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Chapter 3
Beaches of the Amazon Coast: Amapá and West Pará

Valdenira Ferreira dos Santos, Andrew D. Short, and Amilcar Carvalho Mendes

Abstract The Amazon river flows into the funnel-shaped Amazon Gulf with its shoreline stretching for hundreds of kilometers in either direction. The river delivers massive amounts of mud and some sand to the coast, which is dominated by the river flow, macro to mega-tides, general low easterly waves and the strong Brazilian Current. While most of the coast consists of wide intertidal mud flats and muddy riverbanks, there are approximately 500 sandy beaches located in five Amazon sub-provinces. These are the northern Amapá coast with some longer beaches; the Amazon river Amapá and Pará shores with beaches located on the outer interdistributary islands and some small beaches along river banks; and the northern coast of Pará's Marajó island of which more than half is tide-dominated sandy beaches.

3.1 Introduction

Brazil's northernmost coastal province is dominated by the Amazon River and its equatorial location between 4°N to 1.5°S. The Amazon shelf and river mouth were flooded during the postglacial marine transgression forming the 200 km wide Amazon funnel-shaped estuarine-river mouth occupied by the two major channels together with numerous inter-distributary channels and islands. The high discharge and sediment load, combined with macro to mega-tidal ranges, in a hot wet tropical

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Table 3.1 Shoreline characteristics of the Amazon coast

	Amazon coastal sub-provinces	Coast length (km)[a]	Beach number	Beach length (km)
1[b]	northern Amapá coast (inc. Ilha de Maracá 125 km)	675	16	142
2[b]	southern Amapá Amazon (ocean beaches)	495	3	44
	Canal do Norte do Rio Amazonas (pocket)		14	4
3[b]	Pará Amazon Coast (inc. Canal do Sul do Rio Amazonas)	1500	~50	~110
4[b]	Pará: Marajó Island (north & east coast)	390	168	121
	Sub-total (this chapter):	3060	~260	~420
5[c]	Pará: east coast	790	247	n/a
	Total:	3850	~510	n/a

[a]Note distances in the river mouth are approximate and minimal
[b]This chapter
[c]Chapter 4

environment have all contributed to the present coastal environment, which is dominated by river channels with muddy shorelines backed by mangrove forests and inundated varzea lowlands. The entire coast has undergone substantial Holocene progradation on the order of kilometres, together with considerable northerly transport of the Amazon mud as far as Venezuela. Sandy beaches with wide sand flats and mud flats, only occur in more exposed locations, the latter mainly along the northern Amapá coast and on Pará river mouth islands.

The Amazon Coastal Zone (ACZ) is a physiographic feature extending for 2700 km from the Orinoco Delta in the Venezuela to Baia de São Marcos in Maranhão State, and includes the coasts of the Republics of Guyana and Suriname, French Guyana and northern Brazil. This chapter will focus on the Brazilian section of the ACZ, specifically the coasts of Amapá and western Pará.

The Amapá-Pará section of the ACZ coast extends for approximately 3850 km from the border with French Guyana at Cabo Orange to Pará's eastern border near Cabo Gurupi. This section can be divided into five sub-provinces (Table 3.1 and Fig. 3.1): (1) the northern open Amapá coast including Maracá island; (2) the southern Amapá Amazon coast extending along the Amazon's North Channel and including Bailique archipelago and other islands; (3) the Pará Amazon mouth which includes Canal do Sul do Rio Amazonas, together with of several inter-distributary channels and river mouth islands; (4) Pará's Marajó island north and east coasts; and (5) the eastern Pará coast. This chapter is concerned with the Amapá and western Pará coast, including the Amazon river mouth and the northern and eastern shores of Marajó Island, a coastline of approximately 3060 km. The eastern Pará coast, commencing at Belém, is covered in Chap. 4.

Although some studies were undertaken in the late twentieth century, it is only since 2002 that scientists from Instituto de Pesquisas Científicas e Tecnológicas do Estado do Amapá-IEPA, Museu Paraense Emílio Goeldi-MPEG and Universidade Federal do Pará-UFPA, commenced detailed studies of the Brazilian Amazon coast and shoreline as part of a research network concerned with environmental monitor-

Fig. 3.1 The Amazon coast of Amapá and Pará states (Source: Google earth)

ing of areas affected by the oil industry (Rede 05-PETROMAR, PIATAM Mar, PIATAM Oceano and Cartas SAO FZA projects) together with monitoring and modelling of erosion and coastal occupation (Millennium Institute Project, INCT-Ciências do Mar) and other projects to support the management plans for coastal conservation units. This chapter will review our growing knowledge of this coast and in particular the sandy beaches that occur along this predominately muddy mangrove-lined, tide-dominated coast at the mouth of the world's largest river. Our present knowledge however remains preliminary, as most beach investigations have been superficial with detailed studies yet to be undertaken.

3.2 The Amazon Coastal Environment

3.2.1 Geology and Physiography

This coast is located in the outer part of the Amazon basin where the sediments of the ACZ have developed a wide Quaternary plain in Amapá and Pará states (Fig. 3.2). The plain is backed in the north by pre-Cambrian rocks of the Amazonian craton (crystalline basement) described by Tassinari and Macambira (1999), while in the south of Amapá state and southeastern of Pará state the sequences from the Amazonas and Parnaiba sedimentary basins outcrop with sediments from the

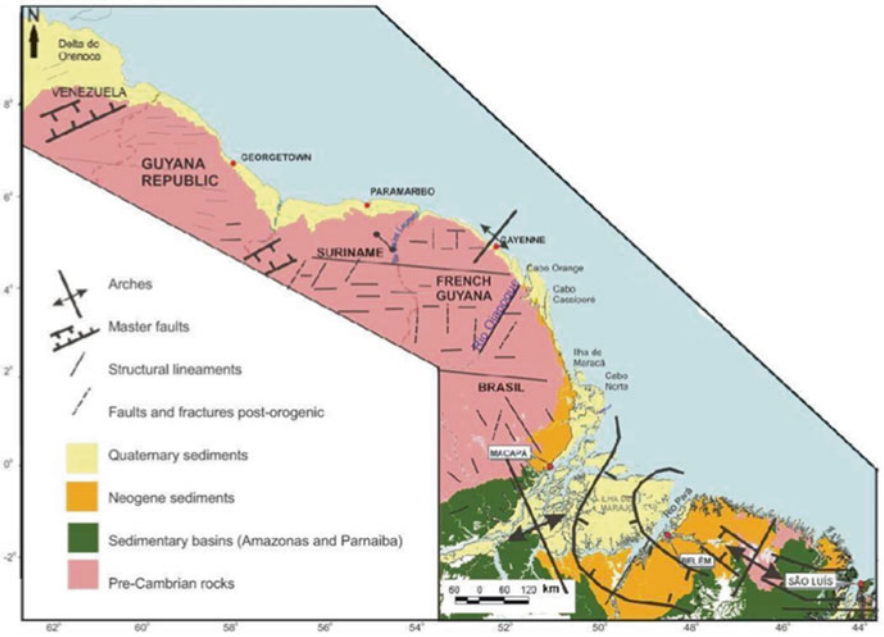

Fig. 3.2 Geological structure of the Amazon coast (Source: Modified from Santos 2006)

Barreiras Formation and Pós-Barreiras, which reaches the coast in Pará state (Fig. 3.2). Several estuaries cross the coastal plain, aligned by the regional structure. The most representative estuaries are, from the north to south: Oyapock, Cassiporé, Cuñani, Calçoene, Araguari, and the Amazon itself, and the estuary of the Pará River. Most of the Amapá and western Pará shoreline consists of intertidal mud or sand flats up to a few kilometer wide on the open coast, but narrowing along the river banks, all backed by wide dense varzea forests with transition to mangrove towards the Amazon mouth. Two nearly continuous zones of sandy sediments occur along the northern coast of Amapá south of Cabo Cassiporé (see 3.3.1), and along the northern and eastern coast of the island of Marajó (see 3.3.4 and 3.3.5), as well as on some of the more exposed sections of the river mouth island, particularly Mexiana Island (see 3.3.3). Elsewhere, small pocket beaches are located along some of the river channels (see 3.3.2). Sandy sediments have also been found elsewhere along the coast in the mouths of estuaries and deposited in cheniers, sand bars, sand waves, sand plains and sand ridges (Augustinus 1989; Prost 1989; Mendes 1994; Silveira 1998; Allison et al. 1995, Souza-Filho and Paradella 2003, Anthony et al. 2014).

The present coast is a product of the Holocene sea level rise, which drowned the Amazon mouth, together with Quaternary sea-level changes, the large fluvial sediment supply and the reworking of relict sediments on the continental shelf. The Amazon shelf has experienced massive sedimentation and is presently more than 300 km wide, gently sloping, with an overall gradient of 1:2240 until the shelf break at 100 m depth (Milliman 1979). The most prominent feature observed in the

adjacent Amapá shelf is the Amazon Cone (Fig. 3.1), situated north of the Amazon river mouth. It is located on the outer shelf and is about 700 km long and 250 km wide, reaching 650 km in the northernmost sector with an area of approximately 162,000 km^2 (Damuth and Kumar 1975).

The four coastal regions covered in this chapter commence with the northern Amapá coast. North of the Capo Cassiporé is an extensive zone of pelitic deposition, the largest on the planet, forming mud banks that extend along of 1600 km of coast including French Guyana-Suriname-Guyana coasts and reach the Orinoco Delta in Venezuela. These mud banks originate from the Amazon sediments and migrate shoreward and then alongshore by a combination of wave forcing, tidal currents, easterly wind-induced coastal currents and proximity to the coast of the North Brazil Current (NBC) (Augustinus 1978; Wells and Coleman 1978; Allison and Lee 2004; Anthony et al. 2013, 2014; Nittrouer and DeMaster 1996). This coast is predominately muddy north of Cape Cassiporé, while sandy sediments with intercalation of mud plains dominate the shoreline to the south until the mouth of the Amazon river.

The eastern Amapá coast has experienced substantial sedimentation with the Cabo Norte area, up to 80 km wide, dominated by three lacustrine belts. According to Silveira (1998) these lakes have largely infilled over the past few hundred years resulting in a palaeo-drainage network with ox-bow lakes such as Lago Duas Bocas, Lago Novo, Lago Comprido de Dentro, Lago dos Botos, and Lago Mutuco forming the Meridional Lacustrine belt. The lakes of the oriental belt are now occupied by extensive mangrove ecosystems over consolidated muddy deposits, which are more than 20 km in width with a predominance of *Rizhophora* species. The tallest mangrove trees and widest mangrove extension in Brazil occur on the wide coastal plain at Cabo Norte with trees up to 40 m high and along the Amapá coast. This area has ideal conditions to maintain mangroves, with a large amount of suspended sediment transported by the Amazon River, high temperatures, large tidal ranges and saline to brackish water (Costa Neto et al. 2006, Rabelo et al., 1994).

The Pará Amazon coast includes the Amazon mouth, which is influenced by the massive Amazon River and dominated by a 300 km wide funnel-shaped estuarine mouth. The river divides into two major channels, the Canal do Norte (North Channel) and Sul (South Channel), together with numerous smaller interconnected channels. The North Channel flows northeast along the Amapá coast and is 14.5 km wide at its mouth adjacent to Curua Island. The South Channel flows east-southeast between Mexiana and Marajó islands and is 17 km wide at its mouth. The broad coastal plain at the mouth of the Amazon and along northern Amapá contains several paleochannels and lines of paleocoast that record the Holocene evolution of the region (Boaventura and Narita 1974; Silveira 1998; Rossetti and Goes 2008; Santos et al. 2009; Jardim et al. 2013) (Fig. 3.3). The cities of Macapá and Santana, located right on the equator, are the principal settlements on this section of coast. These two adjoining cities and their adjacent communities are spread along about 30 km of the Canal do Norte of the Amazon coast. They are located where the first exposures of the higher elevation of Pleistocene deposits occur on the riverbanks enabling part of the cities to be located above the annual flood levels. The Portuguese built a substantial fort on the Pleistocene bluffs at Macapá in 1764.

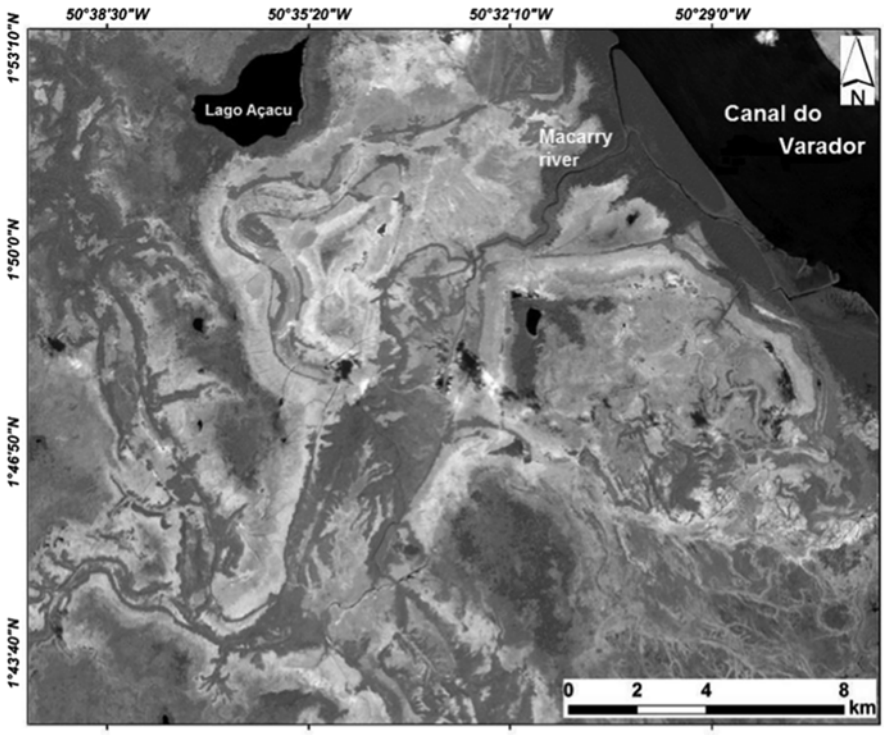

Fig. 3.3 Paleochannel along the Amazon coast. Paleo-Macarry in front of Ilha de Maracá (Source: Landsat 7 ETM+, band 4, 18 November 2000)

The Marajó Island coast is dominated in part by the elevated Pleistocene deposits which form most of the island and bluffs and headlands where exposed at the coast, particularly along the eastern shore of the island. Holocene deposits form a narrow coastal plain along the northern coast, which widens to about 10 km at Cabo Maguari on the northeastern tip of the island. The coastal deposits then narrow south into Marajó Bay until the Paracauari river, with the older deposits being exposed south of the river forming the coastal plateau (França and Souza-Filho 2006). Sandy beaches occupy about one third of the coast the remainder dominated by mangroves.

3.2.2 Climate

The Amazon coast straddles the equator and is exposed to a hot, wet tropical climate (Koppen Af), with temperatures averaging between 25 and 27 °C. The weather is modulated by the position of the Intertropical Convergence Zone (ITCZ), which shifts from around 14°N in August to 2°S in March-April. Trade winds blowing

towards the ITCZ dominate the wind regime and arrive predominantly from the north through east, with wind velocities averaging 2–4 m s^{-1}, increasing up to 10 m s^{-1} during September. Rainfall averages 2600 mm at Macapá increasing both northward to reach 3750 mm at Cayenne, and eastward reaching 2900 mm at Belem. Most of the rain arrives during the January to May wet season, while humidity is high year round and usually above 80 %.

Climatic variations are produced by La Nina and El Nino events, causing precipitation to be higher during La Nina and lower during periods of El Nino. These conditions are also reflected in river discharge (Richey et al. 1989; Santos et al. 2010).

3.2.3 *Fluvial Processes*

The Amazon River mouth is part of a vast and complex fluvial-estuarine system that includes the Amazon River and dozens of estuaries that contribute to form the largest run-off of water, sediments, dissolved nutrients and organic material found anywhere in the world (Meade et al. 1979, 1985; DeMaster and Pope 1996; Geyer et al. 1996). The enormous fluvial discharge of the Amazon River into the Atlantic Ocean is approximately 20 % of the total discharged on the whole planet. The mean water discharge is around 180,000 m^3 s^{-1} with peaks of up to 220,000 m^3 s^{-1}, occurring in May–June and a minimum of 100,000 m^3 s^{-1} in November–December (Richey et al. 1986). It is assumed the water discharge of the smaller rivers that border the Amazon will have seasonal patterns that are more or less synchronous with that of the Amazon river. Accord Martinez et al. 2009, the water discharge has a weak correlation with the suspended sediment concentration, which presents a significant increase in the budget of the Amazon with a suspended sediment discharge 20 % higher between 1996 and 2007.

Towards the coast the discharge is affected by the macro to mega-tides that are amplified in crossing the broad shelf and within the funnel-shaped mouth and distributaries, with the tide extending up to 800 km upstream to the town of Óbidos (Beardsley et al. 1995; Nittrouer et al. 1995).

The river level rises and falls with the tides in the lower reaches, with asymmetrical flow reversals – a longer ebb and shorter flood, the latter producing tidal bores in some channels, called *pororoca* (Santos 2006). The river level also rises and falls seasonally peaking during the wet season and reaching up to 5 m higher (at Óbidos) during the wet season, before falling during the dry season. El Nino and La Nina events also influence the height of the rises and falls of the river level.

3.2.4 *Sediment Discharge*

The Amazon River delivers a massive sediment load estimated at 754 Mt $year^{-1}$ (+/− 9 %), which is deposited on the inner shelf and then 30 % is transported to the northwest as large migratory mud banks for 1600 km northward towards French

Guyana, Suriname and Venezuela (Anthony et al. 2010, 2014). According to Muller-Karger et al. (1988) the net effect of the Amazon river discharge, the North Brazil Current (NBC) and the trade winds and waves is to mix the river water with the saline water of Atlantic Ocean, forming an immense turbid aqueous plume, with reduced salinity, which extends at least 300 km northwest.

While the suspended load is well documented (Gibbs 1967; Meade et al. 1979, 1985; Nittrouer et al. 1986), there is also a small (~1 % of load) but substantial bedload transported by the Amazon river, estimated at 0.01–0.05 Mt day^{-1} or 3.65–18.25 Mt $year^{-1}$ (Dunne et al. 1998). The bedload consists of medium to fine sand and is deposited as small sandy beaches and sand flats along some riverbanks, and at the mouth as more extensive tide-dominated beaches and extensive sand flats.

Along the northern coast of Amapá tide-dominated sandy beaches are backed in places by beach ridges and/or cheniers. Silveira 1998 pointed out three clusters of chenier plains on the north coast of Amapá with the source of sediments being intertidal sandflats, in addition to material from the crystalline basement which also contributes to the sandy beach sediments (Mendes 1994),

3.2.5 Coastal Processes

Amazon coastal processes are related to the persistent easterly trade winds and associated easterly waves, the macro through mega-tides and their associated currents, coupled with the massive water and sediment discharge from the Amazon, and the northwest flowing NBC.

3.2.5.1 Tides

The 300 km wide shallow Amazon shelf amplifies the tidal range, with the entire coast exposed to semi-diurnal macro-megatides. The presence of the extensive shoal seaward from Cabo Norte influences the tidal behavior (Beardsley et al. 1995; Nittrouer et al. 1995). North of the shoal, the open Amapá coast, including Ilha do Maracá, receives tides as a standing wave in near-resonance with the embayment formed by the shoal and shoreline. In this area the tides range from 4 m in the Ponta dos Índios (Oiapoque river) increasing southwards to 10 m near Ilha do Maracá, the highest in Brazil, then decreasing to 5 m at Ponta Guará in Araguari river mouth. South of the shoal, the tides behave as a progressive wave decreasing from 5 m at the Amazon mouth to 4 m at the Jari River mouth, approximately 300 km upstream. The irregular Pará-Marajó coast is bordered by a series of distributaries of the Amazon, Pará and Tocantins rivers, including Marajó Bay. Tides increase from 6 m to 10 m along the northern shore of Marajó Island, then decrease into Marajó Bay falling to 3 m at Belem. Because of the high tides, strong tidal currents flow along all shores, increasing in strength in the confined river mouths and distributaries. According to Nittrouer et al. (1991a) tidal effects on the Amazon river propagate 800 km upstream to the town of Obidos.

Fig. 3.4 Tidal bore (pororoca) at Araguari river-mouth. Date: 30 October 2008 (Photo: Valdenira Santos, AMASIS Project)

Strong tidal currents (~2 m s^{-1}) are manifest as semi-diurnal tidal currents oriented across the shelf and into the river and its distributaries. The wide shelf also amplifies the tidal wave resulting in tidal resonance in the river mouth (Beardsley et al. 1995; Geyer et al. 1996).

The ideal physiographic conditions associated with the macrotidal regime including a shorter flooding tide, result in the presence of tidal bores called "*pororoca*" (Fig. 3.4) along much of the northern coast of Amapá coast and the Amazon mouth. The phenomenon is stronger at equinox spring tides, when the heights of the waves reach up to 2.5 m (Santos et al. 2005). The velocity of the wave can exceed 23 km h^{-1} in the Araguari river mouth.

3.2.5.2 Waves

The northern Amapá and open Pará coast are exposed to waves generated by the easterly trade winds. They produce easterly ocean waves 1–2 m high, with periods <10 s, 95 % of the year, with the largest waves arriving from January to March when the winds are stronger (Schaeffer-Novelli and Cintron-Moler 1988, Kineke 1993). Very short seas with $H_b \sim 0.1–0.5$ m and T ~ 2–5 s accompany the persistent trades and occur both along the coast and within broad sections of the rivers (Fig. 3.5a). While the waves are higher during the January to March wet season they are more effective in periods of low river discharge from September to November.

At the shore however wave energy is very low to zero and extremely tide dependent. Ocean waves are first attenuated by the wide low gradient inner shelf and then by the often kilometres wide intertidal mud and sand flats, as well as tidal mud and sand river mouth shoals, with lowered waves only reaching the shore at

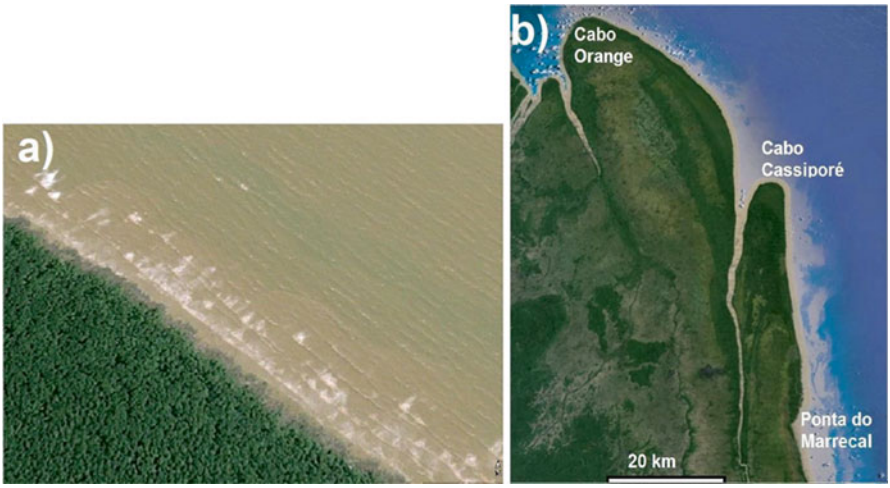

Fig. 3.5 (**a**) Waves breaking across tidal flats near the mouth of the Amapá Grande river (see Fig. 3.6). (**b**) The 85 km long Cabo Cassiporé. (*right*) and Cabo Orange (*left*) coasts have been formed from prograding mud deposits.(Source: Google earth)

high tide, while at low tide they are dissipated across the wide flats often breaking kilometers seaward of the high tide shore. Short seas accompany the swell and are the only waves inside the river and its distributaries. As a consequence wave energy is low to very low for the entire coast, which combined with the high tide range maintains a tide-dominated coast and beaches.

The highest energy section of coast is located between the south of Cabo Cassiporé and Ilha de Maracá where the waves maintain a longshore current that transports sand northward until south of Cabo Cassiporé (Fig. 3.5b). From Cabo Cassiporé northward to Cabo Orange, the shoreline is accreting with prograding mud deposits dominating the shoreline from 85 km south of Cabo Cassiporé to the border with French Guyana. East of Cabo Orange the inter-mudflats are 2–5 km wide (Nittrouer et al. 1991b; Silveira 1998.)

3.2.5.3 Coastal Currents

A strong northwest current prevails along the coast, particularly along the northern Amapá coast. The current is reinforced by the easterly trade winds, wave driven currents and the flooding tidal currents, which move perpendicular to the isobaths of the continental shelf resulting in strong currents across the shelf with speeds exceeding 2 ms^{-1} during spring tides (Beardsley et al. 1995; Geyer and Kineke 1995; Nittrouer and DeMaster 1996). On the muddy plains of the northern Amapá coast, the tidal current velocity can exceed 0.35 ms^{-1} (Allison et al. 1994). Similar velocities have been recorded along the Guyana coasts (Anthony et al. 2010).

The dominance of the easterly winds, waves, tidal and ocean currents all result in east to northeasterly sediment transport along the Amapá coasts. North of the

Amazon mouth, between the Araguari river and Cabo Cassiporé, considerable sand has been deposited as beaches and sand flats. North of the Amapá coast mud dominates the coasts of French Guiana, Suriname, Guyana and part of eastern Venezuela coast, extending in total for 1600 km and forming the longest muddy coast in the world (Allison et al. 1995; Anthony, et al. 2010, 2014).

3.3 Amazon Beach Systems

The Amapá-west Pará-Amazon coast has an open and riverine coastline of approximately 3150 km (Table 3.1), the latter including numerous interdistributary river mouth islands. This section will discuss the sandy beaches located in each of the four sub-provinces listed in Table 3.1.

3.3.1 Northern Amapá Coast (Including Ilha de Maracá)

The northern Amapá coast extends from the Oiapoque river, which forms the border with French Guiana to the southern side of the Araguari river mouth, a distance of 550 km (675 km including Ilha de Maracá) (Fig. 3.6). Sandy beaches occupy 142 km (21 %) of this coastline. Two types of beaches occur on this coast: beach ridge systems and high tide sandy beaches with tidal flats.

Beach ridge systems occupy 109.2 km alongshore of south of Cabo Cassiporé and Amapá Grande river mouth and are arranged in 13 segments along the coast, which is experiencing erosion at rates up to 78.5 my^{-1} (Fig. 3.7) (Silva 2010). Strong tidal currents perpendicular to the coast (with tidal range up 9 m) and the easterly waves maintain the beach ridges (Fig. 3.7a, b), which are up to 50 m wide and have recurved spits at the end of each segment. Beach ridges are migrating to landward with the continuous retreat of the coast, marked by exhumed and overturned Avicennia mangrove. According Mendes (1994) sandy sediments are derived from proximal sources of pre-Cambrian basement and Tertiary sediments carried from the estuaries that cut this coast. Allison et al. (1995) and Nittrouer et al. (1991b) suggest that these areas were formed by ephemeral sandy deposits overlying overconsolidated ("relict") mud on the shoreface deposited during a progradational phase of Amazon mudflats between 500 and 1300 years BP. Chenier clusters deposited during progradational events are also preserved on the coastal plain (Silveira 1998). Anthony, et al. (2014) reported similar eroding chenier systems along the Surinam and Guyana coasts.

Tide-dominated high tide sand beaches fronted by wide tidal sand flats occur in discontinuous accretionary deposits for 32.8 km north of Sucuriju (Fig. 3.7c) and north and south of Araguari river (Araqueçaua and Paratur channels and Vitória island) (Fig. 3.7d). The beaches are composed of fine to very fine 3–5 m thick sand deposits, covering discordantly fine sediments, and are intersected by meandering channels (tidal channels and tidal creeks) that extend from the mangrove vegetation

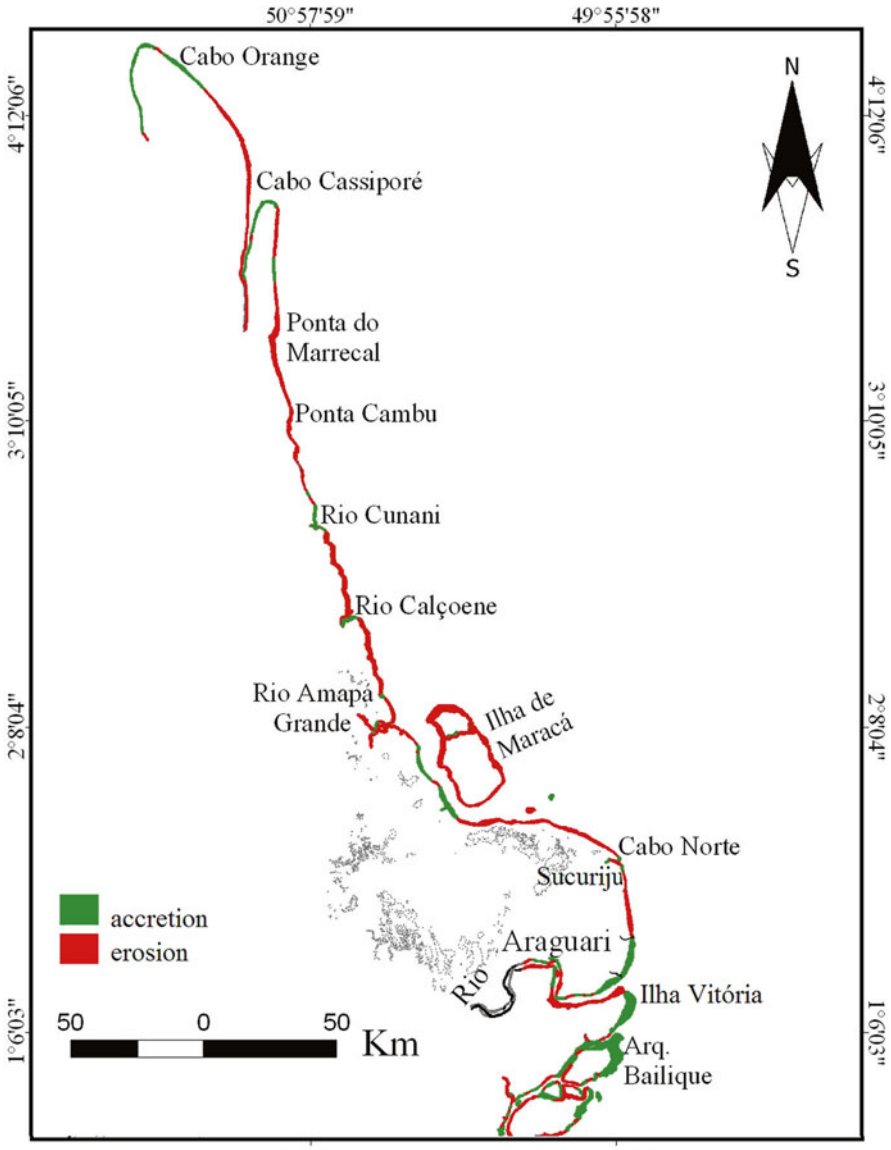

Fig. 3.6 Northern coast of Amapá (Modified from Silva 2010)

to the intertidal zone. The high tide beaches are up to 60 m wide and of low to moderate slope (1–3°).

The upper intertidal zone usually has surface wave ripples but with few physical or biogenic structures. In the mid-tide zone wavy flaser bedding is associated with tidal currents (Mendes 1994). The very low gradient tidal flats up to 3 km wide occupy the mid-lower intertidal. The flats contain wave ripples and patches of muddy sediments.

Fig. 3.7 Beaches on the northern coast of Amapá between Cabo Cassiporé and Araguari River. (**a**) Sand ridges north of Goiabal Beach; (**b**) Goiabal Beach, located near Rio Calçoene; (**c**) Sucuriju beach; (**d**) Ilha Vitoria Beach (Photos: Valdenira Santos, September 2013, Cartas SAO FZA Project)

Sucuriju beach, at Cabo Norte, is a small beach 2.6 km long and 200 m wide, located 1.2 km from Sucuriju village. To the south Paratur and Araqueçaua beaches extend for 22 km but have a narrower high tide beach. Mangroves dominate the landscape behind these beaches and young mangroves grow on the tidal flats. The beach on Vitória island is 650 m long with a tidal channel aligned north-south separating it from the muddy intertidal zone. Behind the beach, a "*varzea*" forest ecosystem dominates with a few mangroves. All of these beaches are exposed directly to tidal bores, which fluidize structures deposited at the limit of the bore.

Goiabal beach, near Calçoene, is one of the few beaches accessible by road and is popular during the summer vacation. It is backed by low vegetated beach ridges and comprises a 70 m wide high tide beach composed of fine sand and sloping at 2°, and then low-gradient intertidal sand flats that extend seaward for at least 2 km (Fig. 3.8).

Mendes (1994) examined the heavy mineral assemblages in the sandy deposits and found they are derived from proximal sources, notably the pre-Cambrian basement which, according to Allison et al. (1995) supplies ephemeral deposits that accumulate at estuarine mouths. Santos (1994) also found bryozoan shells and siliceous spicules in sandy sediments at the mouth of the Araguari river indicating that some sediment is derived from the inner continental shelf. A few pelecypod shells are also found in the beach deposits. During the wet season the ripple troughs are covered by a thin layer of mud and/or organic material, forming flaser deposits.

Due to the difficulty of access, all 16 ocean beaches are in natural state of preservation. Goiabal beach (Figs. 3.7b and 3.8) is the most famous and most popular

Fig. 3.8 View north along Goaibal beach showing the narrow high-tide beach and start of the wide intertidal sand flats (Photo: A D Short)

beach of Amapá State while many of the beaches are used for cattle grazing, with cattle ranches occupying the backing coastal plain.

3.3.2 Southern Amapá Amazon River Coast

The southern Amapá Amazon coast is strongly influenced by the Amazon river with its high discharge and variable water levels and the macro-megatides. This sector has 495 km of mainland shore, including Bailique archipelago, Pedreiras, Cajari and Santana islands, and extends from the Amazon mouth to Jari river mouth, located 350 km upstream, which is also the border with Pará state (Fig. 3.1). The main islands of Bailique archipelago are Franco (109 km^2), Bailique (159 km^2), Faustino (34.5 km^2), Brigue (22.5 km^2), Curuá (345 km^2) and Parazinho (2.64 km^2), which are all part of the Parazinho Biological Reserve.

Two types of beaches occur on this coast: high tide sandy beaches fronted by wide tidal sand flats, and smaller pocket beaches usually fronted by river-truncated mud flats. High tide beaches and wide sand flats (Fig. 3.9b) occupy 43.3 km (8.8 %) of this coastline and are most frequent on the more exposed eastern and southeastern shores of Bailique Archipelago. The best-known high-tide sand beach is located in Parazinho island (Fig. 3.9a). It is 4 km-long and 50 m-wide grading into wide tidal flats (Fig. 3.9a). The pocket beaches occupy 4 km (0.8 %) of coast and occurs along the banks of Canal do Norte of Amazon river located between 120 and 150 km inside the Amazon river mouth, including on either side of Macapá city (Fig. 3.10c).

Fig. 3.9 High-tide beach on Amapa's Parazinho island at the Amazon river mouth (**a**); and (**b**) wide exposed sand flat with mud hollows on Amapá's Farol Praia on Ilha Vitória (Photos: A D Short)

They are all located on the northern shores and represent small narrow strips of high tide sand fronted by intertidal mud flats (Fig. 3.10a) of variable width, and then the deeper river channel, which ranges in width from 16 km in the north decreasing to 13 km in the south. The beaches are all short, the longest being 0.38 km in length decreasing to just 0.1 km long. Most are fringed by varzea forest together with scattered mangroves along the shore (Fig. 3.10b).

From the mouth of the Amazon river to inside Canal do Norte, extensive sand waves occur in the intertidal and subtidal zone, as well as in the tidal bars (Fig. 3.11). The crests are orthogonal or almost orthogonal to the direction of the tidal current, which is predominantly northeasterly, the same direction as that of the ebb tide current. Sand flats in the Bailque archipelago are up to 4 km wide and more than 20 km long and some are accreting at the mouth of the Amazon a rate of 272 myr^{-1} (Silva et al. 2011). The beaches, tidal bars and sand flats are composed of silt and fine to very fine sand derived from the Amazon river bedload discharge (Martinez et al. 2009).

3.3.3 Pará-Amazon Riverine-Island Shores

The western Pará coast commences at the border of Jari river and extends through the Amazon mouth islands towards the Marajó archipelago and the southern shores of Marajó Bay. Its length is dependent on how many of the Amazon interdistributary mouth islands are included and how they are measured. For this study the coast was measured essentially northeast from the mouth of Jari river along the southern shores of Canal do Norte and including the islands of Grande of Gurupá, do Pará, de Serraria, Jurupari, Caviana de Dentro, Caviana de Fora, Canivete, Janaucu and Mexiana and then east following the southern shores of Canal do Sul along the north (~1500 km) and then the east coast of Marajó Island (390 km), providing a total length of 1890 km (Table 3.1, Fig. 3.12).

The riverine shorelines of the islands are dominated by fluvial processes, as well as tidal fluctuations and low fetch-limited wind waves. The shores are dominated by

Fig. 3.10 Beaches of the Amazon river coast. (**a**) Pocket beaches fronted by intertidal mud flat; (**b**) pocket beach bordered by varzea forest; and (**c**) river pocket beach near Fazendinha (Macapá) (Photos: Valdenira Santos, July 2014, Cartas SAO FZA Project)

Fig. 3.11 Sand waves in the intertidal zone at Canal do Norte of the Amazon river (Photo: Valdenira Santos, October 2013, Cartas SAO FZA Project)

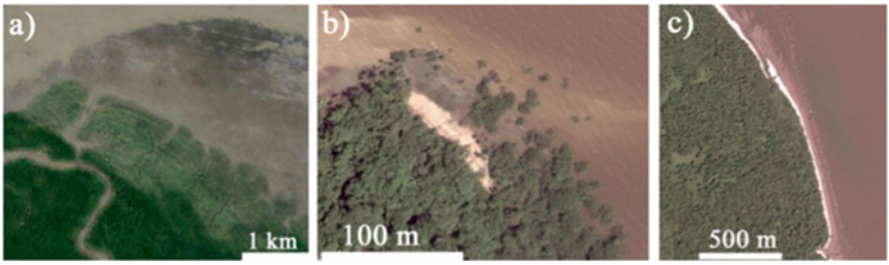

Fig. 3.12 (**a**) 4 km wide sand flats on Janauçu island; note the backing series of vegetated beach ridges; (**b**) 130 m long pocket beach on river bank on Mexiana Island; and (**c**) 1.3 km long high-tide beach and flats on the exposed eastern tip of Mexiana island (Source: Google earth)

mud banks and mud flats backed by inundated lowlands, with mangroves increasing towards the Amazon river mouth.

Based on a view of the coast using Google Earth, about 50 beaches were detected along the Pará-Amazon coast. They had a total length of 109 km, occupying 7.2 % of the shore, with an average length of 2.1 km. Many are however poorly expressed and highly irregular; some appeared as eroding and others were littered with vegetation debris, usually large logs. They are all located on five river mouth islands including Caviana de Dentro (6 beaches), Janauçu (3), Caviana de Fora (7), and in particular the east-northeast coast of Mexiana (30). The beaches are of three types: wide sand flats possibly backed by a high-tide beach or beach ridges and grading into varzea forest, with the flats extending up to 20 km longshore (Fig. 3.12a); small pockets of sand on the banks of the river channel (Fig. 3.12b); and well developed high-tide beaches fronted by sand flats (Fig. 3.12c).

3.3.4 Marajó Island – North Coast

The northern coast of Marajó Island extends east-west for 200 km between Chaves and Cabo Maguari. The first 80 km faces north across the 7–16 km wide Canal do Sul, the southern channel of the Amazon River, while the remainder are exposed to the Atlantic. The shoreline is predominately sandy with at least 39 low-energy tide-dominated beach systems (Figs. 3.13 and 3.14) that average about 1 km in length and occupy at least 40 km of the coast. In profile the beaches consist of a steep high-tide sandy beach, some backed by eroding bluffs of the Pos Barreiras Formation, others by low beach ridges or dunes, while they are fronted by intertidal sand flats up to 1 km wide.

The remainder of the coast consists of forest-fringed sandy tidal flats, 20 large tidal creeks and numerous smaller creeks, together with several low islands between 100 km to 150 km (east of Chaves). The islands are mangrove-fringed with some containing sandy beaches on their more exposed north to eastern shores. The easterly wind waves and swell produce westerly longshore sediment transport manifested by several west-trending recurved spits (Fig. 3.15).

The eastern 100 km of coast has advanced with former beaches, recurved spits and creek channels extending up to 10 km inland, particularly in the lee of the northeastern tip of the island at Maguari Cape. This low-lying section of coast is also rich in mangrove forests grading into varzea forests.

Fig. 3.13 The beach at Chaves is backed by steep eroding bluffs, partly protected by a seawall. The jetty extends 200 m out across the sand flats (Photo: Valdenira Santos, Cartas SAO FZA Project)

Fig. 3.14 Narrow high-tide beach on the north coast of Marajó island (Photo: José Roberto Pantoja, January 2014, Cartas SAO FZA Project)

Fig. 3.15 A 2 km long beach-spit on the northeastern coast of Marajó island. The beach is fronted by 400 m wide ridged sand flats and backed by older beach ridges and spits (Source: Google earth)

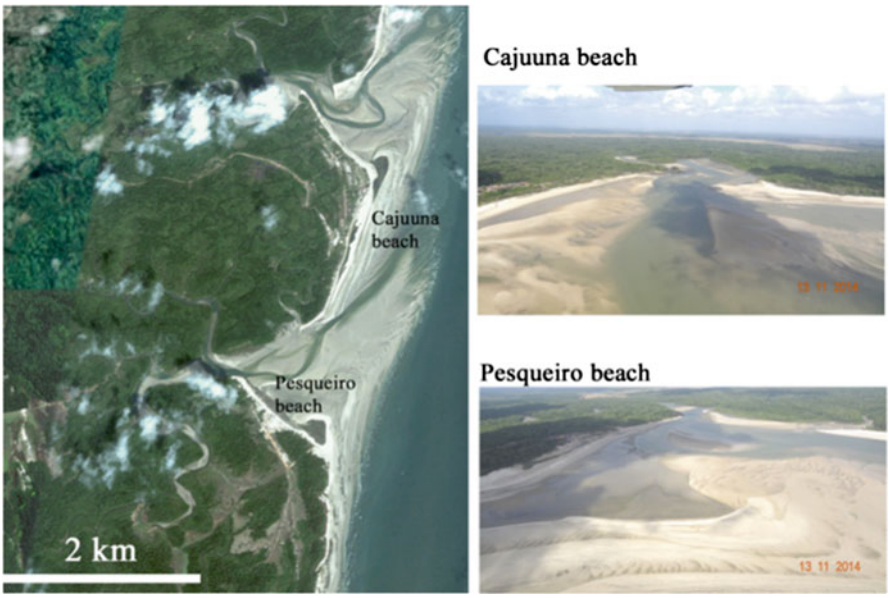

Fig. 3.16 Tide-dominated beaches consisting of a high-tide beach fronted by 500 m-wide ridged sand flats adjacent to creek mouths at Cajuuna (Source: Google earth; photos: A G Miranda, Cartas SAO FZA Project)

3.3.5 Marajó Island – East Coast (Marajó Bay)

The eastern coast of Marajó island extends for 190 km between Cabo Maguari and Ponta do Malato. While it faces into the easterly trade winds, it also faces across Marajó Bay, which narrows from 60 km at its mouth to 15 km in the south. This is still sufficient for Atlantic swell to impact the first 50 km of coast and for the trade winds to generate short seas along the entire shore. The large tide range (10 m decreasing south to 3 m) generates strong shore-parallel tidal currents, as well as cross-shore currents associated with the numerous small inlets and tidal creeks along this section of coast. The coast consists of mangroves, tidal creeks and generally short tide-dominated beaches fronted by intertidal sand ridges, sand flats and tidal sand flats, some of the latter containing transverse to sinuous sand shoals. The sand flats average 200–300 m in width widening to several hundred meters in front of creek mouths. The ridged sand flats contain low (<10 cm amplitude) shore-parallel evenly spaced sand ridges with spacing averaging about 80 m (Fig. 3.16) This is similar to sand ridge spacing on tide-dominated Australian beaches (Short 2006).

The east coast can be divided into two sectors either side of the Paracauari river. To the north is the 60 km long 'low' coast, which is exposed to higher waves (Atlantic swell and seas) and has longer, more continuous, beaches separated by tidal inlets and composed of fine sand resulting in low gradient high-tide beaches and sand flats. The beaches average 2.5 km in length and occupy 72 % of this sector. This section also has numerous tidal creeks and inlets and associated ebb tide shoals,

with mangroves extending 2–3 km inland. It has experienced shoreline regression of between 1 and 10 km, with the former shorelines marked by stranded beaches and recurved spits (Fig. 3.17).

As a consequence there is little development along this section of coast. South of the river is the 130 km long lower-energy 'high' coast backed by steep bluffs and slopes, with fewer tidal channels and mangroves. The beaches are composed of medium to coarse sand (França and Souza-Filho 2003) and tend to be embayed between protrusions in the bluffs, forming small pocket and embayed beaches. They average only 0.33 km in length and occupy only 30 % of the shore. The remainder of the shore is composed of the bluffs, and in the south, mangroves. Because of the coarser sand and decreasing wave height the high-tide beaches are steeper but still fronted by both ridged sand flats and tidal flats.

In total, beaches occupy 82.5 km (43 %) of the shore, and are generally short with a mean length of 0.64 km ($\sigma = 0.94$ km), and the longest only 4.9 km in length. Overall, there tends to be a net sand transport to the south on at least 20 of the beaches, as manifested by southerly spits, while at some creek mouths the beaches are convex with spits curving to the north and south, and on seven beaches just to the north. The spits are maintained by both the easterly waves and strong tidal flows. Thirteen of the beaches between Jubim, Joanes and Monsarás and around Santana and Santa Maria, are backed by steep bluffs and slopes and are 'embayed'. Mangroves increase in occurrence to the south and some grow on some of the tidal flats along the beaches, with the southernmost 15 beaches all fronted by some mangroves. Overall this is a very low wave-energy shoreline, with generally low narrow high-tide sandy tide-dominated beaches fronted by wide sand flats. Most beaches consist of a single ridge, some overwashed and/or backed by low dunes, with only a few beaches indicating shoreline regression leaving a series of beach ridges.

3.4 Discussion and Conclusion

The Amazon coast is a large complex coastal system involving the interaction of the world's largest river in terms of discharge and sediment in a broad funnel-shaped gulf dominated by macro to megatides, generally low easterly waves, strong coastal currents, and dispersion of sediments along the coast, deflected in the ocean by the NBC. While 99 % of the sediment load is suspended, the 1 % bedload is still estimated at a massive 3.65–18.25 Mt year^{-1} (Dunne et al. 1998). The transport of much of the mud northward along the Amapá coast and beyond as far as Venezuela is well-documented (Anthony et al. 2010, 2014); however there has been little investigation of the bedload and its contribution to channel, river mouth and coastal sedimentation, particularly in the form of tide-dominated beaches and sand flats.

Recent investigations undertaken around the Amazon mouth as part of the Research Network 05-N/NE (AMASIS and AMASTRAT subprojects) and Cartas SAO FZA project, have visited a number of the approximately 260 beaches that have been identified along this predominately muddy coast. These beaches occupy approximately 12 % of the 3150 km long Amapá and western Pará Amazon coast.

Fig. 3.17 Regressive shoreline at Soure showing the inner beach ridges, mangrove-filled interbarrier depression and modern coast with beaches fronted by 200–300 m wide tidal sand flats (Source: Google earth; photo: A G Miranda, Cartas SAO FZA Project)

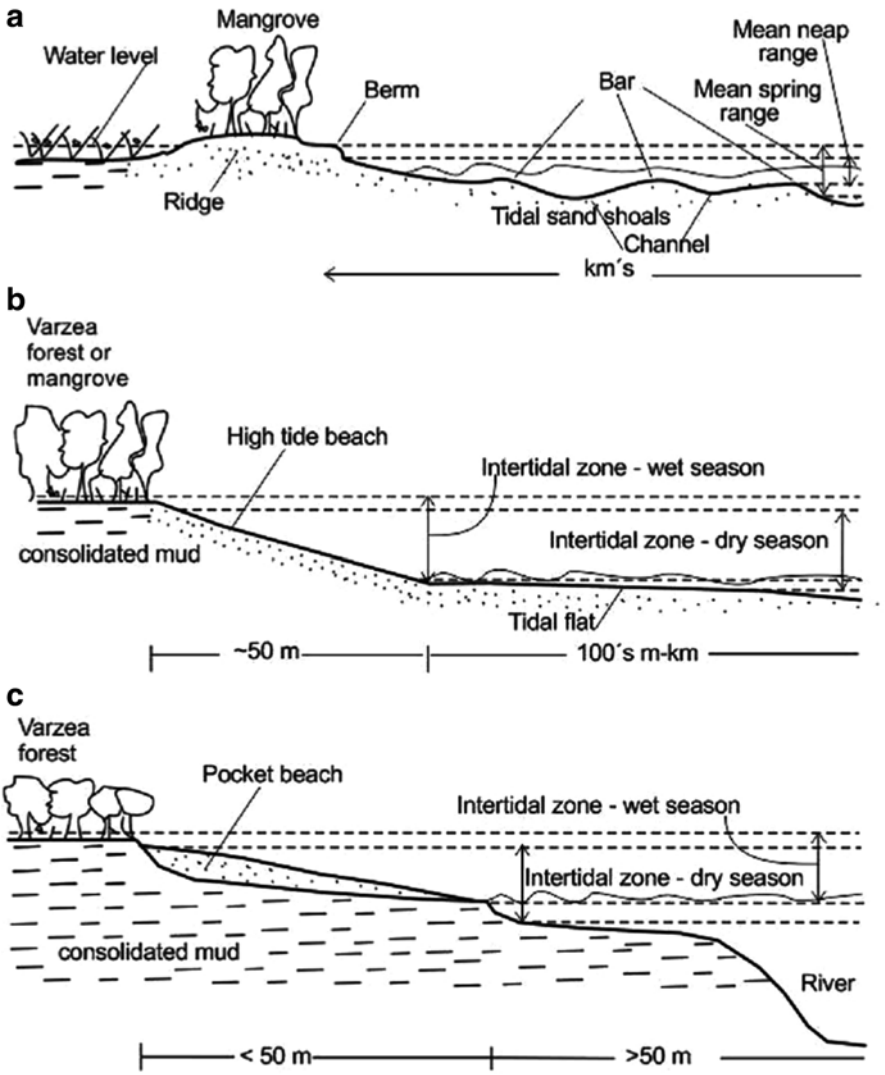

Fig. 3.18 The three typical beach types found along the Amazon coast. (**a**) low beach ridge grading into intertidal tidal sand shoals, which may be kilometers wide (See Figs. 3.7, 3.9 and 3.12); (**b**) steeper high-tide beach fronted by intertidal sand flats (See Figs 3.15 and 3.16); and (**c**) small (and short) pocket beach found along some river banks (See Figs. 3.10)

The beaches are of three types (Fig. 3.18). At the river mouth are extensive areas of wide intertidal sand flats extending several kilometers along the coast and up to a few kilometers in width, which may or may not have a small high-tide beach and/or beach ridge (Fig. 3.18a), similar to those reported by Anthony, et al. 2014. These flats are often host to mangroves and grade landward into older beach ridges and varzea forest or swamp. Second are the best developed beaches which occur on the

most exposed shores, including the northern Amapá coast; the exposed eastern side of some of the river mouth islands; and in particular on the north and east coasts of Marajó island, where they occupy 30 % of the shore. They usually consist of a well-developed steeper high-tide beach usually at least 50 m wide, then intertidal sand flats from a few meters (on river channels) to kilometers wide. The flats may be ridged, featureless or contain tidal drainage features, and may grade seaward into mud flats. Mud pockets can also be found on some of the inner flats (Fig. 3.18b). These beaches contain the four tide-dominated beach states (Short 2006). The third type is found along the river banks where there are occasionally small pockets of sand usually less than 200 m in length deposited at high tide on the riverbanks and often composed of medium to coarse fluvial sand, usually overlying mud deposits (Fig. 3.18c). The most accessible of these are at Macapá city where they are used for recreation.

This chapter is the first to report on preliminary inspections of some of these beaches. There is still much to be done in order to fully understand the transport pathways of the Amazon bedload, and the role the beaches and sand flats play in the overall sedimentation process. Many of the beaches are also unstable and experiencing erosion and/or associated longshore sand transport, while others are bordered by dynamic tidal channels and associated tidal shoals. Vegetation debris including large logs litters many of the upper beaches. The beaches are just a small part of a highly dynamic Amazon coast, the whole of which requires more thorough investigation.

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