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Fluvial sand, Amazon mud, and sediment accommodation in the tropical Maroni River estuary: Controls on the transition from estuary to delta and chenier plain

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ABSTRACT

The Maroni River, South America, is a tropical estuary encased in a narrow lower valley with a limited area of estuarine tidal flat development, and displays a channel with large downstream-migrating sandy bedforms linked to a large sand-filled shallow mouth. The sand-rich nature of the lower Maroni River reflects significant fluvial bedload supply, and the Maroni is among rivers with the lowest suspension-sized sediment load in the world. During the dry season, the estuary shows high suspended sediment concentrations near the bottom (several g/l) that are due to the ingress of mud streaming alongshore from the Amazon River delta. However, Amazon mud is expelled from the estuary during the high-discharge rainy-season, and seems to be essentially restricted to this seasonal intrusion along the main channel with little net estuarine sedimentation because of limited channel overbank sediment accommodation space. Sand actively supplied by the Maroni River to the coast has been diverted by wave-generated longshore transport westwards, towards the Suriname coast. This has resulted in the construction of numerous sandy cheniers within a muddy coastal plain built from Amazon mud. This sediment-source dichotomy is an important original feature of the Guiana Shield estuaries. The asymmetric progradation at the mouth of the Maroni fingerprints the westward growth, in the vicinity of river mouths, of the muddy, chenier-studded, coastal plain of the Guianas. The propensity for these rivers to supply sand to the coast, eventually evolving into deltas, depends on the ability of their estuaries to limit westward (downdrift) deflection by long-term updrift coastal sedimentation. The Maroni estuary has tended to evolve towards a delta built from both Maroni river sand and Amazon mud, a stage, among the Guiana Shield Rivers, that only the large Essequibo River estuary in Guyana has achieved. Further studies will be needed in order to constrain the infill pattern of the Maroni River estuary and its mouth.

1. Introduction

River mouths occupy a transitional zone that has been summarized by Dalrymple and Choi (2007) as one that is representative of some of the most profound spatial changes in depositional conditions that can be found anywhere on earth, because of the dramatic variations in many factors that influence the nature of the deposits. This transitional zone is potentially one of significant trapping of both fluvial and marine sediment. Bedload is trapped in the so-called bedload convergence zone, the BLC, whereas fine-grained sediment is commonly concentrated in an estuarine turbidity maximum, the ETM (Dyer, 1997; Uncles, 2002; Wolanski, 2007). It is usual to consider that a river supplies both bedload and suspended load, the proportion of the latter tending to increase in tropical rivers with large catchments subject to long-term chemical weathering (Milliman and Meade, 1983), but it is also common to have marine bedload, generally derived from alongshore or from the shoreface, intruding into an estuary (Anthony, 2009).

Both the BLC and the ETM illustrate the long-term sediment-trapping capacity of estuaries. Although fine-grained sediment is

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commonly transported from estuaries onto the coast, especially during high-discharge phases, thus contributing to enhancing turbidity levels alongshore, it is not common to have important fine-grained sediment intrusion into estuaries from the open coast. This can occur, however, in circumstances where large rivers supply massive amounts of mud that are then transported alongshore, sometimes for hundreds of kilometres, in mud dispersal systems driven by wind-, wave and/or tide-induced currents. Such systems can source mud intrusion into smaller rivers located downstream. Lateral mud dispersal is associated with a number of deltaic systems such as the Jaba and Purari in Indonesia (Wright, 1989), the Ayeyarwady, the mud supply of which penetrates into the Sittang River estuary (Shimozono et al., 2019), and the Ganges–Brahmaputra, the mud supply of which maintains the Sundarbans mangroves several hundred kilometres west of the active delta distributary mouths (Bomer et al., 2020). The world's largest and muddiest coast is situated along the Guianas in northern South America between the mouths of the Amazon and the Orinoco Rivers. Mud concentrations exceeding several hundreds of g/l (Gratiot et al., 2007) occur, potentially affecting the numerous smaller Guiana river mouths located between these two big rivers along this 1500 km-long coast. Marine mud sourcing of estuaries can also occur where an alongshore mud belt results from seasonal resuspension of mud on the inner shelf, as along the coast of West Africa between Sierra Leone and Guinea-Bissau (Anthony, 2006).

Both the BLC and the ETM serve as zones of high sediment concentration but the nature of bedload implies that the BLC is often important to long-term estuarine channel infill, whereas sediment concentrated in the ETM may constitute a much more mobile pool (Uncles, 2002) that may nevertheless be also an important source of fine-grained sedimentation under favourable conditions (Geyer et al., 2004). Sediment from both these features can be transported through the estuary to the open coast, but this can only occur in a sustained way supporting coastal progradation where significant estuarine infilling has occurred, enabling delta growth (Boyd et al., 1992). In addition to sediment supply, the infill transition from estuary to delta is, under conditions of stable sea level, modulated by: (a) the morphological attributes of the lower river valley in which the estuary is encased, the coastal plain and the inner shelf, which determine potential accommodation space for sediments, and (b) the prevailing river, wave and tidal processes which condition sediment concentration, storage and dispersal. A high fluvial sediment supply and small estuarine accommodation space would invariably lead to rapid evolution of estuaries towards deltas where the coastal and shoreface morphology and processes are favourable to sediment accumulation. This is a feature common in the Mediterranean where there is a plethora of deltas associated with small river catchments (Anthony, 2015). The influence of: (1) bedload supply, (2) mud supply, and (3) accommodation space in determining aspects of estuarine development and evolution towards the delta stage are examined for the Maroni River in South America (Fig. 1a). The Maroni is, as shown below, a tropical river particularly rich in bedload supply potentially favourable to coastal progradation, but one also having a narrow estuary potentially subject to the ingress of mud in transit alongshore from the mouths of the Amazon located approximately 750 km to the southeast. This combination of fluvial bedload supply and mud from the Amazon expresses a major original feature regarding the sedimentary dynamics and geomorphic development of this tropical estuary. The present study examines the way these two sediment sources have, together with the inherited estuarine morphology, played out in the long-term morphological development of the Maroni river mouth.

2. Study area and methods

2.1. Maroni river and estuary

The Maroni River (Fig. 1) is 612-km long and has a catchment area of 66,184 km^2, making it one of the larger of the numerous 'small' rivers of the Guiana Shield between the mouths of the Amazon (catchment size: 3.6 million km^2), and the Orinoco (catchment size: 1.1 million km^2). The Maroni catchment experiences a humid tropical–equatorial seasonal climate modulated by the north–south movement of the Intertropical Convergence Zone (ITZC). The rainy season lasts from the end of December to July and the dry season from August to December. The rainy season is usually interrupted by a 1-month 'little' dry season in March. Rains are generated by onshore-directed northeast trade winds, whereas offshore southwest trade winds are dominant when the ITZC moves offshore of the South American coast during the dry season. The Maroni has a mean water discharge of ∼1700 m^3/s, with a range from ∼774 m^3/s during the dry season to ∼2400 m^3/s during the rainy season, when the maximum can exceed ∼3500 m^3/s (Rousseau et al., 2019; Abascal Zorrilla et al., 2020). The mean discharge is over 100 times less than that of the Amazon. Rousseau et al. (2019) showed that the Maroni's seasonality index, defined as the ratio between the highest and lowest monthly discharge, is much higher than that of the Amazon, thus highlighting the strongly seasonal character of the river's water discharge as well as a catchment-dampening and flow-smoothing capacity on water discharge that are much smaller than those of the much larger Amazon. The Maroni has been identified as among the world's rivers with the lowest suspended sediment concentrations (Sondag et al., 2010), a characteristic shared by other Guiana Shield rivers (Oliveira and Clavier, 2000). This reflects, no doubt, the highly crystalline basement rocks but also the still largely forested nature of the catchments. Rousseau et al. (2019) found marked differences in the geochemical composition (Al/Si ratios, weathering indices, $^{87}Sr/^{86}Sr$) of suspended particulate matter (SPM) in the Amazon, Orinoco and Maroni Rivers, and noted that the Sr isotopic composition of SPM appears to be mostly controlled by weathering processes and/or mineralogical sorting, rather than being indicative of sediment provenance. A >200% increase in SPM in the Maroni since 2009 has been reported by Gallay et al. (2018) who attributed this to anthropogenic activities, notably gold mining and deforestation. The Maroni River forms much of the frontier between French Guiana and Suriname and its banks host the twin towns of St. Laurent du Maroni (French Guiana) and Albina (Suriname) about 30 km upstream from the estuary mouth. These are among the fastest growing towns in the Guianas, notably St. Laurent du Maroni, where port facilities capable of handling large ocean-going vessels are being planned, providing a further justification for a better understanding of the functioning of the Maroni's estuarine system. Following an early preliminary study on the suspended sediment regime of the river (Jouanneau and Pujos, 1988), the lower Maroni and its estuary have attracted attention in a number of recent studies that have focused on field monitoring of bedforms at the mouth (Bureau de Recherches Géologiques et Minières, 2017, 2019), the estuarine tidal structure and flows (Sottolichio et al., 2018; Ross et al., 2019), modelling of the tidal circulation (Do et al., 2019), and remote-sensing and field-based analyses of recent shoreline geomorphic changes at the estuary mouth (Jolivet et al., 2019a,b), and the dynamics of the estuarine turbidity maximum (Abascal Zorrilla et al., 2020).

Tides in the Maroni estuary are mesotidal and semidiurnal, with a range of up to 2.5 m during spring tides at kilometric point (KP) 0 (Fig. 1b), and a slight amplification to a maximum of 2.65 m at about KP 15 (Sottolichio et al., 2018). Two large

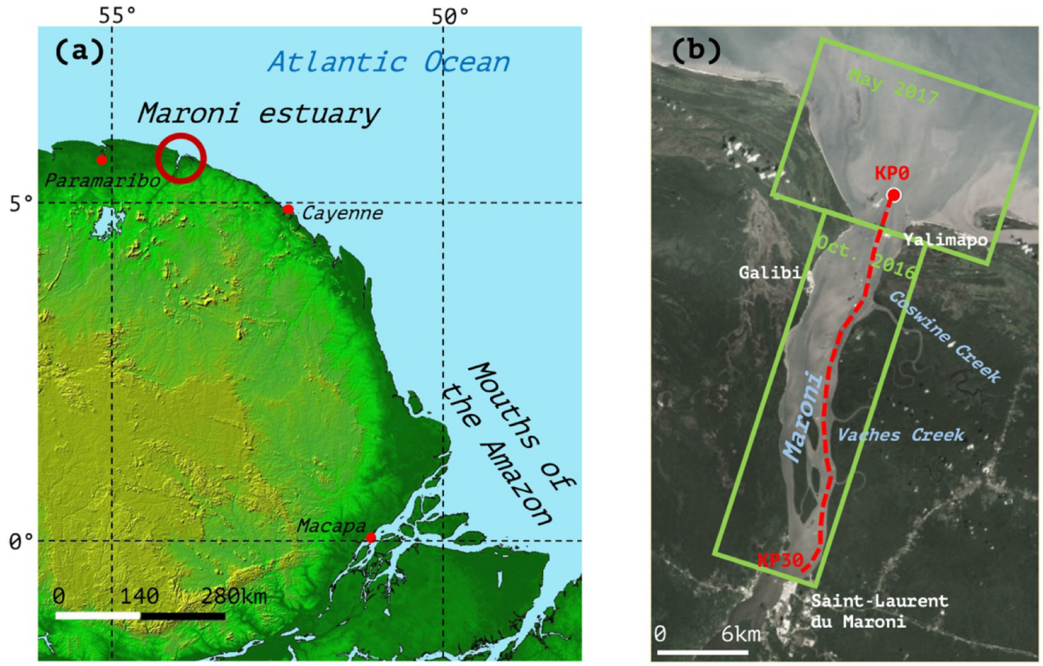

Fig. 1. Regional setting of the Maroni River, South America, ~750 km northwest of the mouths of the Amazon (a), and the estuarine reach of the Maroni from kilometric point (KP) 0 at the mouth to St. Laurent du Maroni at KP 30 (b), with broken red line showing transect along which the September 2019 salt and suspended sediment concentrations were measured, and area encased in green corresponding to two separate bathymetric surveys (October, 2016 and May, 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tidal creeks, the Coswine and the Vaches, debouch on the east bank of the estuary near the mouth, and a series of shoals and vegetated islands have accumulated between KP 15 and KP 26.5 (Fig. 1). Waves in the Maroni estuary area arrive from an east to northeast direction in response to the predominant trade winds (Gratiot et al., 2007). Waves with significant heights exceeding 2 m prevail between October and May, while waves are lower (significant wave heights <1 m) from June to September. Waves undergo important dissipation over an east–west migrating mud bank that has been encroaching on the estuary since 2011, as well as over the large shallow sand banks at the mouth of the estuary (Jolivet et al., 2019a).

2.2. Methods

The morphology of the Maroni estuary and the adjacent coasts of French Guiana and Suriname has been characterized from Landsat and Sentinel 2A satellite images and aerial photographs, thus, providing a template for identification of multi-decadal patterns of sediment redistribution, extent of the estuarine plain, and the ensuing coastal accretion. Shoreline changes in the vicinity of the estuary mouth have been reported by Anthony et al. (2019a) and Jolivet et al. (2019a,b), respectively, for the Suriname and French Guiana sectors.

In order to characterize the subtidal morphology of the estuary, two complementary bathymetric surveys were conducted in October 2016 and in May 2017 using a Valeport Midas echosounder with a dual-frequency (33–210 kH) single beam and integrated DGPS. The DGPS precision is ±2 m and that of the echosounder 0.01 m. The October 2016 survey concerned the estuarine reach from the mouth to Saint Laurent du Maroni (Fig. 1b), and was conducted using a cross-channel transect spacing of 350 m, yielding a total of 70 transects. The data was treated to generate a digital elevation model (DEM) with 10 m-cells. Water level fluctuations due to tides were corrected using records from three pressure sensors evenly spaced along the 30-km channel axis. Observations of intertidal bedforms on the large estuarine sand platform and adjacent beaches were also conducted in the course of this survey. The May 2017 survey covered the large sandy platform in the estuary mouth and the shoreface (Fig. 1b). In the course of this survey, hydromagic software was used for synchronization of the data with the recorded positions from the DGPS. The survey was conducted along 8 transects spaced 2 km, and 200-m DEM cells were generated.

Measurements of salinity and suspended sediment concentrations (SSC) were conducted in the course of several seasons in the water column from the surface to the channel bottom between KP 0 and KP 30 (Fig. 1b). The measurements reported here are part of an on-going series of surveys (see Do et al. this issue, for details). Here, we focus on the situation observed on 29th September, 2019, in the course of a semi-diurnal spring tidal cycle during the dry season. The measurements were made every 1 km at high tide during slack water along a profile in the channel using the moving vessel method (Savenije, 1989). Salinity was measured using a conductivity-temperature-depth probe (CTD CastAway © SonTek), and turbidity using a turbidity probe (OBS 5+ © Campbell Scientific). The turbidity signal was converted into SSC using a calibration curve built in the laboratory.

3. Results

The Maroni exhibits a relatively narrow estuarine valley and a wide mouth displaying an asymmetric pattern of coastal accretion on either side of the estuarine axis (Fig. 2). The main channel and the narrow estuarine valley are flanked by a coastal plateau comprising Pleistocene deposits and basement rocks (Grua and Cautru, 1993; Augustinus, 2004; Wong et al., 2009), with little in terms of contemporary intertidal estuarine deposits. Coastal accretion at the mouth of the estuary has been more important on the Suriname side than on the French Guiana side, and consists of numerous sandy chenier ridges interspersed in a muddy progradational plain with freshwater marshes. South of Galibi in Suriname, these ridges occur as 'bayside' cheniers (in the

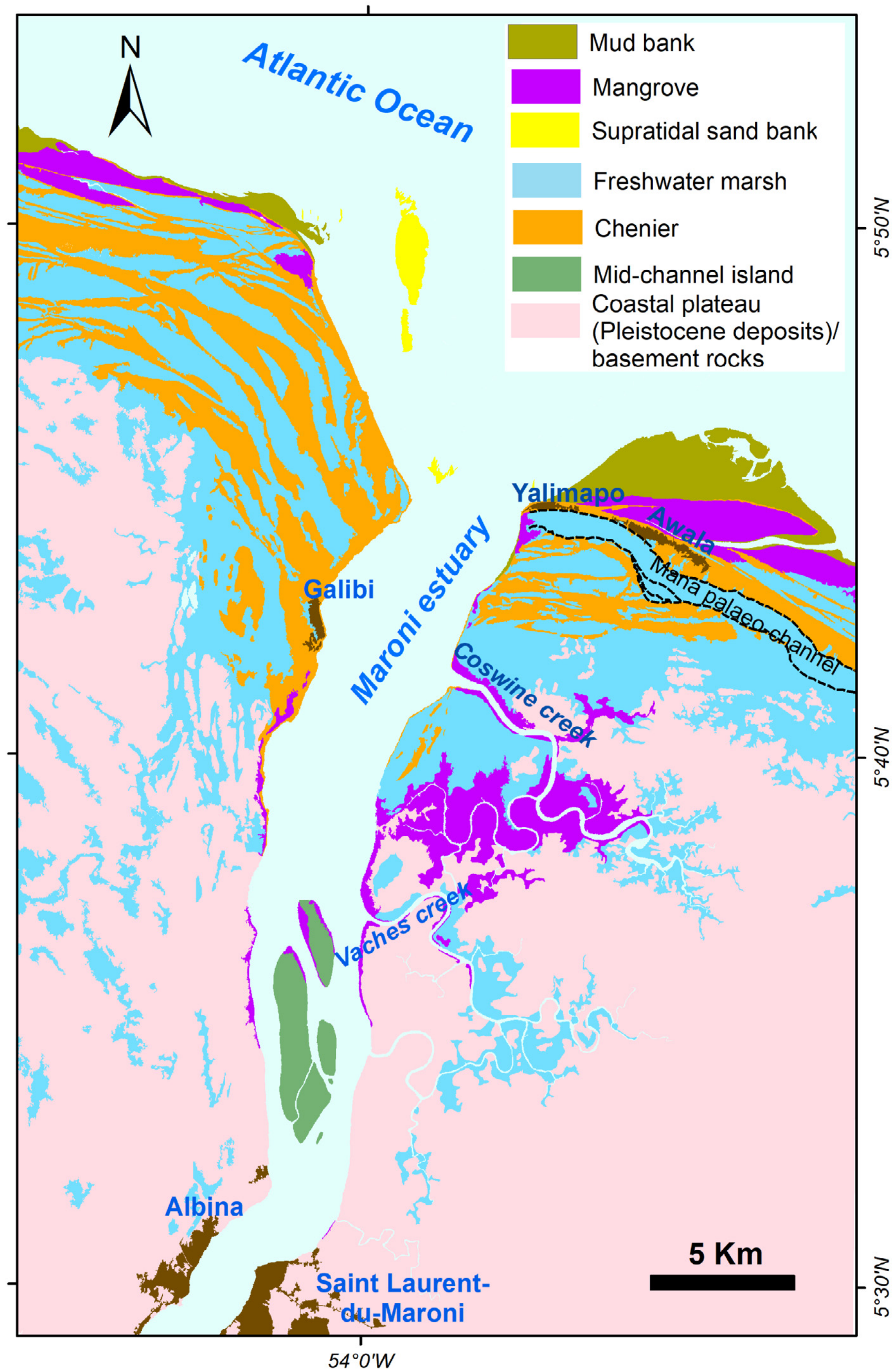

Fig. 2. Map of morphological units of the Maroni River estuary and adjacent coast. The undifferentiated Pleistocene and basement units have been identified following Grua and Cautru (1993), and Augustinus (2004).

terminology of Otvos and Price, 1979) flanking the main estuarine channel and oriented virtually south–north. North of Galibi, the cheniers undergo a change in orientation from south–north to southeast–northwest in phase with the transition from estuary mouth to the open-coast shoreline, and then east–west to follow the current open shoreline trend on this part of the Suriname coast (Fig. 2). Progradation has been less pronounced on the French Guiana bank, although several cheniers are also identified within a muddy coastal plain dominated by freshwater swamps. The earlier ones are also bayhead cheniers, but the coast-parallel cheniers appear to have been constructed from sand supplied by the smaller adjacent Mana River. The mouth of this river was, as suggested by an ancient abandoned trace on aerial photographs, and in agreement with the regional east–west longshore transport on this coast, diverted in the past towards the Maroni estuary (Jolivet et al., 2019b). Further south, the east bank of the Maroni is characterized by high stands (up to 20 m) of *Avicennia germinans* mangroves that give way inland along the tidal Coswine creek into shrubby (<5 m) *Rhizophora racemosa* mangroves up to the contact with the older continental deposits where freshwater marshes prevail. Vaches creek is essentially flanked by freshwater swamps. The upstream islands near St. Laurent du Maroni are covered by 10–20 m-tall stands of freshwater forests (Fig. 2).

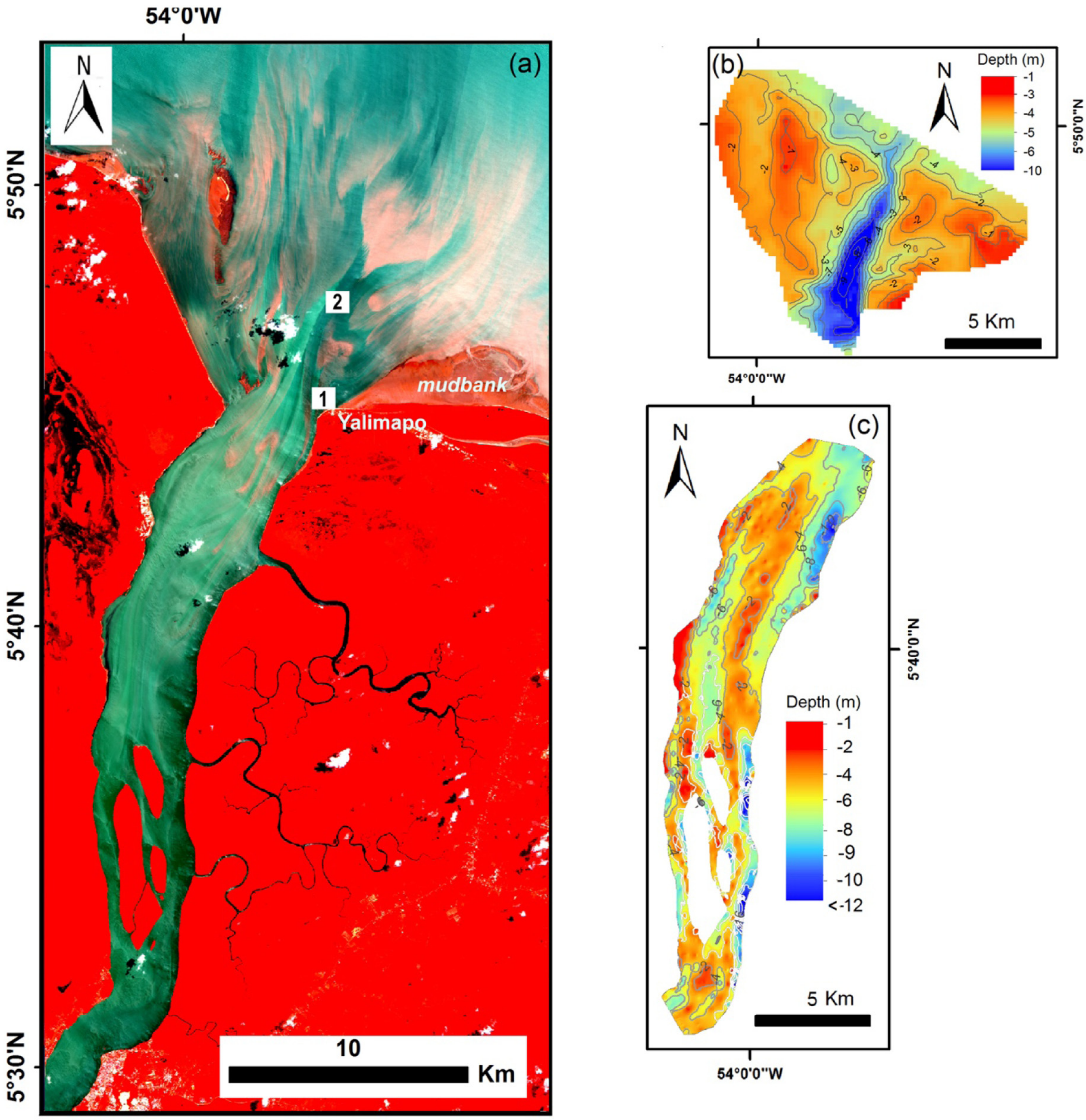

Fig. 3. Sentinel 2B satellite image showing the mouth of the Maroni (a), bathymetry of the large estuary-mouth sand platform (May 2017 survey, b), and of the estuarine reach up to KP 30 (October 2016 survey, c). 1 and 2 show locations of bedforms shown in Figs. 4 and 5.

The estuary mouth exhibits a wide, relatively shallow platform (Fig. 3) with large areas ranging in depth from 2 to 4 m below French hydrographic datum (0 m). Although much of the platform is sandy, a large area in the east is composed of mud much of which is <1 m below 0 datum, highlighting the encroachment of the leading edge of a mud bank, parts of which have welded ashore on the French Guiana coast (Fig. 3). The platform is cut by a moderately deep (down to −10 m) and relatively straight single channel running north-northeast on the French Guiana side, virtually in contact with the open-coast sandy shoreline at Yalimapo (Fig. 3). Much of the surface of the platform is covered by hydraulic dunes (Figs. 4, 5) composed of medium to coarse quartz yellowish sand, fine gravel and broken shells. These dunes are medium-sized (0.5 to 2 m), 2D to 3D forms, according to the terminology of Ashley (1990). The dunes show a residual migration in the direction of ebb flow, except in the main flood-dominated channel, and observations at low tide show that this migration occurs over a hard pavement of packed coarse sand and, locally, fine gravel (Jolivet et al., 2019a).

Upstream from the mouth, the channel bathymetry shows a complex pattern of shoals corresponding to elongate sand banks alternating with deeper areas with fluid mud. The sand here is reddish compared to the yellow sand of the estuarine platform, thus probably indicating progressive downstream loss of the ferruginous coating associated with fresh inputs from the catchment. Depths are up to 20 m in some areas, even close to the river banks and preliminary on-going bed sampling (not reported here) shows that these areas comprise weathered bedrock and laterite. Shallow areas occur in the vicinity of Vaches creek and downstream of Saint Laurent du Maroni where sand banks line the river bank, but even in these creeks, there are areas where the channel bottom consists of bedrock. Boomer seismic observations (Bureau de Recherches Géologiques et Minières, 2017, 2019) show that the main estuarine channel is rich in sand waves with steep stoss slopes oriented downstream.

The salinity intrusion length in the Maroni varies seasonally, reaching ∼27 km upstream from the mouth during dry season (Fig. 6a) but only ∼5 km during the rainy season (Do et al.

Fig. 4. Photo of 2D to 3D dunes exposed at low tide on the inner shoreface adjacent to the beach at Yalimapo (see 1 in Fig. 3). These dunes migrate eastward under the influence of ebb-dominant residual flow.

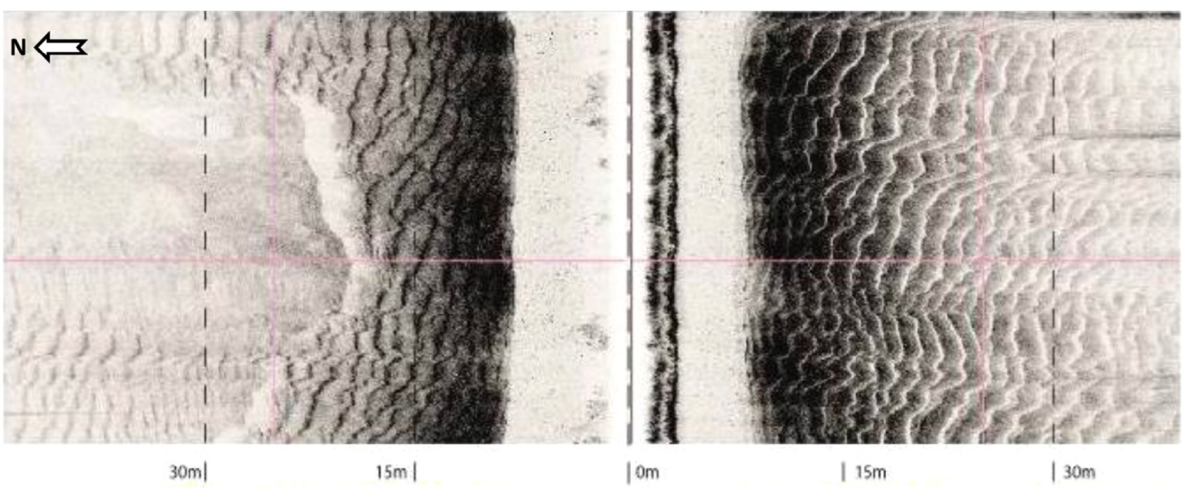

Fig. 5. Side-scan sonar images of flood-dominant bedforms in the main Maroni channel (see 2 in Fig. 3; with kind permission from the Bureau de Recherches Géologiques et Minières, 2019).

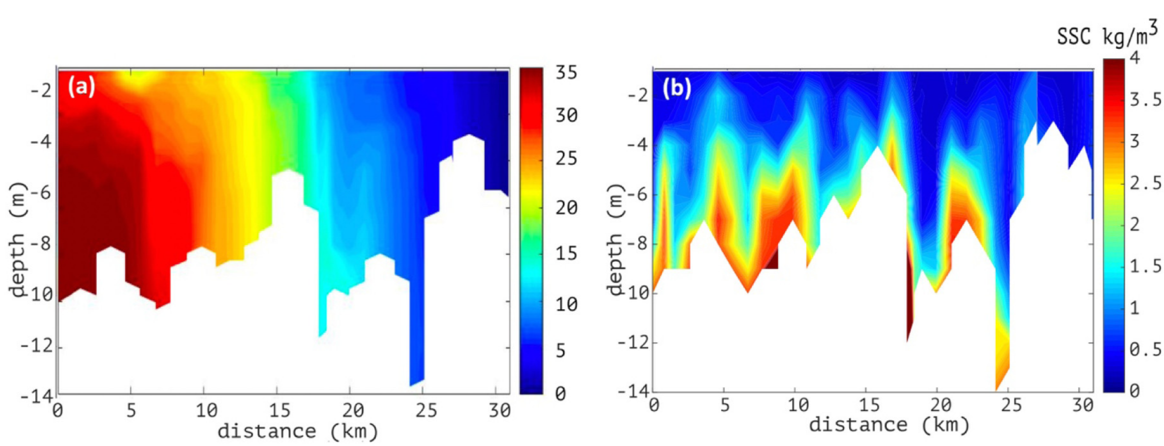

Fig. 6. Salt (a) and suspended sediment concentrations in kg/m^3 (b) in the Maroni estuary between KP 0 and KP 30 (see transect in Fig. 1b) measured on 29th September, 2019.

this issue). The dry season measurements carried out on 29th September 2019 show a clear stratification marked by a salty mass of water at the bottom (salinity values up to 33) in the downstream part of the estuary up to about KP 6 (Fig. 6a). The water mass then becomes more mixed, with salinity decreasing progressively up to KP 27. There is little vertical change in salt values from KP 6 to KP 33 (Fig. 6a), and this corroborates the dry-season observations of Sottolichio et al. (2018). These authors also highlighted a high degree of seasonality in the estuary's turbidity and identified an ETM during the rainy season at the mouth.

The SSC values show a clearly vertical structure with a diminishing trend towards the top of the water column (Fig. 6b). High SSC of 2.5 to about 4 kg/m^3 form layers 1–2.5 m-thick over variable channel-bed topography, and up to KP 27 km upstream the mouth (Fig. 6b).

4. Discussion

Between the mega river-mouths of the Amazon and the Orinoco are numerous smaller rivers debouching onto the Atlantic Ocean, such as the Maroni, and the estuaries of which lie, thus, along the coastal migration pathway of mud banks from the Amazon. One long-term effect of Amazon mud has been deflection of the mouths of many of these estuaries by large-scale sedimentation in the form of mud capes (Augustinus, 1978, 2004; Anthony et al., 2010; Jolivet et al., 2019b). These mud capes are systematically oriented northwestward or westward (depending on the regional coastal trend), reflecting the influence of the northeasterly trade-wind waves that are the main driver of mud-bank migration and long-term muddy sedimentation along the Guianas coast (Gratiot et al., 2007). Another important effect is that as the banks impinge on these smaller estuaries, they serve as an important external source of mud that is transported upstream by tidal currents (Orseau et al., 2017, 2020; Abascal Zorrilla et al., 2020). The extraneous mud supply, thus, has implications not only for the short-term estuarine dynamics but also for the longer-term estuarine morpho-sedimentary development. These smaller rivers drain the crystalline basement rocks of the Guiana Shield, and are, thus, potentially important purveyors of sand that can eventually be supplied to the coast to build cheniers in this predominantly muddy setting (Anthony et al., 2019a). The propensity for these rivers to supply sand to the coast, eventually evolving into deltas, depends, however, on the ability of their estuaries to limit westward (downdrift) deflection by long-term updrift coastal sedimentation.

To conceptually gauge the long-term capacity of river mouths in countering the alongshore deflective effect of mud from the Amazon on the morphological plan shape of Guiana Shield estuaries, Anthony et al. (2013) identified two basic types of estuaries. The first is characteristic of the small-catchment rivers (catchment size $< 20{,}000$ km^2) and the discharge of which is too low to counter the alongshore deflective effect. The second type concerns the larger rivers (catchment size $> 20{,}000$ km^2) characterized by water discharge and tidal pumping strong enough to keep the estuary non-deflected and open, although mud may accumulate on either side, and commonly significantly intrudes up-estuary, as discussed below. The authors assimilated this counter-deflection to a 'hydraulic-groyne' effect (Todd, 1968) that may favour accretion on the updrift coast without the emergence of a mud cape. The Maroni is a fine example of this estuarine type (Fig. 1b). Its mouth shows a stationary non-deflected position relative to the rectilinear axis of the estuarine channel. Notwithstanding this, however, the Maroni River estuary occupies a complex coastal setting where an important accumulation of fluvial bedload has co-existed with extraneous mud from the Amazon. The long-term estuarine infill and coastal accretion reflect this specificity, which is expressed by spatial variations in sedimentology and geomorphology (Fig. 2).

The dry-season salinity and SSC structure in the axis of the Maroni estuary shows the pervasive influence that mud supply associated with migrating mud banks appears to have in the seasonal estuarine dynamics. The large dry-season SSC values reported here following the brief experiment in 2019 (Fig. 6b) do not appear to correspond to a classic ETM associated with the freshwater–salt water convergence. However, longer time series of measurements led Do et al. (this issue) to identify a dry-season ETM that they attribute to possible resuspension by tidal currents and convergence of gravity circulation, a point also raised by Abascal et al. (2020). Do et al. (2019) and Do et al. (this issue) show, indeed, strong seasonal contrasts in suspended solid concentrations, with a very turbid estuary in the dry season and clearer waters in the rainy season. They also highlighted the persistence of an ETM near the mouth in the course of the latter season. The authors identified the dry-season ETM location upstream, in the vegetated island sector. Both Do et al. (2019) and Ross et al. (2019) also showed from velocity measurements that the Maroni is largely characterized by residual ebb-dominated flow, especially when rainy season discharge enhances outflow.

The high dry-season SSC values in Fig. 6b are not likely to represent mud derived from fluvial sediment discharge, given the and low river flow and low SSC from the Maroni catchment, even when the recent anthropogenically-induced increase in fine-grained sediment supply (Gallay et al., 2018) is taken into account. We deduce that intrusive mud is: (1) derived from the nearby high-concentration mud pool represented by the mud bank that has been migrating across the Maroni mouth since 2011 (Fig. 2), and (2) transported essentially through the eastern channel that links up with the main estuarine axis. Ross et al. (2019) identified this channel on the French Guiana side as flood-dominated. This mud is trapped near the bed (Fig. 6b), consistent with the upstream salt intrusion (Fig. 6a) which probably drives this SSC structure. Trapping appears to be dynamic, rather than topographic, as the dense mud lenses are not necessarily found in pools within the channel. They are, thus, probably mobile. Abascal Zorrilla et al. (2020) have reported from detailed analysis of OLI Landsat images that the ETM developed in the Maroni estuary during the rainy season is significantly sourced by Amazon mud, an observation consistent with those of Orseau et al. (2017) on another estuary in eastern French Guiana, and Asp et al. (2018) on an estuary in Brazil affected by Amazon mud. All of these observations highlight the complementarity between the geomorphic approach adopted here and both physical modelling (Do et al. this issue) and remote sensing approaches (Abascal Zorrilla et al., 2020) in gaining a better understanding of the dynamics and evolution of estuaries.

The muddy deposits associated with the small areas of tidal flats on the French Guiana side, and the vegetated islands near St. Laurent du Maroni (Fig. 2) likely reflect input from Amazon mud in their long-term sedimentation. This is expected, given not only the importance of Amazon mud intrusion but also the extremely low values of terrigenous suspended loads brought downstream by the river. This fluvial suspension load mixes with mud from the Amazon (Jouanneau and Pujos, 1988). As a consequence, the expected geochemical signature of the estuarine SSC will not display differences between the Maroni and the Amazon noted by Rousseau et al. (2019), who sampled the Maroni at the hydrological station of Langa Takaki about 80 km upstream of the mouth, well above the estuarine zone. Estuarine sedimentation sourced by Amazon mud has been rather limited from a surface area perspective, given the narrow nature of the Maroni valley, but its vertical extent, dependent on the depth of valley incision during the last sea-level lowstand, is not known.

Potentially, the ETM, involving Amazon mud and a low river-derived contribution, and shown to expand during the present phase of mud bank intrusion on the Maroni (Abascal Zorrilla et al., 2020), has acted as a seasonally mobile mud pool. From this pool, sediment, mobilized by high discharge in the rainy season and by tidal pumping, especially during spring tides, is deposited to build up the small areas of peripheral tidal flats, as well as the island sector. Do et al. (this issue) identify a strong rainy-season flushing effect on the ETM resulting from the significantly higher Maroni water discharge, this leading to clearer waters in the estuary during this season. Potentially, therefore, although suspended sediment can reach high concentrations in the Maroni estuary, the dynamics are probably dominated by up-estuary (dry season) and down-estuary (rainy season) movement of the mobile high SSC pool, with limited peripheral accumulation in intertidal areas. The limited area of tidal flat development in the estuary reflects, in itself, inherited antecedent geomorphic control at the end of the post-glacial marine transgression c. 5-6000 years ago when a relatively narrow Maroni valley was invaded by the sea to form the current estuary, initiating infill. The morphology and sedimentology of the bed of the estuary and the large estuary mouth show the overarching dominance of sand in the estuarine infill and peripheral coastal accretion, with a clear asymmetry between the Suriname and the French Guiana sides.

The lower valley and estuary have, thus, been largely infilled with sand supplied by the river, although Jolivet et al. (2019a) also speculated that the large estuary-mouth sand platform may also have received sand from the adjacent Mana River in the east. The Mana is a small (catchment size: 12,090 km^2; mean discharge: 320 m^3/s) type 1 river the mouth of which was diverted westward by a large 10 km-long mud cape since at least the mid-19th century (Plaziat and Augustinus, 2004) to join up with the Maroni near Yalimapo. Massive erosion and demise of the cape have occurred over the last 60 years, resulting, in 2011, in the relocation of the mouth of this river several kilometres eastward of its former historical mouth near that of the Maroni (Jolivet et al., 2019b). The large sand platform at the mouth of the Maroni does not correspond to the classic river-mouth BLC wherein sand converges from both the river and the shoreface, as classically observed in estuaries, and which is important in driving estuarine infill (Dyer, 1997; Uncles, 2002; Dalrymple and Choi, 2007). The Maroni sand platform occupies a zone of convergence of fluvial outflow and tidal intrusion that also lies in the regional Amazon mud-bank migration pathway. Jouanneau and Pujos (1988) suggested that sand supply from the Maroni on the platform may have been greater during the periods of lower sea level during the Quaternary. However, the lack of bedload supply from the shoreface, due largely to blanketing of relict shoreface sand by this pervasive mud supply from the Amazon (Anthony et al., 2002), has implied that the BLC is virtually exclusively composed of bedload supplied by this Guiana Shield river, the catchment of which is composed of rocks that liberate quartz and ferruginous sand and gravel. Sand accumulation at the mouth of the estuary may also have been enhanced by viscous energy dissipation of tidal and river outflow involved in the liquefaction of mud banks as they slowly migrate across the mouth of the Maroni. The significant downstream accumulation of fluvial sand also reflects the present dominance of downstream-directed residual currents in the estuary highlighted by Do et al. (2019) and Ross et al. (2019). The latter authors identified a shallow ebb channel at the west bank of the estuary (Suriname) in addition to the flood-dominated channel on the French Guiana side. Upstream from the infilled mouth, the elongated sandy shoals and banks that have accumulated in the Maroni estuarine channel testify to the progressive downdrift migration of fluvial sand. These deposits will have to be dredged in the future to allow access to container ships in the developing port of Saint Laurent du Maroni.

Coastal accretion sourced by sand from the Maroni and mud from the Amazon has been more limited on the French Guiana side, as attested by optically stimulated luminescence ages >2000 years B.P. about 200 m behind the present beach at Yalimapo (Brunier et al., 2019). Multi-decadal scale shoreline mobility on this side of the river mouth has been shown to be relatively weak, largely within error margins (a few metres) of analysis, although more marked mobility occurs where the estuarine flood channel lies close to the beach at Yalimapo (Jolivet et al., 2019a). The asymmetric accretion pattern of the Maroni on either side of its mouth clearly shows, thus, that part of the bedload supplied by the river has been incorporated into the numerous bundles of cheniers that line the Suriname coast, first as bayhead cheniers at a time when refraction and dissipation of waves from the northeast across the estuary mouth were much less than at present due to less sandy infill. The changes in the orientation of these cheniers to a more open-coast east–west alignment have gone apace with the northward asymmetric progradation of the Suriname side (Fig. 7). The cheniers are incorporated in a muddy plain built from Amazon mud. Sand stored by the large estuarine sand platform has been redistributed along the Suriname coast as cheniers as far west (nearly 150 km) as the approaches to the next estuary on this coast, the Suriname River estuary (Anthony et al., 2019a). Multi-decadal shoreline mobility on this Suriname side has been shown to fluctuate largely with episodes of welding of mud from passing mud banks when rapid accretion of up to 100 m can occur, followed by nearly proportionately important erosion of mud attended by shoreline reworking and concentration of sand to form cheniers (Anthony et al., 2019a). The long-term infill pattern and chronological frame of the accretion dynamic on this coast, involving chenier ridges and muddy progradation from Amazon mud, still need to be determined. The present Maroni river-mouth setting and morphology involve a complex series of primary mud and sand transport processes and pathways, as well as more local sand pathways that are conceptually summarized in Fig. 8. These pathways result from a combination of large-scale drivers, such as river outflow, tidal pumping within the axis of the estuary, wave modification and wave-generated longshore transport downdrift of the mouth on the Suriname coast, and morphological feedback effects such as mud-bank migration and mud intrusion into the Maroni estuary. But there are also more local effects at play, such as sand transport rotation involving counter-drift along the beach adjacent to the estuary on the French Guiana side (Jolivet et al., 2019a).

Notwithstanding an asymmetric pattern of accretion, the mouth of the Maroni has significantly prograded, generating a morphology akin to that of a delta, rather than an estuary. This pattern of coastal development in the vicinity of a river mouth involving muddy growth with interspersed cheniers is a common feature of many deltas associated with an adequate supply of bedload-sized sediment in a context of ambient mud abundance, as in the cases of the deltas of the Huanghe (e.g., Saito et al., 2000), the Changjiang delta (Hori et al., 2001), and the Mississippi (McBride et al., 2007). However, in some deltas such as the Red River (van Maren, 2005), the Mekong (Tamura et al., 2012), and the Ayeyarwady (Anthony et al., 2019b), sandy deposits form discrete barriers separated from each other by distributary mouths. These barriers develop from mouth-bars that progressively aggrade under the influence of waves, and notably swash processes, to finally isolate back-barrier spaces that are eventually filled by mud, giving a superficial impression of chenier-plain development. Intermediate stages such as those shown by the Maroni are also associated with estuaries (e.g., Anthony, 1989, 2006; Hein et al., 2016).

It is possible to further distinguish, among the type 2 estuaries identified by Anthony et al. (2013) on plan-view morphological

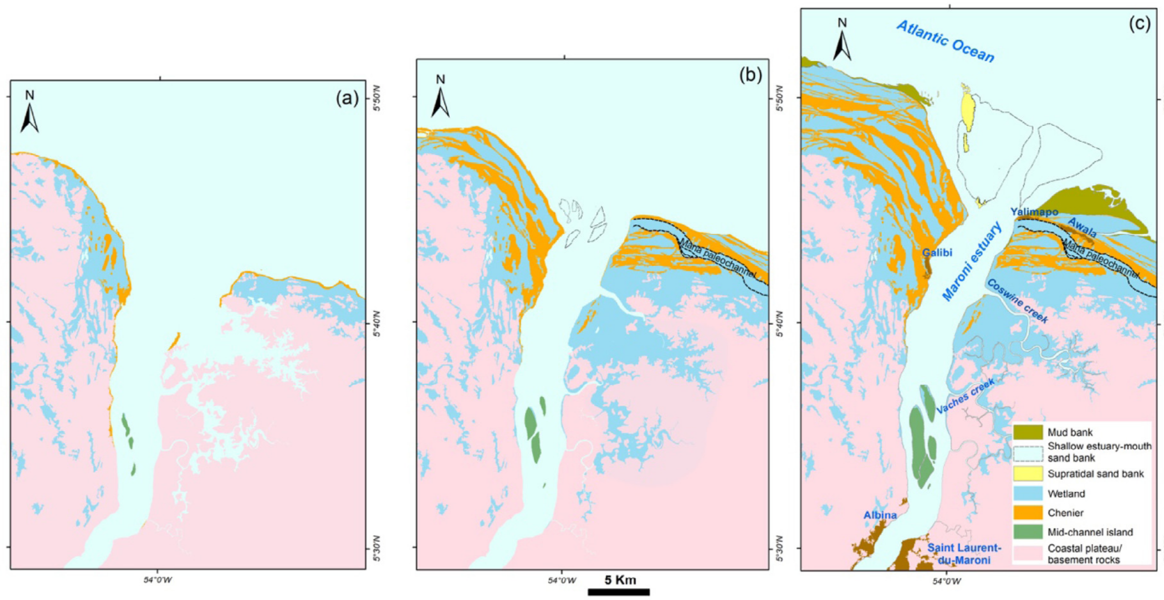

Fig. 7. Simple schematic three-stage evolution of the Maroni estuary following the Holocene sea-level rise and still-stand: (a) young estuary flooded following the post-glacial rise in sea level and comprising bayhead cheniers; (b) median stage of estuarine development showing the increasing development of cheniers associated with the development of a coastal mud plain sourced by the distant Amazon, (c) present largely infilled estuarine stage and transition to delta associated with Maroni sand supply to the downdrift Suriname coast.

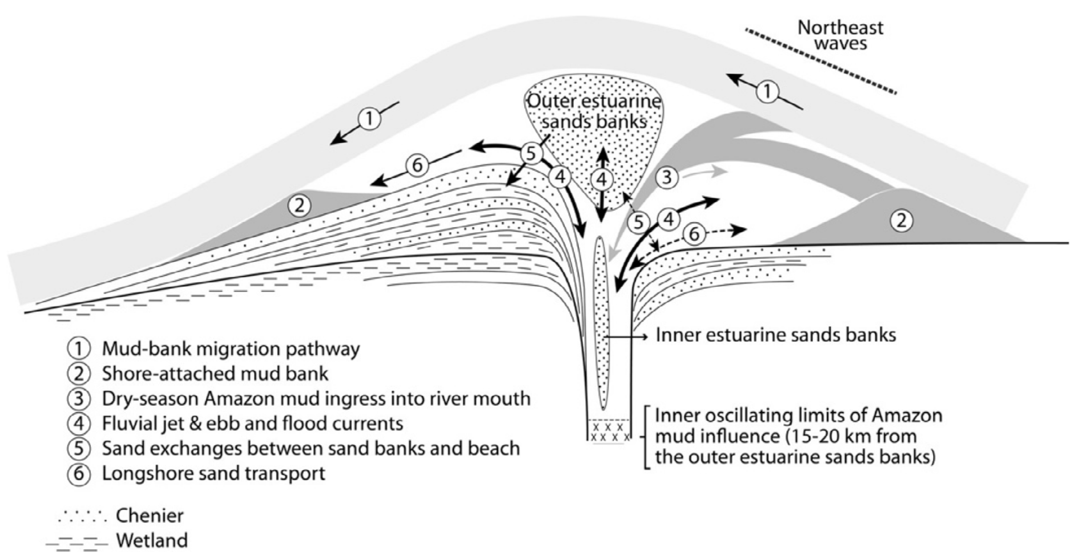

Fig. 8. Sediment transport processes and pathways in the Maroni estuary.

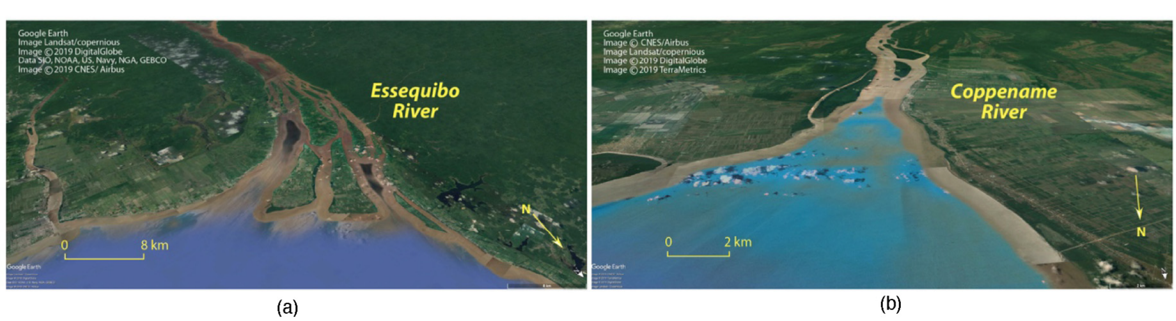

Fig. 9. The mouths of the Essequibo River, Guyana (a), showing advanced infill and evolution towards a delta, and the Coppename River (b) where a large infilling estuary is still prevalent.

grounds, between those close to a delta morphology and those that are still far from this morphology. Among the former, the only one that appears to fit into this category with the Maroni is the Essequibo River (catchment size: 154,860 km^2) in Guyana (Fig. 9a). Although several other estuaries are characterized by a relatively 'rectilinear' main channel axis with no diversion by a mud cape formed from Amazon mud, they are estuaries still largely subject to infilling, a fine example being the Coppename River (catchment size: 54,000 km^2) estuary at the border between Suriname and Guyana (Fig. 9b). These estuaries are still far from the delta stage, while a few estuaries pertaining to the 'small' type 1 category have fairly rectilinear estuaries with mouths fixed by bedrock (Gardel et al., 2019). In being a significant purveyor of fluvial sand for open-coast chenier development in Suriname, without having received marine sand as is commonly the case of many infilling estuaries, the Maroni has progressively acquired the makings of a delta. It has developed from a deep open estuary with bayside cheniers to a strongly infilled ebb-dominated estuary and a deltaic purveyor of sand for coastal progradation (Fig. 7). Morphologically, the dominant influence of the river, aided by strong tidal pumping, is clearly manifest in the open and non-diverted nature of the large mouth, reflecting clear mitigation of wave influence (Anthony, 2015), and by the pervasive ebb-dominated orientation of the dunes on the estuarine sand platform. Within this overall deltaic development, advection of Maroni sand towards Suriname has been the overarching driver of river-mouth and coastal accretion. This corresponds to the dominant longshore transport direction on the Guianas coast downdrift of the wave-dissipating Maroni estuarine sand platform where open-coast wave influence in Suriname becomes strong once more. The ebb-dominated channel identified by Ross et al. (2019) on the Suriname side is clearly consistent with estuarine infill and with this sand export pathway, whereas ingress of the Amazon mud, which we deem to be largely mobile up and down the estuary, without dominating long-term estuarine infill, occurs through the flood-dominated channel in the east, also identified by these authors. As infill has proceeded, wave influence has diminished, reflected by the change from bayside cheniers to open-coast cheniers. This wave influence is now limited to the peripheral beaches, and especially the Suriname chenier coast downdrift of the mouth. This wave influence has always been periodically mitigated by the dissipative effect of passing mud banks since the inception of the Maroni River estuary.

5. Conclusions

1. The Maroni River exhibits an estuary encased in a narrow lower river valley with a limited area of estuarine tidal flat development, while displaying a large sand-filled shallow mouth. The estuary lies in the pathway of mud banks migrating alongshore from the mouths of the Amazon to those of the Orinoco.

2. The sand-rich nature of the lower Maroni River reflects significant fluvial bedload supply from the crystalline catchment rocks, while Amazon mud seems to be essentially restricted to seasonal dry-season intrusion in the estuary and rainy-season expulsion with little net sedimentation because of limited overbank estuarine sediment accommodation space.

3. The geomorphic observations reported here show complementarity with both physical modelling (Do et al., 2020) and remote sensing approaches (Abascal Zorrilla et al., 2020) in gaining a better understanding of the dynamics and evolution of estuaries.

4. Advanced infill of the Maroni River estuary and active fluvial sand supply to the coast have led to the emergence of a delta marked by the construction, in Suriname, of numerous sandy cheniers within a muddy coastal plain built from mud supplied by the Amazon. This pattern of geomorphic development, from an estuary to a delta incorporating cheniers, is typical of many river deltas elsewhere.

5. The infill pattern of the Maroni River estuary, its evolution towards a delta, the associated asymmetric coastal progradation, and the geochronological frame of these events, will require further studies.

CRediT authorship contribution statement

Antoine Gardel: Conceptualization, Methodology, Field work, Writing - original draft. **Edward J. Anthony:** Methodology, Field work, Writing - original draft, Reviewing and editing. **Valdenira F. dos Santos:** Field work, Visualization. **Nicolas Huybrechts:** Methodology, Validation. **Sandric Lesourd:** Methodology, Field work. **Aldo Sottolichio:** Methodology, Validation. **Tanguy Maury:** Field work. **Morgane Jolivet:** Field work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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