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# Genesis and sedimentary record of blind channel and islands of the anabranching river: An evolution model

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ABSTRACT

Blind channel (BC) is a fluvial feature formed by attachment of a lateral sand bar to an island or riverbank. It consists of a 10- to 20-m wide and hundreds to thousands meters long channel, parallel to the island or bank, closed at its upstream end by accretion to the island. It is an important feature in anabranching rivers that plays an important role in both the island formation and river ecology. This paper discusses the formation processes, functioning, evolution, and the sedimentary record of a blind channel, related landforms, and its context on island development in the Upper Paraná River. The evolution of this morphologic feature involves (1) formation of a lateral or attachment bar beside an island with the development of a channel in between; (2) vertical accretion of mud deposits during the flood and vegetal development on the bar; (3) the upstream channel closure that generates the blind channel; and (4) annexation of the blind channel to the island. A blind channel is semilotic to lentic, that is not totally integrated to the dynamics of the main active channel and that acts as a nursery for fingerlings and macrophytes. The sedimentary facies succession of BCs are relatively simple and characterized by cross-stratified sand covered by organic muddy sediments. Based on facies analysis of 12 cores, we identified a succession of environments that contribute to the formation of islands: channel bar, blind channel, pond, and swamp. Blind channel formation and its related bar-island attachment are relevant processes associated with the growing of large island evolution in some anabranching rivers.



## 1. Introduction

Blind channel (BC) is a channel closed in its upstream mouth developed alongside islands or riverbanks through processes of lateral bar attachment (Stevaux, 1994; Leli et al., 2013). It is a very common morphology in the Upper Paraná River (Leli et al., 2013; Leli, 2015) — where it is locally called *ressaco* — and is also registered in other tropical anabranching rivers such as the Madeira, Amazonas, and Negro (Latrubesse and Stevaux, 2015). Based on a four-decade analysis of aerial-photography and satellite images, Stevaux (1994) presented the first reference to the BC in the Upper Paraná, identified lateral bar attachment as a main process in BC generation and floodplain development, and estimated a lateral growth rate of 500 mm $y^{-1}$. Lateral bar attachment is the pioneer process in BC formation, and they are related to zones of low-flow velocity generated by flow separation at the head of preexisting islands (Santos, 2010). As an environment protected from the river flow, BCs offer sustainability for specific species and act as a link between the lentic and lotic conditions. Consequently, BC environment has remained the focus of study by biologists and ecologists in the Upper Paraná River (Agostinho et al., 2004a, 2004b). In this paper, we present a model for genesis and evolution (from the bar formation phases to its complete incorporation to the island), functioning (hydrodynamic and water quality characteristics), and stratigraphic architecture (facies analysis and model) of the BC in the Upper Paraná River (Fig. 1).

## 2. Study area

The Upper Paraná River and its main tributaries are practically a sequence of large artificial lakes constituted by 150 large reservoirs (>15 m in height). A 235-km reach from Porto Primavera to Itaipu Hydroelectric Power Station is the only sector without direct impoundment and the focus of this study (Fig. 1). The flow of the Upper Paraná is regulated and experienced strong changes in its flow regime (magnitude, recurrence, and permanence), tension (flattering in the annual hydrograph), suspended sediment concentration (reduction more than 100 times after dam construction), and armoring effect in the

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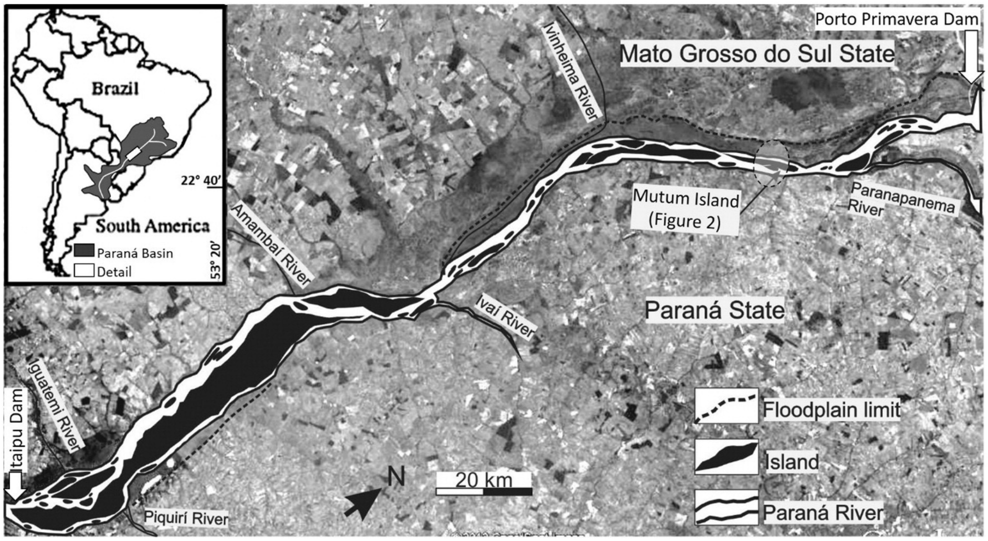


**Fig. 1.** The Upper Paraná River at the study reach. The anabranching reach of the Upper Paraná River from the Paranapanema River mouth (top right) to the Piquirí River mouth (bottom left) with 264 islands.

bed channel (Stevaux et al., 2009). As most of the large rivers of the world, the Upper Paraná River is anabranching and has been described as low to moderate anabranching with low sinuosity and a relatively abundant sandy load (Latrubesse, 2008). Elongated islands and sandy bars (Fig. 1) characterize the channel in the studied area. The islands are varied in terms of size (since few tens to thousands of meters in length), age (decades up to thousands of years), and genesis (intra- or extra- channel processes) (Stevaux et al., 2009; Leli, 2015). The river channel in the study reach is 4 km wide and is controlled in its left bank by the erosion-resistant sandstone of the Caiuá Formation. The BC research has concentrated on Mutum, Porto Rico, and Santa Rosa Islands, which are located near Porto Rico Town, 25 km downstream of the Paranapanema River mouth at the border of the states of Paraná and Mato Grosso do Sul, south of Brazil (Figs. 1, 2).

The BCs were surveyed with a topographic differential global positioning system (PROMARK 100–200). Water flows were measured with an ADCP RD, Rio Grande, 600 kHz; bathymetry was surveyed with a FURUNO GP 1650-F echo sound; and water parameters were measured with an Horiba multiparameters equipment. The decadal temporal and spatial evolution of the BC was reconstructed using vertical aerial photographs from 1963 and 2013 satellite images. Facies analyses were based on the study of 12 cores (Fig. 2), and absolute dating (9 $^{14}C$ and 1 luminescence dating) allowed the estimation of sedimentary rates and to sustain a temporal model for BC evolution. Vegetation data were obtained from Fachini (2001), Corradini et al. (2008), Stevaux et al. (2013), Ramirez (2014), and Zviejkovski (2013).

## 3. Morphology, hydrology, and limnology

The BC is a geomorphological element developed approximately parallel to islands and river banks, 10- to 20-m wide upstream closed and downstream open, with linear extent of hundreds to thousands of meters (Fig. 3). Water depth in the BC varies with the variability of the river stage hydrology; but in average, it reaches 3 m at the mean

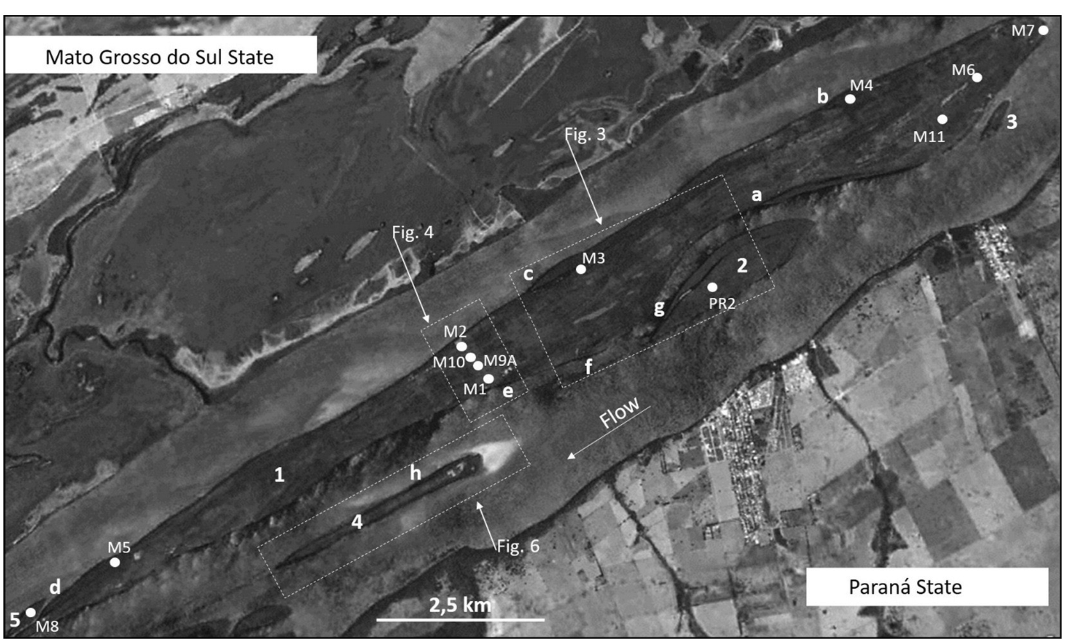


**Fig. 2.** Mutum and satellite islands. Detail of the study area: Mutum (1), Porto Rico (2), Catarina (3), Santa Rosa (4), and Nanini (5); a, b, c, d, e, f, g, h studied blind channels; M1, M2, … borehole sites.

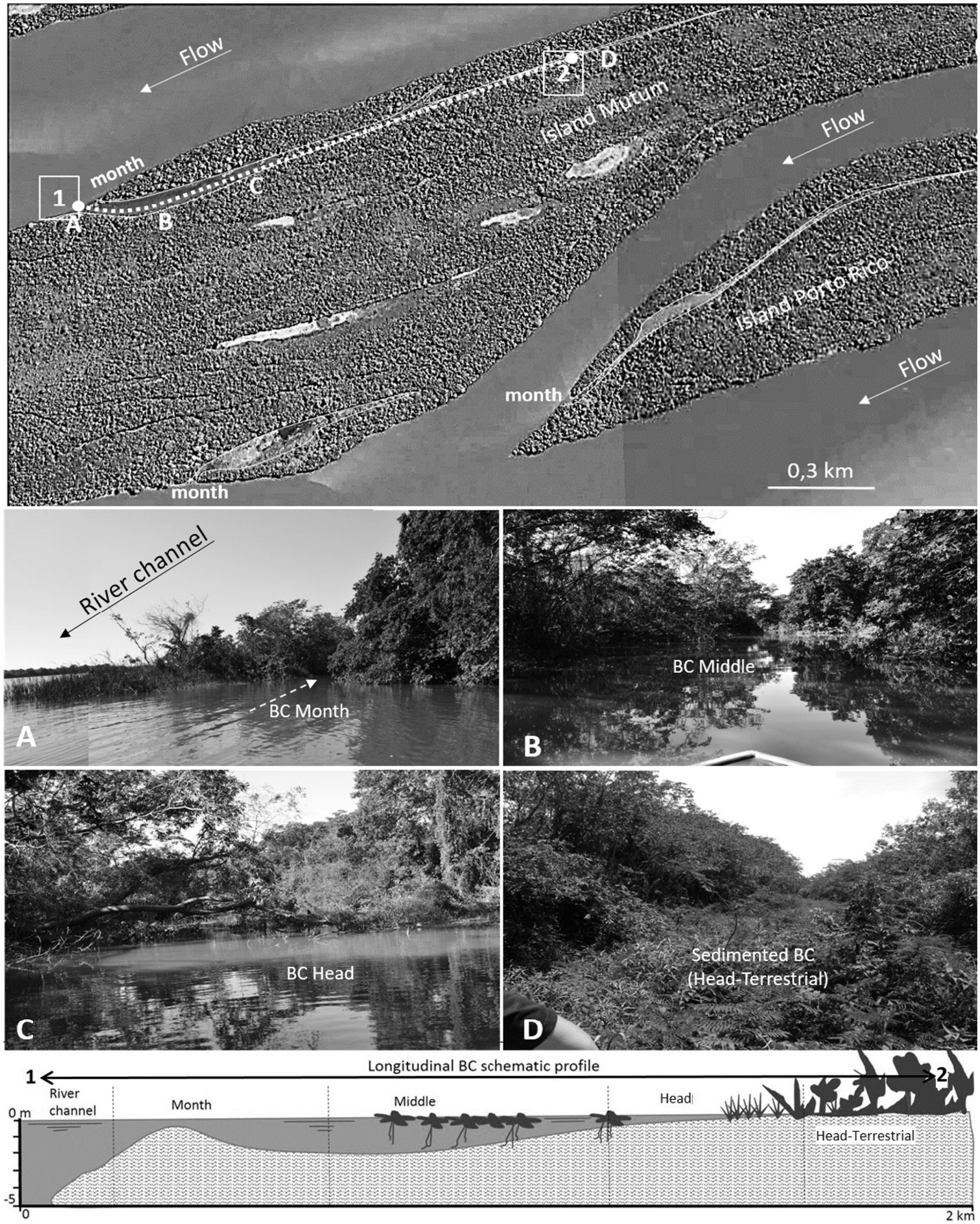


**Fig. 3.** The BC subenvironments and transversal topographic profile. Top: BCs in the Mutum and Porto Rico Islands (yellow traced lines). See over the island surface the scars of ancient BCs that evolved to elongate lakes or swamps. Middle: The Mutum Island BC subenvironments (see the upper photo for localization). Bottom: Schematic topographic longitudinal profile (with traced line in top photography) (A) mouth reach, note mouth bar with grassy vegetation (eupotamic environment); (B) middle reach, typical channel morphology, but with very low velocity or lentic flow (parapotamic environment); (C) head reach (parapotamic to paleopotamic environment); and (D) head-terrestrial reach (explanation in the text). Topographic data were conducted with transit level and total station.

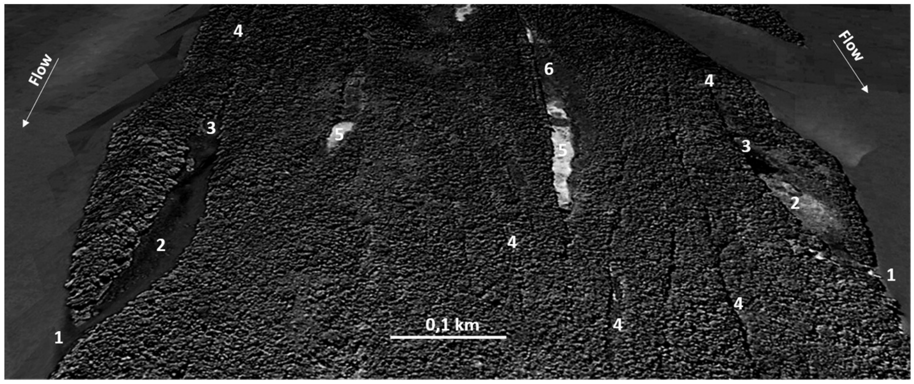


**Fig. 4.** Morphologic features on Mutum Island. Subenvironments of active BCs: mouth (1), middle (2), head (3), and head-terrestrial (4). After its incorporation to an island, BC becomes an elongated lake (5) and swamp (6).

**Table 1**
Connectivity degrees and physical characteristics of river channel and BC reaches.

| Reach | River channel | Mouth (Fig. 3A) | Middle (Fig. 3B) | Head (Fig. 3C) | Terrestrial (Fig. 3D) |
|---|---|---|---|---|---|
| Flow condition | Lotic | Semilotic | Semilotic- Lentic | Lentic | |
| Connectivity degree[a] | Eupotamic | Eupotamic-parapotamic | Parapotamic | Paleopotamic | Terrestrial |
| Vegetation | Algae, macrophytes | Macrophytes, algae and grass (in the mouth bar) | Macrophytes, algae and grass | Grass, algae | Shrubs, trees, grass |
| Bottom sediment | Fine-medium sand | Fine-muddy sand | Mud and organic mater | Mud and organic mater | Muddy soil |

[a] According to Ward and Stanford (1995) classification.

water level (Komatsu, 2003; Bubena, 2006). At local scale, depth along the BC becomes shallow toward the upstream direction (Fig. 2).

The ecological connectivity in the BC ecosystem also varies with the hydrological river stage and with the position along the channel. Using as a reference the mean annual water stage, characterizing four subenvironments for hydrologic connectivity is possible: mouth, middle, head, and head-terrestrial reaches (Figs. 3, 4; Table 1). The *mouth reach* is characterized by a *eupotamic* condition (in the concept of Ward and Stanford, 1995), with an active exchange between the river and BC water. The sediment transported by the river is deposited in the BC mouth and forms a *blind channel mouth bar* that emerges at mean water level (Figs. 3, 4). However, this morphologic feature can be eroded under specific hydrological conditions.

The *middle reach* undergoes semilotic to lentic flow under *parapotamic* conditions at the mean river water level. The transference of water from the river channel to the BC does not occur in the middle reach. It has a predominant influence of terrestrial variables (phreatic water and vegetal remains from trees of the island and soil sediment transported from the island to the BC by Hortonian flow during the rain). The *head reach* of the BC is a *paleopotamic* swampy environment with root vegetation development. This reach can dry out during low water level stage. The *head-terrestrial reach*, located in the upstream sector, is very similar to that of the island itself. Shrub and tree vegetation are common, and initial pedogenesis may occur.

The river water level controls the BC hydrology under four conditions (Figs. 2, 3): (i) *River phase* occurs in high water level with the

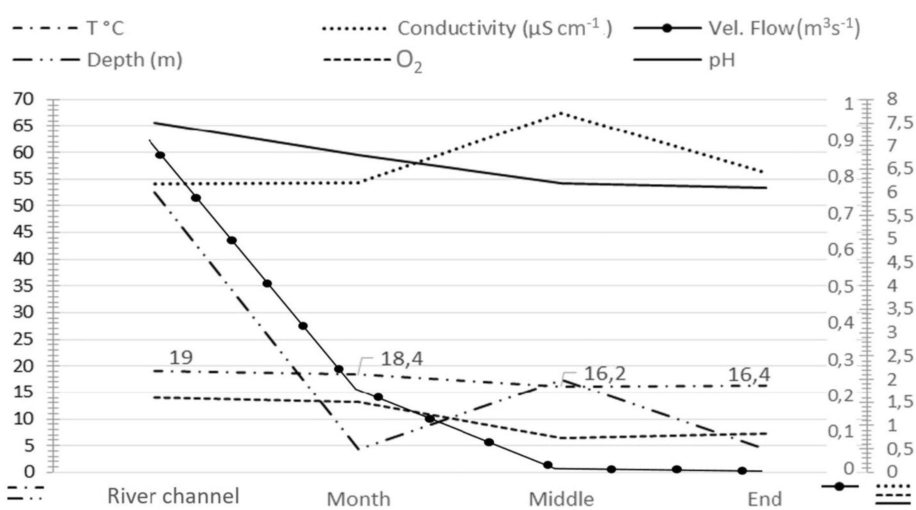


**Fig. 5.** Abiotic water parameters in river channel and BC reaches in the winter period.

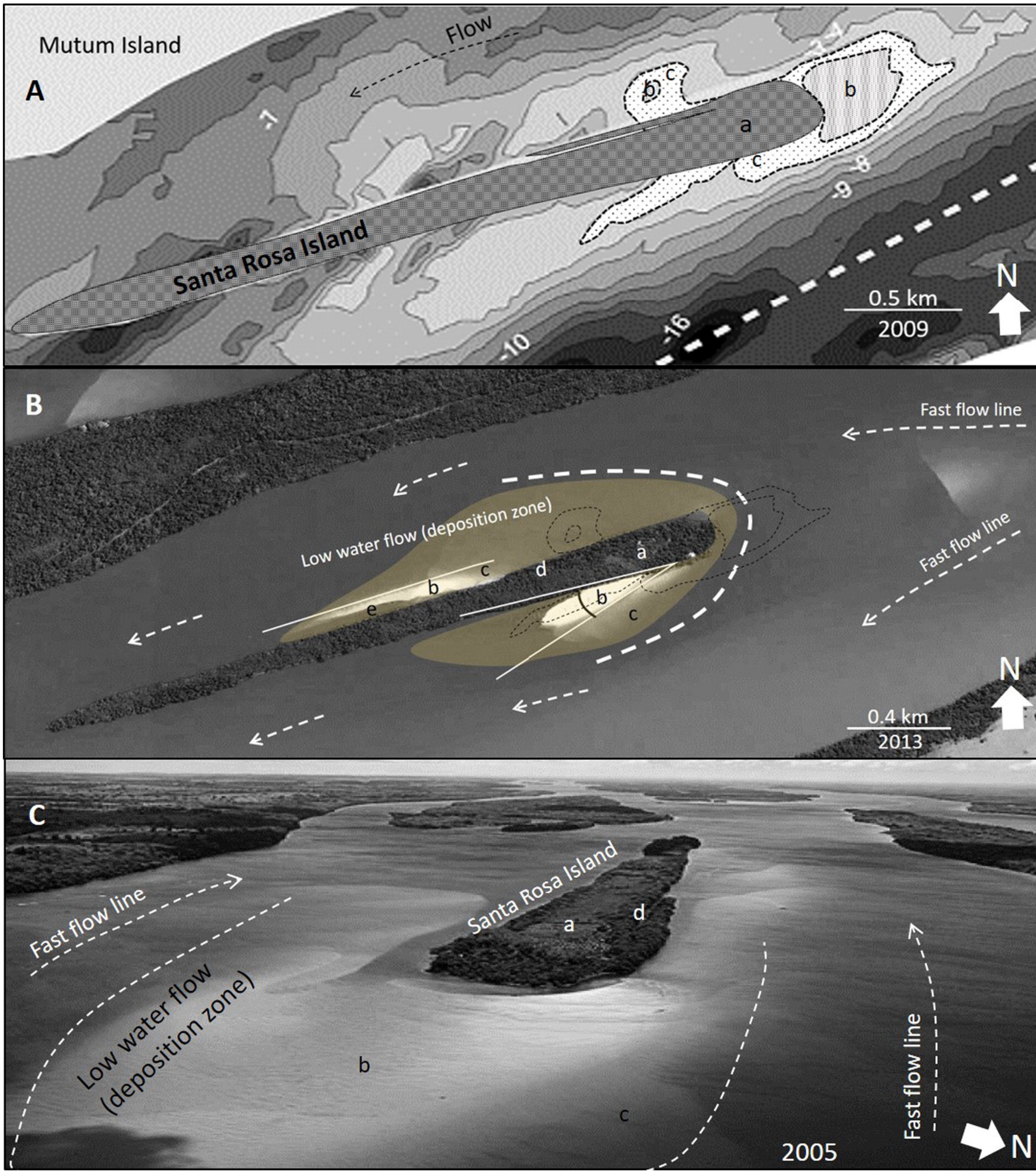


**Fig. 6.** Flow separation at Santa Rosa Island. (A) Bathymetrical map (isobates in meters): Santa Rosa Island (a), lateral (c), and frontal (b) attachment bars, blind channel (d), channel thalweg (traced white line). (B) Island divides the river flow (yellow traced arrows) and generates a zone of low flow velocity (U-shape yellow traced line) that controls bed material sedimentation and bar formation. Oblique (25°) and parallel lateral bars. Observe wide deposition area defined by low velocity zone and bar-island channel formation (e). (C) Frontal view (2005). Frontal and lateral depositional area defined by low velocity flow line. Source: (A) Mod. Santos (2010); (B) Google Earth™, sensor SPOT, 2013; (C) Mod. Moss and Moss (2005).

water flows into the BC, generating a waning flow into the BC. At this phase, not only water but also sediment, nutrients, and even fish enter into the BC environment. (ii) *BC phase* occurs during the water level drop and the water stored in the island runs to the river in an inverse flow through BC. The BC can also trap incoming sediment and organic material (especially vegetal remains) from the island soil erosion; (iii) *Lentic phase* occurs during major time, in which the water body acts like a pond. This phase is marked by intensive biological activity (Agostinho et al., 2004a, 2004b); (iv) *Reactivation phase* occurs in extreme floods when the river water overflows the BC, erodes the occluded upstream mouth, and reacts with the ancient bar-island channel (see the definition below of bar-island channel). The reactivation can be temporary or permanent, resulting (sometimes) in a new island.

Physical parameters of a BC's water vary in each subenvironment and for different hydrological phases (Fig. 5; Table 1). Dissolved $O_2$ and pH decrease from the river channel to the BC. Lentic flow conditions with high biological activity in the BC consume dissolved $O_2$ and, in extreme cases, tend to eutrophication. High organic content leads to

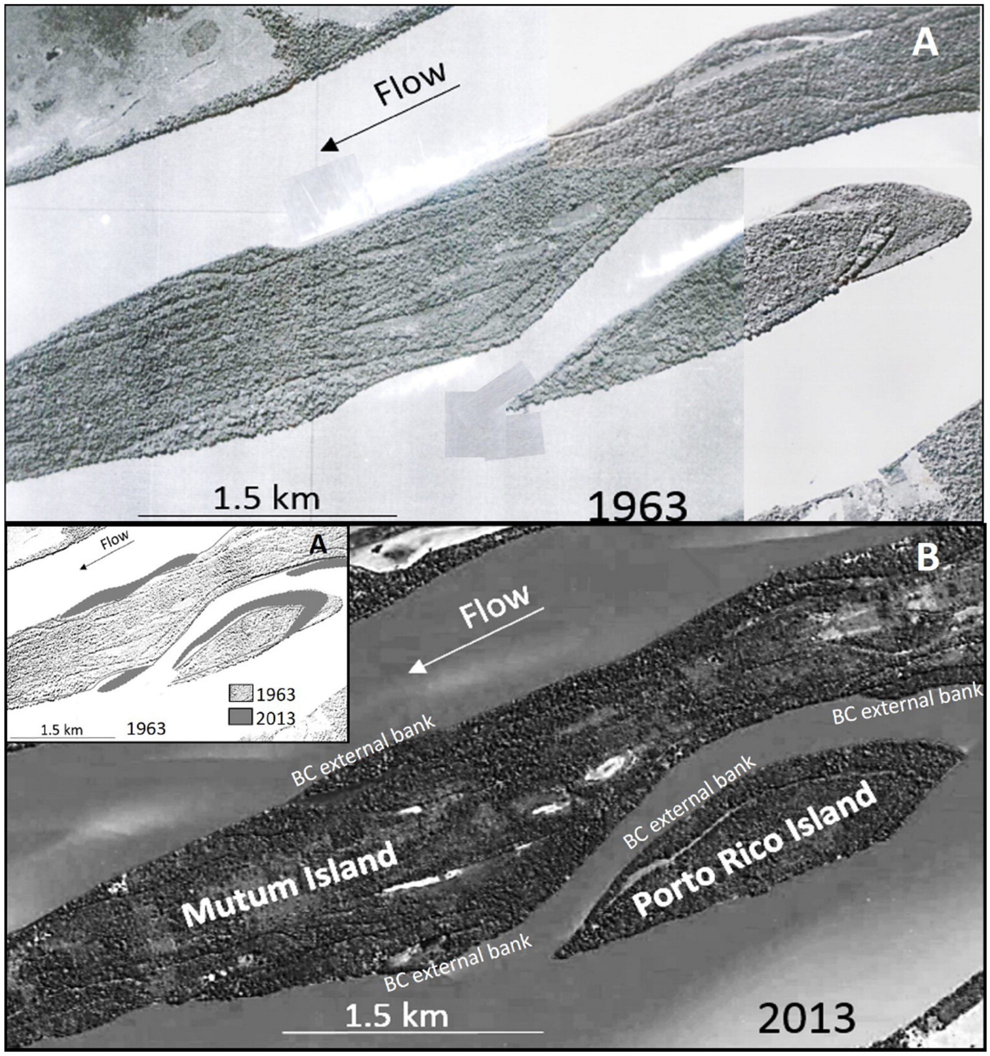


**Fig. 7.** Landscape changes in a time-lapse of 50 years: from lateral bar to BC in the Mutum and Porto Rico islands. Top: 1963, lateral bars and bar-island channels developed beside islands. Bottom: situation in 2013. Middle: Yellow areas are island accretion in 50 years. Sources: (A) 1963 aerial photography (ITCF); (B) Google Earth™, SPOT sensor, 2013.

increasing water acidity (pH 6.1), which is lower than the slightly alkaline river water (pH 7.6). Once the BC has shallow depth and slow to lentic flow, high water temperature would be expected; but the opposite happens. Unlikely to expected, the water temperature is 2° to 3 °C lower than the river channel water because the BC is characterized by shady environments, with high trees on the banks, and reduced insolation (Figs. 3, 5).

## 4. Genesis and evolution

The Mutum Island divides the main channel of the Paraná River into two secondary channels: the left one with 1720-m width, *Qm* 7500 $m^3 \cdot s^{-1}$, 5-m average depth, and 10-m thalweg; and the right one with 980-m width, *Qm* 2500 $m^3$ $s^{-1}$, and 3-m depth average. Flow division generates a U-shape lower velocity zone immediately upstream from the island (Fig. 6).

The low velocity zone prevents bedload transportation, and an elongated bar (*lateral and attachment bars*) begins to be formed at 10 to 25 m from the island forming a *bar-island channel* (Santos, 2010). It marks the beginning of the BC formation (Stevaux, 1994; Santos, 2010). The bar-channel width and shape (angle between the bar and island) is controlled by the flow velocity and the island head morphology. Souza Filho (1993), Drago et al. (2013), and Leli (2015) identified similar processes in sand bars formed at the upstream face of islands in the Upper and Lower Paraná River. Between the bar and an island, a *bar-island channel* is then formed, and the BC originates (Fig. 6). Lateral bar stabilizes by vegetal cover (grass and shrubs), and sand deposition continues to happen in the downstream end by progradation, which leads to an increase in the bar-island channel length. Once stable, the bar evolves by vertical aggradation of fine mud, sandy mud during the floods. The vertical accretion process continues until the bar reaches the island height, which is approximately correlative to bankfull stages. During floods, bed channel sediments, logs, and branches tend to jam the upstream sector of the bar-island that, once attached to the islands or margin banks, create the BC. Island vegetation (trees and shrubs) colonizes the BC external bank, and the taller species are found in the most emerged areas where vertical aggradation was more active (Zviejkovski, 2013). The evolution of some BCs of the Mutum and Porto Rico islands is compared from 50-year interval images (Fig. 7). In 1963, lateral bars and the corresponding bar-island channels at the right and left margins of the Mutum Island as well as in the right margin of the Porto Rico Island are present. Fifty years after (2013), all the lateral bars are more developed and the presently active BCs were created.

Through time, the downstream mouth of BC can also be closed, forming elongate ponds, which are entirely incorporated to the island (Fig. 3). The continuity of this process gives to the island a peculiar surface morphology with linear parallel scars related to the accretion of ancient BCs (Figs. 3, 4, 7). Overtime, the scars tend to disappear owing to

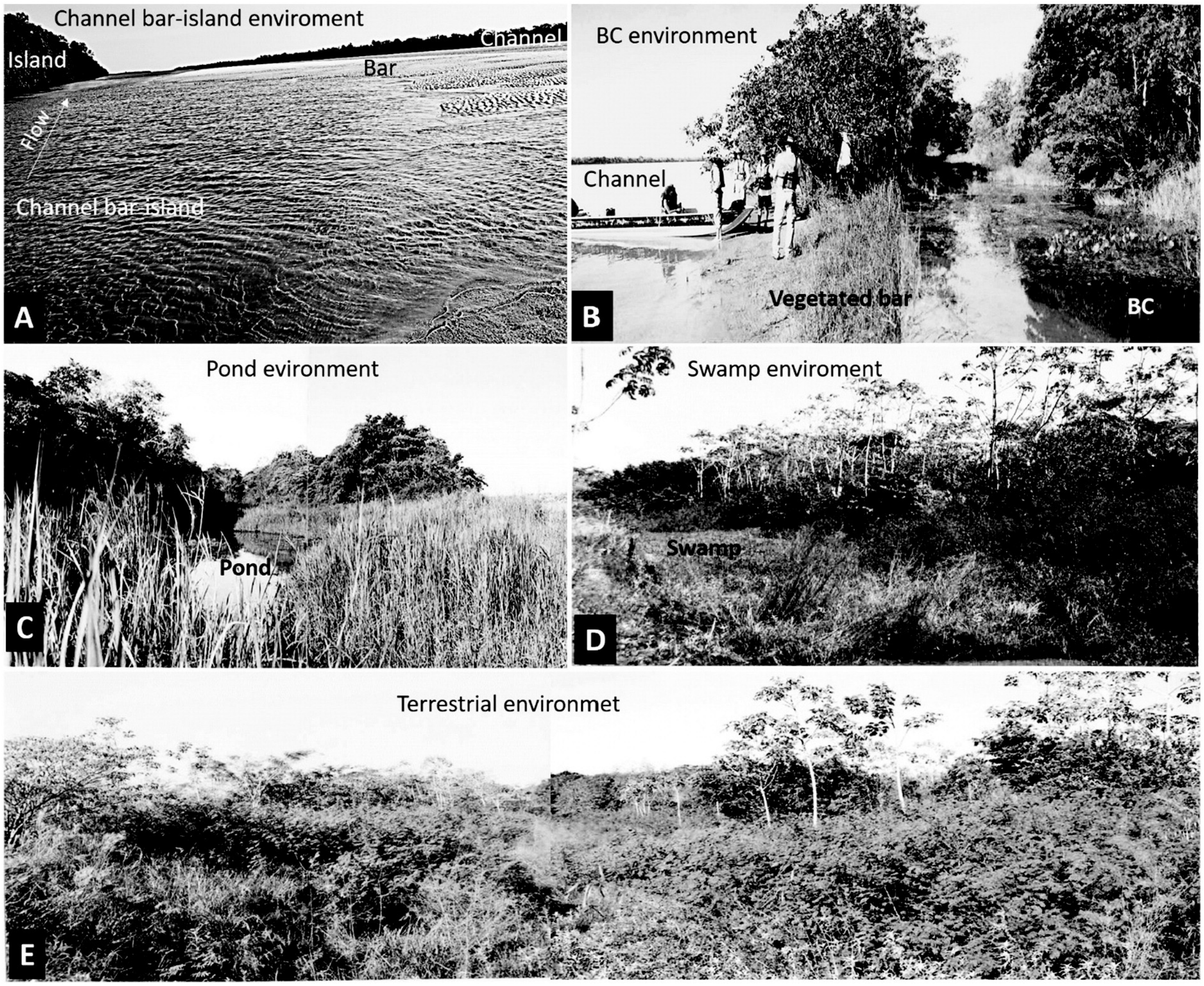


**Fig. 8.** Evolutional phases from BC formation to its incorporation to the island. Integrated illustrative environmental evolution of the vegetation succession by integrating units at different locations in the Mutum Island. (A) Bar phase: downstream mouth of a bar-island channel in eupotamic condition; (B) BC phase: view of BC mouth under parapotamic condition (observe macrophytes in BC, grass in the lateral bars, and trees and shrubs in the external bank of a blind channel); (C) lake phase: BC was closed in upstream and downstream mouths; (D) swamp phase: the progressive sedimentation by floods changes lake to swamp; (E) terrestrial phase: island surface is totally covered by tree vegetation typical of island forest.

the continuity of overbank sedimentation, pedogenesis becomes active on the island alluvial deposits, and Eutrophic Neosoil starts to develop (Stevaux et al., 2006). Based on pollen analysis, Zviejkovski (2013) concluded that the complete evolution of the island riparian forest succession over the newly formed surface at the Porto Rico Island took over 150 years (Fig. 8).

In summary, formation, evolution, and incorporation of BC to the island involve five successive phases with the related growing in vertical accretion: 1 – lateral bar deposition and bar-island channel construction (Fig. 8A); 2 – bar-island channel is closed at the upstream end, becoming a BC (Fig. 8B); 3 – BC closes at its downstream end and became transformed in a pond (Fig. 8C); 4 – with the active overbank sedimentation, the pond changes to swamp (Fig. 8D); and 5 – the continuity of overbank sedimentation generates a totally terrestrial condition, and the new surface begins to be colonized by typical riparian forest. Depositional surface can reach the elevation of the major island by vertical accretion (Fig. 8E).

## 5. Facies analysis and sedimentation

As discussed above, once formed, the BC can be totally incorporated/accreted into the island. The sedimentary record of the BC evolution and incorporation to island was identified by the analysis of 12 cores drilled in the Mutum and Porto Rico islands (Fig. 2). The complete vertical profile (Fig. 9) for island deposits starts with fine to medium cross-stratified (Facies Sp, St), massive sand (Facies Sm which is related to channel processes and bed sediments), and the generation of lateral bar and the bar-island channel. The channel facies are overlaid by laminated muddy fine sand (Facies Fl) intercalated with massive muds (Facies Fm) and rippled and massive fine sand (Facies Sr, Sm), with vegetal remains (leaves and fragments of branches) deposited in the BC. Organic laminated mud, rich in leaf and branch remains (Facies Fm and Fls), records the pond phase. The preservation of lamination indicates that water depth was sufficiently large to prevent the development of root vegetation and sediment bioturbation. The stage of swamp is identified by mottled mud (Fm facies). Pedogenesis and initial soil formation can be present at the top, evidencing a transitional terrestrial condition.

The BC vertical accretion rates were estimated by $^{14}C$ dating of the sediments recovered in Mutum Island (Table 2). In the case observed in the core M1, after bar-island channel, BC acted for 130 years to evolve to pond at a sedimentary rate of 3.8 mm $y^{-1}$. The next phase took 400 years (sedimentary rate of 1.5 mm $y^{-1}$). Terrestrial phase extended for 300 years at a sedimentary rate of 2.6 mm $y^{-1}$, with evidence of pedogenesis mainly the last 150 years. It is remarkable that as the age of terrestrial phase formation obtained by facies and chronological analysis is very similar to that obtained for forest formation. Based on botanical criterion

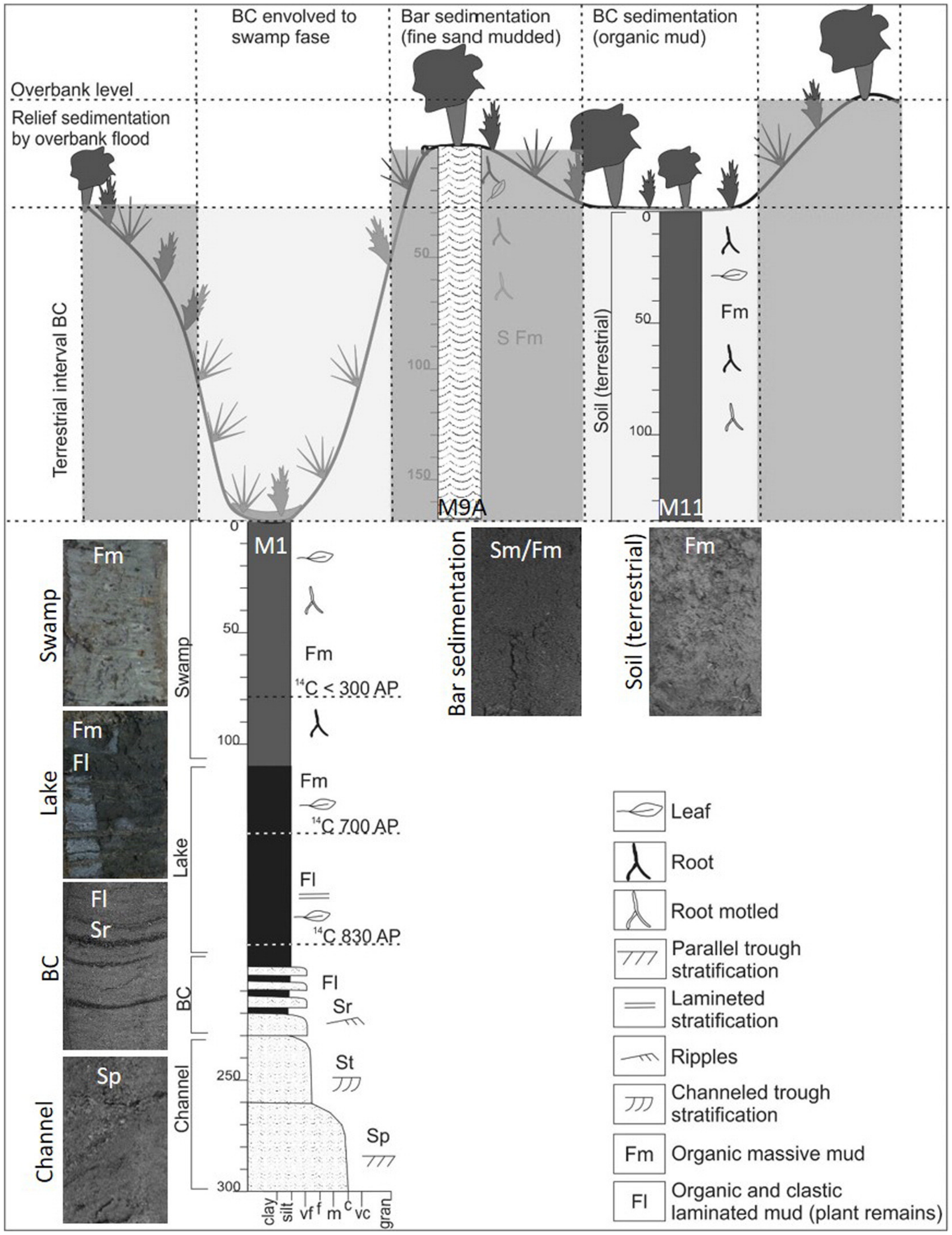


**Fig. 9.** The ideal vertical profile for Mutum Island is composited by cores M1, M9A, and M11. The Sp and St facies correspond to channel and bar environment. The Sr and Fl facies correspond to BC and lake environment; Fm by root bioturbation of the swamp environment and Fm with pedological evidence of island environment. Topography is also schematic.

(trunk diameter), a period of 134 years was estimated for forest installation (Zviejkovski, 2013).

The vertical facies model for the entire sequence of island deposits was constructed by using cores M1, M9A, and M11 (Fig. 9).

## 6. Blind channel and island evolution

The oldest age of sediments observed in the geological cross-section on Mutum Island was $^{14}$C 8200 BP at the center of the island. Younger ages of $^{14}$C 3600 BP, $^{14}$C 830 BP, and $^{14}$C 700 BP were obtained consecutively from the center to the border (Fig. 10). The nuclear-core island formed around 8.5 ky BP (M9A), when the river bed was positioned at a lower level compared to the present. The growing was not gradual, but probably abrupt episodic stages, according to lateral bar and BC formation. Vertical growth developed at a sedimentary rate varying from 0.7 to 3.0 $mm \cdot y^{-1}$ (estimated at M1 and PR2). Sedimentary rates are very similar to those found by Stevaux and Souza (2004) for the floodplain in the same area.

A model for island growth by BC accretion in this is postulated in Fig. 11. From a primitive central bar (phase 1), the nuclear island was

**Table 2**
Core ages at Mutum and Porto Rico islands, (loc. of cores in Fig. 2).

| Core | Depth (cm) | Age (cal. to $^{14}C$) | Dating methods | Location | Laboratory |
|---|---|---|---|---|---|
| M1 | 78 | Modern | $^{14}C$ | 22°45.734′S/53°17.764′O | CAIS |
| | 140 | 700 | $^{14}C$ | 22°45.734′S/53°17.764′O | CAIS |
| | 190 | 830 | $^{14}C$ | 22°45.734′S/53°17.764′O | CAIS |
| M2 | 35 | Modern | $^{14}C$ | 22°45.538′S/53°17.882′O | CAIS |
| M8 | 320 | 585 | $^{14}C$ | 22°46.724′S/53°21.088′O | CAIS |
| M9A | 515 | 8.200 | $^{14}C$ | 22°45.700′S/53°17.778′O | CAIS |
| M10 | 450 | 3.600 | $^{14}C$ | 22°45.593′S/53°17.854′O | CAIS |
| M11 | 200 | 1.700 | $^{14}C$ | 22°45.170′S/53°15.621′O | BA |
| PR2 | 260 | 920 | $^{14}C$ | 22°45.448′S/53°15.946′O | CAIS[a] |

CAIS - Center for Applied Isotope Studies, Geórgia, USA; BA – Beta Analytic, Flórida, USA; M = Mutum Island, PR = Porto Rico Island.
[a] Zviejkovski (2013).

first established. When this island began to divide river flow, the low-velocity zone was established and the lateral bar began to be formed. Vertical aggradation in this bar permitted BC formation and annexation in phases 2, 3, and 4. In phase 5, another lateral bar is forming, and the process continued to enlarge the island. The maximum height of the island is reached, controlled by bankfull level. The intensive alteration on sedimentary load introduced by dam regulation prevents the inclusion of hydrosedimentary data in this model.

## 7. Conclusion

Some questions and inferences can be made based on the obtained results concerning BC processes, morphology, and evolution.

### *7.1. Is there a limit for island growth and BC formation?*

In anabranching rivers, where the presence of an island is a necessary fundamental element, BC formation would continuously operate and expand up to reaching a possible equilibrium between valley space availability in straight zones for the available channel width. In the presented study case, the constitution of bank material (hard sandstone in the left margin and cohesive clay deposits in the right one) is a limiting factor for channel width (Stevaux et al., 2013) and consequently for the lateral aggradation of the islands and lateral mobility/migration of the channels.

### *7.2. What does history tell facies analysis?*

Although with minor variations, the sedimentary sequence found in island deposits is basically formed by two lithosomes: cross-stratified sand covered by organic muddy deposits. This relatively simple lithology, very common in large river architecture (Latrubesse, 2015), is an obstacle for generation of a more realistic facies model. The sandy facies can be interpreted as a lateral bar or other channel bedform. The exact differentiation of both deposits is almost impossible in this case, as their sand grain size and sedimentary structures are practically the same. The muddy sequence can also indicate the different environments with very similar facies. Laminated mud (very fine sandy mud) indicates not continuous sedimentation in a lentic water body deep enough to avoid bottom fixed vegetation and root bioturbation development, suggesting a pond environment. Although there are on studies on this subject, during field work we observed that a 1.0 m water depth is sufficient to avoid root vegetation but root fixed vegetation increased in shallow water swamps. Thus, mottled mud facies bioturbated by roots are indicators of a swamp environment. Pollen (Gonçaves, 2011) and seed (Ramirez, 2014) analyses in island deposits corroborate the lithofacies interpretation. The occurrence of BC associated with an island is common in large tropical rivers (Amazon, Negro, Low Paraná), and the accretion of islands to a floodplain is also a characteristic process in these rivers (Stevaux and Souza, 2004; Latrubesse and Franzinelli, 2005; Lewin and Ashworth, 2014; Latrubesse, 2015; Leli, 2015).

### *7.3. Can the presented model predict future conditions?*

Although it was not the objective of this paper, some comments can be made about the future changes in the presented model. The construction of the last large dam only 40 km upstream of the study area (Porto Primavera Dam) introduced several impacts in the river system, especially in the flow regime, suspended sediment concentration (from 30-50 to 0.3 mg $l^{-1}$), and bedload grain size (Stevaux et al., 2009). Under this condition, imagining a reduction or total elimination of the aggradation processes and BC formation is possible. On the other hand, the current *clean water* increases flow erodibility, and the river tends to recompose its original load by an autophagic process of erosion of the floodplain and the island, as observed and measured by Chien (1984) in a different downstream reach of Chinese dammed rivers. Thus, an imbalance condition imposed by river regulation jeopardizes, the functioning of the river and its dependent ecology. Under these new conditions, the evolution of a BC lateral bar, concerning its vertical

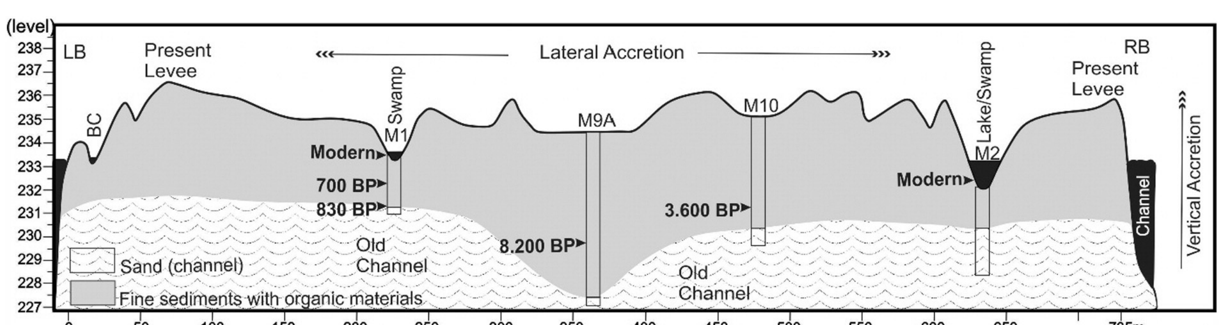


**Fig. 10.** Topographic and geological cross-section of Mutum Island. Deposits can be divided into sandy (lower) and muddy (upper) lithosomes.

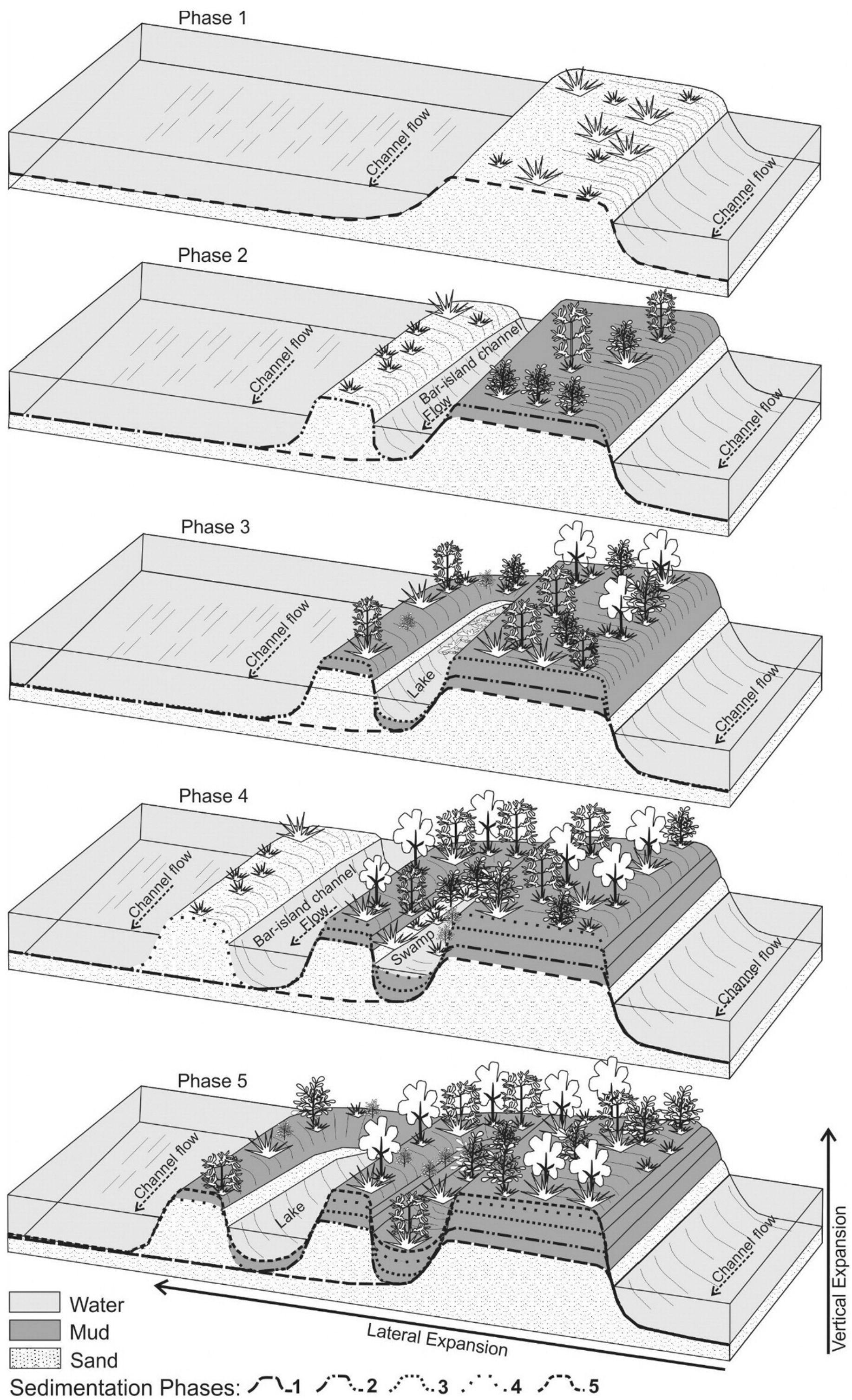


**Fig. 11.** Model for island growth from BC attachment.

aggradation is strongly disturbed, once large floods and mud supply practically disappeared from the system.

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