large, single and complex, multiple spits occur as e.g. on Ilha de Santana, on the coast north of Primeira Cruz, near Ponta do Mangue, Paulino Neves, and immediately west of the Rio Parnaiba in Maranhão State.

Narrow beaches, spits, and small active transgressive dunefields occur on many of the islands to the east in the Baia de Tubarão region. The vegetated transgressive dunefields predominantly comprise relict deflation plains dominated by gegenwalle ridges, trailing ridges, elongate dune lobes (former precipitation ridges?) and some hummocky to chaotic dune terrain.

The largest dunefield in Brazil, and one of the largest in the world, occurs at Lençóis Maranhenses National Park (Figs. 10.4 and 10.5). At its widest, the active portion is 31 km wide (measured in the dune migration direction), and the total dunefield including the vegetated portion is approximately 120+km wide. This massive prograded barrier extends 76 km alongshore and is dominated by transverse, barchanoidal transverse and barchan dunes (Fig. 10.5) migrating landwards along a NE-SW line. The latest active phase is just one of many Holocene and Pleistocene phases, and is migrating into and over mangrove and channel systems and older dune phases. The dunes are flooded during the wet season and interdunes may have water levels several metres deep on occasion. The older phases variably comprise vegetated transverse dunefields, deflation plains dominated by gegenwalle ridges and trailing ridges, or a combination of these two types.

To the east of Lençóis Maranhenses, there are a series of prograded barriers dominated by active transgressive dunefields which become relatively smaller from west to east (12–0.5 km wide), again principally comprising barchans, transverse dunes and deflation plains (Fig. 10.6a, b, c). Total Holocene barrier widths are considerably larger. For example, in the Delta do Parnaiba area immediately east of Tutóia, east of Canárias, and west of Luis Correia, there are extensive preserved deflation plains situated in the middle of mangrove dominated, large islands and deltaic plains (Fig. 10.7).

10.6 Coastal Geomorphology and Barriers of Piauí State

The coastal barrier systems of Piauí are very similar to those of eastern Maranhão. However, bedrock outcrops form reefs and headlands in the western half of the State and the barriers have formed in headland-bay beaches, displaying more NE-SW orientations (Parnaiba River mouth to just west of Ponto do Anel). The transgressive dunefields are wide (10–12 km in the Cutia and Pedra do Sal bays) and comprise extensive deflation plains, barchan fields, transverse dunefields, sand sheets, and occasional parabolic dunes. While parts of these barriers may be prograded barriers, some, or parts of them are attached barriers. From Barra Grande to the border with Ceará, the coastline trends more WNW-ESE, there is considerably less sediment in the system and the barriers and dune systems are much smaller.

Fig. 10.4 Lençóis Maranhenses transgressive dunefield. The active phase is just one of several phases extending ~120 km inland

10.7 Coastal Geomorphology and Barriers in the State of Ceará

The State of Ceará, located between the latitudes 2°S and 7° S and longitudes 37° W and 41°W, has a coastline that extends for 573 km (Fig. 10.1), with a variety of morphologies. In general, the east coast is characterized by a rockier coast and attached barriers due to the presence of cliffs and palaeocliffs, while the north coast is characterized by the presence of prograded barriers, spits, headland bypass dunefields, dunefields and mangrove systems (Figs. 10.1 and 10.8). Longshore sediment transport rates are very large and up to 700,000 m^3/yr (Maia et al. 2005).

10.7.1 Attached Barriers

While alongshore-progradational barrier spits occur across the river-estuary mouths along the northern coast, and also where the coastline orientation changes to a more E-W trend, attached barriers dominate the coast of Ceará State, and are particularly common to the west and southeast of Jericoacoara (Fig. 10.1). Transgressive dunefields also dominate the surficial landforms of these barriers. Attached barriers are barriers which are “attached” in some manner to older terrain, whether Pleistocene barriers or country rock, or straddling headlands and covering cliff tops (Hesp and Short 1999).

Jericoacoara is situated on a large headland which trends NW-SE on the eastern side, with a coastline orientation which faces directly into the dominant winds. The extensive modern coastal dunefield is a headland bypass transgressive dunefield, and attached barrier. The Holocene system is underlain by older (Pleistocene) dunes and the Barreiras formation, which is eroding along the eastern margin (Fig. 10.9).

Fig. 10.5 Barchanoidal transverse dunes at Lençóis Maranhenses. Note the interdunes are flooded during the wet season

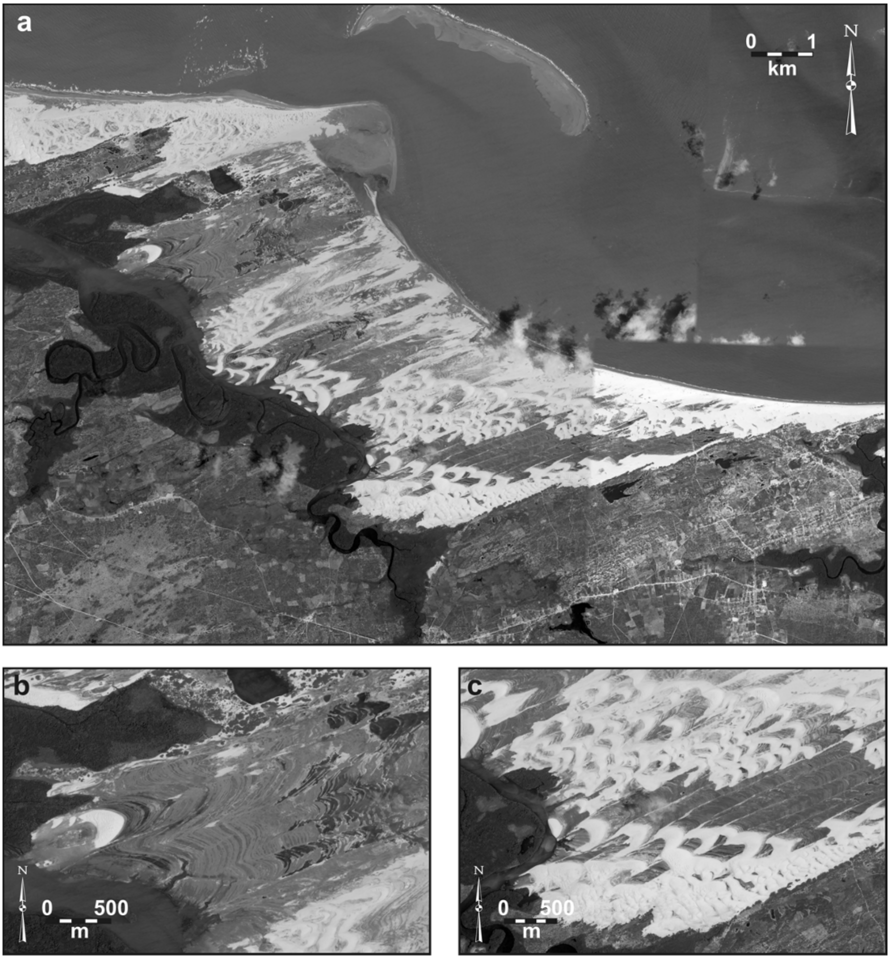

Fig. 10.6 Tutóia dunefield. (**a**) general view of the barrier system, with older dunefield phases to the southwest and south. (**b**) deflation plain dominated by gegenwalle ridges indicating the tracks of former dunes, and a single large barchans migrating into the tidal channel. (**c**) field of dunes with a chain of large discrete barchans and their trailing ridges

The active dunefields comprise sand sheets and stringers near the eastern coast, extensive deflation plains, large barchans, barchanoids, and barchanoidal transverse dunes which shed trailing ridges and gegenwalle ridges, and some parabolic dunes. In this region wind velocities are high (mean – 7.8 ms^{-1}), and rainfall is near zero in the dry season which extends from August to December, so dune migration rates can be high. Barchans 60 m high and 500 m long have average migration rates of ~17 m/yr, while sand sheets display rates of 10 m/yr (Jimenez et al. 1999; Maia et al. 2005). Older vegetated dunefields extend downwind of the active dunes and comprise similar types to the active ones. The dunes migrate across the Jericoacoara headland and into the sea and alongshore on the west and north facing coastlines of the promontory. These feed downdrift spits and fill estuaries, lagoons and mangrove swamps (Claudino-Sales and Peulvast 2002).

Along the east coast, promontories and zeta-form bays or headland-bay systems are common, and are again primarily dominated by attached barriers comprising transgressive dunefields, and, in a few cases, parabolic dunefields. Figures. 10.10 and 10.11 illustrate some examples.

Figure 10.10 illustrates the barrier near Paracuru. The sinuous shoreline is a response to the many reefs in the nearshore, which are common all along this coast. The barrier comprises a narrow new phase of active sand sheets and small dunes immediately downwind of the beach, a largely vegetated, deflation plain-parabolic and barchan dunefield (with multiple gegenwalle ridges), and a downwind active transverse and barchan (13–25 m high) dunefield.

To the south of Fortaleza, the attached barriers are generally much narrower (with the exceptions of Aracati, Beberibe and Aquiraz), presumably because the coastline orientation is more N-S, waves approach the coastline at high obliquity and the coast roughly parallels the littoral drift and there is less sediment supply. Many barriers are complex barriers comprising a landward attached barrier portion where transgressive dunes override

Fig. 10.7 30 km NW of Luis Correia, Maranhão, illustrating a modern prograding spit system with active dunefield, mangrove system and older barrier deflation plain dominated by gegenwalle and trailing ridges

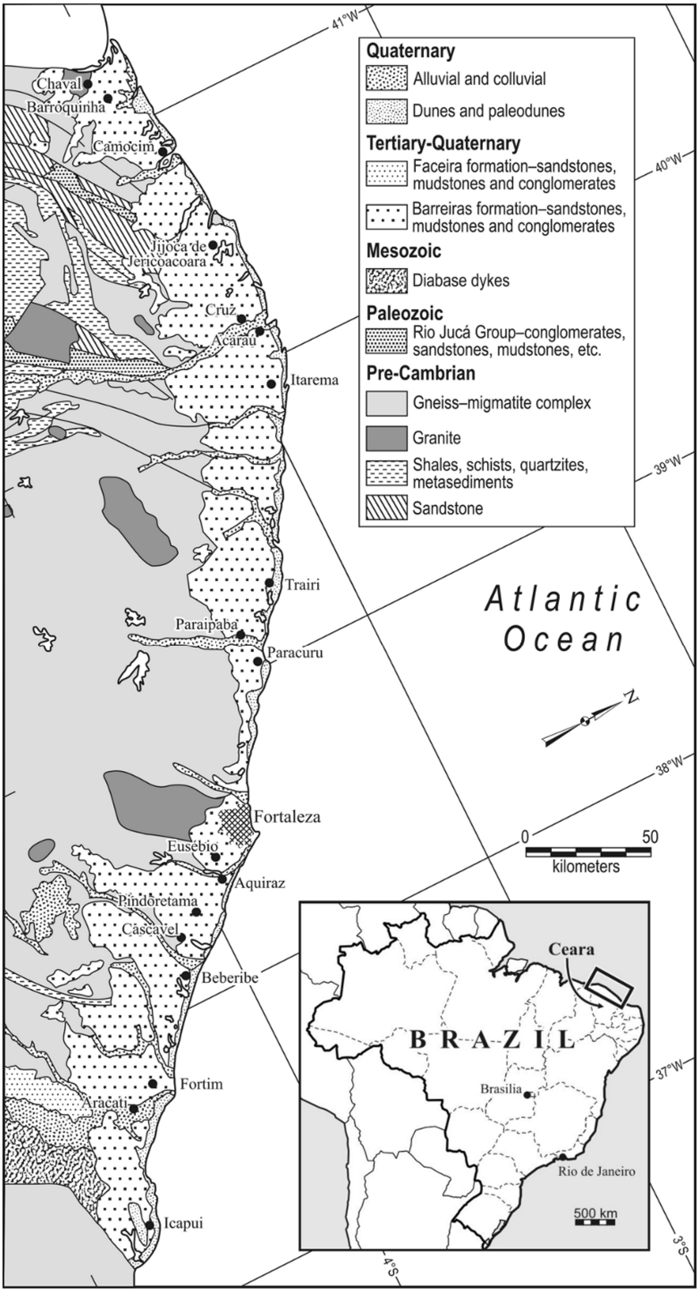

Fig. 10.8 Geology of Ceará State (modified from Governo do Estado do Ceará 1997)

Fig. 10.9 Jericoacoara headland bypass dunefield – an attached barrier

a palaeocliff, and a seaward transgressive dunefield or parabolic dunefield portion which in some cases may be progradational, and in other cases is also attached onto an erosional platform. Figure 10.11 illustrates an example at Ponta Grossa, a headland formed of the Barreiras Formation. The attached barrier comprises a transgressive dunefield with a few parabolic dunes at the southern end. The coast is erosional, and dunes are forming from erosion of the Barreiras sediments with possibly an additional longshore supply. On the western side of the headland, progradational spits are formed.

10.7.2 Barrier Spits

Barrier spits are well developed at Bitupita, Camocim, to the immediate west of Jericoacoara, from just east of Jericoacoara to Patos, near Maceio, near Ponta Grossa, and at Icapui in Ceará State (Fig. 10.12).

In the vicinity of the estuary of the Acaraú River, the spits are a result of local fluvial supply. Cores drilled through one of these spits (Morgado beach and spit; Fig. 10.12) indicates a stratigraphy characterized by the presence, between depths of 0 m and 3.5–5 m, of fine and medium gray sands, little compacted, poor in silt, sometimes micaceous, with fragments of shells and gravels. From these depths to 15 m, the deposit grades to finer materials (clay, silt) with the presence of gravels, sometimes with coarser beds, often with yellow and red colors. In the base of the deposit, sediments of the Barreiras Formation are present, and these underlie the entire area.

Fig. 10.10 The Paracuru attached barrier

Fig. 10.11 Ponta Grossa bypass dunefield attached barrier and downdrift prograded barrier spit system

Fig. 10.12 The Morgado spit (Acaraú estuary area), which displayed an extension of ~480 m and a retreat of 6.5 m/y between 2001 and 2004 (Quickbird image, 04/09/2004)

Morphological analyses based on satellite images of 2001 and 2004 also show a westerly migration of 483 m of the Morgado spit, resulting in erosion of the adjacent shoreline. During the same period the spit retreated 28.5 m (6.45 m/y) towards the mainland beach. High levels of erosion have also been detected in another spit of the Acaraú estuary area (Volta do Rio spit). This spit migrated 950 m between 2001 and 2004, resulting in the erosion of 124 m (31 m/y) of the adjacent shoreline. Transgressive dunefields are common on most spits, as in this case, and sands from the spits feed mainland dunefields as the spits attach (Fig. 10.12). Downdrift erosion also leads to destabilization of the coast and creates further dune migration.

Systems of spits reappear in profusion in the area between Mangue Seco and Camocim (north coast), and downdrift of Jericoacoara headland, and are in these cases nourished by transgressive dunefields that bypass the headland, in association with sediments supplied via littoral drift. They isolate small lagoons that are colonized by mangroves.

Double and multiple spits are common along some sections of the coast, as, for example, at the Pirangi River, between the mouths of the Choró and Malcozinhado rivers, the Malcozinhado River, the Pacoti River, the Curú River, the Mundaú River, between Icaraí de Amontada and Almofala, near the Aracatiaçu and Aracatimirim Rivers, and in Barroquinha.

In the region around Itarema, successive and multiple spits occur, sometimes stretching 13 km, with widths of some hundreds of meters (e.g. 400, 700 m) (Fig. 10.13a and b). It is likely that the sand supply necessary to build the spits comes primarily from littoral drift, as the spits extend down drift from erosional coastal segments. The spits are dominated by transgressive dunefields variously comprising sand sheets, transverse dunes, barchans and parabolic dunes. Multiple spits have formed over the Holocene, and the shallow back barrier bays have become mangal systems. In places the spits have been welded to the mainland beach by the downwind migration of transgressive dunes, which have filled the lagoons with sand (Fig. 10.13).

10.7.3 Foredune Plain Prograded Barriers

In the Gamboa–Icapuí–Melancias region, on the lower eastern coast (Fig. 10.14), the coastline orientation changes from NNW-SSE, where the angle of wave incidence is near 45º, to NW-SE. The angle of wave approach changes markedly, beaches are less steep than in the southern area, and a reduction in littoral sediment transport takes place, resulting in the development of a complex foredune plain-transgressive dunefield barrier (Fig. 10.14).

Near Melancias the barrier is approximately 1 km wide and comprises vegetated transgressive dunes. By Ibicuitaba the barrier has widened to around 2 km and displays a suite of foredune ridges. A Pleistocene (?) cliff forms the landward margin and is covered by climbing and clifftop dunes. To the north, towards Icapui and extending past the Icapui inlet, the barrier widens to a maximum of ~2.5 km and comprises suites of foredunes, the only foredune plain in the entire three states.

10.8 Discussion: Dunes in the Tropics

It is clear from the discussion above, that large-scale transgressive dunefields are very common virtually right up to the equator in Brazil. Jennings (1964) noted that aeolian sand dunes were either very poorly developed, or largely absent in the "humid tropics" and sparked a debate focusing on why this should be so. While he was specific about only referring to the humid tropics, an impression developed over time that, in general, the tropics displayed limited dune development, except in a few cases (e.g. the parabolic dunefields of the Cape Flattery region; Bird, (1965). Various theories were postulated for the apparent lack of dune development in the tropics including beach moisture (Jennings 1964), low sand supply (Bird 1965), lower wind velocities (Jennings 1965; Trenhaile 1997), and tall vegetation reducing wind velocities (Swan 1979).

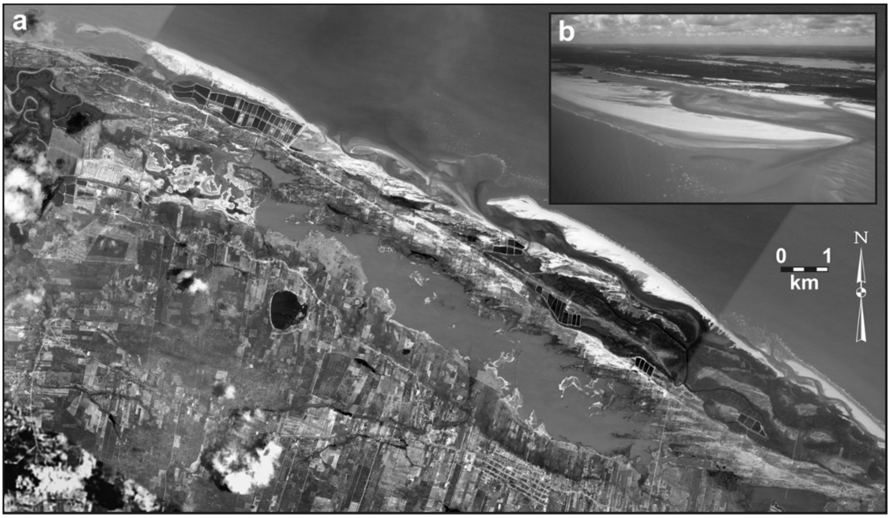

Fig. 10.13 The Itarema multiple spit system (**a**), and an oblique aerial picture of the spit (**b**) (Photograph Jean-Pierre Peulvast)

The northern Brazil coast experiences a pronounced dry season, and, in fact, the dry season in Ceará leads to significant aridity. As Swan (1979) noted in the case of Sri Lanka, a pronounced dry season will result in a much higher potential for dune development. This factor, in combination with a high littoral drift and coastal erosion leading to a significant sand supply, are probably the principle reasons why the coasts of these three states are dominated by barrier systems with small to large-scale transgressive dunefields extending to the very equator.

10.9 Conclusions

The barriers in the three states of Maranhão, Piauí and Ceará are principally prograded barriers, barrier spits or attached barriers. Prograded barriers predominantly occur on the Maranhão, Piauí and northern coast of Ceará, while attached barriers and headland bypass dunefields are characteristic of the NE and eastern coast of Ceará. There is only one prograded barrier with a foredune plain; all others comprise sand sheets, parabolic or transgressive dunefields with the majority falling in the latter type. Little research has been carried out on the Holocene or Pleistocene barriers of these States, and the opportunities to examine the dynamics and evolution of these dunefield-dominated barrier types are limitless.

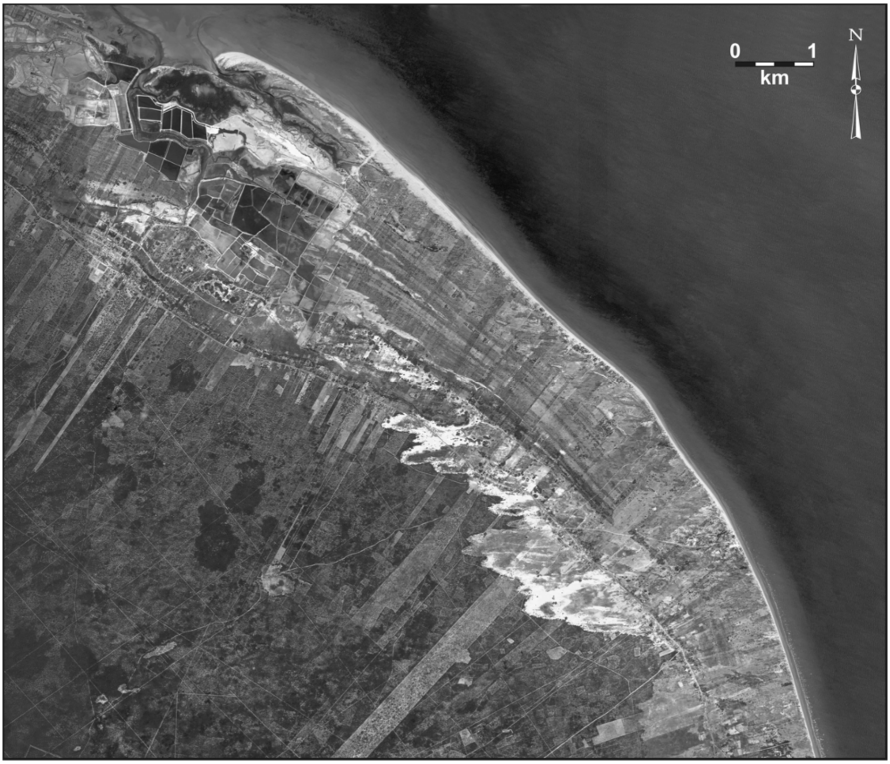

Fig. 10.14 A prograded barrier comprising a foredune plain and some transgress-sive dunefields at Ibicuitaba

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