Contrasting sand beach morphodynamics in a mud-dominated setting: Cayenne, French Guiana

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ABSTRACT

The 15 km-long bedrock promontory of Cayenne, French Guiana, comprises three headland-bound fringing sandy beaches (>2< 5 km-long and referred to as type 1 beaches), and numerous, more or less highly embayed, short pocket beaches (0.1-1 km-long, type 2 beaches) exhibiting variable morphodynamic changes in response to mud banks migrating from the Amazon. Aerial photographs, satellite images and field studies of these mud-affected beaches show alternations between ‘mud-bank’ phases, when mud banks migrating northwards from the mouth of the Amazon River attain the Cayenne area, leading to extensive wave energy dissipation, ‘inter-bank’ phases, characterised by relative scarcity of mud and enhanced wave activity, and transitions between these two phases. During inter-bank phases, higher incident waves lead to the cleanout of mud from the intertidal beach and induce ‘normal’ beach morphodynamics. Transitional phases are associated with the variable presence of mud on these beaches, and result in the largest morphodynamic variability on the longer type 1 beaches. These beaches undergo alternations in longshore drift direction that are associated with a rare form of beach rotation induced by wave-mud interaction. These phases are associated with short-lived sand bed collapse features affecting the intertidal beach profile. Profile changes on type 2 beaches are much weaker, and are basically cross-shore, with little or no evidence of longshore sand drift, because of the poor propensity for development of longshore gradients in wave energy in these short embayed beaches. The presence of mud alters the behavioural patterns of beaches on the Amazon-influenced coast of South America, which is normally influenced by seasonal changes in wave energy due to trade-wind activity.

ADDITIONAL INDEX WORDS: Amazon mud supply, mud banks, longshore drift, muddy beach, beach rotation

INTRODUCTION
The profiles of sandy beaches generally reflect an adjustment between, on the one hand, grain-size and grain-packing properties, and, on the other, hydrodynamic processes related to waves, tides and water-table fluctuations. This combination generates profiles ranging from steep to shallow, with linear, concave, convex or barred configurations. Intertidal beaches permanently rich in mud (10-20%) on wave-dominated coasts are extremely rare, because of hydrodynamically controlled non-deposition of mud, and the common lack of substantial nearby mud supplies. Mud-rich beaches are generally found associated with high fine-grained discharge deltas such as the Mekong (Tamura et al., 2010). More generally, beaches affected by mud are subject to spates of more or less important mud mobilization from nearby sources such as offshore mud shoals, as on the Kerala coast in India (Tatavarti and Narayana, 2006), or of lagoonal mud as in the case of the Cassino beach and lagoon system in Brazil (Calliaure et al., 2009). Fine examples of permanently mud-rich beaches in an open-coast, wave-dominated setting occur in Cayenne, French Guiana, along a 15 km-long bedrock promontory on the 1500 km-long muddy coast between the mouths of the Amazon and the Orinoco Rivers (Figure 1). Field studies of the beaches in Cayenne have shown that their intertidal portion may incorporate significant percentages (10-80%) of mud, depending on the longshore migration of individual mud banks that are 10-60 km-long and separated by ‘inter-bank’ zones (Anthony et al., 2010). Depending on the length of individual beaches, which ranges from less than 100 m to 5 km, the beach behavioural patterns differ. These beaches fall into two categories, highly embayed short beaches (0.1-1 km-long), locally referred to as anse (literally small bays), and three, longer (>2< 5 km-long) more open beaches, Montabo, Montjoly and Rémire beaches (Figure 1). The longer beaches, referred to as beach type 1, range from mildly to strongly embayed, while the short beaches (beach type 2) are typical pocket beaches. The aims of this paper are: (1) to highlight contrasts in the morphological behavioural patterns of these two types of mud-affected beaches, (2) to show the effects of sediment heterogeneity, associated with mud-sand interaction, on beach morphodynamics.
THE MUDDY COAST OF FRENCH GUIANA

The muddy coastal setting of the sandy beaches of French Guiana is dominated by the fine-grained sediment discharged by the Amazon and progressively concentrated into individual mud banks which may number up to 15 or more at any time. The banks are up to 5 m-thick, 10 to 60 km-long, and 20 to 30 km-wide (Gardel and Gratiot, 2005; Gratiot et al., 2007). As these banks migrate alongshore towards the mouth of the Orinoco under the influence of waves and coastal currents, they imprint marked coastal geomorphic changes (Gratiot et al., 2008; Anthony et al., 2010) that can be summarised in terms of alongshore-alternating ‘bank’ and ‘inter-bank’ phases (Anthony and Dolique, 2004). 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 (Gardel et al., this issue; Gensac et al., this issue). Inter-bank areas between the dissipative mud banks are associated with a deeper shoreface, and are either subject to rapid shoreline retreat (Anthony et al., this issue) over timescales corresponding to the inter-bank phases (order of years) where the coast has previously accreted through mud bank ‘welding’ onshore, or exhibit, where sandy beaches are present, typical beach morphodynamic behaviour.

The Amazon-influenced coast is dominated by trade winds from the northeast that are mainly active from January to April, although the wave regime also comprises during the weak trade-wind season (May to December) swell waves generated by North Atlantic depressions and by Central Atlantic cyclones. Waves essentially arrive from an east to northeast direction. Wave periods range from 6 to 12 s, indicating the mix of trade wind-waves and longer swell, while offshore modal heights are up to 1.5 m. Tides are semi-diurnal and low-mesotidal (ca. 3 m) along the French Guiana coast.

BEACH MORPHODYNAMIC VARIABILITY

The 15 km-long Cayenne promontory in French Guiana forms one of the only two hard-rock shorelines on the 1500 km-long muddy alluvial coast of north-eastern South America, the other being the neighbouring 0.5 km-long coast in Kourou, French Guiana, site of the European Space Agency satellite launching pad. These hard-rock shorelines are formed by migmatites and granulites that crop out as hilly bedrock headlands and as rocky islets. The embayments between these headlands are bound by narrow (<500 m) sandy fringing beaches that generally abut older, probably Pleistocene, deposits that form a stiff, widespread reddish clay deposit. Locally, pronounced beach erosion may lead to exposure of these deposits in the backshore area. Bound between the bedrock headlands, these beaches show hardly any progradation during the Holocene, most probably as a result of blanketing of potential sand sources for progradation by the massive accumulation of Amazon-derived mud on the inner shelf (Anthony et al., 2002; Anthony and Dolique, 2004). Constrained between their bounding headlands, these beaches show rapid short- to medium-term changes in sediment dynamics, morphology and plan shape induced by spatial and temporal variations in the interactions between Amazon-derived mud banks and waves. The waxing and waning of mud-bank activity is characterised by ‘bank’, ‘inter-bank’ and ‘transitional’ phases (Anthony and Dolique, 2004). During bank phases, the Cayenne promontory beaches are subject to zero wave energy, while inter-bank phases are associated with relative mud scarcity and exposure of the beaches to normal wave processes.

Both beach types are characterised by relatively uniform coarse to fine quartz sand, a variable amount of heavy minerals and a very small fraction (<1%) of shelly debris. The sand sorting is highly erratic on all beaches, ranging from well to poorly sorted, with no clearly defined longshore or shore-normal trends. The heavy-mineral suite of beaches on the Cayenne promontory is dominated by amphibolites, followed by staurolite, epidote, and pyroxenes. On all pocket and open beaches, the sand gives way in the lower intertidal or subtidal zones to muddy deposits that thicken rapidly offshore. The surface contact between beach sand and mud occurs above or below the low spring tide level depending on exposure to waves. The mud may incorporate layers of fine to coarse sand, sometimes evolving into a mixture of fine ferruginous, quartz and shelly gravel. The beach mud deposits vary markedly in their fluidity, mobility, consolidation and inter-bedding with sand.

Patterns of beach evolution are closely hinged on interactions between waves, inshore and shoreface mud, and beach sand. During the presence of mud banks, mud directly wets onto the beaches for periods ranging from months to years. This leads to a rare example at the world scale wherein ocean-facing beaches are temporarily ‘fossilised’ under a protective mud cover that may become rapidly colonized by mangroves. Extreme manifestations of mud-bank activity thus lead to temporary muting of classical sandy beach processes as the beaches become entirely mud-bound (Figure 2a). In both beach types, ‘normal’ wave-beach interactions associated with inter-bank phases result in mud erosion (Figure 2b), and in longshore drift to the northwest (in response to the prevailing east to northeasterly wave approach window) on type 1 beaches. The main difference between the two beach types resides in the way they react to the variable presence of mud during the transitional phases, notably the bank-to-inter-bank phase.

Typical profile changes of the two beach types during the last transitional bank-to-inter-bank phase in 2002-2005 are shown in Figure 3. The marked fluctuations in profile width in type 1 beaches (profiles a and b) are the signature of rapid longshore
redistribution of sand in the intertidal profile within each embayed beach in a context of medium-term (order of years) beach rotation, a process of periodic alternations in longshore drift whereby erosion at one end of the beach is accompanied by accretion at the other end, with reversals in time, the overall beach sediment budget remaining constant. Type 2 beaches (profiles c and d) show limited change essentially characterized by cross-shore sand redistribution and are hardly subject to longshore drift (Figure 3). The reasons for this contrasting behaviour are summarized below with reference to each beach type.

**Type 1 beaches**

The morphological changes shown by type 1 beaches are essentially hinged on longshore variability during transitional phases due to the variable presence of mud inshore. In these type 1 beaches, mud is trapped during the inter-bank-to-bank transition in updrift (towards the southeast) beach sectors, resulting in differential wave energy dissipation. This generates 'counteractive' longshore drift to these low-energy mud-bound southeastern sectors (relative to the usual northwest drift direction during the 'normal' inter-bank phase). In contrast, during the bank-to-inter-bank transition, as a mud bank migrates northward past Cayenne, mud is trapped downdrift in the lee of headlands, in the northwestern beach sectors, which act as dissipative, low-energy zones.

Changes are most marked during this bank-to-inter-bank transition, the complex morphodynamic behaviour being governed by interactions between mud and sand. This phase is marked by a sharp longshore gradient in high-tide wave breaker heights. These generally decrease from maximum values of 1-1.5 m in areas where mud has been eroded from the intertidal zone (southeastern sectors), to no more than 10 cm in the low-energy mud-bound sectors (northwestern sectors), where significant mud accumulations may persist up to the high spring tide level. This transitional phase involves a change alongshore from beach cut in...
Beach erosion does not lead to offshore sand transfer, but rather to the high-energy sectors to sedimentation in the low-energy sectors. Beach erosion does not lead to offshore sand transfer, but rather to the high-energy sectors to sedimentation in the low-energy sectors. Longshore gradients in incident wave energy due to differential refraction and dissipation, reinforce the ‘usual’ sand drift to the northwest generated by waves. The open, type 1 beaches therefore respond to the waxing and waning of mud-bank activity by rotation over a scale of several years (< 10 yr).

The variable persistence of mud during this transitional phase thus generates longshore sediment heterogeneity associated with a marked longshore wave energy gradient. This longshore gradient is progressively phased out as mud is eroded from the latter sectors. This longshore wave-energy gradient also explains the occurrence of beach subsidence and collapse features (Figure 4). These features appear mainly in the mid-beach area, and are generally strictly limited to a longshore-migrating sand front ranging in length from a few tens of metres to over 100 m, and consisting of well-sorted and well-packed quartz sand. The mechanism that appears to explain these features is hydraulically-driven adjustment of the underlying mud to sand loading (Anthony and Dolique, 2006). Adjustment of the mud-rich beach profile to sand loading in the intertidal zone appears to occur through a combination of dispersive flow of the upper fluid mud and further dewatering of in situ underlying under-consolidated mud. These two processes generate accommodation space to which the overlying sand above the water exfiltration zone responds by forming subsiding packages of non-saturated sand delimited by cracks alongshore. The lower part of the deformation zone is affected by water exfiltration associated with sand piping and water undermining processes and with spatial differences in mud consolidation. The whole phase of collapse-feature formation may range from 3 to 6 months, but the features at any one stage on the beach are ephemeral because they are formed in a zone of intense wave activity and are washed out by a tide-controlled succession of breaking waves (low tide) and surf-swash motions (rising tide) as the tide rises. Trenches cut in the beach during the formation of the features are very unstable, but show that the vertical failure planes are not preserved and that mud is progressively buried under a thickening sand sheet.

**Type 2 beaches**

The numerous small pocket beaches of Cayenne are particularly prone to prolonged trapping of mud, because of their commonly highly embayed plan shape, even during transitional phases (Dolique and Anthony, 2005), a notable exception being the more exposed Anse Gosselin (Figure 1). As a result of the prolonged protection offered by mud in these embayed settings, changes in upper beach morphology are rather mild, even during inter-bank phases (Figure 3). However, on all pocket beaches, transitional and inter-bank phases are characterized by an increase in incident wave breaker heights that goes apace with erosion of subsisting mud inshore and lowering of the muddy low-tide surface.

During these phases, sand released by seasonal erosion of the upper beach is transported offshore, forming diffuse sand blankets overlying mud. During the low-energy season, this sand is washed out of the muddy profile and transported back up the beach. The recovery trend is thus characterized by seasonal beach behaviour. As the full inter-bank phase occurs, more significant erosion of mud by larger incoming waves leads to an important seaward relocation of the mud-sand contact. Observations of the overall beach morphology suggest that the temporal profile variability of these pocket beaches basically involves fluctuations in the level of the lower beach mud surface and mild cross-shore sand movements. The profile changes and observations of alongshore morphology suggest little longshore movement of sand.

**DISCUSSION AND CONCLUSIONS**

The presence of mud significantly alters the behavioural patterns of beaches on the Amazon-influenced coast of South America, which is normally influenced by seasonal changes in wave energy due to trade-wind activity. The chief effect of mud banks on the morphodynamics of drift-aligned headland-bound type 1 beaches is periodic alternations in longshore drift that lead to a rare form of beach rotation that does not result from seasonal variations in deepwater wave approach directions, as is generally reported for non-mud bank-affected beaches (e.g., Ranasinghe et al., 2004; Short and Trembanis, 2004). In the case of the French Guiana beaches, beach rotation is a medium-term (order of a few
The short, type 2 mud-affected pocket beaches do not show the rotational response of the longer open beaches. In these highly embayed pocket beaches, this situation is due to both the more limited sand accommodation space which goes with a lower overall beach volume, and marked refraction of waves. Due to the short length of these pocket beaches, longshore wave energy gradients generated by variations in the nearshore mud cover cannot develop properly. Beach plan-shape morphological changes are therefore much less spectacular than those affecting the longer beaches (Figure 3). Changes are essentially cross-shore, involving profile erosion and trapping of sand within the inshore mud prism and recovery during the low-energy season. This seasonal frame of beach morphological change occurs essentially during the inter-bank phase, as these short pocket beaches can be significantly mud-bound even during the transitional phases. The spectacular beach collapse and deformation features associated with longshore migrating sand found on the longer type 1 beaches are also much less developed on type 2 beaches.

The morphodynamic changes evinced by the mud-affected beaches of French Guiana are embedded within the cycle of mud-bank activity and the accompanying inter-bank phases. Modeling and prediction of the time frame of the morphodynamic response patterns of these beach to mud banks will necessitate monitoring the properties and migration rates of these mud banks between Brazil and French Guiana, through both remote sensing techniques and field work.

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LITERATURE CITED


