Regional Environmental Change (2022) 22: 101
https://doi.org/10.1007/s10113-022-01944-w

ORIGINAL ARTICLE

Dynamics of mud banks and sandy urban beaches in French Guiana, South America

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Received: 1 June 2021 / Accepted: 26 May 2022 / Published online: 2 August 2022

Abstract

Beach rotation is a widely described process characterized by periodic alternations in sediment transport involving erosion at one end of the beach and accretion at the other. The 1500-km-long coast of the Guianas, South America, is a unique system dominated by large migrating mud banks, muddy, mangrove-rich shorelines, and rare sandy beaches. Interactions between waves and the rare beaches on this coast are affected by the mud banks which are separated by 'inter-bank' areas. Kourou beach is situated near the site of the European Space Agency's satellite-launching pad in French Guiana. The beach has maintained multi-decadal stability, but its interaction with mud banks has led to phases of severe erosion. To understand these changes, which constitute a risk for the urban front of Kourou, we combined a mesoscale temporal (1950–2017) analysis of shoreline fluctuations with a short-term approach based on photogrammetric monitoring of beach change conducted in 2017–2018 and on bathymetric surveys of the nearshore zone. The results show that Kourou beach evolves in a context of 'rotation', a process involving periodic alternations in beach erosion and recovery. Rotation is characterized during inter-bank phases by 'normal' sand transport to the northwest generated by the prevailing NE waves, and during mud-bank phases by drift reversal to the southeast generated by refraction of these waves at the leading front of a bank. Due to the aperiodic nature of these bank and inter-bank phases, erosion and accretion involved in beach rotation may prevail over variable periods of time (several years to decades). The large mud banks migrating from east to west first protect the southeastern sector of the beach, blocking the 'normal' northwestward longshore sand transport, but generating, through differential refraction, southeastward counter-drift. These processes and the irregular timescale of beach rotation they entail have not been compatible with the recent urbanization of the beach front in the southeastern sector, resulting in erosion and a sense of threat to beachfront property. Insight gained from an understanding of the rotation process and its irregular timescales should contribute to better beach-front management.

Keywords Beach rotation · Beach erosion · Amazon mud · Mud banks · Beach management · French Guiana

Communicated by Emma Michaud and accepted by Topical Collection Chief Editor Christopher Reyer

This article is part of the Topical Collection on *The highly dynamic French Guiana littoral under the Amazon influence: the last decade of multidisciplinary research*

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Introduction

Beach rotation is a widely described process involving periodic alternations in sediment transport 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 (Short and Masselink 1999; Harley et al. 2015; Loureiro and Ferreira 2020). These periodic changes can have important management implications, notably where erosion temporarily prevails at one or the other end of beaches in a developed context with infrastructure and beach recreational installations and facilities. In such instances, there may be a need to adopt beach development setback lines that can adequately accommodate temporary beach retreat in order to avoid damage to infrastructure and installations. A detailed analysis of the process and an exhaustive list of references are provided by Loureiro and Ferreira (2020). Rotation, as summarily defined above, is generally associated with two controls: (1) a geological control imposed by headlands between which occurs the rotation process; and (2) changes in wave direction that generate alternations in sediment transport. Although rotation is commonly considered as being due essentially to reversals in longshore sediment transport, Harley et al. (2015) have identified rotational modes wherein the process may be a subtle combination of dominant cross-shore processes alongside longshore variations. Robinet et al. (2020) identified different timescales for these two modes, with longshore transport occurring at monthly to seasonal timescales and cross-shore processes at shorter timescales. A bidirectional wave climate has been advocated as the main driver of beach rotation (e.g. Klein et al. 2002). This can occur within the frame of seasonal wave climate variability such as in Monsoon settings (e.g. Jeanson et al. 2013), but also multi-annual climatological changes associated with various atmospheric indices (Wiggins et al. 2020).

A particular type of beach rotation complying to the aforementioned lateral headland boundary condition has been identified on the mud-impacted promontory of Cayenne, in French Guiana, South America, where periodic reversals in longshore sand transport, ranging in timescales of years to over a decade, have been shown to be generated by refraction of trade-wind waves by large mud banks migrating alongshore from the mouths of the Amazon River in Brazil to those of the Orinoco in Venezuela (Anthony et al. 2002; Anthony and Dolique 2004; Brunier et al. 2016; Jolivet et al. 2019). In Cayenne, the rotation process has been shown to be incompatible with rapid back-beach development pressures involving notably housing and infrastructure that have become exposed to beach erosion (Anthony and Dolique 2004). A similar beach rotation process is identified in the present study in Kourou, in French Guiana (Fig. 1), and, thus, under the influence of Amazon mud. Kourou beach is located close to the rocket-launching pad of the European Space Agency (ESA), and fronts a city that has undergone significant population growth over the last five decades from an agricultural settlement with 660 inhabitants in the early 1960s to 28,000 in 2020. Severe erosion, starting in February 2016, has become a source of anxiety to both the municipality of Kourou and the ESA, leading to hasty attempts to mitigate this risk in the urbanized southeastern sector of the beach.

The aim of this study is to identify the links between a background beach rotational framework occurring at an irregular regional temporal scale of years to decades and management decisions that may have exacerbated beach erosion. We show how unravelling the rotation and erosion processes contributes to an improved understanding of beach dynamics and management in this mud-dominated region.

Study area

The French Guiana coast is part of the 1500-km-long Amazon-influenced coast of the Guianas (Fig. 1), a unique system in the world characterized by large-scale muddy sedimentation in spite of exposure to waves from the Atlantic (Anthony et al. 2010). The mud, supplied by the Amazon, is organized into large banks migrating alongshore, driven by waves and currents, separated by 'inter-bank' zones. Mud banks dampen waves (Fig. 1b) and their inner part can weld onshore (Gratiot and Anthony 2016; Orseau et al. 2020), creating new land, aided by rapid mangrove colonization, whereas during inter-bank phases, higher wave energy leads to rapid shoreline erosion that can be mitigated by sandy/shelly beaches and cheniers, which also assure recreational and ecological functions, notably providing nesting sites for marine turtles. Since mud banks migrate alongshore, the prevalence of bank and inter-bank zones along any sector of the shoreline also changes over timescales that are quite variable (years to over a decade).

The Guianas coast comprises a Holocene-Pleistocene coastal plain (Wong et al. 2009) built essentially of Amazon mud, varying in width from a few hundred metres to over 10 km in places, and exhibiting cheniers that are particularly well developed downdrift (westward) of the numerous rivers draining the Guiana Shield. Among these is the 5-km-long Kourou beach, comprising a 2.5-km-long southeastern sector in front of the city of Kourou that has been undergoing erosion over the last 5 years (Fig. 1c). Kourou beach is bounded in its updrift end by a prominent rocky headland, Pointe des Roches, but is open northwestwards, merging into open-coast mangrove wetlands. Shoreline outcrops of Guiana Shield rocks occur as promontories in only one other location on this 1500-km-long coast: in Cayenne, the capital of French Guiana. Other small outcrops occur as a few scattered islets and rock masses not far out at sea. Apart from the headland-bound beaches of Cayenne, other sandy and shell-rich beaches on the Guianas coast are cheniers that form shallow (<5 m) individual ridges or bundles of ridges on the dominantly muddy coastal plain (Anthony et al. 2019; Gardel et al. 2021; Brunier et al. this issue). These beaches alternate alongshore with the muddy mangrove coasts that are the dominant shoreline type on the Guianas coast.

Kourou beach corresponds to this configuration of a persistent chenier, comprises rock outcrops, including a mildly protruding point, Pointe Charlotte (Fig. 1c), that is not a drift boundary. The northwestern end of the beach fluctuates between Pointe Charlotte and the mouth of a small unnamed stream draining the coastal plain and beyond which the

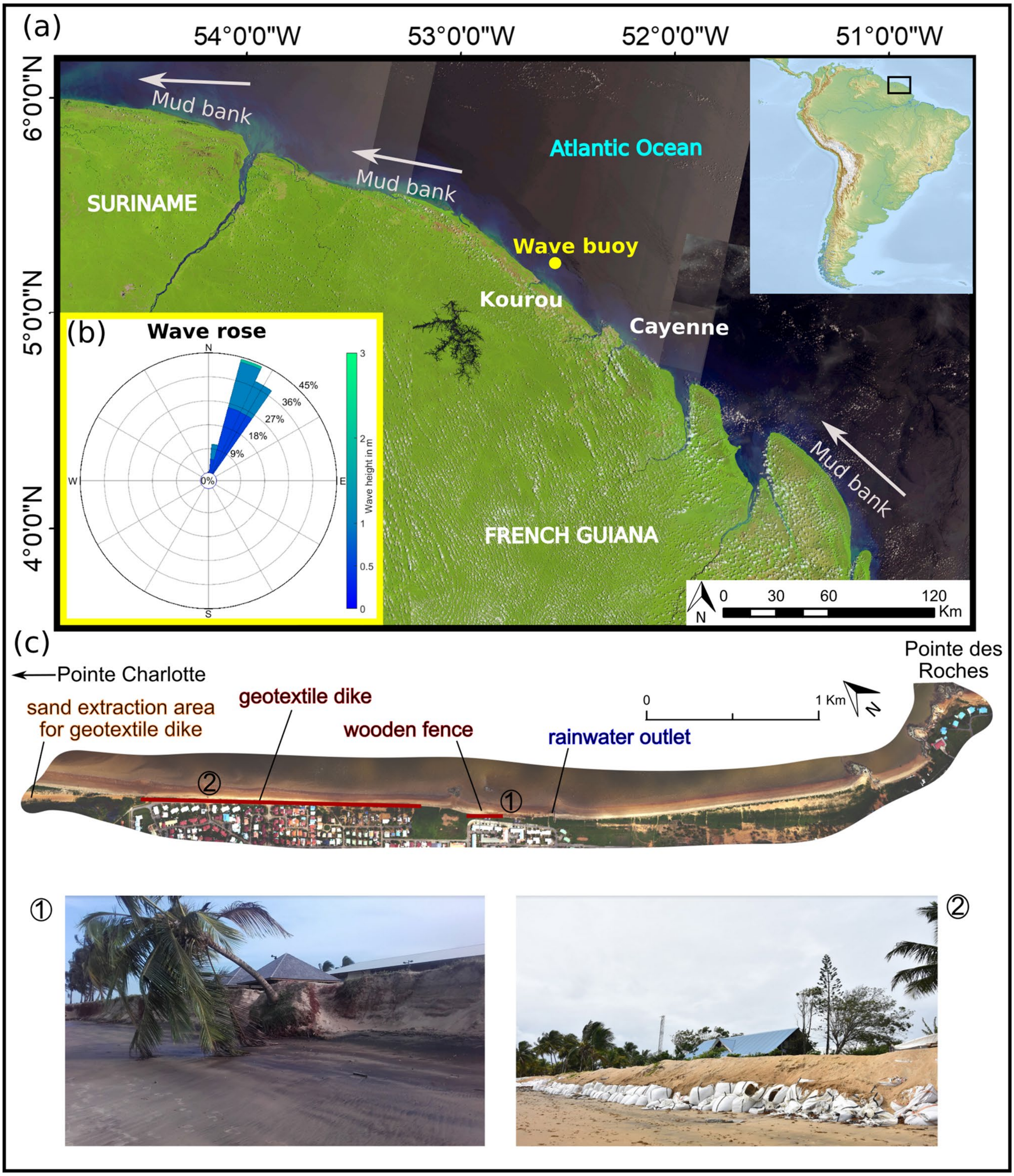

Fig. 1 Kourou beach in French Guiana: **a** regional setting showing mud banks migrating westwards (arrows); **b** regional wave approach directions; **c** 2017 aerial photograph of the beach with location of ground photographs showing urban front exposed to erosion (photographs 1 and 2) since 2016 that has motivated the emplacement of an 860-km-long dike made of sand-filled geotextile bags and a wooden wall

shoreline is permanently muddy with mangroves. Kourou beach is affected by a seasonal wave regime (Fig. 1b). The highest waves (peak significant wave height ~ 2.5 m) occur during the rainy season from December to May. Waves are lower during the dry season. This seasonal pattern is hinged on the regional wind regime. Waves are from north-northeast to northeast and are mainly generated by trade winds in the central Atlantic. The pervasive presence of mud on the shoreface, especially during bank phases (Fig. 1a), leads to significant dissipation and refraction of waves. The seasonal wave regime favours beach berm-building during the dry season and berm erosion and beach lowering during the rainy season. The beach experiences a semi-diurnal tide with a spring tide range of about 3 m. Following a phase of marked erosion starting in February 2016 along the urbanized front of the beach, the coastal management authorities hastily emplaced a wooden wall to protect beach-front restaurants from imminent destruction, and a soft dike made of large geotextile bags, which, by 2019, had a length of 860 m and necessitated a total of nearly 8900 m^3 of sand taken from the relatively stable and non-urban northwestern sector of the beach (Fig. 1c).

Materials and methods

We combined a mesoscale temporal (1950–2017) analysis of shoreline fluctuations northwest of Pointe des Roches with a short-term approach based on photogrammetric monitoring of beach change conducted in 2017–2019. Except where specified otherwise, all the data generated by the study were archived and analyzed using ArcMap and MATLAB software.

Multi-decadal shoreline change

Multi-decadal shoreline fluctuations were analyzed from 10 aerial photographs over the course of 67 years (from 1950 to 2017), with an interval of 2 to 18 years (Supplementary Table 1). An additional SPOT 6 satellite image taken in 2015 was also consulted in order to better constrain the context of a strong erosive phase in the southeastern sector. The geometry of the photographs was corrected by georeferencing using a second-order polynomial transformation following generation of > 500 control points compared to the 2011 orthomosaic provided by the IGN (French National Institute for Geographic and Forest Information), referenced in the Universal Transverse Mercator zone 22 North on the World Geodetic System 1984 ellipsoid. The photographs were then merged in order to obtain photomosaics. To quantify beach shoreline change, the limit between land and sea was identified using the vegetation line which provides a sharp contrast with non-vegetated areas on French Guiana beaches (Anthony et al. 2002). Beaches are, however, mud-bound during bank phases or in sectors where mud welds onshore and forms large mudflats (hundreds of metres to kilometres) that are rapidly colonized by mangroves. As a result, sandy beaches are disconnected from the sea and no sandy shoreline changes appear during such phases or in these sectors. Statistical analyses of identifiable beach shoreline variations were carried out using the Digital Shoreline Analysis System DSAS v4.4 tool in ArcMap (Thieler et al. 2017). The analysis consisted of a total of 450 transects spaced 10 m, drawn perpendicular to a baseline following the coastal orientation (Fig. 2a). The accuracy of the derived shoreline changes depends on a combination of errors from image resolution (0.5–7 m), digitizing (± 0.5 m) and geo-referencing. This last error was defined as the average of the root mean square errors derived from geo-referencing of each image, given the large number (10–15) of images for each date, with a global mean of 8 m for all dates. The planimetric error calculated by the data providers for the orthomosaic (IGN) and SPOT 6 imagery (European Space Agency) is also presented. We then combined these three sources of error to obtain a total error rounded to 10 m.

Short-term beach photogrammetric and bathymetric surveys

Six photogrammetric surveys were conducted during spring low tides in the eroding southeastern half of Kourou beach (transects 0–250 Fig. 2a): two in May 2017, and one in December 2017, June 2018, November 2018, and July 2019. These surveys revealed patterns of morphological beach change, sediment transport, and fluctuations in the beach sediment budget. Aerial photographs were taken with a Sony Alpha7R camera with a 32 mega-pixel resolution, fixed on the wing of a motorized ultra-light aircraft. Elements from the photographs, such as ground-size pixels, ground distances, and numbers of photographs per survey, are shown in Supplementary Table 2. The photographs were processed using the structure-from-Motion (SfM) workflow (Westoby et al. 2012), with stereo pair-alignment based on ground control points (GCPs), consisting of marked cardboards deployed on the beach and geo-referenced with a Trimble Real Time Kinetics (RTK) DGPS. Measurements were operated in the Universal Transverse Mercator (UTM) 22 North zone combined with the WGS 84 datum, using the Earth Gravitational Model 1996 (EGM96) geoid as the vertical datum. The SfM-photogrammetry workflow was implemented using Agisoft Photoscan Professional Software. The planimetric and orthometric references are based on the GCPs identified on every photographic scene, resulting in the construction of a georeferenced topographic dense point cloud. Dense point clouds were processed in the free software Cloud Compare that clears out vegetation, water,

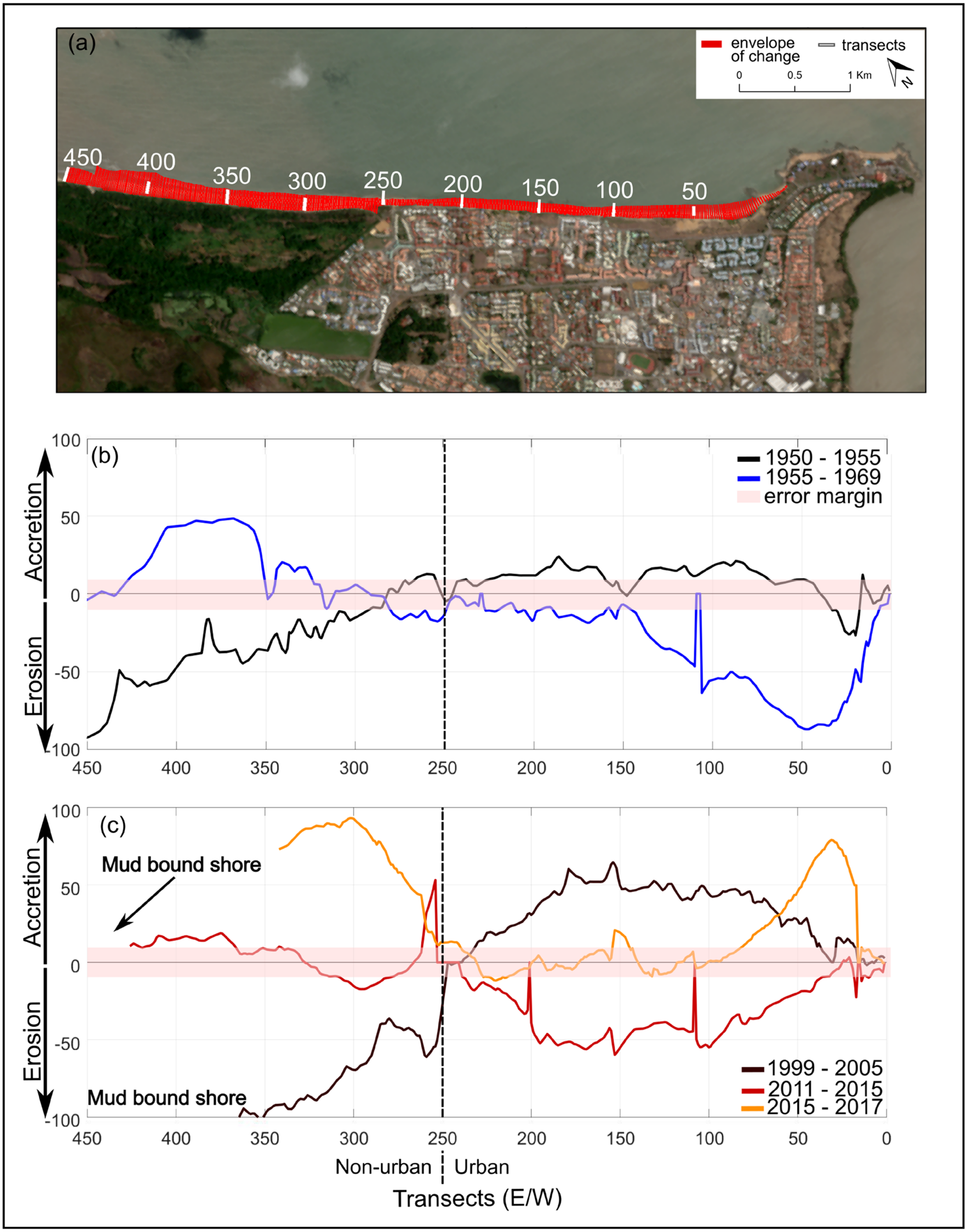

Fig. 2 Multi-decadal shoreline fluctuations determined for 450 transects spaced 10 m apart on Kourou beach together with the envelope of change in red **a**, over six intervals between 1950 and 2017 depicted, for clarity, in two panels (**b**, **c**), with the error margin specified in the pink transparent bands. Note that the period 1970–1999 was characterized by sustained welding of mud banks onshore and 2005-2011 by fluid mud, that shut down beach mobility. The transects in the southeast include a short segment of beach with rock outcrops. Transects in the northwestern sector of the beach are ignored because this part of the beach was mud-bound over some of the intervals of analysis

and human artefacts in order to obtain points corresponding to an elevation model. To perform the differential analysis, we compared our temporal series of dense point clouds with the 'C2C' tool in Cloud Compare. Dense point cloud results of elevation models and differentials were interpolated and exported as DEMs (digital elevation models) and DoDs (DEMs of difference) with a 0.50-cm optimal resolution. To estimate the quality of the planimetric and vertical reconstruction of the model, our DEMs were compared to ground truth points (GTPs) and topographic transect elevations measured with the DGPS. GTPs were also obtained from marked cardboards deployed and photographed on the beach, but were not used in 3D model construction in the SfM workflow (Supplementary Table 2). This comparison highlighted a mean error of 5 cm for the *Z* coordinate on the DEMs that needs to be added to the error of the GPS measurements. The RTK base station was deployed on an IGN French ordnance datum benchmark, with an *X*, *Y* error of 5 cm and a *Z* error of 0.5 cm. The manufacturer error margin for the RTK-DGPS is 1 to 2 cm for *X*, *Y* coordinates and 2 to 3 cm for the *Z* coordinate. We applied a total error margin, inclusive of the RTK-DGPS error and SfM reconstruction, of 10 cm to our DEM results.

Beach profiles, DoDs, and sediment budgets were computed from the 2D and 3D data from these surveys. Only DEMs at the annual scale are used for the differential analysis and volume calculations, in order to avoid seasonal variations and focus on longer term rotation-related changes in the sediment budget. These DEMs correspond to the following two intervals: May 2017–June 2018 and June 2018–July 2019. All the beach profiles used in this study were extracted from the DEMs. Sediment budgets were calculated for three beach sectors (i, ii, iii). To enable comparison between these three sectors, the sediment budget was expressed as a volume in cubic metres proportionate to the longshore length (l.m) of each sector, to give m^3/l.m.

Bathymetric surveys were conducted on the shoreface of Kourou beach in December 2017 and October 2018, using a Valeport Midas echosounder with a single beam dual-frequency (33–210 kHz). A Trimble Real-Time Kinetics (RTK) DGPS antenna with a centimetre precision, referenced on the IGN benchmark, was connected to the sounder with Hydromagic software for tide corrections. Bathymetric surveying was carried out along transects spaced 10 to 40 m, parallel to the beach. Due to the lack of an inertial motion system, deployments were conducted exclusively during calm sea conditions. In the absence of real-time correction for waves and oscillations with the inertial motion system, the error margin was estimated at 20 cm. Data were interpolated in order to create DEMs of 20-m pixel resolution that were then compared to evaluate bathymetric changes between the monitoring dates. The aim here is not to provide a precise analysis of the bathymetric changes but to highlight spatial variations in muddy shoreface accretion of Kourou beach associated with an approaching mud bank. These variations are important in terms of characterization of the beach rotation processes.

Results

Multi-decadal shoreline change

The shoreline variations over the period 1950–2017 are shown for the 450 transects (Fig. 2a), over distinct phases (Fig. 2b, 2c).The northwestern limits of the beach varied as a function of mud-welding on the shoreline, which tended to be more frequent in this sector close to the permanently muddy mangrove shoreline (T350-450) than in the southeastern sector. Shore-normal retreat or advance can be up to 100 m over periods of only a few years. Between 1950 and 1969, marked longshore changes occurred in the context of a prolonged inter-bank phase favourable to active beach dynamics. From 1950 to 1955, the beach was characterized by erosion essentially at its northwestern end, much of the rest of the change being mildly positive (accretion) but within the error margin. A substantial change occurred over the period 1955–1969 marked by a dominance of erosion in the southeastern sector (T0-T150) and significant accretion in the northwestern sector (T320-T430) that levelled out further west, while much of the central sector showed relative stability/mild erosion but within the error range. Between 1970 and 1999, a prolonged phase of mud-bank welding onshore led to muting of beach dynamics over much of this interval. This welding was accompanied by mangrove colonization notably after 1981. A 1987 aerial photograph shows, at the southeastern extremity of the shoreline, the shore-attached beach evolving westwards into a free chenier (Supplementary Fig. 1) migrating over these mangrove swamps, which were also subject to important anthropogenic downcutting and removal in this sector of the coast. Following this bank phase, between 1999 and 2005, complete erosion of mud and a return to an inter-bank phase led to a different dynamic beach regime with significant accretion in the southeastern sector and a sharp switch at about transect 250 to similarly marked erosion in the northwestern sector. Transect 250, at the western limit of the urban beach front, is the site of a natural urban rain-water outlet on the beach. A phase of overall stability prevailed from 2005 to 2011, marked by overlap with the active alongshore passage of a mud bank that did not weld onshore. A new reversal in beach dynamics occurred between 2011 and 2015 during which the southeastern sector underwent significant retreat while the northwestern sector showed mild advance. Between 2015 and 2017, there was significant recovery and advance of the northwestern sector and equally important advance in a restricted part of the southeastern sector between transects 10 and 80.

Short-term beach morphological and bathymetric variations

The shoreface bathymetric changes and sediment budgets are shown in Fig. 3. The bathymetric survey differential between December 2017 and October 2018 (Fig. 3a) highlights generalized muddy shoreface accretion that marks the impingement, in the southeastern sector of the beach, of a new mud bank migrating alongshore. The beach changes determined from the photogrammetric surveys in the urbanized southeastern sector between May 2017 and July 2019 are shown in Fig. 4a. Compared to the fluctuations associated with the multi-decadal frame of analysis (Fig. 2), the vertical morphological changes highlighted by the DoDs (Supplementary Fig. 2) are relatively mild (− 3 to + 3 m), but these values assume significance when viewed in the short time frame of change, and cannot be considered as negligible. In the longer-term frame of analysis, significant planimetric shoreline fluctuations exceeding 50 m were recorded over periods lasting less than a decade. The DoDs show strong variations between the two intervals (2017–2018 and 2018–2019), with a reversal in erosion and accretion tendencies, the latter dominant in large parts of sectors (ii) and (i) as well as on the upper beach of sector (iii), which, however, exhibited erosion on the lower beach that generated a steep profile. The sediment budgets calculated from the DoDs (Supplementary Fig. 2) show a deficit in all three sectors (Fig. 3b): − 8.5 m^3/l.m in sector (i), − 6 m^3/l.m in the urban rain-water outlet sector (ii), and − 17 m^3/l.m in sector (iii) corresponding to the diked urban front (Fig. 3a). The three sectors lost overall 28,300 m^3 of sand. This loss is partially offset by the nearly 8900 m^3 of sand contained in the geotextile dike in sector (iii).

A selection of profiles in Fig. 4b shows the variations in the morphology of the beach. The installation of the wooden seawall between transects 100 and 150 and of the geotextile dike between transects 175 and 250 (Fig. 2a) has an influence on the elevation of the upper beach in a zone where the urban front is particularly dense (Fig. 1c). The two profiles of sector (i) are both affected by erosion but show a clear contrast in morphology, with a relatively mild beachface backed by a wide retreating berm (transect 30) evolving alongshore into a steep beach backed by a retreating bluff

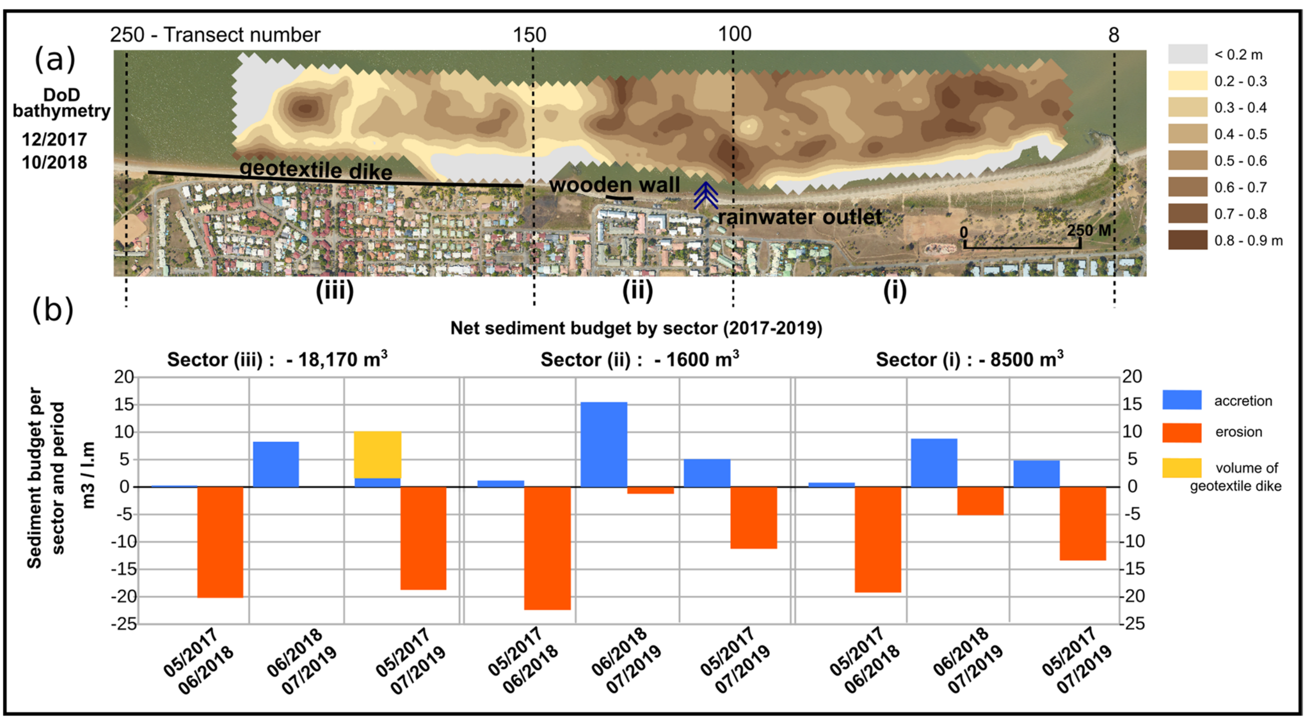

Fig. 3 **a** Bathymetric differencing between 2017 and 2018 in the southeastern sector of Kourou beach showing shoreface accretion generated by the arrival of a new mud bank. Transect numbers (8, 100, 150, and 250) define the limits of the three monitored beach sectors: sector (i) downdrift (under normal northwestward longshore transport conditions) of Pointe des Roches headland, a short sector (ii) comprising the urban rainwater evacuation outlet and a rock outcrop, and sector (iii) covering the dense urban front; **b** overall sediment budget (2017–2019) is expressed in m^3 and detailed graphs of the sediment budget for the three sectors in m^3/l.m for the intervals (2017–2018 and 2018–2019). The yellow box in sector (iii) shows the volume of sand emplaced in the geotextile dike between 2016 and 2019. DoDs of the three sectors analyzed from aerial photogrammetry are shown in Supplementary Fig. 2

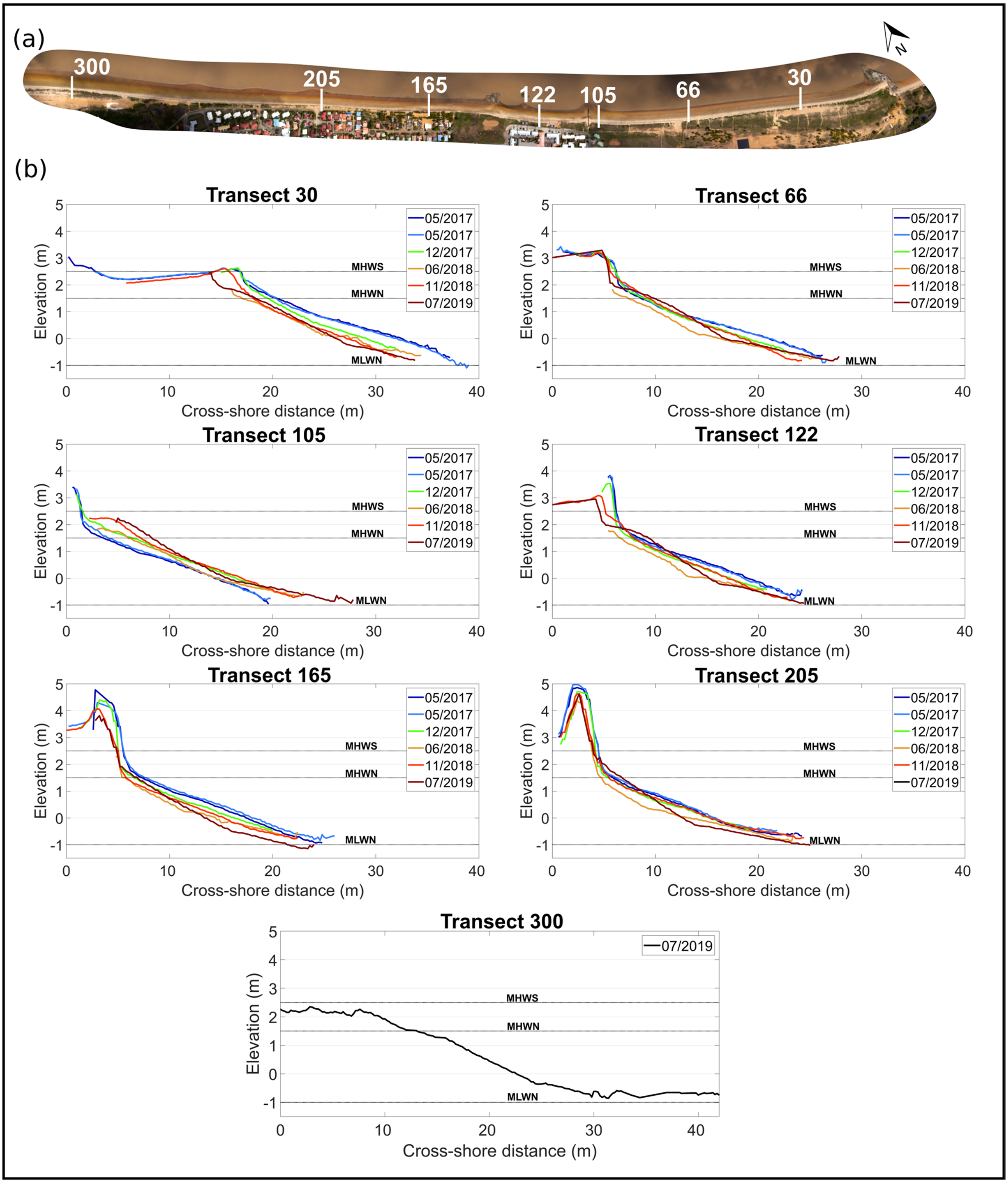

Fig. 4 **a** High-resolution photograph of Kourou beach in 2017 showing the locations of a selection of transects used in the shoreline fluctuation analysis of the southeastern sector. **b** Beach profiles for selected transects between 2017 and 2019 extracted from DEMs. Mean levels of spring and neap tides: MHWS, mean high water spring tide level; MHWN, mean high water neap tide level; MLWN, mean low water neap tide level. For purposes of comparison, a profile from the non-urban northwestern sector of the beach field-surveyed in July 2019 is also shown

cut into the berm (transect 66). Sector (ii) corresponds to a transitional one characterized by a change from a low accreting beachface and berm (transect 105), just updrift of the rainwater outlet, to a steep, reflective retreating beachface topped by the wooden wall and showing a distinct break in slope between the base of the wall and the rest of the beach. Sector (iii) shows a clear prevalence of this steep beach morphology with the backing geotextile dike. The top of the beach in this sector shows a higher elevation caused by the geotextile dike. An additional profile from the non-urbanized northwestern area shows a relatively wide beach with a mild slope (Fig. 4b).

Discussion

Kourou beach shows a clear rotation process at a multi-decadal scale that is expressed by the significant switches in advance and retreat at alternating ends of the beach over the period 1950–2017 (Fig. 2). These alternations correspond to the classic pattern of mud-induced beach rotation that has been identified in the embayed headland-bound beaches of Cayenne (Anthony et al. 2002; Anthony and Dolique 2004). In contrast to Cayenne, however, beach rotation in Kourou occurs between the bedrock headland of Pointe des Roches and the muddy mangrove coast west of Pointe Charlotte. This would suggest that the drift reversal and associated sediment transport that define the rotation process are determined by the overarching bank phases, and simply controlled by wave refraction processes at the leading front and inner edge of a mud bank, and the contact of which with the sandy beach is not restrained by a headland in the downdrift direction (Fig. 5). The trailing edge of a mud bank preceding an inter-bank phase is, inversely, associated with normal longshore transport towards the northwest. It is important to note that the presence of a headland, Pointe des Roches, bounding the updrift sector, sets a southeastward limit to the drift reversal process that results in accomplishment of rotation.

The foregoing comments bring up three pertinent related questions regarding long-term (multi-decadal) beach rotation in a muddy context: (1) the degree to which such drift reversal can actually lead to a complete return of sand and recovery of the updrift (southeastern sector), given that this process is maintained by refraction at the leading front, (2) the alongshore extent of the drift reversal process, in the context of an unbounded northwestern sector, and (3) the fulcrum or pivoting point of rotation. In addition to these questions, the discussion will highlight the limitations of the methods and the general implications of our findings in terms of a better understanding of beach rotation.

Dynamics of beach rotation in a muddy setting

The 1950–2017 aerial photographic coverage shows the permanence of a muddy shoreline northwest of Kourou beach (Fig. 2). It would appear that the pivoting section is located where there is a shift in the direction of wave approach, leading to an inversion of the alongshore sediment transport direction (Loureiro and Ferreira 2020). On Kourou beach, this can be located just west of Pointe des Roches as the mud bank starts impacting the Kourou area, and it moves northwestward as the bank migrates. The mud banks can range in length from 10 to 60 km (Anthony et al. 2010). The leading front is slightly diverted offshore by the Pointe des Roches bedrock promontory. This mild offshore diversion is sufficient to drive refraction of waves along several kilometres of beach downdrift of the promontory, thus favouring the prevalence of drift reversal along the entire Kourou beach, as has been proposed for the beaches of Cayenne (Anthony and Dolique 2004; Brunier et al. 2016). This leading mud-bank front can be several kilometres long with mud in various

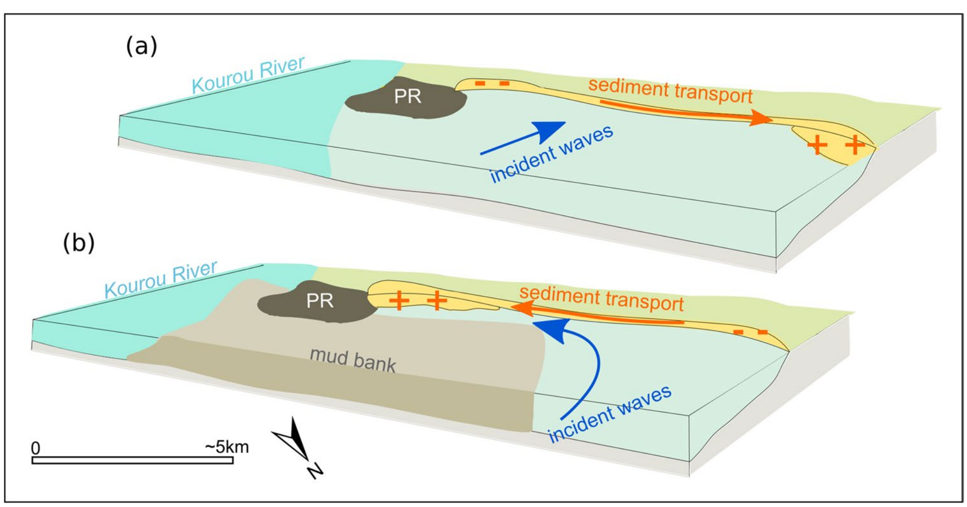

Fig. 5 Conceptual model of beach rotation in Kourou associated with a bounding updrift southeastern headland (PR — Pointe des Roches) and a northwest downdrift sector with no bounding headland. Normal longshore transport generated by the regional wave regime during inter-bank phases is to the northwest **a**, and the inverse transport to the southeast **b**. Drift reversal to accomplish aperiodic rotation is controlled by refraction of trade-wind waves from the NE at the leading front and inner edge of mud banks

stages of fluidization (Gratiot and Anthony 2016; Orseau et al. 2020). Sand transported seaward is progressively shielded from waves by the passing mud bank, eventually leading to the complete muting of beach processes onshore of the bank.

The foregoing processes clearly imply long-term stability of the beach sand budget, in the context of aperiodic rotation, the northwestern downdrift side being stable due to effective wave dissipation over a muddy shoreline. The 28,300 m^3 of sand (minus the volume in the geotextile dike) missing between transects 0 and 250 in the southeastern sector between 2017 and 2019 is not lost but is probably simply temporarily stored in the northwestern sector, consistent with the strong beach advance from transects 250 to 350 between 2015 and 2017 (Fig. 2c). Since 2017 a new mud-bank phase is active, highlighted by the muddy shoreface accretion (Fig. 3a) but with no shore-welding. Field observations in 2020 show the start of a new drift reversal process, with sand moving from the northwestern sector towards the eroded southeastern urban sector under the influence of this bank. Additional monitoring will be needed, however, to quantify this drift reversal.

By virtue of the specific context and processes identified above, Kourou beach is exempt from monotonous northwestward sand transport that would require renewal from an updrift source such as the Kourou River, the catchment of which is rather small (area: 2000 km^2) and of low elevation to supply sand on a significant basis. The river mouth is, in fact, constantly encroached on by mud and dredged to keep the channel deep enough to enable ocean-going vessels transporting commodities for the rocket-launching pad near Kourou. The beach sand and the bundles of cheniers occurring inland in this part of the French Guiana coast are probably derived from inherited inner shoreface sand (Anthony and Dolique 2004) and from earlier inputs at a time when the Kourou River probably joined the sea west of Pointe des Roches. An age of 370 year ± 0.02 ka obtained by Optically Stimulated Luminescence dating of chenier sand (Brunier et al. this issue) about 300 m from the present beach near Pointe Charlotte shows overall secular shoreline stability.

The urbanization of the beach front over the last 50 years has culminated in some of the emergency shoreline stabilization measures described earlier (Fig. 1). Kourou as a city is less than 50 years old. The growth of this small agricultural settlement into a city was spurred by the creation of the European Space Centre's rocket-launching pad in the 1960s. The bulk of this urban development took place from the 1970s to the 1990s. The earlier urban core developed around Pointe des Roches, but spread rapidly westward over the muddy coastal plain, parts of which were drained swamps. The urban pressure led to the encroachment of residences and restaurants on the beach, especially during the course of the long phase of mud-welding (1970–1999) when the shoreline was up to 2.5 km offshore of the inter-bank beach position. The progressive impinging of the urban front, especially during the phase of rapid urban growth between 1970 and 1990, and with a muddy shoreline far offshore, implies that residences and restaurants built within a distance of 100 m from the top of the beach berm between transects 100 and 250 can now be exposed to the envelope of change of active beach rotation (Fig. 2a). Over the 67-year aerial photo coverage, this envelope attains a maximum of 106 m. The rapid urbanization and a poor knowledge of the beach mobility associated with rotation underpin the hasty attempts undertaken since 2016 to stave off erosion. A poorly designed system of urban runoff discharge on the beach at transect 108 has been instrumental in driving persistent erosion. This rain-water outlet has seen a considerable increase in water discharge with the growing urbanization of Kourou, and now, following shoreline retreat, acts as a protruding groyne that impedes sediment transport both ways. The installation of a wooden seawall between transects 100 and 150 and of the geotextile bags between transects 175 and 250 (Fig. 3a) are hasty responses to the threat of localized erosion in this sector. The beach morphology and associated sand dynamics have been quite variable over this recent period in this urban part, compared to the non-urban northwestern sector of the beach, and this is probably a consequence of the soft beach engineering measures. This difference is expressed by the beach cross-shore morphology, which ranges from relatively mildly sloping and dissipative (transects 30–105) where sand transport northwestwards is impeded by the rainwater outlet, resulting in accretion (Fig. 3b), to steep reflective (transects 122–205) and erosive where the beach is backed by the wooden wall and the geotextile dike.

Limitations of methods and approach

In this study, we combined a mesoscale temporal (1950–2017) analysis of shoreline fluctuations with a short-term approach based on photogrammetric monitoring of beach change conducted in 2017–2018, and additional surveying of bathymetric changes. Our study has not involved in situ hydrodynamic measurements. The longer-term approach covers phases of mud-welding onshore that can mute, to varying degrees, beach mobility, but that also complicate, or render impossible, the task of determining the beach sediment budget at shorter intervals or for given sectors of the beach. This can be exacerbated by rapid mangrove growth over welded mud. The intervals covered by this longer-term analysis also varied widely from 2 to 18 years depending on the availability and quality of aerial photographic and satellite data. At the shorter timescale of the beach and bathymetric surveys, the pervasive presence of mud on the lower beach constitutes a limiting factor as far as the production of accurate beach sediment budgets involving the sand component are concerned. The presence of mud also generates a beach morphodynamic regime that has not been investigated in this study, other than in terms of defining simple reflective or dissipative-type profiles. More work will be needed in the future in deciphering the beach morphodynamic signatures associated with both the cross-shore and longshore components of rotation. The deployment of sensors to measure waves and currents will constitute an important step in better understanding these processes. Aspects of both local-scale wave energy dissipation induced by mud and the larger-scale wave refraction processes over mud banks will require more precise bathymetric monitoring of the nearshore zone and numerical modeling efforts.

Insight gained on beach rotation in general from the study site

Beach rotation, whatever the geographical location, invariably involves erosion at some time of some given part of the beach. This dynamic process generally involves significant alongshore beach mobility. Such mobility is generally embedded, however, in long-term beach stability, except where exceptional events (cyclones, tsunami) or anthropogenic activities such as sand mining, beach engineering, or sediment supply perturb the beach sediment budget. In Kourou, the attempts at fixing a beach shoreline that is mobile over the short term but stable over the long term have perturbed the sediment transport processes involving aperiodic rotation of the beach. There would have been no need for these beach defence structures had urban management benefited from a better understanding of beach cross-shore mobility related to normal drift and to counter-drift caused by mud banks. An understanding of this rotation process would have weighed in favour of proscribing development close to the beach front.

A unique aspect of Kourou beach is that rotation occurs downdrift of a headland but the downdrift limit of rotation is not bound by a headland rendering this rotation process quite different from the classical headland-bound rotation described in the literature (e.g. Short and Masselink 1999; Harley et al. 2015; Loureiro and Ferreira 2020). In the absence of a bounding headland, the downdrift limit of rotation fluctuates with the mobility of the leading front of the mud bank and with eventual mud-welding onshore. In exceptional circumstances, parts of the alongshore-migrating mud banks can weld onshore for decades, as between 1970 and 1999. These processes are driven by the regional dynamics of multi-annual mud bank migration that are unpredictable as they are driven by still largely unknown mechanisms such as variations in mud supply from the Amazon and ocean–atmosphere interactions that lead to variations in the regional wave climate. These likely involve significant changes in wind and wave directions (Eisma et al. 1991; Augustinus 2004; Gratiot et al. 2007), wherein more shore-normal wave incidence drives banks onshore rather than alongshore. These aspects are currently being investigated. They contribute, together with the aperiodic passage of the mud banks, in rendering rotation irregular on Kourou beach, and different from classical beach rotation.

Conclusion

Kourou beach in French Guiana shows a form of beach rotation operating downdrift of a southeastern rocky headland but unbounded northwestward. This appears as an original feature, inasmuch as rotation generally operates on beaches locked between two distinct headlands. Kourou beach has maintained multi-decadal stability but the rapid development of the city of Kourou over the last 50 years led to dense urban infringement on the backbeach area and close to the upper beach. This growth now infringes on beach cross-shore morphological change associated with the rotation process, generating hazards for beach-front houses and restaurants. The example of Kourou beach highlights the necessity for a better understanding of sediment dynamics for efficient beach management in the particular context of the Amazon-influenced coast of the Guianas because of the temporal irregularity of rotation, which is determined by mud-bank activity. An understanding of this temporally irregular rotation process should be useful in the elaboration of guidelines of development close to the beach front. The overall lesson from this case study, however, is the need and importance of quantifying the envelope of beach change associated with erosion and accretion, including in non-muddy contexts, which are, by far, the norm on the world's beaches, in order to better support coastal planning and develop appropriate coastal management interventions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-022-01944-w.

Acknowledgements Aerial photographs were provided free of charge by the IGN, and downloaded from the website https://remonterletemps.ign.fr/. The SPOT 6/7 image of 2015 was provided by CNES (distribution Spot Image S.A.). This is a contribution from the French GDR LIGA researcher network. We thank Carlos Loureiro and Florin Tatui and the Editor-in-Chief and Guest Editors for their insightful and constructive comments on the manuscript.

Funding M. Jolivet benefited from a PhD grant by the University of French Guiana. We acknowledge financial support from the European Regional Development Fund for the project OYAMAR. Additional funding was provided within the framework of the projects GUIABEACH, GUIACHENIER, MORPHOMAR, and DYALOG supported by the 'Pépinière Interdisciplinaire de Guyane' of the CNRS. E. Anthony acknowledges a 2018–2020 CNRS-funded sabbatical in French Guiana.

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