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The Amazon-influenced muddy coast of South America: A review of mud-bank–shoreline interactions

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A B S T R A C T

The 1500 km-long coast of South America between the Amazon and the Orinoco river mouths is the world's muddiest. This is due to the huge suspended-sediment discharge of the Amazon River ($10^6 \times 754$ tons $yr^{-1} \pm 9\%$), part of which is transported alongshore as mud banks. Mud-bank formation is controlled by the physical oceanography of the continental shelf seaward of the Amazon River mouth, an initial seafloor storage area for much of the suspended sediment discharged from the river. In this area, rapid and sustained fluid-mud concentration and trapping are associated with fresh water–salt water interaction and estuarine front activity on the shelf due to the enormous Amazon water discharge (ca. 173,000 $m^3 s^{-1}$ at Obidos, 900 km upstream of the mouth). Fluid mud is transported shoreward and then along the coasts of the Guianas by a complex interaction of wave and tidal forcing, and wind-generated coastal currents. The mud banks, which may number up to 15 or more at any time, are up to 5 m-thick, 10 to 60 km-long, and 20 to 30 km-wide, and each may contain the equivalent mass of the annual mud supply of the Amazon. As the banks migrate alongshore, their interaction with waves results in complex and markedly fluctuating shorelines that are associated with space- and time-varying depositional 'bank' phases and erosional 'inter-bank' phases. Bank zones are protected from wave attack as a result of wave-energy dampening by mud, and undergo significant, albeit temporary, coastal accretion accompanied by rapid mangrove colonization. The dampening of waves in bank areas as they propagate onshore is accompanied by the shoreward recycling of mud, commonly in the form of individual mud bars. These bars progressively undergo desiccation and consolidation, and thus constitute a major pathway for rapid and massive colonization by mangroves. Erosion by waves propagating across relatively mud-deficient shoreface zones in inter-bank areas can lead to muddy shoreline retreat rates of tens of metres to several kilometres over a few months to a few years, accompanied by massive removal of mangroves. Notwithstanding the higher incident wave energy on inter-bank shores, inter-bank shorefaces are permanently muddy due to the pervasive influence of the Amazon muddy discharge. Inter-bank and transitional bank-to-inter-bank phases are associated with both periodic sandy chenier formation and extreme forms of rotation of rare headland-bound sandy beaches.

The high mud supply from the Amazon has been the overarching geological control on the Quaternary evolution of the northeastern South American coast, having led to the growth of a muddy shelf clinoform at the mouth of the Amazon and more or less important progradation throughout this coast. Net progradation reflects an imbalance in favour of deposition during each mud-bank–inter-bank cycle. The high mud supply has presumably blanketed shelf sand deposited by smaller rivers during eustatic lowstand phases. The shelf clinoform structure at the mouth of the Amazon and the muddy coastal progradation throughout the coast of the Guianas and into Venezuela provide analogues of the geological record on muddy shorefaces.

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1. Introduction

Muddy shores and adjacent shorefaces are found along several open coasts of the world. They are generally associated with the dispersal pathways of rivers that discharge large quantities of fine-grained sediment. While deltas constitute the typical setting for such muddy coasts, longshore redistribution of sediment from high-discharge rivers may lead to the formation of significant stretches of muddy coasts downdrift of sediment source(s) (Wright and Nittrouer, 1995), and associated significant clinoform development (Walsh and Nittrouer, 2009). Examples include the Mississippi chenier coast (McBride et al., 2007), the Gulf of Papua (Walsh and Nittrouer, 2004), the East China Sea downdrift of the Chanjiang/Yangtze (Liu et al., 2006; Wei et al., 2007), and the Mekong delta coast (Tamura et al., 2010). The longest of these muddy coasts, however, is the 1500 km-long stretch between the mouths of the Amazon and the Orinoco Rivers in northeastern South America (Fig. 1), which is strongly impacted by the mud supply from the Amazon. This large supply of mud constitutes the overarching geological control on this coast, having led to the growth of a shelf clinoform structure at the mouth of the Amazon and more or less important coastal progradation throughout the coast of the Guianas and into Venezuela. By inducing macroscale geomorphic and bathymetric changes, the high mud supply also has considerable coastal ecological and economic impacts on all the countries between the mouths of the Amazon and the Orinoco: Brazil, French Guiana, Surinam, Guyana and Venezuela.

Much of the earlier earth-science research on this coast concerned the mouth of the Amazon and the adjacent continental shelf (summarised by Nittrouer and Demaster, 1986). Later, the AmaSSedS (A Multidisciplinary Amazon Shelf Sediment Study) project (Nittrouer and Kuehl, 1995; Nittrouer et al., 1995a) provided impetus for ground-breaking research on the processes of fluid-mud accumulation and fine-grained sedimentation on the coast of the Amapà area in the vicinity of the mouth of the Amazon (Fig. 1). Efforts on the rest of this coast, dominated by mud-bank dynamics, from the Cabo Cassipore area through the three Guianas (French Guiana, Surinam and Guyana) to the Orinoco have been more sparse, but have nevertheless been precursory in the understanding of patterns of behaviour, at various timescales, of wave-dominated shores subject to high mud supply. These studies have notably focussed on processes of mud-bank migration, mud-bank interaction with the shore, and the influence of such banks on mangrove dynamics. Commencing with the publication by Choubert and Boyé (1959) on variations between muddy shore phases and phases of mud erosion attributed to sunspot activity, and an important grey-literature report by Nedeco (1968), these efforts were followed by the bench-mark publications of Augustinus (1978), Wells and Coleman (1978, 1981a,b), and Froidefond et al. (1988). Further research on the coast of French Guiana and western Surinam was carried out within the framework of a French Guiana project (2000–2004) on the dynamics of mud banks and their relationship with the mangrove-fringed shores, the results of which were published in a special issue of the journal *Marine Geology* in 2004 (Baltzer et al., 2004). The Amazon-influenced muddy coasts have continually attracted research efforts, notably regarding the interactions between mud and the hydrodynamic forcing, between mud and shoreline, and between mud and mangroves. The aim of this review is to bring together a comprehensive summary of the relationships between the hydrodynamics, mud supply and mud-bank formation, and the morphodynamic interactions between mud banks and the shoreline, while also highlighting the impacts of mud-bank activity on the mangrove system. The efforts reviewed here depict a highly complex system characterized by strong estuarine frontal activity on the continental shelf at the mouth of the Amazon that serves as a precursor to the mud-bank regime.

The recent findings examined in this research review have been based on a wide range of methodological procedures and techniques, including new field and remote-sensing approaches. Field studies on mud banks and on the muddy shoreline involve considerable logistical difficulties, including the challenge of accessing experimental sites. Field approaches have included: measurements of cross-shelf wave dissipation on mud beds (Wells and Kemp, 1986), deployment of instrumented tripods and seismic profiling (Allison et al., 2000), high-resolution *in situ* topographic mapping of a mud bank (Lefebvre et al., 2004; Anthony et al., 2008), monitoring of mud-bank sedimentation rates through ultrasonic altimetry (Gratiot et al., 2007), and *in situ* instrumented monitoring and time-lapse photography to monitor changes in the surface properties of a mud bank (Gardel et al., 2009). Given the problems of accessibility, remote

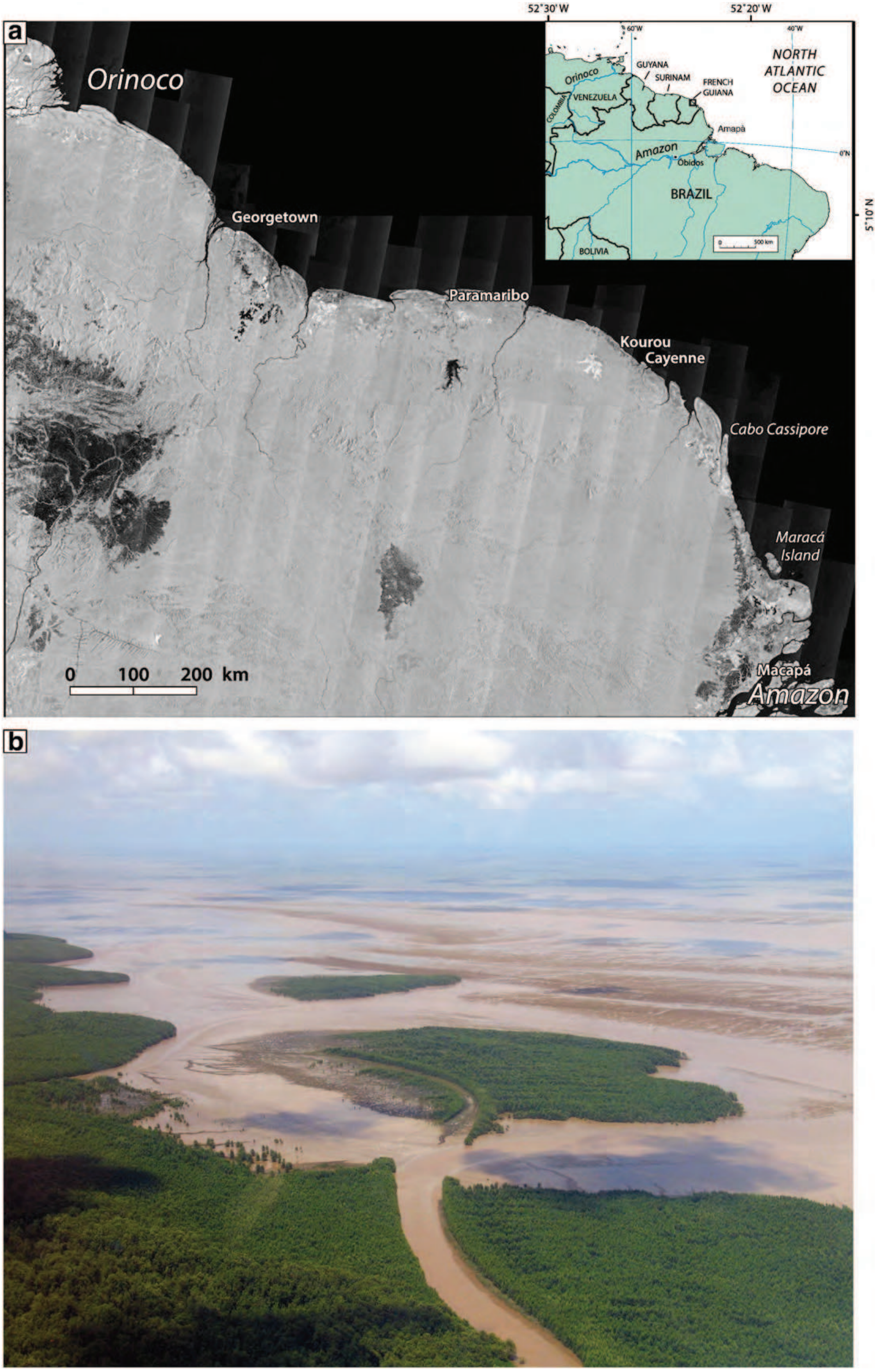

Fig. 1. A 2006 JERS-1 satellite image of the muddy Amazon–Orinoco coast, the world's longest muddy coast (a). Mud banks start forming in the Cabo Cassipore area rather than along the coast nearer to the mouth of the Amazon. This is due to the significant offshore location of the non-confined estuarine turbidity maximum of the Amazon and westward along-shelf deflection of this maximum towards the coast near Cabo Cassipore, directly south of which the Amapà coast appears to be mud-starved (see text). The oblique aerial photograph (b) shows a typical mud bank in French Guiana partly colonized by mangroves and cut by drainage channels. The bare part of the mud bank in the background shows a series of linear mud bars. This mud bank is one of several (up to 15 or more) banks migrating at any time from the mouth of the Amazon River in Brazil to that of the Orinoco River in Venezuela.

sensing has been widely used for the analysis of coastal forms, physical processes, and mangrove ecology at various scales (e.g., Anthony et al., 2002; Allison and Lee, 2004; Baghdadi et al., 2004; Froidefond et al., 2004; Baghdadi and Oliveros, 2007; Proisy et al., 2007). In particular, topographic data extraction from sequential satellite images has been used with success to highlight mud-bank dynamics and coastal evolution (Gardel and Gratiot, 2004, 2005; Gratiot et al., 2008), while LIDAR has been shown to hold promise for highlighting both topographic variations (Anthony et al., 2008) and patterns of opportunistic mangrove colonization (Proisy et al., 2009), although cost is a serious limitation given the extensive length of muddy shoreline. Radionuclide signatures have been used by Allison et al. (1995a,b), Zhu et al. (2002), Aller et al. (2004), and Allison and Lee (2004) to determine mud-bank history and dynamics, notably *in situ* mud residence times, and accumulation and recycling rates.

The objectives of this review are to examine six issues on the relationship between Amazon-derived mud and the evolution of the Amazon–Guianas coast, and to discuss their relevance to studies of other, similar coastlines. These issues are: (1) a description of the mud-bank system and of the environmental context of this South American coast preceded by data on the Amazon water and sediment discharge; (2) mechanics of the estuarine interactions that lead to mud-bank formation; (3) wave–mud-bank interactions and processes involved in cross-shore mud translation; (4) mud-bank interaction with mangroves; (5) the longshore migration of mud banks and its spatio-temporal variability; and (6) sand concentration processes and the influence of mud banks on sand bodies. The overall mud-bank cycle that follows the original sequence of mud supply and concentration, and mud-bank formation, migration, and interaction with the shore, and the geological significance of muddy shoreface aggradation and shoreline progradation are then discussed, followed by a comparison with other high mud-supply shores.

2. Amazon mud supply, mud-bank characteristics and environmental context

2.1. Mud supply

The Amazon is the world's largest river system with a drainage basin of 6.1×10^6 km^2 (Organization of American States, 2005). The mean annual water discharge at Obidos (Fig. 1), 900 km upstream of the mouth, has been estimated at 173,000 m^3 s^{-1} by Martinez et al. (2009) from continuous gauging between 1995 and 2007. Readers interested in the hydrology of the Amazon River basin should consult the special volume edited by Guyot and Walling (2009). Estimations of sediment discharge published over the last four decades have ranged from 5 to 13×10^8 m^3 yr^{-1}, according to a review by Martinez et al. (2009). These authors obtained a mean annual mud discharge of about 754×10^6 tons yr^{-1}, with a coefficient of variation of 8.6% (Fig. 2) from monitoring of a suspended-sediment discharge network at Obidos run by the French–Brazilian research programme HYBAM (http://www.ore-hybam.org) between 1995 and 2007. Martinez et al. (2009) highlighted a good agreement (to within 1.8–3%) between their suspended-sediment concentrations and data derived from a MODIS space-borne sensor. The mean value obtained by these authors appears to be a robust estimation of the suspended-sediment discharge of the Amazon compared to earlier estimations based on limited field measurements (e.g., Meade et al., 1985; Dunne et al., 1998; Filizola, 2003). About 90% of the total sediment load of the Amazon is considered as being composed of silt and clay (Milliman and Meade, 1983; Wright and Nittrouer, 1995; Dagg et al., 2004). Bedload estimates are difficult to obtain. Strasser et al. (2002) computed a bedload discharge of 4.7×10^6 tons yr^{-1} from bedform structures, a value corresponding to 6% of the suspended load computed by Martinez et al. (2009).

About 15–20% of the muddy discharge progressively forms highly turbid suspensions (>1 g l^{-1}) in the vicinity of the mouth of the Amazon, and subsequently mud banks that migrate alongshore off the French Guiana–Surinam–Guyana coasts (Augustinus, 1978; Wells and Coleman, 1978; Eisma et al., 1991; Allison et al., 2000; Warne et al., 2002). In any year, the number of actively translating mud banks throughout the 1500 km-long coast of the Guianas may be 15 or more. The banks are spaced at intervals of 15 to 25 km, are up to 5 m-thick, 10 to 60 km-long and 20 to 30 km-wide, and migrate at velocities ranging from 1 to >5 km yr^{-1} (Gardel and Gratiot, 2005). They translate in water depths of <5 to 20 m over a modern inner shoreface mud wedge created from deposition from previous mud banks (Allison et al., 2000). The spatial (and temporal) imprint of the waxing and waning of mud-bank activity is characterized by 'bank' and 'inter-bank' phases, and locally by 'transitional' phases (Anthony and Dolique, 2004). Over time, the rhythmic nature of these alternating phases has an overwhelming impact on the coast, inducing rapid shoreline accretion and/or erosion, as well as important ecological changes involving the development and destruction of mangrove forests. The migrating mud banks tend to imprint a northwestward deflection of the river mouths on the coast (Fig. 1). The updrift coastal sectors of these river mouths comprise

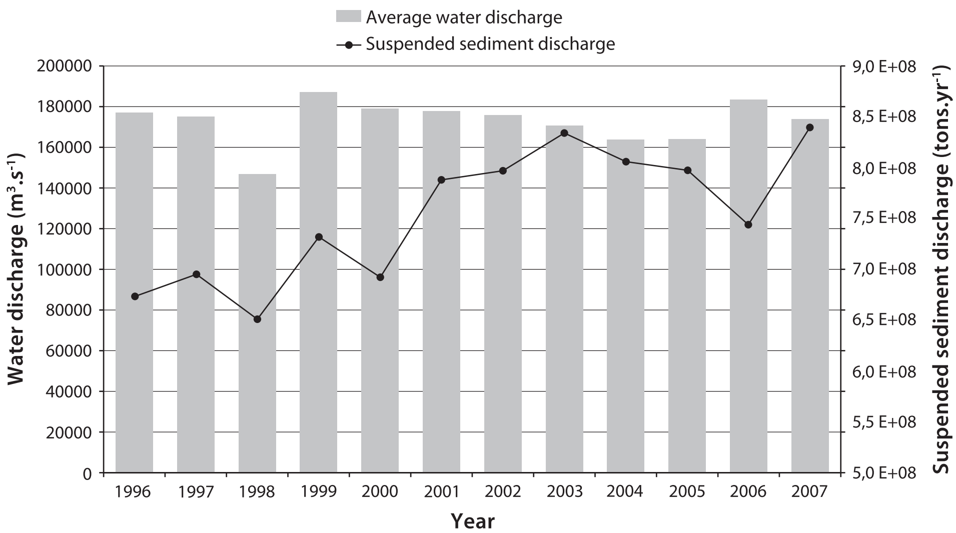

Fig. 2. Annual river and suspended-sediment discharge of the Amazon River at Obidos, 900 km upstream of the mouth, from 1996 to 2007. From Martinez et al. (2009).

large areas of water of normal oceanic salinity trapped inshore by the lower-salinity Amazon water advecting alongshore (Lambs et al., 2007).

2.2. Mud-bank sediment concentrations, topography, internal structures and biogeochemical recycling

Fluid mud, the term most commonly used to evoke the rheology of mud banks, develops at concentrations at which the settling velocity of the mud particles starts to be impeded by inter-particle interactions, and has been described by Mehta (2002) as an energy-absorbing slurry with typical densities ranging from 10 to 300 g l^{-1}. The densities of mud en route from the Amazon to the Orinoco are, in reality, extremely variable, the mud showing various stages of concentration and consolidation (Gratiot et al., 2007), depending on history, proximity to the shore, elevation within the tidal frame, and liquefaction processes. In bank phases, these stages range from very high suspended-sediment concentrations (1–10 g l^{-1}), through fluid mud, to settled mud, which, in turn, ranges from under-consolidated (≤650 g l^{-1}) to consolidated sediment beds (≥750 g l^{-1}). Inter-bank zones are generally associated with less turbid waters (SSC of <1–5 g l^{-1}).

Gratiot et al. (2007) have suggested that the km-scale mud-bank and inter-bank profiles conform to those of accretion- or erosion-dominated muddy shore profiles (Kirby, 2000, 2002; Mehta, 2002). Inter-bank areas are characterized by receding, low and concave erosion-dominated profiles of consolidated mud (and sometimes chenier sands, see Section 7.2) while mud banks are characterized by prograding, high and convex accretion-dominated profiles of soft mud colonized by mangrove vegetation in the highest elevations, albeit with marked micro-scale topographic heterogeneity caused by variations in wave reworking and consolidation, dewatering processes, and drainage channels, especially near the terrestrial shoreline. The wave–seabed interaction patterns that lead to these two basic types of profiles are discussed in Section 4. Lefebvre et al. (2004) highlighted, from a combination of aerial photographs and field monitoring, the presence of a narrow linear topographic high over a mud bank. Such linear features are clearly identifiable from SPOT images and low-flying aircraft and are commonly dissected by channel networks (Fig. 3). From the meshing of data from SPOT images, LIDAR, and high-resolution field monitoring, Anthony et al. (2008) have mapped the topography of a typical mud-bank surface near the contact with the terrestrial shoreline (Fig. 4). The generated profile shows a lower intertidal zone (below mean water level (MWL)) characterized by relatively regular linear bar features and an upper intertidal zone (above MWL) exhibiting a topography of highs and lows.

Mud banks have been observed to contain abundant internal structures, but coring to observe such structures is only generally possible when the mud is consolidated (≥750 gl^{-1}). Fresh mud can form homogeneous beds commonly ranging from a few decimetres to over 1 m-thick. Rine and Ginsburg (1985) identified alternations of massive structureless mud beds up to as much as 2 m-thick, with beds often exhibiting parallel, wavy and lenticular laminations and, rarely, micro cross-lamination. Laminae of silt, and rarely fine sand, alternate with more clay-rich laminae, indicating grain-size sorting, and orientation of clay minerals is common (Rine and Ginsburg, 1985; Allison et al., 1995b). Debenay et al. (2007) have highlighted the role played by diatom biofilms in the formation of such laminations. These internal structures are also well observed in areas where the shoreline undergoes erosion, resulting in exposure of consolidated beds that are sometimes topped by fresh fluidized mud driven ashore (Lefebvre et al., 2004). Overall, the preservation of internal structures in these mud banks very likely reflects high rates of sediment accumulation relative to bioturbation (Kuehl et al., 1996). As noted by Walsh and Nittrouer (2004) from a study of similar deposits in the Gulf of Papua, it is likely that the large mud supply may lead to dilution of organic matter levels and preclude peat development despite the local abundance of mangrove leaf and propagule litter.

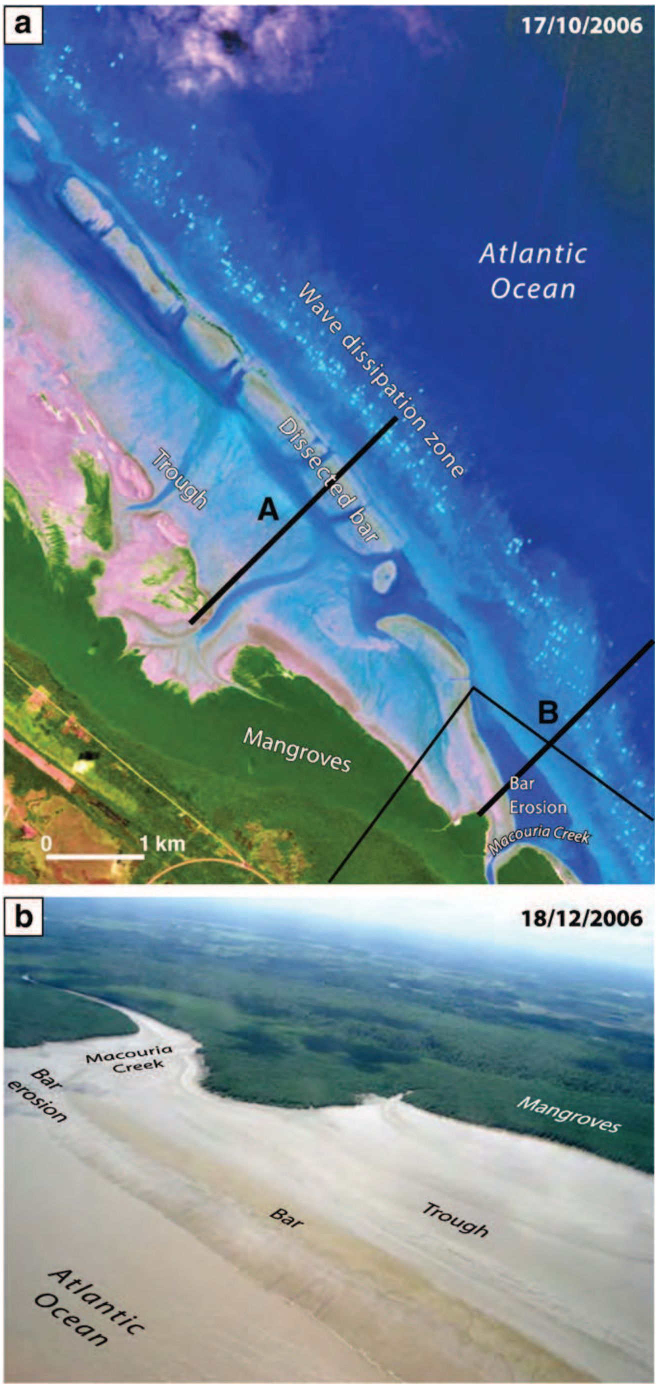

Fig. 3. SPOT image (a, 17 October 2006) and oblique aerial photograph (b, 18 December 2006) showing linear bar features characterizing mud-bank topography (trailing edge of the Macouria bank in French Guiana). The bars are drained by tidal channels. Lines A and B show locations of profiles generated from SPOT images in Fig. 4. Lower left corner of (a) shows erosion of the trailing edge of the bank, resulting in a flat consolidated bed and an offset between the distal edge of the bar and the eroding proximal edge and the terrestrial shoreline. From Anthony et al. (2008).

Mud at concentrations below those of settled mud typically undergoes significant and repeated remobilization by tides and waves and is subject to diagenetic processes before its ultimate burial (Zhu et al., 2002; Aller et al., 2004; Allison and Lee, 2004; J.Y. Aller et al., 2010; R.C. Aller et al., 2010). Aller et al. (2004) employed a broad range of tracers such as ^{234}Th ($t_{1/2}$ = 24 days), ^{210}Pb ($t_{1/2}$ = 22 years), seasonal Cl^{-} profiles, and non-steady-state diagenetic models of pore-water

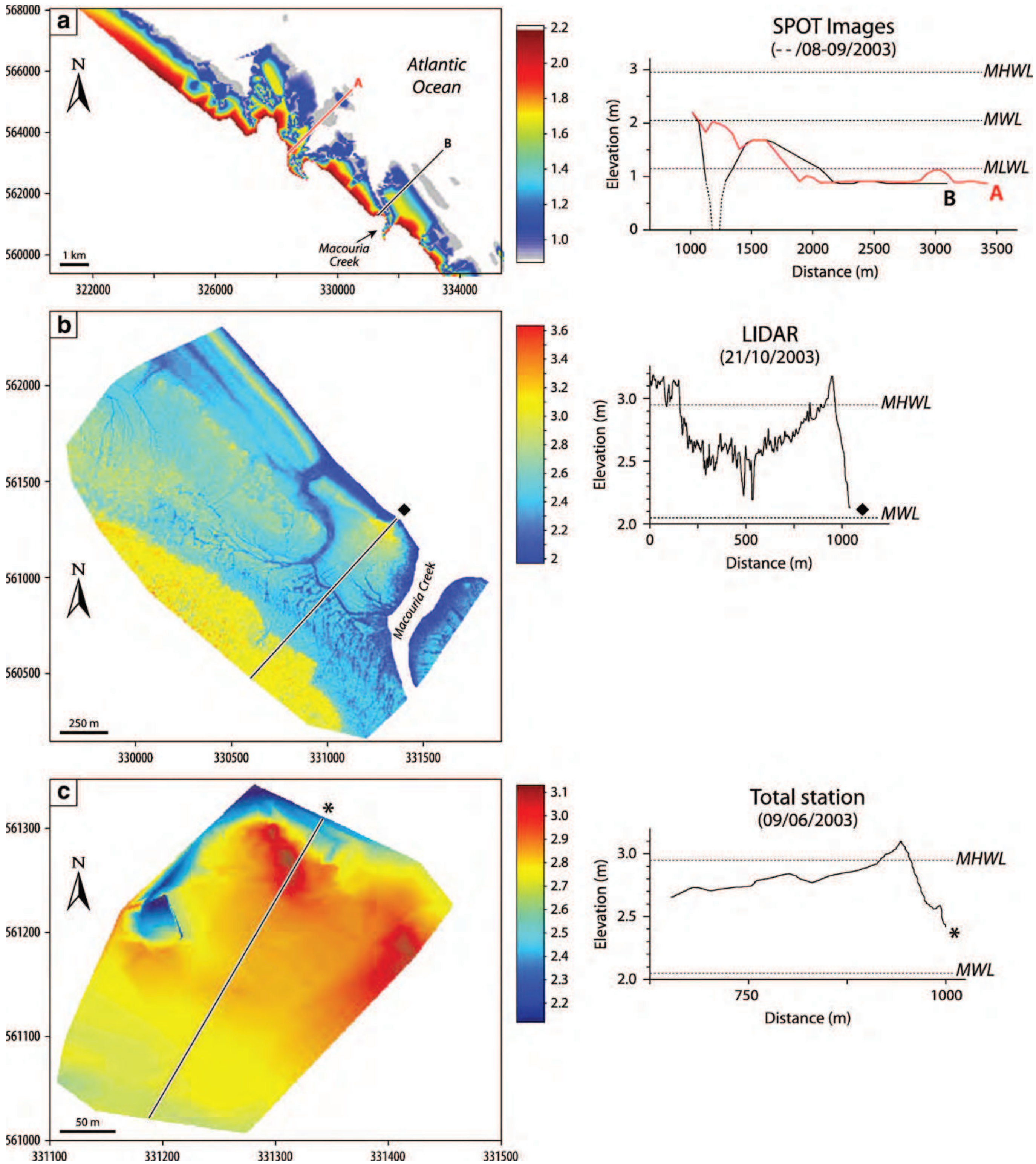

Fig. 4. Digital elevation models and representative topographic profiles of a typical mud bank (Macouria mud bank, French Guiana, shown in Fig. 3) constructed from the meshing of data from: (a) SPOT images, (b) a LIDAR image, (c) a field survey. MHWL = Mean high water level; MWL = mean water level; MLWL = Mean low water level. From Anthony et al. (2008).

concentrations and oxidant-reductant relationships to demonstrate that mud banks are characterized by extraordinarily intense sedimentary and biogeochemical recycling that considerably exceeds that of stable coastal systems, such as salt marshes, in material exchange with the sea. The upper 0.1–1 m of deposits are reworked and exchanged with overlying water on timescales of <10 days to seasonally. In such areas, the seafloor, thus, acts as a massive "suboxic batch reactor", entraining and processing reactive marine plankton, regenerating Fe, Mn oxides, exchanging metabolites and nutrients with the oxygenated water column, and generating non-sulfidic authigenic minerals (Aller et al., 2004). It has been suggested that these conditions of intense biogeochemical recycling are favourable to the generation of biosphere diversity over geological time (J.Y. Aller et al., 2010; R.C. Aller et al., 2010).

2.3. Mud-bank oceanographic setting: winds, waves and currents

The Amazon-influenced coast is affected by trade winds from the northeast that are mainly active from January to May. These winds generate waves from an east to northeast direction (Gratiot et al., 2007). Waves have significant periods (T_s) of 6 to 10 s, and significant offshore heights (H_s) of 1 to 2 m (Fig. 5). Large swell waves generated by North Atlantic depressions in autumn and winter and by Central Atlantic cyclones in summer and autumn are probably responsible for the longer-period waves (>8 s). These longer waves have a directional range from north to north-northwest. The most energetic trade-wind waves are observed between December and April in response to peak wind activity while swell waves appear to be most frequent in autumn and winter, reinforcing the relatively energetic winter to early spring wave regime induced by the trade winds. Trade winds also generate rains from December to July, with an intervening relatively dry month in March. The annual rainfall in the coastal zone varies from 2 to 3 m. Tides are semi-diurnal and the spring tidal range decreases from macrotidal (up to 8 m) at the mouth of the Amazon, where the large shallow continental shelf induces tidal amplification, to microtidal to low-mesotidal (ca. 1.8 to 3 m) along the rest of the coast. Little is known of inshore tidal current patterns. Shore-normal tidal currents along the Guianas coast can locally reach 0.45 m s^{-1} (Bourret et al., 2008). In addition to energetic forcing by near-resonant semi-diurnal tides and by large buoyancy flux from the Amazon River discharge, the shelf is also subject to stress from the northeasterly trade winds, resulting in strong along-shelf flow associated with the North Brazil Current (Geyer et al., 1996).

3. Mud-bank formation

The formation of distinct mud banks that migrate alongshore is a predominant geomorphological characteristic of the Amazon-influenced coast of South America. The formation of such discrete banks suggests periodic (order of several years) and localized mud concentration mechanisms that are still not well understood. Allison et al. (2000) have shown that mud banks originate in the vicinity of Cabo Cassipore, 350 km northwest of the mouth of the Amazon (Fig. 1). The volume of each mud bank can contain the equivalent of the annual mud supply of the Amazon (i.e., 750 to 800 × 10^6 tons). This, combined with the large number of mud banks migrating at any time, suggests that periodic bank formation is a multi-year process. Martinez et al. (2009) showed that half the annual mud load (51% on average over the period 1995–2007) is discharged between January and April, with little variability from year to year. These authors highlighted, however, more significant inter-annual variability in sediment discharge, in contrast to the relatively regular Amazon water discharge over the same period. There is a need for better correlation of regional river basin water and suspended-sediment discharge data, as have attempted, for instance, Gratiot et al. (2008) in their calculations of longshore mud budgets (see Section 6).

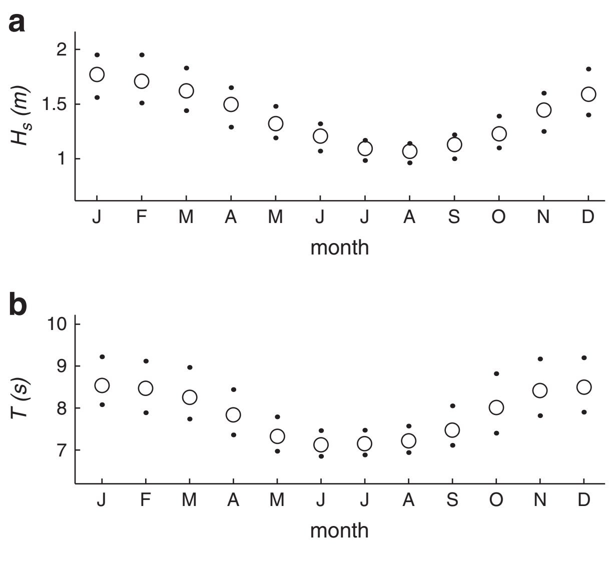

Fig. 5. Daily averages of wave-climate parameters concerning the Amazon-influenced coast of South America, H_s and T_s, derived from a 44-yr record (1960–2004) of the ERA-40 (European ReAnalysis) wave dataset generated by the European Centre for Medium-Range Weather Forecasts (ECMWF) for the location 5° N, 52° W. Dots correspond to the first and third inter-quartiles, and circles to the median values. From Gratiot et al. (2007).

Mud-bank formation is controlled by the physical oceanography of the continental shelf seaward of the mouth of the Amazon, which is an initial seafloor storage area for much of the suspended sediment discharged by the river (Trowbridge and Kineke, 1994; Geyer and Kineke, 1995; Kineke et al., 1996; Geyer et al., 2004). These authors have highlighted rapid and sustained fluid-mud concentration and trapping associated with fresh water–salt water interaction and front activity over the shoreface, a precursor condition for the formation of the mud banks. Specifically, estuarine circulation taking place on the shelf instead of within the river mouth (due to the enormous water discharge) generates rapid sediment deposition on the shelf in water depths of about 20–60 m. This sediment is then remobilized and transported shoreward and then alongshore by a complex combination of wave forcing, tidal currents, and wind-induced coastal currents. Nikiema et al. (2007) have shown, from coupling of a 3D hydrodynamic model with the bathymetry and the coastline, that a strong coastal current associated with the mesoscale North Brazil Current generates permanent northwestward extension of the sediment-charged Amazon plume, confirming earlier observations that attributed this net northwestward plume and ambient shelf water motion to a large-scale pressure gradient associated with this current system (Geyer et al., 1996). Relaxations of this current due to mesoscale changes in wind intensity, as hypothesised by Eisma et al. (1991), and subsequently by Allison et al. (2000), could be responsible for the periodic formation of mud banks. Mud concentrated in this frontal zone is then advected along the inner shelf west of the Amazon by waves and currents. Molleri et al. (2010) have shown from satellite images of seawater salinity that the northwestward flow of the Amazon plume occurs in a narrow coastal band from January to April, a period corresponding to the annual peak of both mud discharge (Martinez et al., 2009) and trade-wind and wave activity.

Allison et al. (2000) highlighted a zone of relative water-column mud 'deficit' close to the northwestern approaches of the mouth of the Amazon south of Cabo Cassipore (Fig. 1), and showed that the proto-mud banks started forming in the vicinity of this muddy 'cape'. In this equatorial setting, the extension of the Amazon muddy plume is little affected by the Coriolis force but is strongly modulated by the trade winds. This plume extension presumably leaves behind the mud-deficient zone between the mouth of the Amazon and Cabo Cassipore, where the estuarine front of the Amazon is deflected. Allison et al. (1995b, 1996) have suggested that up to 150 × 10^6 tons of mud (ca. 20% of the annual mud discharge monitored by Martinez et al. (2009)) may be stored in a year in the Cabo Cassipore area. Kuehl et al. (1996) identified periodic deposition and resuspension of seabed layers as much as a metre thick over most of the inner shelf, shoreface and foreshore north of Cabo Cassipore. The strata formed as a result of this process consisted of decimetre-thick mud beds separated by hiatal (scour) surfaces. These authors suggested that the volume of sediment resuspended seasonally from the inner shelf surface layer is of the same order of magnitude as the annual input from the river, indicating that resuspension is an important control on suspended-sediment distributions in shelf waters. Most resuspension from the inner shelf surface layer occurs during November–May, a period that includes both autumn swell wave active and high winter to early spring trade-wind stress. This resuspended sediment could contribute to shoreface accretion north of Cabo Cassipore (Kuehl et al., 1996), as well to the sourcing of the mobile mud belt.

4. Mud-bank morphosedimentary processes

Downdrift of the mouth of the Amazon, once mud banks are formed, the coastal sediment dynamics depend essentially on: (1) interactions between the associated mud (both suspended and settled) and trade-wind-generated waves, incident swell waves, wave-generated currents, and tidal currents; (2) interactions between the mud and the shoreline; and (3) *in situ* changes associated with physical intertidal processes (and biogeochemical changes briefly highlighted in Section 2.2 but not treated further in this paper), and with mangrove dynamics. Both field and remote-sensing approaches are progressively illuminating these fine-scale interactions, which involve wave-energy dampening, mud-bank liquefaction, cross-shore and alongshore mud advection, mud-bank consolidation, and mangrove colonization and removal.

4.1. Wave–mud interactions

The formation of fluid mud leads to significant and complex interactions between the bottom and waves that are still not well understood. Mehta (2002), Winterwerp et al. (2007) and Jaramillo et al. (2009) propose a sequence of events involved in the erosion of a visco-plastic muddy bed in response to increases in bottom stress initiated by wave forcing. Cyclic pressures induced by incoming waves start by generating small elastic deformations within the seabed. As these stresses exceed bed strength, internal failures commence, resulting in the inception of bed liquefaction, a process reported by these and other workers (e.g., De Wit and Kranenberg, 1997) to be very rapid, on the order of tens of seconds and up to a few minutes at most. These processes generate a fluid-mud layer and an increase in sediment concentration towards the shoreline. As additional waves come in, they generate internal waves at this liquefied mud–water interface and these are dissipated by internal friction within the mud layer. In reality, aspects of stress and liquefaction should depend on the intrinsic properties of the mud, its degree of consolidation, the wave climate, and water depth, as Rogers and Holland (2009) and Holland et al. (2009) have suggested from a combination of field measurements and modelling efforts of waves over a mud bed associated with the shoreface of the Patos Lagoon estuary in southern Brazil.

In the cross-shore dimension, waves maintain the fluid mud in suspension but wave heights decrease dramatically with distance shoreward due to energy dissipation. This important energy-dampening effect of thick mud beds on waves has been demonstrated by Wells (1983) and Wells and Kemp (1986), and confirmed on other muddy shorefaces, such as those of the Kerala coast of India (Mathew and Baba, 1995; Mathew et al., 1995; Jiang and Mehta, 1996; Tatavarti and Narayana, 2006; Narayana et al., 2008), and Louisiana (Sheremet and Stone, 2003; Jaramillo et al., 2009). Wells (1983) and Wells and Kemp (1986) measured a dissipation rate that grew from 88% to 96% for wave heights at three muddy shoreface locations off the Surinam coast. The water depths at this site decreased from about 7 to 3 m over a distance of about 7 km. These authors highlighted the rapid dissipation of both short and longer-period waves, although the latter underwent greater dampening. Sheremet and Stone (2003) compared wave dissipation rates over sandy and muddy portions of the Mississippi delta shoreface and observed wave heights 70% lower over the muddy bed, and attributed this to enhanced attenuation. They also noted that the dampening affected the entire wave frequency. Gratiot et al. (2007) suggested, from remote-sensing data and field observations, that waves over a French Guiana mud bank did not deviate significantly from the 2nd order Stokes theory up to about 5 m water depth (11–13 km off-shore), but were rapidly dampened at water depths less than 1 m (6–8 km offshore). This dampening effect (Fig. 6) has been shown in numerical wave models (Winterwerp et al., 2007; Rogers and Holland, 2009). van Ledden et al. (2009) showed, from a SWAN model analysis of a 3-day spate of high swell waves in Surinam, that while the mud banks significantly dampened the wave heights, they had almost no effect on the peak periods.

4.2. Cross-shore mud dynamics and mud-bank 'attachment' to the terrestrial shoreline

Observations carried out in French Guiana show that mud mobilization is particularly marked following long periods of low wave forcing (essentially during the dry season from July to October, Fig. 5) and during neap tides. Following such periods of low wave energy, even moderate-energy events, generally in autumn, can generate significant mobilization of mud (Gratiot et al., 2007). Periodic swell waves from the North Atlantic such as those reported by van Ledden et al. (2009) are expected to cause massive event-scale reworking of mud-bank sediments and of muddy inter-bank shores. The onshore arrival of fluid mud is, thus, generally hinged on such higher-energy pulses.

Under strong wave action, fluid-mud advection shoreward against gravity occurs by Stokes' drift (Gratiot et al., 2007; Winterwerp et al., 2007). It is expected that such advection is largely one of fluid-mud flow, as opposed to upward entrainment of sediment into the water column, because most of the sediment mass tends to spread near the bottom. Near the terrestrial part of a mud bank, fluid-mud pushed shoreward during the neap-to-spring cycle results in overall accretion and increase in bank elevation. Wave mobilization of mud has also been inferred from remotely-sensed estimates of suspended particulate matter using SPOT satellite imagery (Froidefond et al., 2004). From an 80-day record of bed-level and water-level changes in the intertidal zone of a mud bank near Cayenne monitored using an ultrasonic altimeter coupled with a pressure transducer, Gratiot et al. (2007) identified a sequence wherein a 1–3 m-thick mud layer liquefied by the cyclic wave pressure gradients is transported *en masse* shoreward by wave drift due to wave asymmetry. The mobilized mud layer formed a mud bar feature (see Figs. 3, 4) that was translated shoreward as gel-like fluid mud, especially when high waves prevailed.

Gratiot et al. (2007) further showed that the bars on South American mud banks are formed from gel-like fluid mud in the intertidal zone at locations where wave dampening is completed. Shore-normal tidal currents also probably contribute to shoreward mud transport. Once wave action ceases, the muddy profile may become more consolidated once again through gelling and under its own weight, but these processes, further discussed in Section 5, require days to weeks.

Linear shore-parallel bar accumulations are typical of wave-formed shore bodies, such as those commonly found in sandy beach environments (Anthony, 2009). The fundamental difference here, however, is that these muddy features, unlike non-cohesive sand grains, are formed from wave drift of cohesive gel-like mud that becomes progressively consolidated in areas of complete wave dissipation. Although these linear features generally occur as shore-parallel bodies in the inner mud-bank areas near the terrestrial shoreline, bar-like features with an angular offset relative to the terrestrial shoreline are observed at the eroding trailing edges of mud banks, where they are reworked by the obliquely incident northeasterly trade-wind waves (Fig. 3b). Successive bands of linear shore-parallel bars may reflect successive phases of wave-induced shoreward

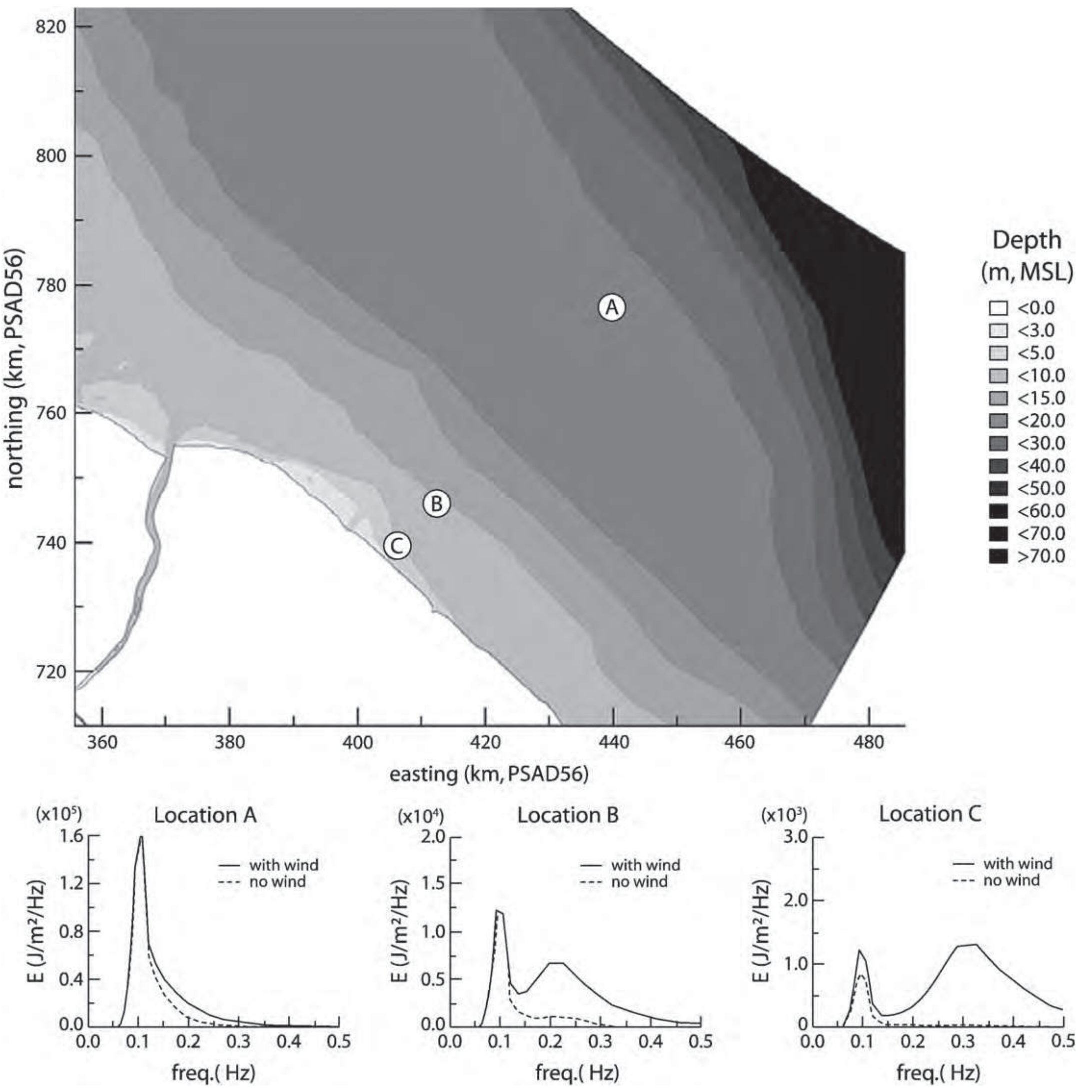

Fig. 6. Computed wave spectrum at three locations of the Amazon-influenced Demerara coast of Surinam showing progressive wave dampening shoreward over the muddy shoreface and changes in spectral frequency. From Winterwerp et al. (2007). Solid and dotted lines show, respectively, conditions with and without locally generated waves. Note the different scales.

transport of mud under seasonal variations in wave energy, in combination with neap-spring tidal range variations. The imprint of tidal range has been clearly highlighted by Gardel et al. (2009) from a 4-week-long time-lapse photographic monitoring experiment of a mud bar surface during the 2008 equinoctial spring tides. The effects of seasonal variations in sea level also need to be invoked, although data on these are lacking.

The physical oceanographic measurements carried out by Gratiot et al. (2007) support the suggestion by Allison and Lee (2004), based on radionuclides (^{7}Be, ^{137}Cs, and ^{210}Pb signatures) in sediment cores from inner (<5 m water depth) mud-bank areas, that wave-generated fluid-mud suspensions constitute the primary mechanism for delivering sediment across the intertidal zone of a mud bank, thus, enabling accretion at the shoreline. ^{210}Pb and ^{14}C geochronology of vibracores obtained by Allison and Lee (2004) from mudflats indicated rapid sediment accumulation (0.24–2.0 cm yr^{-1}) landward of the 2-m isobath, produced from a thick (50–150 cm) seasonal surface layer. These authors proposed a model in which the mud bank is disconnected from the shoreline, and sediment reaches the upper intertidal zone to generate shoreline accretion by fluid mud being driven onshore during periods of coastal setup and flood tide (Fig. 7). This differs from an earlier conception of the relationship between the mud bank and the shoreline in which the former is envisaged as a shore-welded feature (e.g., Augustinus et al., 1989).

4.3. Inter-bank zones

Inter-bank areas associated with deeper shoreface zones are subject to significant shoreline retreat over timescales on the order of years. In these areas, wave breaking occurs directly on the shore, and breaker heights increase as tidal range increases in the course of the neap-to-spring tidal excursion. An inter-bank shoreline is composed of either stiff mangrove-colonized consolidated mud that may be rapidly eroded (Fig. 8a,c) resulting in a flat, furrowed bed, or of sandy bodies that may be substantial enough to form coherent beaches and cheniers (see Section 7.2) commonly subject to over-wash. Both chenier-free and chenier-bound muddy shorelines are fronted by a shoreface of over-consolidated mud. On over-consolidated shoreline mud, the erosion process may result in the breakage and transport of large mud clasts yielding mud ‘pebbles’ away from the breaker zone.

The large-scale (1–5 km) plan shape of the shore in inter-bank areas may sometimes comprise rhythmic alternations of shoreline protuberances (megacusps) and embayments (Fig. 8b). The overall

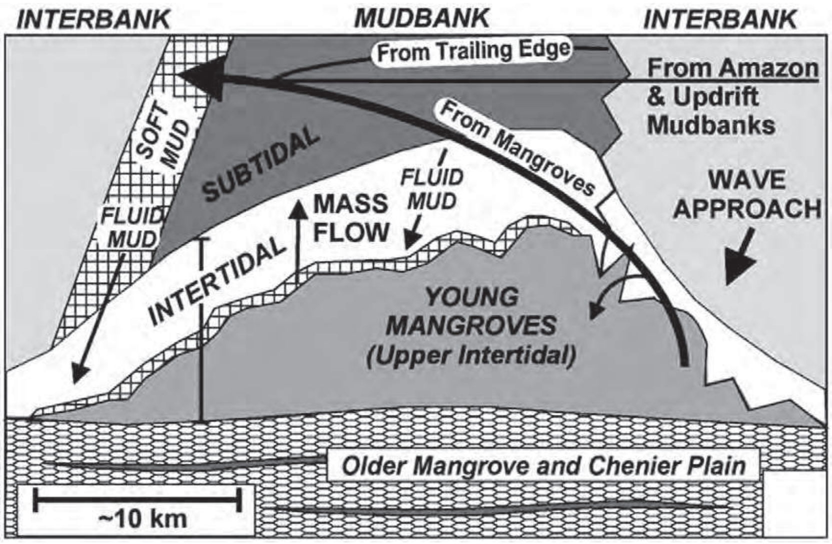

Fig. 7. Conceptual model of the dynamics of the inner part of a mud bank and its relationship with the terrestrial shoreline. From Allison and Lee (2004). In this model, which differs from earlier models, the mud bank is disconnected and sediment reaches the upper intertidal zone to generate shoreline accretion by fluid mud driven onshore during periods of coastal setup and flood tides. Some of this sediment may return offshore during ebb-tide fluid-mud transport and/or mass flows. Arrows reflect the relative magnitude of sediment supply to the leading-edge deposition on the inner mud bank. The largest quantity is derived from erosion of the trailing-edge mangrove fringe, with additional material coming from erosion of the trailing edge and inter-bank intertidal–subtidal surface, and from updrift mud banks and the Amazon River.

dynamics underlying these alternations of megacusps and bays are, however, not known (Lakhan and Pepper, 1997). We infer that their regular spacing alongshore precludes control related to differential consolidation levels of the mangrove-colonized substrate, as suggested by cusp horns associated with apparently resistant 'headlands' of mangrove. These features are probably the muddy equivalents of sandy beach megacusps and embayments associated with infragravity wave-energy cascades or with self-organised patterns of coastal morphology (e.g., Coco and Murray, 2007) that may develop from irregular initial alongshore variations in the resistance of over-consolidated shoreline mud.

5. Mud banks and mangrove dynamics

The mangrove-colonized shorelines of the Amazon-influenced coast of South America fluctuate at significant short-term (order of weeks to a few years) rates of several tens of metres to several kilometres in the cross-shore direction. The dynamic 'connection' of a mud bank with the shore commonly creates an intertidal mudflat of several square kilometres in a few months, with very dense mangrove development in a few years, followed by rapid erosion of mangroves and their substrate during the inter-bank phase. These processes have created one of the most extensive and most sedimentologically dynamic mangrove coasts in the world. The large mud supply also implies that *in situ* mangrove ecological dynamics are closely controlled by topographic changes brought about by mud redistribution. Smothering of pneumatophores and suffocation of older mangroves commonly occur, for instance, as a result of fresh mud inputs that are driven ashore from the bank (Fromard et al., 1998; Anthony et al., 2008).

Where the mud banks are in such dynamic 'contact' with the shore, it has been shown that their surfaces may be characterized by marked topographic heterogeneity (Anthony et al., 2008). On a typical mud-bank surface, the innermost bar features, variably dissected by drainage channels, form a dynamic 'suture' zone with the muddy intertidal terrestrial shoreline (Fig. 3). Fig. 3 shows, however, a clear difference between a lower intertidal zone (below mean water level (MWL)) characterized by relatively regular linear bar features, and an upper intertidal zone (above MWL) exhibiting an intricate topography of highs and lows associated with significant drainage channel activity. Such a complex mud-bank profile reflects a primary control by waves. Other closely related influences include topographic feedback on patterns of mud settling during the tidal excursion, consolidation processes due to evaporation and dewatering, dissection by intertidal drainage channels, and colonization by mangroves. The linear bar-like features are formed, as indicated in Section 4.2, from gradual accumulation of fluid mud inshore within a framework of predominantly tidal modulation of the vertical excursion of wave activity. These bars show marked cross-shore variations in the degree of consolidation (Fig. 9) that reflect three factors: (1) intertidal elevation; (2) trapping of fluid mud in depressions between the bars; and (3) mud remobilization and fluidization by wave activity. Once in the upper intertidal zone, the bars become immobilized over fairly long phases of low wave energy, and, thus, progressively dry out. This involves changes in physical parameters, notably yield stress and pore-water salinity because of evaporation and dewatering (Fiot and Gratiot, 2006; Gardel et al., 2009).

Field measurements and remote-sensing observations suggest that the bars have a feedback influence on subsequent patterns of fluid-mud accumulation and channel development (Anthony et al., 2008). In the course of the tidal excursion, the troughs isolated by these bars are seen to trap high concentrations of suspended mud that progressively consolidates, protected from direct wave remobilization. The observations lead us to infer that mud remobilization can lead to marked spatial variability in fluid-mud concentration levels that are especially well expressed by bars in the lower intertidal zone still subject to onshore mobility. The channels dissecting these bars (Fig. 3) serve as drainage networks for ebbing tides, for water yielded from dewatering of the fluid mud as it becomes consolidated, and for rainfall. The combination of such drainage networks and variations in fluid-mud consolidation can generate decimetre-scale variations in the elevation of the mud bank at any given time, while channel dissection results in the substitution of the linear bar forms in the upper intertidal zone by more complex topography. There is a need, however, for quantification of the sediment transport processes operating over these bars.

In the upper intertidal zone, rapid drying and compaction are associated with the development of mud cracks and diatom biofilms (Fig. 10), typically during neap tides. Wetting and drying cycles have been shown to vary considerably with elevation (Fiot and Gratiot,

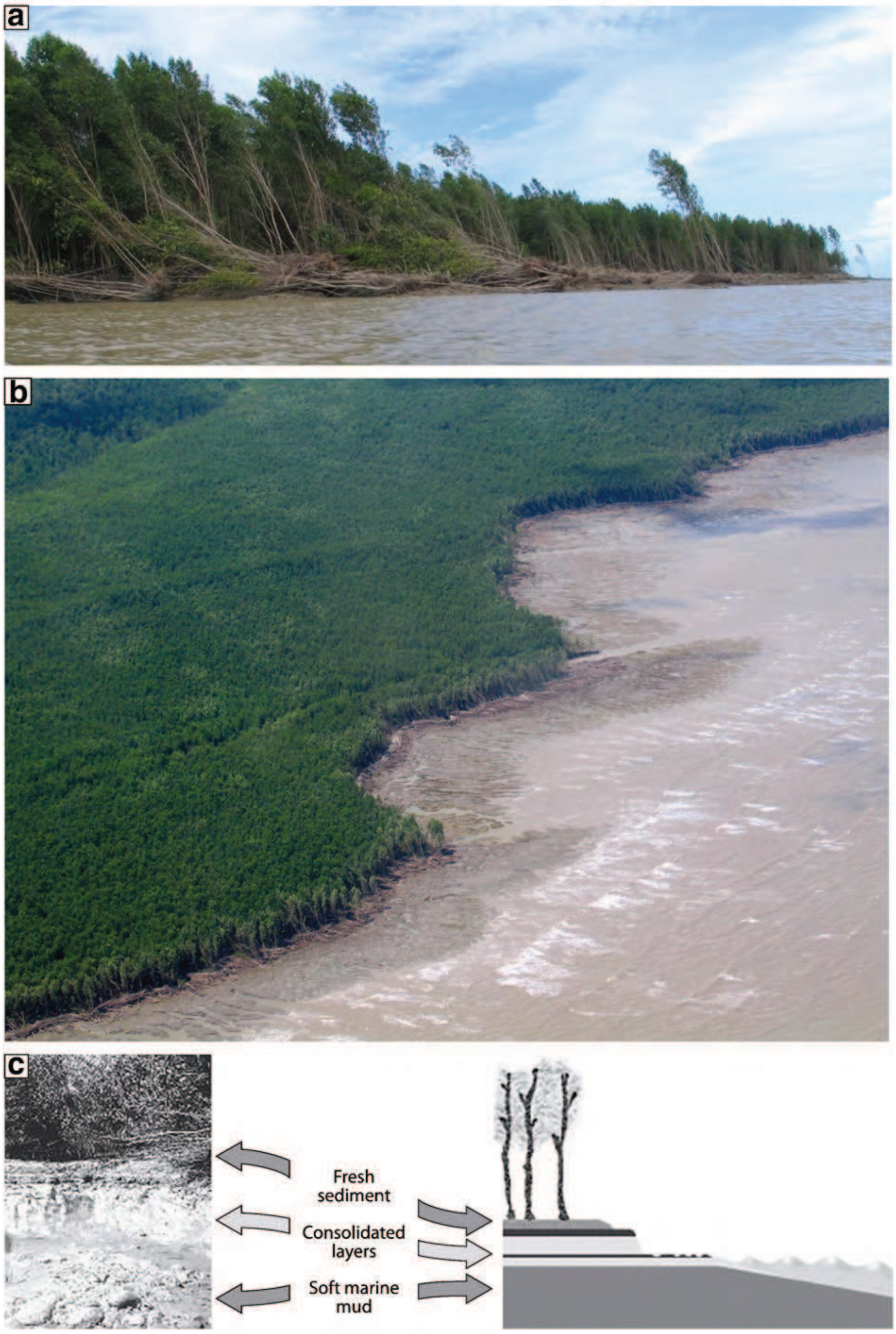

Fig. 8. (a) Large-scale shore erosion and mangrove destruction during an inter-bank phase; (b) alternations of megacusps and embayments associated with large-scale coastal erosion; (c) substrate layering pattern following the erosion and retreat of a consolidated muddy mangrove substrate. Fresh mud may be deposited over the marsh surface but net retreat leads to scarping and the formation of mud pebbles that are visible above the freshly deposited mud; (c) from Lefebvre et al. (2004).

2006). Changes in physical parameters, such as sediment erodibility, water loss and pore-water salinity, indicated progressive mudflat compaction as well as fluctuations related to the successive wetting and drying cycles (Fiot and Gratiot, 2006). Mud cracks are features that reflect the effects of contractional stresses (Yesiller et al., 2000). Mud cracks observed by Fiot and Gratiot (2006) were apparently ephemeral features that (re)opened after a few days of dewatering and (re)healed during the subsequent wetting. Gardel et al. (2009) showed through a field experiment that included time-lapse photography, high-resolution topographic monitoring, collection of meteorological data and measurements of the water contents of the upper 30 cm of a mud bar, that consolidation of mud and mud-crack development were mainly controlled by elevation. Water loss occurred by drainage, modulated by the local tidal signal, with weather conditions (notably temperature changes, and eventual wetting by rainfall) playing a secondary role.

Desiccation cracks can enable the trapping of floating propagules of the mangrove *Avicennia germinans* as tides ebb (Proisy et al., 2009). Mangrove seedling establishment has been observed to be particularly dependent on topographic changes, with very subtle elevation changes in the upper intertidal zone (order of a few centimetres) having a strong influence on successful colonization (Fiot and Gratiot, 2006; Proisy et al., 2009). Under favourable elevation conditions, mangrove colonization rapidly ensues with plant densities exceeding

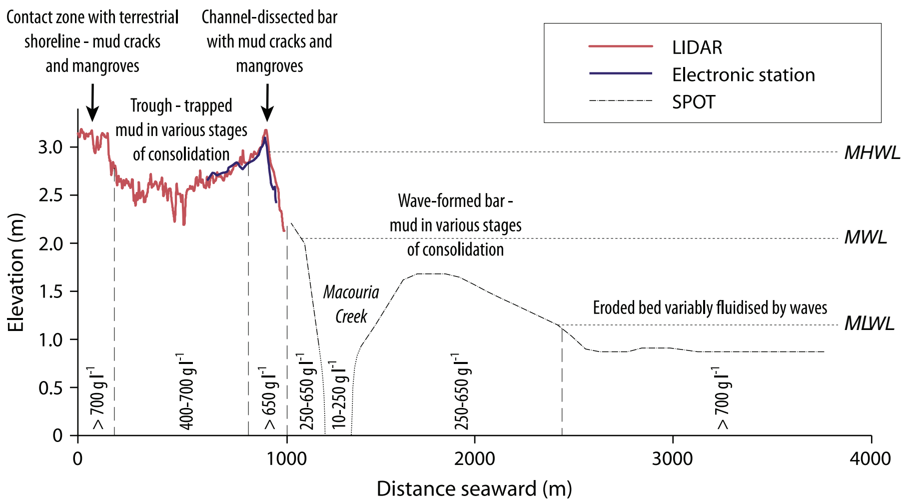

Fig. 9. Cross-shore profile across the Macouria mud-bank surface, compiled from the three methods depicted in Fig. 4, synthesizing patterns of mud consolidation and mangrove colonization. Levels of consolidation are derived from field observations in the light of both published data (Fiot and Gratiot, 2006) and unpublished data provided by Sandric Lesourd. Variations in relative mud consolidation in the lower intertidal zone (below MWL) reflect the preponderant role of wave remobilization and fluidization, while consolidation and mud concentration levels in the upper intertidal zone (above MWL) reflect both trapping of mud spilling over into troughs and depressions and *in situ* drying out and consolidation processes. From Anthony et al. (2008).

30/m². Once colonization commences (Fig. 10), extremely rapid mangrove growth (rates up to 2 m yr^{-1}) leads to the establishment of a fringe of young mangroves and mud stabilization (Fig. 11).

Although large waves are expected to account for high rates of mud liquefaction and mobilization, Gardel and Gratiot (2005) showed that such waves might not necessarily have a destructive impact on mangroves. Their analysis of shoreline changes in French Guiana over the period 1995–2000, characterized by high wave energy, showed that mangroves in inter-bank areas underwent very active retreat (150 to 200 m yr^{-1}), but at the same time the mud-bank areas experienced mangrove colonization. This embodies an apparent contradiction, because intense wave forcing should lead to strong mud-bank mobilization. Possible explanations are: (1) the active remobilization of mud by more energetic waves and its shoreward migration towards the upper intertidal zone where mangrove colonization occurs; and (2) variations in wave-energy dissipation hinged on wave period. With cessation of wave forcing, remobilized mud forms bars that are the primary substrate for pioneer mangrove formation. Since wave attenuation is frequency-dependent, wave spectra are significantly distorted, as Jiang and Mehta (1996) showed

Fig. 10. Mud cracks and a diatom film on a mud bank in French Guiana.

Fig. 11. Rapid colonization by opportunistic *Avicennia germinans* mangroves of fresh mud translated across-shore during the onset of a bank phase in French Guiana. This freshly translated mud will progressively stifle the older mangroves in the background.

from field measurements on the seasonal shore-attached mud banks of Kerala (India), and Winterwerp et al. (2007) in Surinam (Fig. 6). Thus, it is likely that swell energy is almost entirely expended on the mobilization of mud bars while short waves propagate to the coast with a significant impact on inter-bank mangroves (Gardel and Gratiot, 2005).

Reworking of the topographic highs inherited from the linear bars by high-energy waves will likely affect mud dispersal over the adjacent terrestrial mangrove substrates. Mud moved shoreward and impinging on established mangrove swamps can lead to burial and asphyxia of mangrove pneumatophores, resulting in the death of 'old' mangrove trees (Fromard et al., 1998, 2004). Adjacent to these areas are often found opportunistic rapid-growth juveniles (Fig. 11) adapted to the new substrate topography (Anthony et al., 2008). The relaxation of wave activity during the low wave-energy season enables the subsequent survival of the young pioneer mangroves. On the seaward part of the nearshore profile in the subtidal and lower intertidal zones, wave reworking leaves behind a flat furrowed mud-bank surface that will eventually be completely eroded as the narrow trailing edge of the mud bank recedes towards this contact zone.

6. Mud-bank migration and medium-term (order of years) shoreline dynamics

Wave liquefaction of mud includes a longshore component that is fundamental to mud-bank migration. Following Wells and Coleman (1978, 1981a), a number of theoretical efforts and a few field investigations on this and other mud-affected coasts have suggested a leading role for wind-generated waves in this process (Jiang and Mehta, 1996; Rodriguez and Mehta, 1998, 2001; Chevalier et al., 2004; Tatavarti and Narayana, 2006; Gratiot et al., 2007; Chevalier et al., 2008). A 44-yr record (1960–2004) of the ERA-40 wave dataset (see also Fig. 5) was used by Gratiot et al. (2007), together with complementary field investigations in French Guiana, to define both event-scale and longer-term patterns of mud-bank migration. Following the work of Rodriguez and Mehta (1998), these authors singled out the ratio H_0^3/T^2, combining wave height (H) and period (T), and the angle of wave incidence (α), as the most relevant parameters for describing wave forcing. Gratiot et al. (2007) showed that notable phases of increased wave energy were accompanied by higher annual rates of longshore mud-bank migration (Fig. 12), but that the correlation was rather poor between the wave forcing parameter H_0^3/T^2 and migration rates because of the contribution of other mechanisms to bank migration. These are discussed next.

Mud-bank migration rates can vary significantly both alongshore and in time, reflecting variability in bank and inter-bank dynamics. The banks in French Guiana exhibited low multi-annually averaged migration rates (0.2–1.8 km yr^{-1}) in the early 1980s and high rates (1.8–3.0 km yr^{-1}) from the mid-1990s to 2005 (Gardel and Gratiot, 2005). The mean mud-bank migration rate from 1995 to 2000 was twice that from 1979 to 1984, for instance, even though the wave forcing parameter, H_0^3/T^2, identified by Gratiot et al. (2007) from the 44-yr record of the ERA-40 wave dataset was only 33% higher. Temporal changes in H_0^3/T^2 aside, there are several potential reasons for these variations. These include unknown sediment sourcing aspects such as variations in mud supply from the Amazon and fluctuations in the temporal frame of mud-bank formation. Changes in the intensity and direction of the trade winds and their effects on waves have been held responsible for temporal variability in mud-bank migration rates (Eisma et al., 1991; Allison et al., 1995a, 2000). Eisma et al. (1991) used the angle of incidence of winds as a surrogate for assessing temporal variations in the intensity of wave-generated longshore drift, and, hence, mud-bank migration rates. This approach was further used by Augustinus (2004) to explain changes in the rates of mud-bank migration and the lengthening of mud banks in Surinam. Augustinus (2004) suggested that a more oblique orientation of

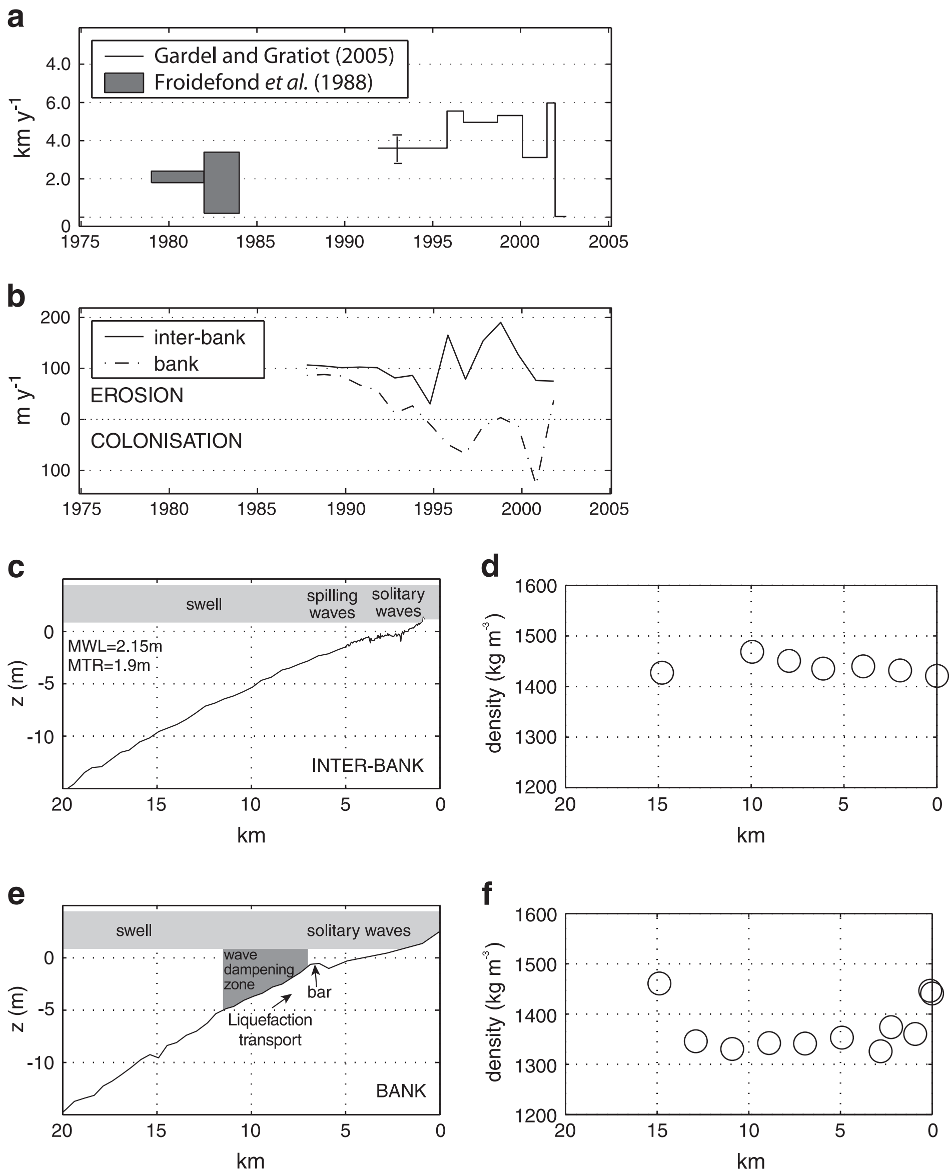

Fig. 12. Mud-bank migration rates and wave dynamics in French Guiana. From Gratiot et al. (2007): (a) longshore mud-bank migration rates between Cayenne and Kourou (Fig. 1), from 1979 to 1983 (based on aerial photographic interpretations by Froidefond et al. (1988)), and from 1992 to 2002 (based on satellite image interpretation by Gardel and Gratiot (2004, 2005)); (b) bank and inter-bank mangrove shoreline evolution trends between Cayenne and Kourou from 1988 to 2002 (based on satellite image interpretation by Gardel and Gratiot (2005)); (c), (d) inter-bank and mud-bank profiles and schematic wave attenuation patterns. MWL is the mean water level and MTR the mean tidal range deduced from tidal signal series; (e), (f) associated sediment surface concentration profiles; the circle diameter is representative of the vertical error bar.

incident waves along the Surinam coast, related to a change in the angle of the coast itself, compared to the French Guiana coast, explained the larger mud-bank migration rates, and longer but less wide mud banks (due to alongshore 'stretching') on this coast. It may be inferred from these observations that differences in migration rates may also account in part for variations in the spacing between the banks. Temporal variations may also be generated by changes in distant storm tracks and intensity patterns in the North Atlantic, such as those associated with the North Atlantic Oscillation and El Niño and La Niña events.

Another set of factors involves local irregularities in the alongshore mud-bank migration corridor such as island and nearshore bedrock outcrops and rocky headlands in French Guiana that trap mud (Anthony and Dolique, 2004). River mouths and river discharge patterns have also been invoked as sources of migration-rate variability (Gardel and Gratiot, 2005). Closely related to this set of factors is the plan shape of the coast itself, which, in inter-bank areas, may comprise the aforementioned megacusp-like alternations (Fig. 8b) that should affect wave-drift gradients alongshore. Another source of variability is the response of mud-bank rheology to wave stress. The rheological behaviour of the mud shows a strongly non-linear and thixotropic response to wave stress (Fiot and Gratiot, 2006). Beyond a threshold forcing, the apparent mud viscosity decreases considerably, and this could, in turn, strongly affect mud-bank migration rates. Variability in mud-bank migration rates must also be induced by a combination of other forcing mechanisms, notably geostrophic forcing associated with the North Brazil Current (Nikiema et al., 2007), tidal currents propagating northwestwards (Bourret et al., 2008), density currents due to the Amazon fresh water plume, the effect of impinging wind stress on the shore and the generation of compensatory northwestward flows due to north to northeasterly winds during the active trade-wind season. Currents generated by wind stress would depend not only on wind velocities and incidence relative to the coast but also on shoreline morphology. These ancillary sources of hydrodynamic forcing provide scope for future studies.

Evidence, for instance, for an overprint of the 18.6 yr nodal tidal cycle on bank migration rates and attendant changes in shoreline dynamics has been presented by Gratiot et al. (2008). The demonstration by Gratiot et al. (2008) concerned, in particular, the shoreline of French Guiana, and is based on 60 satellite images covering 39 dates from October 20, 1986 to January 15, 2006. A 'typical' stretch of coast was analysed by Gratiot et al. (2008), and consisted of five alternating regions of mangrove colonization (bank areas) and erosion (inter-bank areas) each 30–40 km-long. These areas shifted northwestward and formed the fingerprints of mud banks migrating from Brazil to Surinam (at rates of 1–3 km yr^{-1}). Gratiot et al. (2008) calculated from computation of topography from SPOT satellite images variations in sediment balance that reflected this cyclic behaviour. Over the period 1988–1999, the coastal sediment balance had a deficit of approximately 37×10^6 tons yr^{-1}, resulting in shoreline retreat. The trend has reversed since 2000, with an estimated excess of 35×10^6 tons yr^{-1} of shoreline sediment. These patterns were similar to those observed in neighbouring Surinam from 1966 to 1970 (Augustinus, 1978). The calculations carried out by Gratiot et al. (2008) showed that time slices of erosion and progradation initially identified by Choubert and Boyé (1959) appear to correlate with the 18.6 yr nodal cycle. These results emphasise the plausibility of the hypothesis proposed by Wells and Coleman (1981b) on the role of this cycle in generating periodic phases of higher high-tide water levels. Such higher water levels are not only favourable to more efficient wave-energy incidence and erosion of this muddy coast, but may also impact the capacity of mangroves in colonizing higher parts of the mud banks by diminishing bank-surface exposure to desiccation and the resulting development of mud cracks that favour such colonization (see Section 5).

7. Mud banks and sand bodies

The Amazon-influenced coast receives variable amounts of sand and mud from the local rivers west of the Amazon that drain the Quaternary coastal-plain and adjacent crystalline Guiana Shield. On this mud-dominated coast, sand is an important economical and ecological component because sandy deposits provide locations for human settlement. The rare beaches on this part of the South American coast are also fundamental for the ecology of protected leatherback turtles (*Lepidochelys olivacea*, *Chelonia mydas*, *Eretmochelys imbricata*, *Dermochelys coriacea*). These species require mud-free sandy beaches that are not subject to overwash by waves or tides for successful nesting (Kelle et al., 2007; Caut et al., 2010). Beach overwash and mud and organic matter have been shown by these authors to have damaging effects on leatherback turtle nesting.

The limited presence of sand bodies on this coast reflects the diluting influence of the enormous mud supply from the Amazon during the Quaternary and the limited sediment yield from the local, well-forested drainage basins despite high rainfall. Blanketing of relict fluvial sand by the cover of Amazon mud on the inner shelf has been deemed to preclude shoreward sand reworking to form the beach and barrier systems typical of sand-rich wave-dominated shorefaces (Anthony and Dolique, 2004). Pujos et al. (2000) concluded from analyses of the heavy-mineral assemblages of the quartz-dominated beach sands in French Guiana that these sands are derived exclusively from local sources and not winnowed out from the migrating Amazon mud banks. Coherent sand bodies present on the Amazon-influenced shores are rare. They are either bedrock-bound embayed beaches, notably in the vicinity of Cayenne (Fig. 1), in French Guiana, or, much more commonly, cheniers (Augustinus et al., 1989; Daniel, 1989; Prost, 1989). Cheniers can form significant linear features, and are generally found in eroding, inter-bank areas. In places, they are incorporated in the prograded muddy coastal plain either as individual strands or as bands of cheniers.

7.1. Mud-bank influence on embayed bedrock headland-bound sandy beaches

The only noteworthy sector where bedrock headlands indent the muddy Amazon-Guianas coast is the 15 km-long coast of Cayenne. A 500 m-long stretch of bedrock coast also occurs in Kourou, 35 km west of Cayenne, both in French Guiana (Fig. 1). The Cayenne sector differs from the rest of this fluctuating alluvial coast in that it comprises several headland-bound fringing sandy beaches rather than cheniers. Sandy sedimentation on the Cayenne promontory has been limited, notwithstanding the fact that the bedrock embayments offer accommodation space for potentially significant sandy barrier progradation. The limited progradation of these barriers is probably due to the aforementioned sequestering of sand by the pervasive mud on the shoreface and to the highly protruding nature of the Cayenne promontory relative to the regional-scale mud-bank transport system on the inner shoreface. This embayed bedrock coast differs, thus, in this regard from other swell or trade-wind wave-dominated embayment-rich tropical and mid-latitude coasts, such as the southeastern coast of Australia (Thom, 1984) and the coasts of Brazil (Dominguez et al., 1992) and West Africa (Anthony, 1995), where sandy barrier progradation, commonly involving multiple beach ridges, has been important. The evidence from remote-sensing and field observations suggests that the headland-bound beaches and their associated narrow barrier accumulations in Cayenne have balanced long-term sand budgets. These beaches appear to have been sourced by sand supplied by the local rivers near Cayenne, as suggested by their rich heavy-mineral contents, and winnowed out by waves from ambient mud during ancestral inter-bank phases.

Alternations between mud-bank phases and mud-poor inter-bank phases result in marked spatial and temporal variations in beach dynamics and morphology. The chief effect of the mud banks is to induce periodic alternations in longshore drift that lead to a form of beach 'rotation', which is the periodic lateral movement of sand towards alternating ends of an embayed beach (Anthony et al., 2002; Anthony and Dolique, 2004). Rotation of French Guiana beaches does not result from seasonal variations in deepwater wave approach directions, as is generally reported for rotating beaches not affected by mud banks (e.g., Ranasinghe et al., 2004; Short and Trembanis, 2004) or beaches subject to seasonal or episodic mud supply (e.g., Klein et al., 2002; Aubry et al., 2009; Calliari et al., 2009; Tamura et al., 2010). In French Guiana, beach rotation is due to short to medium-term (order of a few years) changes in nearshore bathymetry induced by the migrating mud banks. These bathymetric changes affect wave refraction and dissipation patterns, inducing strong longshore gradients in waves. These strong wave-energy gradients along sections of the shore facing the leading or trailing edges of the mud banks generate lateral movement of sand in these headland-bound beaches, resulting in alternations of erosion and accretion areas over time (Fig. 13a) These beach morphological changes have been defined in terms of a simple, four-stage conceptual model comprising bank, inter-bank and transitional phases. Anthony and Dolique (2004, 2006) showed that dramatic short-term beach profile oscillations of up to 100 m in two to three years (Fig. 13b) are strongly embedded in the large-scale mud-bank bathymetry-forced rotational process, although smaller-scale self-organised behaviour may be involved in bedform arrangements along the beach. Similar changes in hydrodynamic parameters with marked consequences on sandy beach morphodynamics have recently been documented from field studies on the periodically mud-fast Cassino beach adjacent to the Patos estuary (Calliari et al., 2009; Holland et al., 2009; Rogers and Holland, 2009).

Mud welding onto the headland-bound sandy beaches of the Cayenne area may sequester sand eroded from these beaches. In such bank phases, mud directly welds onto the beaches for periods ranging from months to years, leading to a rare example where ocean-facing

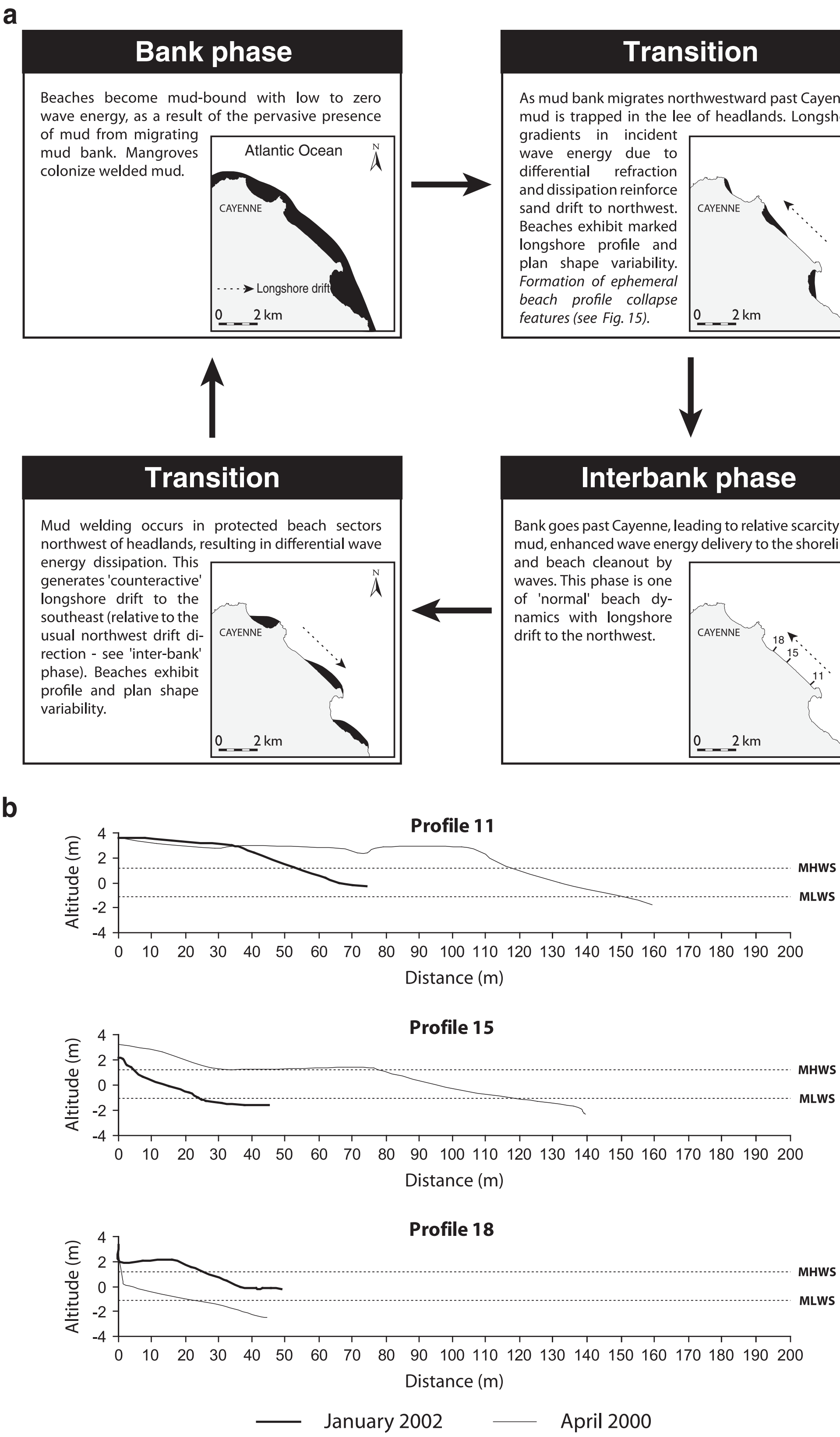

Fig. 13. (a) A four-phase model of sandy beach morphological change involving rotation in response to Amazon mud-bank activity in Cayenne, French Guiana. Modified, from Anthony and Dolique, 2006, with permission from John Wiley and Sons. The cycle comprises a bank, an inter-bank and two transitional phases, as a typical mud bank attains and migrates past the Cayenne headland. The transitional phase between bank and inter-bank phases shows the most rapid (days to months) and most spectacular beach changes because the natural longshore drift (from southeast to northwest) generated by trade-wind waves on this coast is reinforced by longshore gradients in wave height due to inshore dissipation by mud trapped by northwestern headlands. This occurs as the trailing edge of a mud bank goes past each headland-bound beach in Cayenne; (b) An example of the dramatic variations in the width of a sandy beach (Montjoly beach) subject to rotation induced by changes in wave parameters due to the impingement of a mud bank in Cayenne (from Anthony and Dolique, 2004). The profile locations are shown in the inter-bank panel in (a). The changes cover a period of 21 months.

beaches are completely incorporated into a temporarily prograded intertidal to shoreface muddy system. At the height of the bank phase, the muddy shores fronting the beaches become rapidly colonized by mangrove forests, sometimes over cross-shore distances of several hundreds of metres to several kilometres (Anthony and Dolique, 2006). Subsequent mud erosion and mangrove forest destruction by the return of waves during inter-bank phases leads to the resumption of normal beach dynamics. This involves the restitution to the beach sand budget, of sand sequestered in the previous bank phase within shoreface mud deposits. Observations suggest that beach rotation does not affect the medium-term (order of tens of years) beach sand budgets. If illegal sand extractions to satisfy a growing building industry in Cayenne continue to go unchecked, they will impact these budgets. Beach rotation has been shown to be absent in very short (<150 m-long) pocket beaches on this muddy coast, because long-shore gradients in sand transport do not develop (Dolique and Anthony, 2005). In these pocket beaches, profile oscillations are, thus, basically seasonal, and involve cross-shore sand mobility during wave-dominated inter-bank phases, but the profile becomes muted during mud-dominated bank phases.

7.2. Cheniers

Where sand is locally available, and is concentrated by waves, inter-bank areas may be characterized by the active formation of cheniers (Fig. 14). Such sand may also be released by the erosion of older cheniers incorporated in the prograded coastal plain. In the Amapà area of Brazil, at the approaches to the mouth of the Amazon, mud-bank formation is rather incipient (see Section 2), and minor amounts of sand supplied by the various small coastal rivers and/or winnowed out from mud are preferentially transported landward onto the mangrove fringe, producing very fine-grained (10–12 φ mean grain size) accumulations (Allison et al., 1995b; Allison and Nittrouer, 1998). These authors showed that sand bodies supplied by the local rivers in this area are composed of flaser beds, cross beds and massive beds, are up to 5 m-thick, and overlie an erosional mud shoreface. Due to the spatial pattern of mud-bank formation, which starts in the Cabo Cassipore area, these sand beaches form permanent features of the shoreline in this relatively mud-starved zone. Down-drift of this zone, there appears to be a clear gradient in the degree of chenier formation between the Brazil and French Guiana sectors on the one hand, and the Surinam sector on the other. In the former, current chenier formation and fossil cheniers within the prograded muddy plain are relatively rare, while more active chenier formation has prevailed in the latter sector, resulting in the incorporation of numerous bands of cheniers in the prograded Holocene coastal plain (Fig. 14a). This alongshore gradient probably reflects the sand-supply influence of the much larger-sized rivers debouching from the granitic catchments of Surinam compared to the smaller sand-supply rivers in Brazil and French Guiana.

Chenier development occurs through the concentration of sand by waves that are much less dissipated in inter-bank areas (Augustinus, 1978). Chenier-forming processes are limited to high-tide phases, when wave-energy dissipation is less. The process is strongly dominated by sand overwash over muddy, eroded, and commonly organic-rich, substrates (Fig. 14b,c). Where the shoreline exhibits a megacuspate morphology, as outlined in Section 4.3, cheniers are generally formed within the bays between consolidated and temporarily resistant muddy cuspate projections.

7.3. Sand–mud interactions and sand deformation structures

Notwithstanding the overwhelming influence of mud in the dynamics and evolution of the Amazon-influenced coast of South America, the local presence of sand offers sediment heterogeneity, and, therefore, marked divergence in coastal morphodynamics, a theme that has recently been highlighted by Holland and Elmore (2008). Sand concentration over muddy substrates has been observed to lead to the development of unique, but ephemeral, beach deformation and collapse features (Anthony and Dolique, 2006). These features (Fig. 15a) appear to be part of the process of sand accumulation and adjustment to the underlying muddy substrate. Although their development is hinged on the marked sedimentological and geotechnical differences between the sand and mud, their

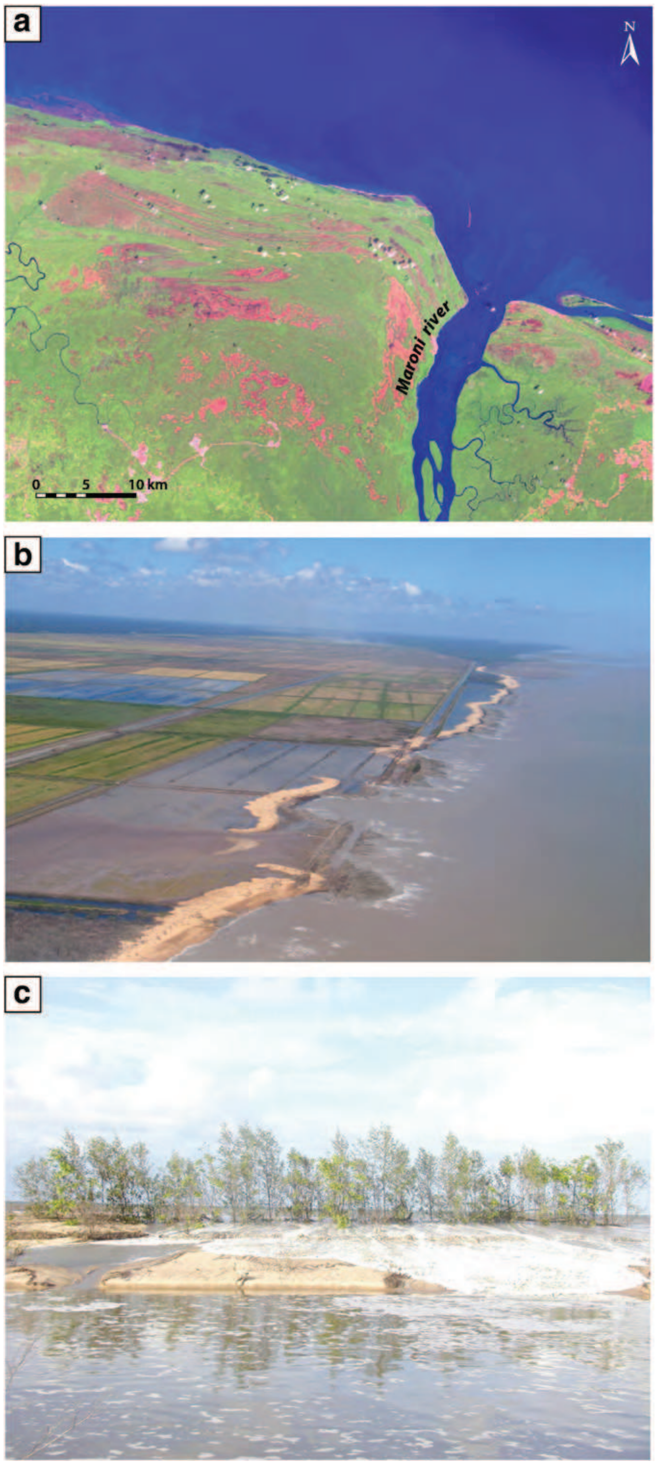

Fig. 14. (a) ENVISAT image (2008) showing significant bands of linear cheniers on the prograded Holocene muddy plain of Surinam; (b) oblique air photograph depicting discrete sandy cheniers migrating shoreward over a muddy substrate comprising eroding rice fields in western French Guiana; (c) ground photographs showing wave overwash at the back of a chenier.

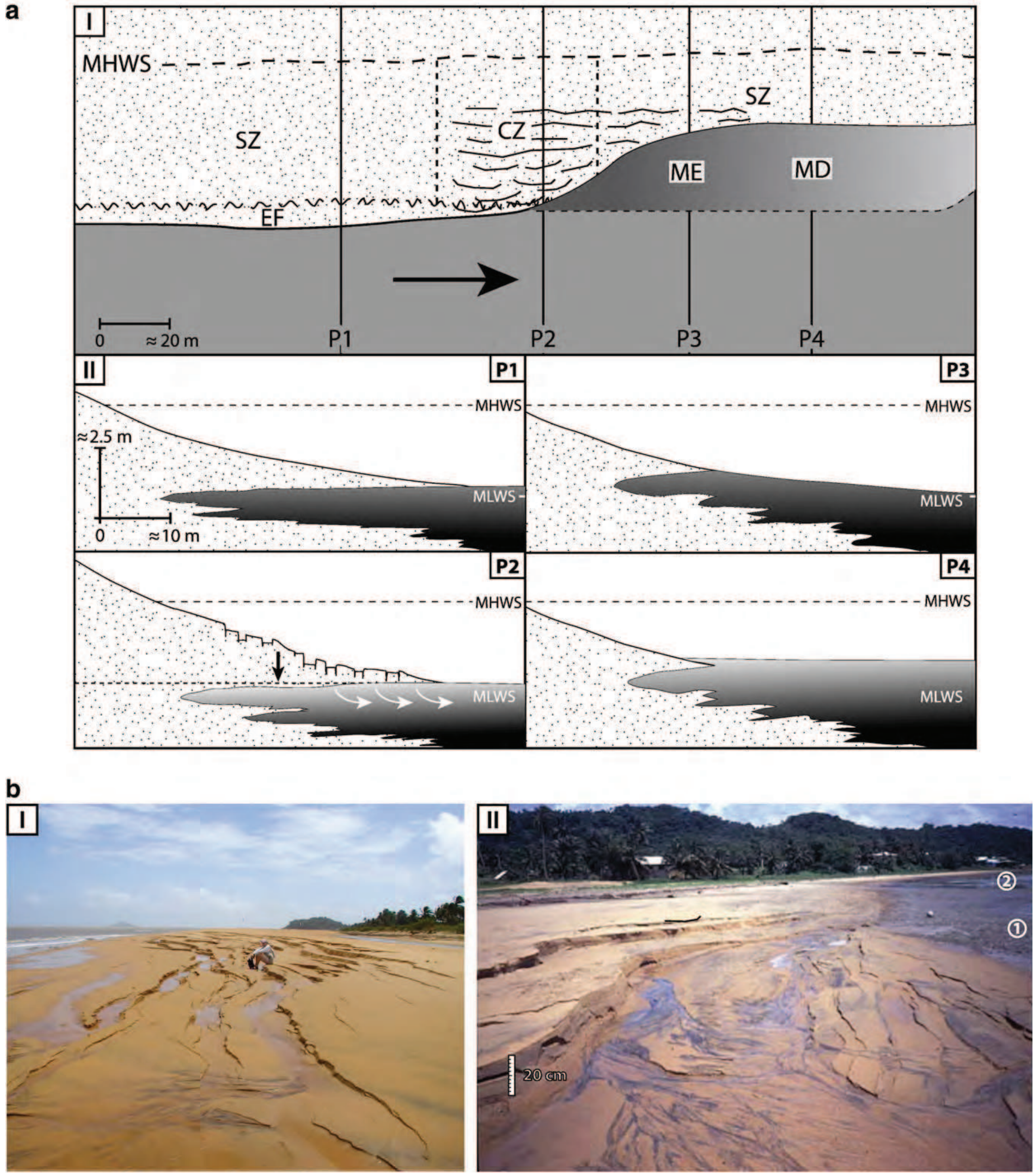

Fig. 15. Beach collapse features due to subsidence of mud underlying a cover of sand in French Guiana. Modified, from Anthony and Dolique (2006), with permission from John Wiley and Sons. (a) Schematic representation of stages of profile subsidence and the formation of collapse features. (I) Plan view: SZ = stable updrift and downdrift beach zones; CZ = profile collapse zone; ME = mud erosion; MD = mud deposition. The profile collapse zone progressively shifts downdrift (arrow) with longshore sand transport, from a high (to the left of panel) to a low wave-energy zone (to the right of panel). (II) Schematic profiles of the various zones shown in (a). Small black vertical and white horizontal arrows in P2 (collapse zone) indicate subsidence and mud dewatering respectively. MHWS: Mean high water spring tide level; MLWS: Mean low water spring tide level. Note the inferred variations in the level of the mud surface (higher mud surface in low-energy P3 area of fresh mud accumulation — light and dark shadings of mud in profile P3 represent, respectively freshly mobilized mud accumulating further downdrift in the MD zone, over older settled mud). Scales are approximate; (b) ground photographs showing collapse features. The collapse zone is preceded by a typical mud-erosion zone, the eroded mud accumulating further downdrift. Circled numbers 1 and 2 on photo II refer, respectively, to settled mud (density up to 1000 kg m^{-3}) undergoing erosion, and to freshly accumulating fluid mud (density: 350–600 kg m^{-3}) derived from updrift erosion.

formation is not due to hydraulic processes at the sand–mud interface, such as sand piping or undermining, nor to collapse of void space such as from encapsulated air within the sand body, since chenier and beach sands are often well packed. The linear nature of the cracks in the sand and their strong development alongshore for tens of metres in the mid- to lower beach zones on both beaches and cheniers and in this muddy environment are most likely explained by hydraulically-driven adjustment of the underlying mud to sand loading (Fig. 15b). Adjustment of the beach profile to sand loading in the intertidal zone occurs through mud dewatering related to evaporation at low tide, when large areas of the foreshore are exposed, and to compaction of the underlying mud. These two processes generate accommodation space into which the overlying sand above the water exfiltration zone responds by forming subsiding packages of non-saturated sand delimited by cracks alongshore (Anthony and Dolique, 2006). Piping processes are, however, well developed in the water exfiltration zone on the lower beach, and commonly generate additional deformation of the observed vertical collapse walls.

8. Discussion

8.1. The mud-bank–inter-bank cycle and overall coastal-plain progradation

The development of the shoreface and of the coastal plain between the Amazon and the Orinoco Rivers reflects both the high mud supply from the single Amazon source and a specific set of favourable oceanographic conditions prevailing on the shelf at the mouth of the Amazon and along the 1500 km-long coast of the Guianas. The high mud supply and the formation of an estuarine frontal zone associated with fresh water–salt water interaction over the shoreface lead to seafloor storage of much of the suspended sediment discharged by the river, forming fluid-mud concentrations that are the precursors of mud banks. A complex combination of wave and tidal forcing and a pressure gradient set up by impinging onshore trade winds leads to fluid-mud concentration in the Cabo Cassipore area of Brazil where mud banks start forming, before migrating along the coasts of the Guianas.

Mud-bank migration involves spatio-temporal alternations of bank and inter-bank phases that imply periodic wave recycling (at timescales of the order of years along any given stretch of shoreline) of muddy sediments and their relatively minor component of chenier sands. Each inter-bank phase results in the partial, or rarely, total removal, of the coastal stratigraphic package (Fig. 16). Total removal of the stratigraphic package deposited during a bank phase can occur during a subsequent inter-bank phase characterized by particularly high wave-energy seasons such as during El Niño years (Gratiot et al., 2008). More commonly, removal is partial, signifying that there is a net coastal-plain growth with each cycle (Allison and Lee, 2004). Where sand has been locally available or concentrated by wave action, individual cheniers, or bands of cheniers in sand-rich contexts, have been incorporated into the prograded coastal plain. The only exceptions to this progradational context are in the Cayenne and Kourou areas in French Guiana where highly projecting bedrock headlands with embayed beaches still prevail, and where mud-bank–inter-bank cycles have not resulted in coastal progradation but are expressed as marked spatio-temporal beach morphodynamic alternations (Fig. 15). In these areas, narrow fringing beaches respond morphodynamically to the mud-bank–inter-bank cycle by rapid (order of months) changes in profile due to cross-shore mud and sand mobility, and, in the longer embayed beaches, to marked gradients in longshore sand drift involving periodic rotation. Having been devoid of fresh sand sourcing, these beaches show balanced sediment budgets over the Holocene timescale.

8.2. Muddy shoreline progradation and large-scale clinoform development

Over geological timescales, the high mud supply from the Amazon has generated a Holocene clinoform structure that attains its maximum development off the mouth of the river, and more or less important coastal progradation throughout the Guianas coast into

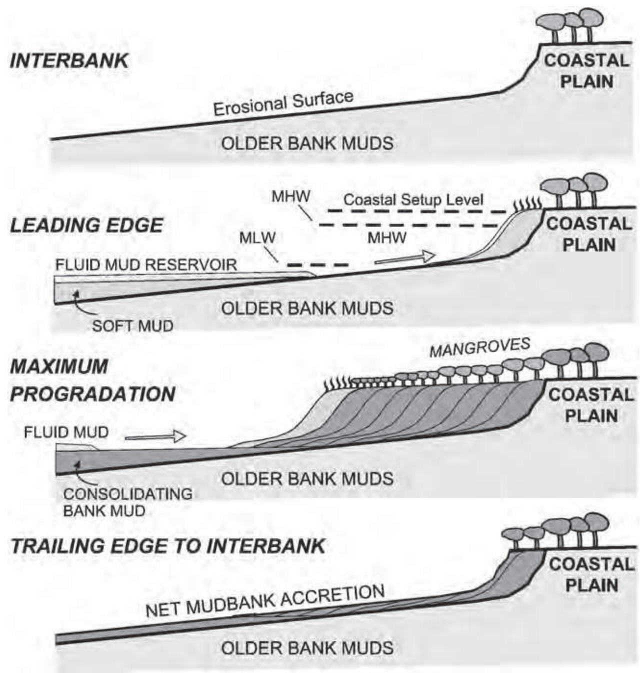

Fig. 16. A model (with high vertical exaggeration of the offshore slopes) for shoreline evolution in French Guiana based on remote-sensing and field observations. From Allison and Lee (2004). The diagram shows a succession of nearshore cross-sections of stratigraphy (top to bottom) with the passage of an offshore mud bank. The eroded, relatively low-porosity inter-bank surface (top panel) is succeeded (second panel) by leading-edge mud-bank deposition in the subtidal zone and the upper intertidal zone driven by fluid mud delivered onshore during phases of coastal setup. Accretion continues (third panel) in the upper intertidal zone as it translates seaward with mangrove stabilization, but ceases offshore with passage of the leading edge of the mud bank. With continued consolidation offshore (bottom panel), wave attack resumes and the coastal stratigraphic package is partially removed. This partial removal indicates that there is a net coastal-plain growth with each mud-bank–inter-bank cycle. Note that sediments deposited in the intertidal zone can later be exposed in the inter-bank subtidal zone (bottom panel).

Venezuela. The uppermost portion in this clinoform structure is the shoreline, the aggradation of which has brought the modern sedimentary deposit to sea level (Allison and Nittrouer, 1998). In the Amapà region in Brazil, shoreline aggradation of 5–10 m has occurred, and the shoreline deposits are prograding across topset strata of the modern subaqueous delta, which is the lowermost and most important part of the compound Holocene clinoform structure (Allison et al., 1995b; Allison and Nittrouer, 1998; Walsh and Nittrouer, 2009). In places, the onshore clinoform is much thicker, but may exhibit a complex pattern of dissection by estuarine channels.

The subaqueous delta extends to a water depth of 70 m, with a rollover point of maximum slope change (e.g., between topset and foreset strata) at 30–40 m. Advective sediment input to the foreset region causes very high accumulation rates (>10 cm yr^{-1}), which control the geometry and progradation of the clinoform structure. Sommerfield et al. (2004) provided stratigraphic evidence of multi-secular (<1 ka) late Holocene changes in shelf sedimentation at the mouth of the Amazon related to fluvial, oceanographic and meteorologic processes, and that are independent of the influence of sea-level variations. Erosional phases on the shelf during the Holocene appear to correspond to phases of significant shoreline storage of mud involving rapid coastal progradation, as outlined previously.

Downdrift of the mouth of the Amazon, coastal progradation is expressed by the overlapping of northward-extending mud capes that are well developed where river mouths debouch and are diverted northwestward (Fig. 1). The overall progradational sequence comprises the three distinct dynamic/morphosedimentary types discussed in the preceding sections: accretional mud, accretional sand

and erosional mud (Allison et al., 1995b), the last two types being associated with mud-deficient and/or inter-bank areas. It is expected that in chenier-forming areas along the Guianas coast, this progradational mud wedge includes thin strands of chenier sands reflecting periodic reworking, and integration within the prograding muddy plain during inter-bank phases, of shoreface sands delivered by the smaller coastal rivers.

In areas of low or no progradation such as offshore of Cayenne, the offlapping mud sequences thin seaward, merging with a relict shelf surface that is overlain further seaward by modern shelf mud (Bouysse et al., 1977; Pujos et al., 1990; Allison and Nittrouer, 1998). In the French Guiana area, the progradational wedge comprises over-consolidated mud on the inner shelf (0 to −20 m) that has yielded radiocarbon ages ranging from over 40 ka to present (Cleac'h, 1999). This over-consolidated mud forms, thus, a relict Pleistocene to Holocene bed surface (Bouysse et al., 1977; Pujos et al., 1990) over which the mud banks comprising fluid and under-consolidated mud migrate (Allison et al., 2000), within a dynamic system of short-term to seasonal sedimentation and resuspension cycles. This dynamic system feeds the long-term inner shelf mud accumulation, with offshore thinning of the mud wedge being dependent on waves, as on wave-dominated shelves. Seismic data from the shelf deposits show that the thin inner shelf mud overlies sandy deposits of presumably fluvial origin that crop out on the middle shelf at depths beyond 20 m (Bouysse et al., 1977; Pujos et al., 1990). Onshore in Surinam, the similarity of the Pleistocene deposits with the modern mud-bank system, both in terms of alternations between bank and chenier-rich inter-bank sequences and of the forcing mechanisms in coastal sedimentation, has been highlighted by Wong et al. (2009).

8.3. Comparisons with other muddy coasts

Other notable examples of open muddy coasts in the world are commonly associated with river-dominated deltas, and include the Texas–Louisiana coast to the west of the Mississippi, and numerous high-discharge rivers in Asia. Such shores are generally flanked by marshes or mangroves and bare mudflats several hundreds of metres to several kilometres wide. Although such systems may be characterized by widespread mud dispersal from the river point sources (e.g., Wright and Nittrouer, 1995), mud-bank formation and migration are not an overarching characteristic of these muddy coasts. The mud-bank system of the Amazon–Guianas coast appears to be unique in terms of both the magnitude of mud migration alongshore and the mud dynamics, due to a combination of extremely large and pervasive mud supply to the shoreface. This sediment supply involves mud concentration processes within an atypical shoreface-based estuarine turbidity maximum, and conservative onshore-alongshore mud transport along an energetic inner shoreface belt stretching for over 1500 km from the mouth of the Amazon to that of the Orinoco. Mud-bank systems on other mud-rich coasts, such as the Jaba and Purari coasts of Indonesia (Wright, 1989), the West African coast between Guinea–Bissau and Sierra Leone (Anthony, 1989, 2004, 2006; Capo et al., 2006), the Gulf of Papua (Wolanski and Alongi, 1995), the Cassino coast of Brazil (Calliari et al., 2002), and the Kerala coast of India (Narayana et al., 2008) are much smaller and some, such as those of the Cassino coast, do not demonstrate longshore migration. Some of these examples also concern mud-bank formation and activity associated with numerous adjacent river mouths, as in the Indonesian and West African examples. The ensuing mud-bank regime is, however, similar to that of the Amazon in that the estuarine turbidity maxima of the various longshore-connected rivers develop at the open river mouths or over a shallow shoreface under high seasonal river discharge, and the mud banks migrate alongshore under the influence of seasonal wind-waves and currents. The mud-bank system on the coast of Kerala, in India, is different, and appears to comprise self-organised forms that undergo a seasonal cycle of dynamic changes involving no longshore or cross-shore dispersal. This coast is fronted by long sandy beaches and lacks rivers liable to supply mud. Narayana et al. (2008) have suggested that the Kerala mud banks are palimpsest, marshy, lagoonal deposits rich in organic matter and derived gas, that were submerged after a marine transgression. The mud-bank regime on the Kerala coast of India has been reported to be an essentially *in situ* phenomenon influenced by seasonal monsoonal wave-energy variations. High-energy monsoonal waves are responsible for the formation and sustenance of the mud banks, and the seabed returns to its pre-monsoon state during the low-energy season. Although some fine sediment disperses alongshore and offshore, most is returned to the seabed as the monsoon declines. Wave refraction over the shoreface bathymetry may lead to shore-fast mud-bank formation at known locations of wave-energy concentration, but such mud is restored back to the shoreface mud-bank reservoir during the non-monsoon season (Mathew and Baba, 1995).

At the geological timescale, significant mud supply can also lead, as in the case of the Amazon, to the development of thick muddy coastal clinoforms under conditions of progradation associated with still-stand conditions. A fine example is that of the Gulf of Papua (Walsh et al., 2004). Allison and Nittrouer (1998) have suggested similarities between the Mississippi–Atchafalaya clinoform system (Neill and Allison, 2005) and that of the Amazon-influenced coast, although a storm-dominated sedimentary signature leads to more complex arrangements in the former, as McBride et al. (2007) have shown. Similar complexity is evinced by Asian deltaic systems (e.g., Hori et al., 2004; van Maren, 2005) where storm events, variations in river discharge, and delta channel switching lead to significant interlacing of muddy and sandy deposits.

Clinoform structures in high mud-supply shores such as that of the Amazon-influenced coast of South America provide analogues of the geological record created there (Wong et al., 2009) and elsewhere for muddy shorefaces (Ginsburg, 2005). Depending on regional characteristics (e.g. more rapid subsidence), large fractions of clinoform structures could be preserved (Nittrouer et al., 1995b). A possible candidate for a fossil example of the Amazon-type shoreface is that of the Alderson Member formation in western Canada (Hovikoski et al., 2008). Ginsburg (2005) considers as other possible candidates the inner shelf and shoreline parts of the thick Tertiary deltaic deposits of the Gulf Coast of the US and the mud rock sequence of the Devonian Catskill Delta of New York. There are many other examples of similar ancient analogues in the Cretaceous western interior seaway of the western United States. These ancient analogues, however, particularly of the shoreface clinoform, may probably be misinterpreted as deep basinal marine deposits due to their homogeneous mud sections and near-absence of fossils.

9. Conclusions

The large supply of mud from the Amazon has led to the growth of an important muddy clinoform off the mouth of this river and to rapid muddy coastal progradation incorporating chenier sands over more than 1500 km of coast northwest of the Amazon. Coastal progradation has occurred through the shoreward translation of mud from mud banks migrating alongshore. Mud-bank formation, migration and interactivity with the shore are associated with specific water-column stratification and wave-dampening processes that determine cross-shore and longshore mud dynamics. These processes also have an overwhelming impact on the ecology and economy of this coast.

Research on the mechanisms of muddy shoreline progradation has been significantly aided by remote-sensing techniques and complemented by field measurements, notably on mechanisms of shoreward mud advection by waves, and on the ensuing mud deposition rates and mud-bank topography. This original sequence of mud supply, concentration, formation, and migration involves processes that require further study. Among themes of particular interest are: (1)

the timescales and interactions involved in the formation of mud banks; (2) wave–mud bed interactions and their modulation by differences in wave characteristics and mud consolidation; (3) processes and timescales of longshore mud-bank migration and the role of mud-supply, oceanographic and geological factors in inducing variations in migration rates the impacts of which are important in terms of ecosystem-based coastal management; and (4) the meso-scale to long-term patterns of coastal erosion and progradation, and the way these are archived in the coastal-plain sediments from the Amazon to the Orinoco, especially at the Holocene timescale. These themes offer scope for significant future research involving innovative field and remote-sensing approaches. The dynamics and deposits on these shores could also serve as archives of conditions prevailing in the Amazon basin and yield insight on the geological past.

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