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6 authors, including:

Olivier Morio

Université de Bretagne Sud

Mouncef Sedrati

Université de Bretagne Sud

Evelyne Goubert

Université de Bretagne Sud

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Morphodynamic of a sandy-muddy macrotidal estuarine beach under contrasted energy conditions (Vilaine estuary, France)

Morio O.[†], Sedrati M. [†], Goubert E. [†], Floc'h F. [††], Furgerot L. [†] and Garlan T. [‡ ††]

[†] Equipe Géosciences Marines et Géomorphologie du Littoral
Domaines Océaniques UMR6538 GMGL
Université de Bretagne Sud,
Vannes, France

[††] Domaines Océaniques UMR6538 UBO
Institut Universitaire Européen de la Mer
Plouzané, France

[‡]SHOM Research Department
Brest, France

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ABSTRACT

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Estuarine and bay beaches are important areas for human activities. These beaches are variably affected by tides, waves, and winds that can commonly generate marked topographic and sedimentological contrasts. Betahon beach (South Brittany, France) is an intermediate-type beach exhibiting a low-tide terrace linked to a steeply sloping gravelly-sandy upper foreshore, and separated by a shore-parallel bluff from a mudflat on the lower foreshore. The beach exhibits linear ridge and runnel (R-R) bedforms perpendicular to the shoreline. Seasonal monitoring of the beach shows mudflat accretion by fluid mud deposition and erosion of R-R bedforms. A core obtained from the mudflat shows alternations of mud and sand. In order to understand the cross-shore dynamics of the beach, topographic surveys and wave and current monitoring were carried out during two contrasting energy conditions. Bed return flows occurred during high-energy events, inducing an infill of runnels by non-cohesive fine sediments and coarser sediments from the reflective upper beach. During low-energy conditions, a longshore flow channel was identified between the shore-parallel low-tide terrace bluff and the mudflat. Throughout the tide, on-shore currents prevailed over the mudflat, inducing the filling of runnels and the base of the bluff with fluid mud.

ADDITIONAL INDEX WORDS: *Estuarine beach, Mixed-sediment, Intertidal mudflat, Ridge and runnels.*

INTRODUCTION

Beaches in estuarine and deeply embayed settings with large tidal ranges typically exhibit two contrasting morphosedimentary types (Anthony, 2009). The upper beach commonly consists of sand, and sometimes gravel, associated with energetic conditions at high tide, and steep slopes, whereas the lower beach commonly evolves in a lower-energy low-tide context associated with gentle slopes and fine-grained sedimentation. Estuarine and deeply embayed beaches are very important areas for human activities (sailing, shellfish farming). Depending on local hydrodynamics and sediment sources, these beaches are exposed to periodic or permanent inputs of clay/silt sediments (Anthony *et al.*, 2011, 2015, Gensac *et al.* 2015*)*. The Vilaine and Seine estuaries, and Arcachon bay are fine examples of such environments in France, , whereas Plymouth bay and the Severn estuary in the UK, and the French Guiana coast are also representative of these settings (Le Hir et *al., 2000,* Anthony *et al.* 2008, Goubert *et al.*, 2010). However, studies devoted to mixed sandy-muddy beaches are relatively rare (Anthony *et al.*, 2015).

Betahon beach, in the Vilaine River estuary (France) is a good example of a mixed beach comprising a reflective gravelly/sandy upper foreshore and a large dissipative lower foreshore mudflat. On this beach with strongly contrasting sediment types, the dune front and the break of slope separating the upper and lower foreshores are commonly subject to erosion under stormy conditions. Ridges and runnels (R-R) also occur on the mudflat. These forms and the patterns they exhibit have been the object of various studies (e.g., Le Hir *et al.* 2000, Williams *et al. 2008,* Carling *et al.* 2009, Friedrich, 2011). The mudflat sediments show alternations of sand and mud that reflect two distinct morphosedimentary regimes, respectively cohesive and non-cohesive. In order to identify the processes associated with each of these two regimes, a study was conducted on the hydrodynamic, topographic and sedimentological characteristics of the reflective and dissipative parts of Betahon beach under high and low energy conditions, along a cross-shore profile. Based on the observations and measurements, a conceptual model is proposed. The paper provides preliminary results that are part of a larger timescale study of Betahon beach that includes seasonal 3D topographic and sedimentary surveys that will be presented in a future paper.

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*Corresponding author: patricio.catalan@usm.cl

ENVIRONMENTAL SETTINGS

The Vilaine River estuary lies on the south coast of Brittany, within Vilaine bay, a triangular re-entrant flanked by rocky coasts (Figure 1a). The bay is separated from the North Atlantic Ocean by a large shoal stretching from the Quiberon peninsula to the tip of the Croisic peninsula and a string of islands. The geology of Vilaine bay has been described by Goubert and Meunier (2005). The bay attains a maximum depth of 30 m, and is partially protected by the shoal from westerly waves (Vested *et al.,* 2013). The Vilaine is a meso-macrotidal estuary (tide range from 2.5 to 5 m at neaps and springs respectively), and consists of three sectors: a meandering inner estuary, a rectilinear intermediate estuary and an outer estuary (figure 1a) totally infilled by marine mud (Goubert *et al.* 2010).

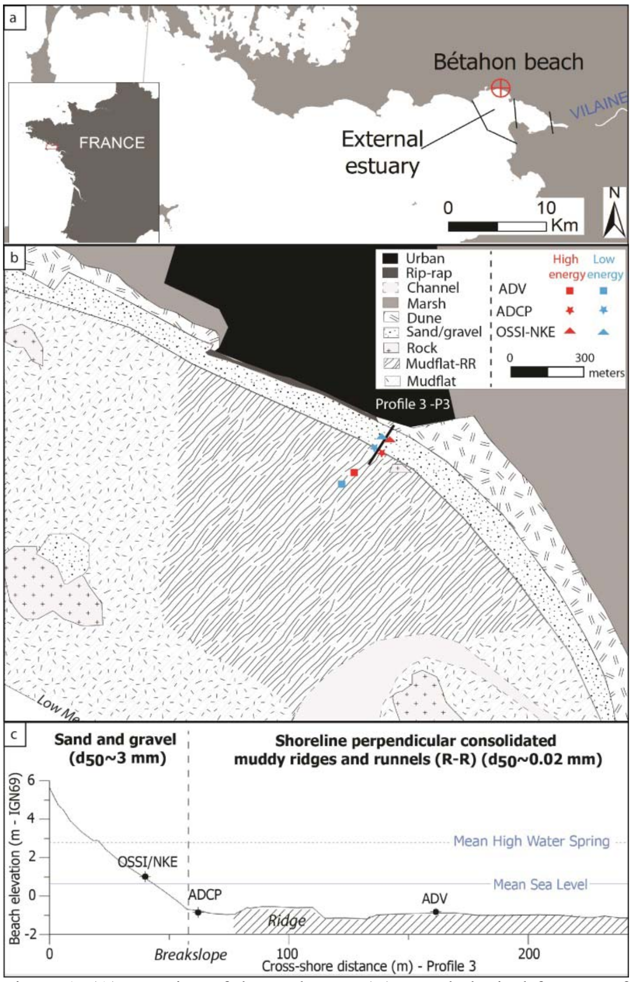

Figure 1. (A) Location of the study area (B) Morphological features of Betahon beach, location of the central profile (P3) and instruments (C) Location of sensors over the central cross-shore beach profile (P3).

Betahon beach is located in the outer estuary (Figure 1a). Compared to adjacent areas of the South Brittany coast, which are sandy, Betahon beach is a former spit exhibiting an atypical intertidal zone (Figure 1b). The general morphology of the beach may be characterized as Low Tide Terrace (LTT) according to the beach classification of Wright and Short (1984). The upper, steeply sloping part of the beach consists of sand and gravel (figure 1c). Sediment grain sizes (according to the Udden-Wenthworth classification) range from fine/medium sand to gravel. In total contrast to the upper intertidal beach, the lower intertidal beach is a large mudflat (Figure 1b, 1c). At the transition between sand/gravel and silt/clay, fine sand occurs just below the break in slope between the mudflat and the upper part of the beach. The mudflat is characterized by a mixture of soft mud/sand commonly exhibiting a complex series of ridges and runnels (R-R) perpendicular to the shoreline. Ridge mud cliffs (90°) are 10 to 40 cm high and the distance between two ridges is very variable, ranging from 20 cm to 2 m (cf. figure 2 a). Seasonal monitoring of the beach shows that the mudflat is characterized by a variable topography and morphology. The runnels on the mudflat can be totally infilled by fluid mud and the mudflat elevation can increase by up to 60 cm.

METHODS

In order to understand the hydro-morpho-sedimentary dynamics of Betahon beach, two field experiments were conducted on the topography and sediment and hydrodynamic conditions affecting the beach under different energy conditions. The first experiment was conducted between February 28th and March 06th 2014 under high-energy conditions (maximum offshore wave height = 4.9 m, maximum wind speed =12 m.s^{-1}, wind direction = SW). The second experiment took place from June 10th to June 19th 2014 under low-energy conditions (maximum offshore significant wave height = 1.08 m, maximum wind speed = 6 m.s^{-1}, wind direction = NE). Both experiments took place under similar spring tide conditions. Topographic surveys were carried out at daytime using a Leica Total Station TS20 (accuracy = ±3 mm) across a central cross-shore beach profile (P3 - figure 1b). Photographic surveys of the beach were also conducted during the field experiments. The complexity of the R-R morphology requires 3D topographic monitoring. In this study, only the photographic surveys and measurements (June experiment) are used to highlight mudflat variations. Regarding waves and currents, a pressure sensor (NKE-SP2 or OSSI 003-003C) was deployed on the reflective section of the beach (figure 1c). A 6MHz Acoustic Doppler Currentmeter (ADV) was installed at *ca.*100/150 m after the break in slope, on a ridge (cell measurement at 0.15 m above the bed). An additional 1200 kHz Workhorse Sentinel Acoustic Doppler Current Profiler (ADCP) was deployed *ca.* 2 m below the beach break in slope (at about the limit between the dissipative and the reflective parts of the beach) to characterize currents between the break in slope and the mudflat (cell measurement 0.65 m above the bed). For each instrument, velocity data were burst-averaged (mean velocities for 5 to 9 min burst data at a 2Hz sampling rate). Geographical currents were rotated on the cross-shore (U) and along-shore (V) components of the beach shoreline. Burst-averaged water levels and wave characteristics were spectrally derived for each instrument from atmospheric-corrected pressure data.

RESULTS

High/moderate energy conditions

Significant wave height reached 0.75 m (peak periods were from 9 to 20 s) for storm 1, and 1.33 m during storm 2 (figure 2a). Wave height increased from the lower dissipative foreshore to the upper reflective part of the beach (0.75 m to 1.04 m in the course of storm 1). The upper reflective beach showed significant topographic variations. Storm 1 induced a lowering of the beach profile, and changes in profile shape. The lower concave part of the beach (P3 - central profile) became convex following accretion, whereas the convex central and upper parts became concave following erosion (figure 3a), inducing a new equilibrium profile. Although storm 2 was more energetic, topographic variations were less significant due to the previous equilibrium state of the beach. A seaward movement of the break in slope occurred during the two storms (+1.1 m for storm 1 and +3.1 m for storm 2). Erosion of the shore-parallel bluff on the mudflat occurred during the February 28th storm, with a seaward movement of the shore-parallel bluff and a reduction of ridge size (figure 3a - photography). Changes in mudflat elevation that could have occurred after storm 1 cannot be ascertained due to the complexity of the R-R system on the mudflat, human errors and disturbance of the topography during the field study. During storm 2, infilling of runnels by fine and coarse non-cohesive particles occurred. Perpendicular and parallel ridges cut into bluffs were eroded, leading to the breakdown of slumped mud blocks that were progressively disintegrated into mud pebbles. Focusing on storm 1 (tide 1 - figure 2a), bed return flows throughout the tide were mainly cross-shore-oriented over the ridge (ADV). Mean cross-shore velocities reached 0.12 m.s^{-1} at the start and the end of the tide (when the relative wave height was highest) (figure 3a). Stronger currents were mainly long-shore-directed and channeled between the shore-parallel mudflat bluff and the break in slope (ADCP - figure 2a). Under moderate energy conditions (Hs≤0.6 m), currents at the ADCP location were dominantly alongshore whereas, over the ridge (ADV location), cross-shore dominant undertows were identified at the beginning and at the end of the tide. Currents were onshore-directed when water levels increased (figure 2a). The break in slope migrated landward following the energetic events (figure 3a).

Low energy conditions

Maximum and minimum wave heights (peak periods from 7 to 15 s) reached respectively 0.16 m during the spring tide and 0.04 m at the end of the field experiment. No variation in Hs occurred between the mudflat and the reflective part of the beach (figure 2b). Insignificant topographic variations were identified (figure 3b). A 0.2 m landward movement of the break in slope occurred with the increasing tidal range. Micro-morphological features, such as berms, disappeared in the course of the field experiment. Fluid mud deposits (silt and clay) of up to 4.9 cm ± 0.3cm in front of the ridge and 2 cm ± 0.3 cm near the break in slope were monitored using iron accretion pins. Runnels were also filled by fluid mud (figure 2b - photography).

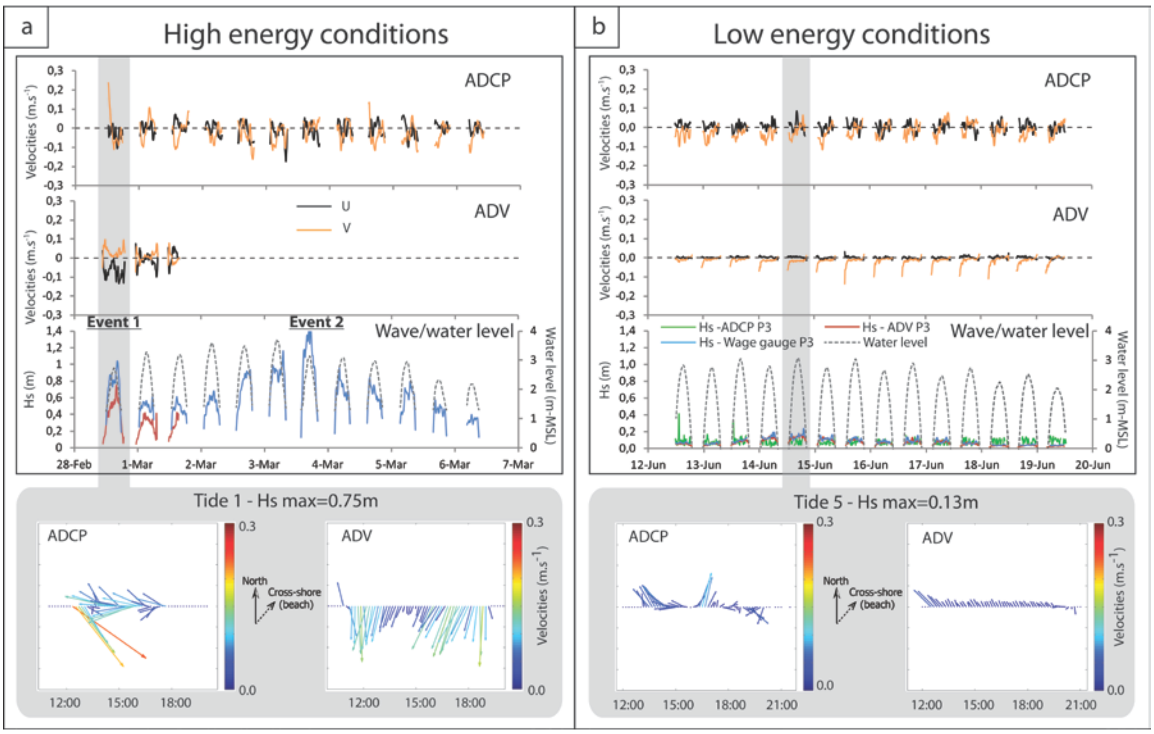

Figure 2. Wave characteristics/water levels at wave gauge and ADV locations; Mean cross-shore (U - positive landward) and long-shore currents (V - positive to shipping channel) at ADCP and ADV locations, (A) Under high and moderate energy conditions and focused on tide 1/storm 1 (B) Under low energy conditions and focused on tide 5.

Variations of the mudflat altitude in figure 2b are artifacts due to the complex topography. Throughout almost the entire tide onshore currents, and alongshore-dominant currents, were measured over the ridge (ADV), (figure 2b).
Mean longshore velocities reached a maximum of 0.05 to 0.1 m.s^{-1} during the first burst. Net onshore velocities of 0.02-0.03 m.s^{-1} during the flood phase were measured. Offshore-directed ebb currents were extremely weak (<1 cm.s^{-1}) up to the final measured burst of tide. The cross-shore currents were almost zero. Velocities at the ADCP location were slightly stronger (0.05 to 0.1 m.s^{-1}). Currents followed a preferential flow corridor between the break in slope and the mud cliff-flat bluff. Circular flow patterns were also observed on this part of the beach.

DISCUSSION/CONCEPTUAL MODEL

A conceptual model of cross-shore dynamics of this Low Tide Terrace estuarine sandy-muddy beach is developed (figure 4). This conceptual scheme is based on observations and measurements realized during the two field experiments and coupled with seasonal observations of the central part of the beach. During high and moderate energy conditions (figure 4a), the upper reflective profile of the beach shows a classical erosion and sediments are exported to the break in slope (Masselink and Hegges 1995, Masselink *et al.* 2006*)*. This dynamics is associated with bed and return flows under breakers, leading to infill of the mudflat runnels by coarser sediments (Le Hir *et al. 2000*, Anthony *et al.* 2008). Currents in runnels are channelled and must be stronger than on the ridges according to William *et al,* 2008. The shore-perpendicular and parallel flanks of the mud ridge are eroded and the slumped blocks broken down by waves to form mud pebbles. This erosion could be reinforced by blasting by coarse sand transported in offshore bed-return flows (Carling *et al.,* 2009). Mud pebbles can be progressively broken down until they become finally fluidized into suspension load (Gensac *et al.* 2015) transported seaward by undertow currents.

Under low energy conditions (figure 4b**)**, currents are onshore and longshore-dominant throughout almost the whole tide on the ridge, and channelled near the break in slope in a preferential alongshore flow corridor. Current in runnels may be also stronger (Williams *et al.*, 2008). Swash bore wash over and put in suspension fluid mud over the 1 km mudflat. Runnels are filled by water first. When water reaches the break in slope and overtops the ridge, sediments begin to settle down (Bassoullet *et al.*, 2000). Backwash currents on the reflective part of the beach are very weak (no breakers) and sediments can also settle down between the break in slope and the mudflat bluff and also in troughs between the runnels. Another hypothesis of a slow fluid-mud transport by onshore-longshore wave-driven currents (good correlation between relative wave height and current mean velocities) can also be proposed, following Gratiot *et al.* (2007) and Anthony *et al.* (2008). Ebb currents are virtually nil such that sediments can be trapped in runnels and near the break in slope as water retreats with the tidal excursion (figure 4b).

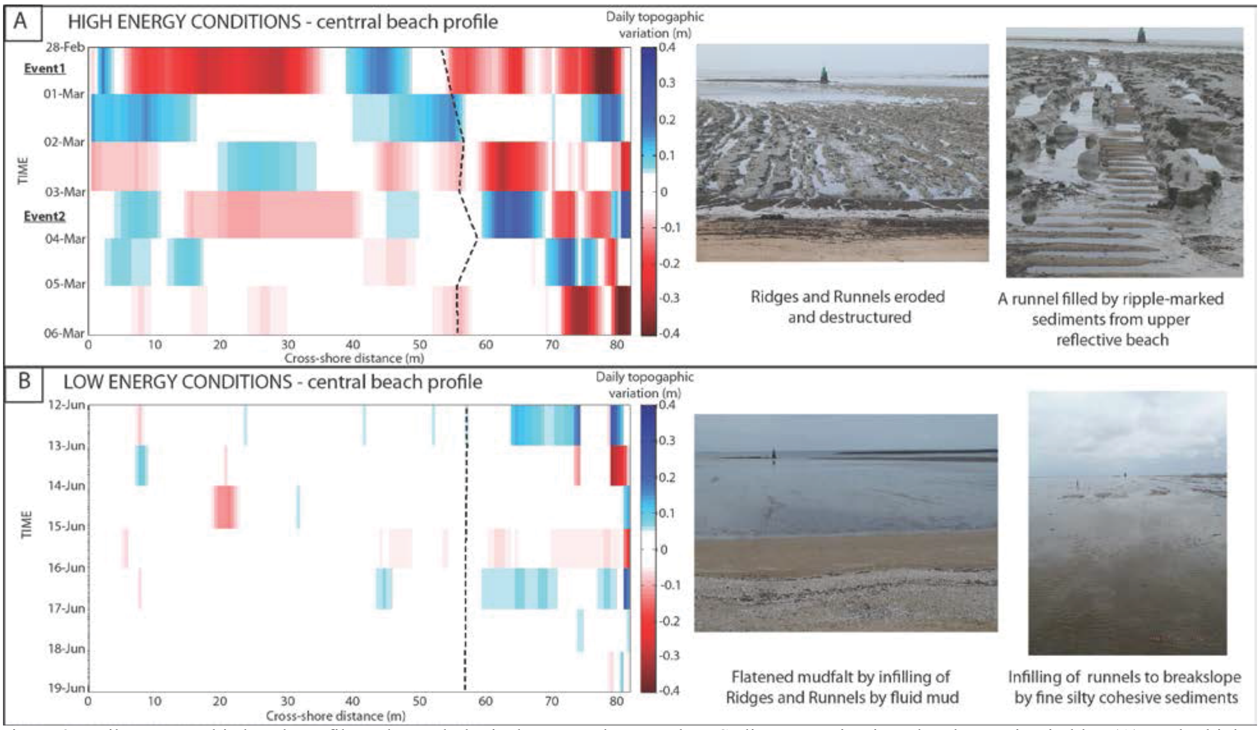

Figure 3. Daily topographic beach profile and morphological pattern photography - Sediment erosion in red and accretion in blue (A) Under high and moderate energy conditions – photography after storm 2 (B) Under low energy conditions – photography after a period of low energy conditions.

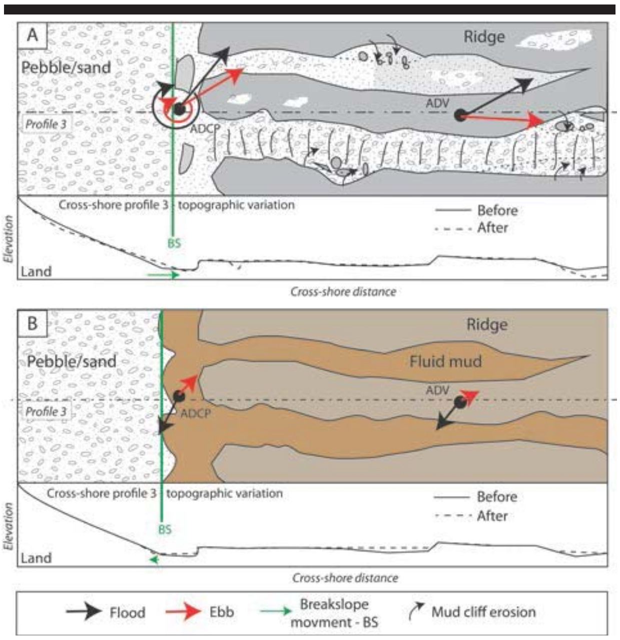

Figure 4. Conceptual model of cross-shore dynamics of Betahon beach (A) Under high/moderate energy conditions (March 2014). (B) Under low energy conditions (June 2014).

CONCLUSIONS

The estuarine beach of Betahon shows two contrasting dynamics. In its central part, coarse non-cohesive sediments from the upper beach are displaced to fill runnels on the lower foreshore mudflat due to bed return flows under high-energy events. Under low energy conditions, runnels are filled by fine cohesive sediments leading to accretion of the mudflat. Successions of high and low energy conditions can also explain the alternations of sand and mud identified in a core sample from the mudflat. These results will help to understand the seasonal dynamics of this beach that should involve short term/monthly topographic and sedimentary monitoring, kite aerial imagery and photogrammetric analyses, core-drilling and mud shear resistance surveys.

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