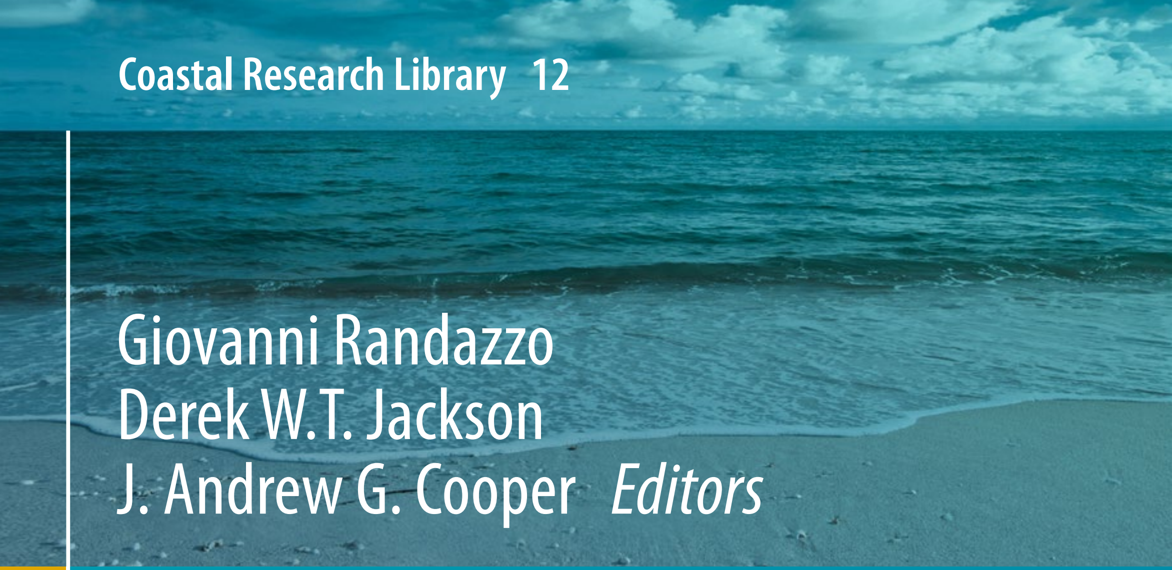

Coastal Research Library 12

Giovanni Randazzo
Derek W.T. Jackson
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Sand and Gravel Spits

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Sand and Gravel Spits

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ISSN 2211-0577 ISSN 2211-0585 (electronic)
Coastal Research Library
ISBN 978-3-319-13715-5 ISBN 978-3-319-13716-2 (eBook)
DOI 10.1007/978-3-319-13716-2

Library of Congress Control Number: 2015936450

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

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Introduction

Among the most dynamic of coastal landforms, spits have been studied for many years. Early studies described their physical form with little attention to their formational processes. Among the first geomorphological studies of spits were those of Douglas Johnston (1919) in the USA. Subsequently Evans (1942) presented a landmark paper on evolutionary aspects of spit development, particularly focused on recurve development. Zenkovich (1959) developed an important model of cuspate spit development based on his work on the Caspian Sea. Schwartz (1972), motivated by the intensification of coastal occupation for industrial, residential and recreational purposes, edited a volume on spits and bars, involving a collection of previously published papers that set out the then state of the art. Since then many studies of individual spits have been undertaken and understanding of the formative processes has been much improved by advances in instrumentation to measure wave and current dynamics, higher frequency of aerial observation and topographic survey and application of new technologies such as ground-penetrating radar. New approaches to conceptual modelling of spit evolution (e.g. Ashton et al. 2001) have shown how small irregularities can create the nucleus for spit formation and, importantly, that such irregularities grow to create previously enigmatic rhythmic shoreline features (including spits) over long timescales.

Spits typically form from longshore transport of material from an up-drift source and accumulation in or across a coastal re-entrant. In several instances, however, downdrift sources are invoked as sediment sources for spit elongation as inlets migrate (e.g. Aubrey and Gaines 1982). Once initiated, spits are responsive to variations in the rate of sediment supply and dispersal, both of which may be strongly non-uniform. Their morphological behaviour is further modulated by the morphology of the re-entrant in which they are accumulating. The shape of the spit at any given time is a major determinant of subsequent morphological change.

Spits form from a variety of materials of varying grain sizes from fine sand to boulders. Gravel-sized grades, often reflecting glacial diamict sources, dominate in higher latitudes while coarse carbonate material (coral rubble) builds spits in the tropics under infrequent high energy events. Sand-sized material is, however, the most common component of spits globally.

Once formed, spits evolve in response to wave energy and sediment supply. Sections may develop planform equilibrium in response to wave energy distribution. When starved of sediment, cannibalisation of existing sediment may cause narrowing and even breaching of the spit. Some of the most important work in this regard was presented in conceptual models by Carter and Orford (1993) working on gravel spits and barriers where slow relaxation times enabled spit evolution to be observed more readily.

With their strong reliance on longshore sediment inputs, spits are highly susceptible to disruption by human interference. Sea defences (seawalls, breakwaters and groins) placed on eroding source areas, interruption of longshore drift by groynes, or interference in inlet bypassing system by jetty construction pose serious threats to the integrity of spits.

Changing climate and sea levels are also likely to prompt future changes in spit morphology. Spits may form and elongate or break down entirely in periods of sea level rise depending on local factors. Under stable sea level phase, they may become sediment-starved as sediment sources are depleted. Under such conditions they may evolve toward swash-aligned equilibrium forms that involve cannibalization of existing sediment and major changes in plan and profile.

Spits tend to be best developed in areas dominated by sea waves (short-period waves that approach the coast at a high angle). As such they are common in relatively sheltered sea environments (North Sea, Mediterranean, Caribbean, Caspian) and less common in swell-dominated areas, where waves are more fully refracted when they reach the shoreline.

This volume contains a series of contemporary studies of spits from around the world ranging from high latitudes of southern Argentina (Bujalevsky et al.) to the tropical Caribbean coast of Columbia (Anfuso et al.) and West Africa (Anthony). The studies reported here involve a mix of sand and gravel spits. Stephan et al. and Regnauld et al. focus on gravel spits of Atlantic France, while Burningham and Bujalevsky et al. describe gravel spits in England and Argentina, respectively. Most studies are concerned with a single spit, although Sabatier and Anthony and Furmańczyk and Musielak present regional appraisals of spit morphology and behaviour on the Rhone delta (Mediterranean Sea) and Polish coast (Baltic Sea), respectively.

Many of the chapters are focused on the historical scale of spits, deduced from cartography and aerial photographs (e.g. Anfuso et al.; Crisà et al.; Taaouati et al.), while some authors have utilised historical sources (Burningham) and archaeological data (Crisà et al.; Del Rio et al.). The role of extreme events, fairweather coastal processes and longer-term geomorphological evolution are reported in studies using ground-penetrating radar (Tillmann, Buynevich et al.). Larson et al. provide a state-of-the-art review of contemporary engineering models of spit evolution.

Linkages between spits and adjacent sedimentary environments are stressed in several of the papers. Kelley et al. describe spit-tidal flat interactions in Maine, USA, noting an important supply from algal-rafted gravel. Buynevich et al. describe an important aeolian dune component on Baltic sea spits linked to historical climate variability while Costas et al. assess links between ebb delta and spit development in an integrated approach that links the topographic evolution of subaqueous and terrestrial landforms.

Spit evolution is often affected by anthropogenic interventions (Anfuso et al.; Del Rio et al.), many of which are associated with the management of river basins (Crisà et al.), especially dam construction (Anthony and Sabatier and Anthony). Others are influenced by progressive reduction in sediment supply under natural conditions, leading to spit disintegration (Devoy) or cyclic changes in morphology (Vespremeanu-Stroe and Preoteasa).

While some authors (Sabatier and Anthony; Regnauld et al.; Anfuso et al.) provide explicit suggestions for future spit management, all of the findings reported in this volume have implications for the future management of spits under near-future climate and sea-level change. The high degree of local influence on spit evolution points to a need for detailed local knowledge to be combined with generic knowledge of spit-forming and spit evolutionary processes when making management decisions.

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Chapter 1
Evolution of Sandspits Along the Caribbean Coast of Colombia: Natural and Human Influences

G. Anfuso, Nelson Rangel-Buitrago, and Iván Darío Correa Arango

Abstract This work deals with the evolution of Bocas de Ceniza-Puerto Caimán, Galerazamba, Isla Cascajo and Punta Canoas coastal sectors, located along the 120 km-long coastline between the Magdalena River mouth and Cartagena de Indias, on the Caribbean coast of Colombia. Comparisons of coastline morphology from reliable ancient charts, modern bathymetric surveys and remote sensing data, show major changes (in some cases at kilometre-scale) related to the rapid erosion and formation of offshore sandy shoals, spits and beaches. These sediment bodies are linked to sediment supply from the Magdalena River. In 1935, after the emplacement of two jetties at the river mouth, sediment was channelled offshore and erosion ensued on the western part of the Magdalena delta. Spits and sandy shoals rapidly migrated down drift. As a result, a spit at Puerto Colombia – present on the 1935 and 1947 aerial photograms – progressively diminished and merged with the coastline between 1953 and 1959. South of this location, a new spit formed before 2000 and it presently shelters a marina at Puerto Velero.

At Galerazamba, a 5 km-long spit at a high angle to the coastline, was present until 1864. It was replaced by a new spit, broadly parallel to shoreline, at some point before 1947. This feature was much smaller than the one previously observed and it has migrated down drift until the present. High rates of accretion were also observed around Isla Cascajo, a rocky island that caused the development of a rapidly growing tombolo. At Punta Canoas, a spit formed between 1947 and 1961 and, then migrated southwards.

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G. Randazzo et al. (eds.), *Sand and Gravel Spits*, Coastal Research Library 12,
DOI 10.1007/978-3-319-13716-2_1

1.1 Introduction

Colombia has coasts on the Pacific Ocean and the Caribbean Sea. They are populated by 4.3 million inhabitants, i.e. 11 % of the national population, distributed into 16 and 30 coastal municipalities along Pacific Ocean and Caribbean Sea coasts, respectively (DANE 2010).

The Caribbean littoral is a 1,600 km-long microtidal environment between Panama and Venezuela (Fig. 1.1). The Caribbean coastal margin of Colombia is a geologically complex region where Quaternary interactions among tectonic, tropical climate and oceanographic processes shaped a varied and unstable coastal zone characterized by spits, bars and beaches along the low coastal plains and deltas, alternating with terraced and cliffed coastlines in rocky areas (Correa and Morton 2010; Martinez et al. 2010).

Along the southern Caribbean coast of Colombia, offshore and onshore mud diapiric intrusions are evidenced by weakened rock zones, domes and mud volcanoes that deeply influence coastal geomorphology (Ramirez 1959, 1969; Correa

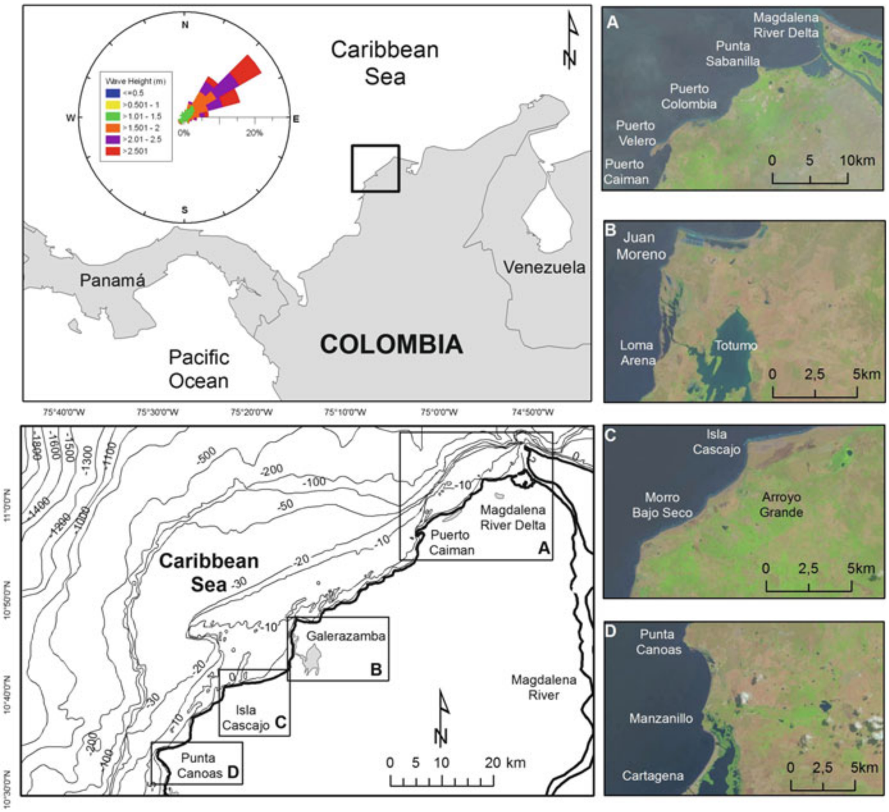

Fig. 1.1 Location map of the four investigated sectors and wave rose

et al. 2007). Presently, some of these mud volcanoes (at Galerazamba, Punta Canoas, Gulf of Morrosquillo and Arboletes) outcrop at or near the coastline and partially affect littoral drift.

Calcareous sediment is common on island beaches (San Andres Islands, San Bernardo and El Rosario archipelagos) and on a few beaches close to Santa Marta and Cartagena de Indias. These sediments are linked to sub-aerial and marine erosion of Plio-Pleistocene to recent coral reefs terraces and living reefs. The supply of coarse terrigenous sediments (sand and gravel) is linked to four large rivers (Atrato, Sinú, Magdalena and Rancheria) and numerous small distributaries draining the Andean region, and to the erosion of granular rocky sectors north of Cartagena de Indias.

Comparisons of coastline morphology from reliable historical charts and modern bathymetric surveys and remote sensing, show substantial, in some cases kilometre-scale changes in morphology of the Caribbean coastline. These changes are most evident in the rapid erosion and accumulation of offshore sandy shoals, spits and beaches (Martinez et al. 1990; Correa 1990). Most cliffed coastlines of this coast are currently in an erosional state depending in part on the presence or absence of frontal intertidal or subtidal depositional features (Correa 1990).

This paper is concerned with the geomorphological change on four of the most rapidly changing sectors of the Caribbean littoral of Colombia, e.g. Bocas de Ceniza-Puerto Caimán, Galerazamba, Isla Cascajo and Punta Canoas (Fig. 1.1).

1.2 Study Area

The four sedimentary systems are located in the Departments of Atlántico (Bocas de Ceniza-Puerto Caiman sector) and Bolivar (Galerazamba, Isla Cascajo and Punta Canoas sectors). They are developed along a 120 km-long coast extending from the Magdalena River mouth to Cartagena de Indias, on the Caribbean coast of Colombia (Fig. 1.1). This coast has two large commercial and touristic cities, e.g. Cartagena de Indias and Barranquilla (DANE 2010) and is the most developed area of the Colombian continental Caribbean.

The first significant human intervention in this zone was the construction in 1893 of a 1,200 m long pier at Puerto Colombia port which was the most important one on the Caribbean littoral of Colombia until the emplacement in 1935 of Bocas de Ceniza jetties to stabilize the main distributary channel of the Magdalena River delta – the entrance to the new port of Barranquilla (Raasveldt and Tomic 1957).

These were followed in the last three decades by the construction of many defense structures (groins and seawalls) and big developments including residential buildings, condominiums and tourist resorts for both large-scale and exclusive use. Most of these developments are presently (or will be in the near future) at risk from the prevailing erosion, so the evaluation of magnitude and causes of coastal change in this area is an essential issue for coastal management.

All the investigated sand bodies, three sandy spits and a tombolo, are composed of terrigenous sand supplied essentially by the Magdalena River which is the largest fluvial system in Colombia. It is 1,600 km long and drains a 257,438 km^2 basin, e.g. a great portion of the Colombian Andes, and has a sediment yield of 560 t km^{-2} year^{-1} (Restrepo and López 2008).

A secondary source of sediments for this stretch of coast is erosion of cliffs north of Cartagena de Indias (Correa 1990).

The Caribbean coast of Colombia is a tropical environment with maximum precipitation of 2,500 mm/year. Seasonal variations in precipitation usually show two rain periods (winter seasons, e.g. April–May and October–November) and two dry periods (summer seasons, e.g. December–March and July–September).

Tides are of the mixed semi-diurnal type, with maximum amplitudes of 60 cm (Andrade 2008; Correa and Morton 2010). Winds mean velocity is lower than 12 m/s, and higher values are associated with winds blowing from NE in the December–March period. Lower values are observed in September–November and are generally associated with winds from E. Surface sea currents are associated with the Caribbean current -flowing during almost all the year from East to West- and the Darien or Colombia current, which flows from Panama northeastward (Thomas 2006).

Significant wave height generally fluctuates between 1 and 2 m, while the average peak period is about 7 s (see wave rose in Fig. 1.1). Most of the year (November to May), the Caribbean wave system is dominated by the presence of swell waves from the NE. For the reminder of the year ower and less frequent waves from NW, WSW and even SW occur. According to INVEMAR (2006) and Restrepo et al. (2012) seasonal variations in wave approach directions are associated with changes in significant wave height values, with the lowest records occurring each year between August and October ($\leq$1.5 m), and the most energetic conditions occurring from November to July, with significant wave heights sometimes exceeding 2 m. Consequently, associated net longshore sand drift has a dominant south-westward component, minor reversal occurring during the rainy periods when southerly winds become dominant in some sectors and set up short, high-frequency waves able to cause significant erosion along cliffed mud coastlines (Correa and Morton 2010).

Erosive events are also related to the impact of hurricanes and cold fronts (Ortiz 2012; Ortiz et al. 2013). Hurricanes, usually originating in the Caribbean area from June to November may affect the Caribbean coast of Colombia with strong winds, heavy rains and storm waves. Cold fronts, occurring during January, February and March, cause strong swell waves which impact may be increased by trade winds blowing from ENE. They usually hit the coast for about 48 h and have an average occurrence of six events per year (Ortiz et al. 2013).

1.3 Methodology

Satellite images and aerial photogrammetric flights were used to reconstruct linear coastline evolution and morphological variations of four sand bodies along the Caribbean littoral of Colombia during different intervals from 1935 to 2013, i.e. the medium to long-term period (Crowell et al. 1993).

Following the methods described by Jiménez et al. (1997), Leatherman (1983), and Pajak and Leatherman (2002), aerial photos were scanned, geo-referenced, and computer rectified to eliminate scale and distortion problems (Chuvieco 2000; Lillesand and Kiefer 1987; Moore 2000). Ground Control Points (GCP_s) for photo registration were obtained from the geo-referenced 2013 satellite image and all information was presented in Projected Coordinate System UTM Zone 18. Taking into account the smooth topography of the study area, a polynomial transformation was applied in the registration process (Chuvieco 2000). The number of GCP_s used varied from one photograph to another (from 9 to 15 units) and their position was located in unequivocal places (Thieler and Danforth 1994).

The error due to document distortion (Moore 2000) was resolved and controlled in the geo-referenced documents by visual observation, achieved by comparing the registered photographs with the base map and deriving the root mean square error (RMSE).

Given that the investigated area is a microtidal environment, shoreline position was defined as the instantaneous water line position at the moment of the photo (Pajak and Leatherman 2002; Boak and Turner 2005).

Wave height effects were not considered because no storm conditions were observed in any of the photographs. In addition, effects of seasonal variation and influence of individual storms on shoreline evolution have limited importance because of considered time span and vast recorded morphological changes (Dolan et al. 1991).

In order to quantify spits evolution, it was used the ArcGis 9.3 extension Digital Shoreline Analysis System (DSAS), v. 3.2 USGS Woods Hole, Massachusetts (Thieler et al. 2005) which uses, as an input, a series of shoreline positions referenced to an arbitrary baseline. In this study, transects perpendicular to the baseline were generated at 100 m intervals and the DSAS allowed calculation of sand shoals surfaces.

Last, wave propagation was carried out using SMC (González et al. 2007) program in order to obtain prevalent current direction vectors along the investigated area.

1.4 Results and Discussion

1.4.1 Coastal Evolution

The evolution of the investigated littoral was strongly influenced and linked to Magdalena River delta evolution, river sedimentary supplies and, to a less extent, the influence of neotectonic processes (Hoover and Bebout 1984; Correa 1990).

During the Pleistocene-Holocene period the Magdalena River delta complex grew toward the WSW (Martínez et al. 1990) and great amounts of sediments moved through the narrow shelf and into a canyon feeding the Magdalena Fan (Shepard et al. 1967; Hoover and Bebout 1984).

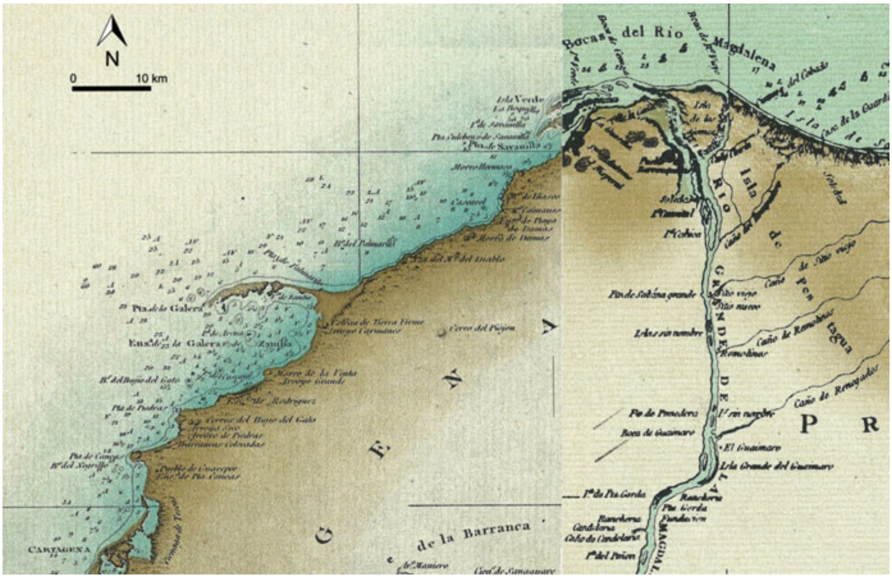

Fig. 1.2 Magdalena River delta reproduced in the historic map of Brigadier Fidalgo dated between 1792 and 1812. Notice the large spit observed at Galerazamba broadly normal to the shoreline

Around 1800, the delta front had a symmetrical form with the main river distributary channel discharging on the west side (Fig. 1.2).

Heavy erosion of the western delta arm started in 1935 when the construction of two 7 km-long jetties was completed. These structures were emplaced on the western side of the Magdalena River delta to stabilise and reduce infilling problems at river mouth entrance – the stabilised channel of the Magdalena River in fact constituted the main entrance to Barranquilla port. After the jetties were constructed it became the most important port on the Caribbean coast of Colombia.

As a result of jetties construction, the western part of the delta in successive decades recorded hundreds of meters of retreat and vast areas of mangrove swamps and coastal lagoons at Boca de Ceniza were eroded (Correa 1990; Matinez et al. 1990).

Probably, this retreat and reconfiguration of the offshore sand bodies is at least in part associated with temporal sediment deficits as a result of several submarine slides. The first was immediately after the construction of the jetties in August 1935, and involved sinking along 484 m of the western jetty and depth changes at the river mouth from 5 to 20–30 m (Koopmans 1971). Ten years later, in November 1945, another submarine slump destroyed 208 m of the western jetty and a new slump was again recorded in July 1963 (Koopmans 1971).

From the Holocene to present, sediments supplied by the river created large sandy shoals, spits and tombolos and constituted the primary sedimentary source for downdrift beaches. Such sedimentary features migrated from NE to SW as far as

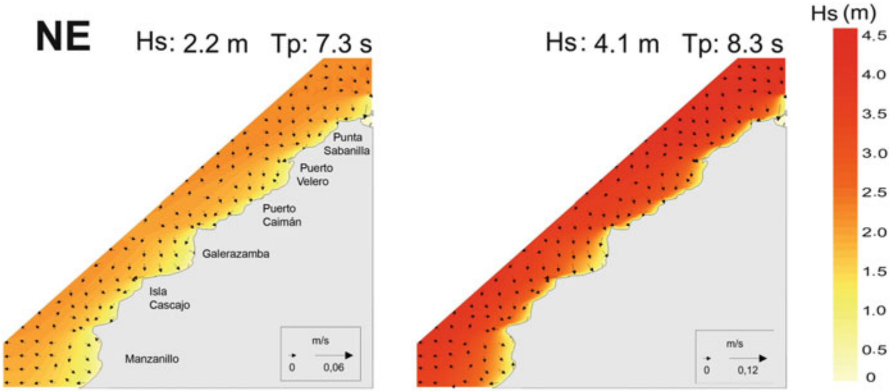

Fig. 1.3 Wave heights and vectors of associated currents for the investigated area

Cartagena de Indias bypassing several rocky headlands and various human and natural structures (Raasveldt and Tomic 1957; Correa 1990). The southward component of sandbody migration was related to diffracted (at jetties) and refracted swell wave fronts originally approaching from NE and ENE which give rise to alongshore drift clearly SW directed (Fig. 1.3). The westerly component was instead linked at places to specific bathymetric conditions (Figs. 1.1 and 1.3) and perhaps to shorter sea waves related to west to east winds with velocities >1 m/s and to eastern sea surface current (e.g. a component of the Caribbean current, Thomas 2006). The specific evolution and behaviour of each of the investigated sectors will be separately discussed from North to South.

1.4.1.1 Bocas de Ceniza-Puerto Caimán

This coastal sector is located immediately on the western side of Magdalena River delta, hence sedimentary features were the largest and most dynamic (Fig. 1.4).

1935 aerial photographs recorded a well developed sand spit that was hundreds of meters wide and >10 km long, with a surface area of c. 4.4 km^2. The spit originated from the mainland south of Punta Sabanilla and enclosed a coastal lagoon (Fig. 1.4).

By **1947** the spit presented smaller dimensions (c. 3.3 km^2) but similar form and orientation (Fig. 1.4). Both the 1935 and 1947 features formed an angle of approximately 40° with the shoreline. This is extremely high since spits are usually almost parallel to shoreline (Carter 1988; Calliari 1994). Such singular orientation was attributed by Martinez et al. (1990) to wave refraction and shoaling processes linked to offshore uplifting of mud diapiric intrusions. Those authors stated that sand spits were temporarily and eventually broke and migrated, but the reason was unknown.

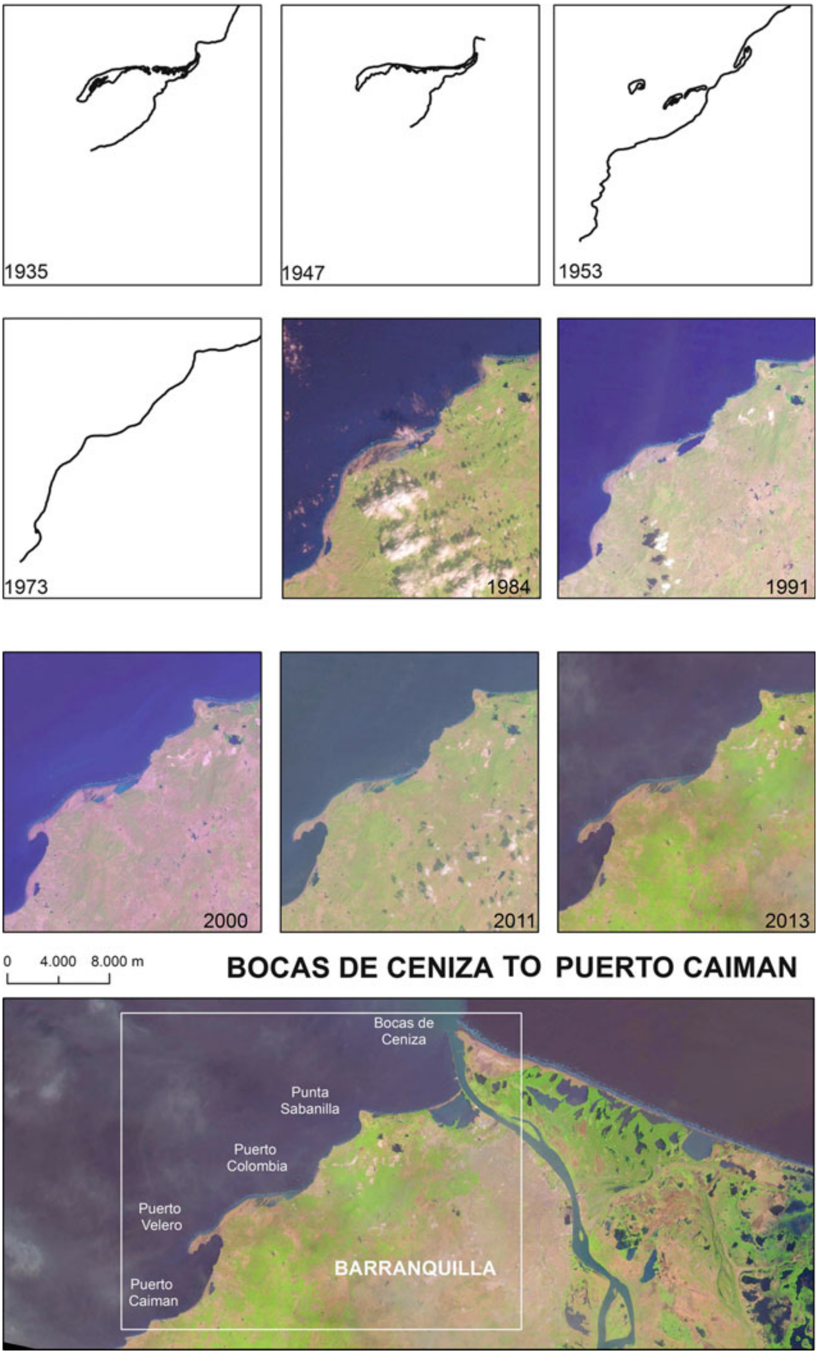

Fig. 1.4 Evolution of Bocas de Ceniza – Puerto Caimán sector between 1935 and 2013

The spit morphology, orientation and migration is related to wave propagation patterns, influenced by jetties at the Magdalena River mouth, and to the bathymetric characteristics of specific areas (Figs. 1.1 and 1.3).

Predominant wave fronts, approaching from NE, experience important refraction and diffraction at the river delta acquiring, south of it, an almost shore parallel orientation as also observed by Ortiz et al. (2014).

As a result of wave action, the spit formed in the 1930s moved to the SW without recording important morphological variations. Immediately south of the delta, the feature probably started to impinge in a shallow area, e.g. a wide zone between −10 and –20 m, and began to adapt its form to the bathymetric contours linked to the existence of a rocky seafloor (Correa 1990, see bathymetric map in Fig. 1.1). Migrating further to the SW, at Punta Sabanilla, the spit migration (and consequently its form) was again strongly influenced by bathymetric lines, specifically the 10 m contour, which runs broadly parallel to coastline until Punta Sabanilla, where it passes close to the headland, and than acquires a very different orientation, i.e. it elongates westward, assuming an oblique orientation with respect to the shoreline, similar to the one shown by the spit in the 1935 and 1947 aerial photographs (see bathymetric map and spits orientation in Figs. 1.1 and 1.4). Wave propagation presented in Fig. 1.3 evidenced as, at Punta Sabanilla, longshore currents present a clear westward component and their velocities strongly increase, this way confirming the importance of a westward directed drift at that point, responsible for spit oblique orientation.

In **1953** the spit presented a very different form compared to previously observations. This was because the sandy feature did not work as a spit sensu stricto, e.g. a drift-aligned feature with a fixed end receiving sediments from an updrift source and a free one migrating down drift (Carter 1988). After the jetties construction, the spit no longer received sediments and thus it turned into a swash-aligned sand shoal rapidly changing and freely migrating SW.

Specifically, in 1953, it appeared segmented into three parts. A sandy island was formed about 4 km offshore of Puerto Colombia. The main body of the spit, breached into two parts, was 4.5 km long and 1.1 km^2 smaller than the 1947 one. The fixed spit edge was located at Punta Pradomar, between P. Sabanilla and Puerto Colombia, and the free one about 2 km from the coast (Fig. 1.4).

The rapid migration observed during the 1947–1953 period (respect to previous time interval) and successive breaching between 1947 and 1953, were related by Martinez et al. (1990) to storm impacts but may be also linked to the impact of Hurricane Fox that in 1952, despite only having a category of Tropical depression, directly hit the coast at P. Colombia.

The successive detachment of the spit occurred between 1953 and **1959** probably because of the landward rolling of the spit associated with normal wave conditions and storm effects (Martinez et al. 1990) and/or the impact of Hurricane Katie that hit littoral – but not directly- in 1955 with the category of Tropical storm.

In **1973** the spit merged with large pre-existing sandy beaches forming a new feature of about 4.6 km^2 elongated south-westward. In the following decade the spit, still merged to coastline, continued its alongshore migration and experienced

Fig. 1.5 Increasing beach erosion at Puerto Colombia, October 2012 (**a**) and 2013 (**b**) Flat beach of fine sediments with umbrellas and chairs (**c**) and human constructions (**d**) at Puerto Velero. Long seawall (**e**) and groins constructed (**f**) south of Punta Sabanilla

0.49 and 0.47 km^2 of areal decrease in **1984** and **1991,** respectively and creating erosion problems at P. Colombia where some beaches totally disappeared (Fig. 1.5a, b). In 1991 the spit reached Puerto Velero headland and in **2000** formed a new small feature rapidly migrating SW as observed in **2011** and **2013** images. Presently the spit shelters a water body where in recent years a recreational marina, Puerto Velero, was constructed (Fig. 1.5c, d). The spit is very flat and low and is therefore strongly threatened by flooding events linked to storm waves. Further, the fixed edge, is very narrow and will likely experience breaching in the near future transforming the spit into a migrating sandy island with serious problems for human settlements developed there.

The small spit which formed the coastal lagoon in 1935 south of Punta Sabanilla persisted for several decades because it was protected by the headland and had a sand supply from updrift eroding coasts such as at Bocas de Ceniza (Correa 1990). In 2012 the spit was totally eroded exposing human settlements to potential erosion. This was counteracted by emplacement of a long seawall and numerous groins

(Fig. 1.5e, f). The groins trapped fine sediments and formed wide, smooth and low beaches rich of quartz, feldspar and mica and heavy minerals that gave a dark colour to the newly formed beaches.

1.4.1.2 Galerazamba Sector

Martinez et al. (1990) reported the existence from 1811 to 1864 of a 5 km-long spit broadly normal to the shoreline at Galerazamba (Fig. 1.2). Such an uncommon orientation was attributed by Martinez et al. (1990) and Correa (1990) to the presence of offshore mud volcanoes (Ramírez 1969) and associated wave shoaling processes that interrupted the drift patterns resulting in spit formation at an angle almost normal to the coastline.

Within this study, it was observed that this ancient spit probably developed in a bathymetric setting very similar to the one observed at Punta Sabanilla. Between P. Caimán and Galerazamba, the 10 m bathymetric contour runs very close to shore but at Galerazamba point it suddenly turns westward (see bathymetric map, Fig. 1.1). Such bathymetric settings have influenced spit formation and orientation blocking alongshore migration of a large sandy shoal that assumed an elongated form parallel to the 10 m bathymetric line. Such observations are confirmed by results of wave propagation: predominant wave fronts (approaching from NE) favour the formation of intensive and clearly westward oriented currents at Galerazamba point (Fig. 1.3).

A new spit, broadly parallel to the shoreline, appeared at some point before **1947** south of Punta Juan Moreno (Fig. 1.6). It is visible in recent aerial photographs and satellite images, although with an area of 1.8 km^2 and it was much smaller than the

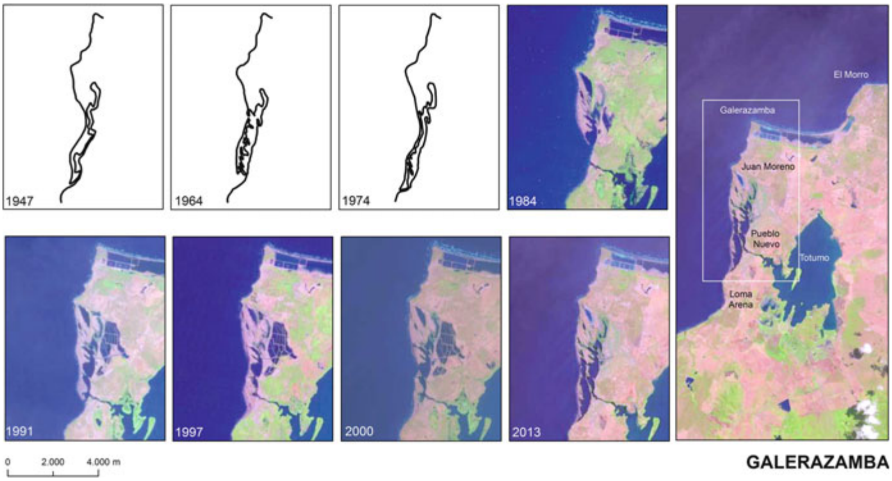

Fig. 1.6 Evolution of Galerazamba sector between 1947 and 2013

ancient one observed until 1864. The modern feature enclosed different small water bodies and migrated and changed its form in last decades (Fig. 1.6).

According to Correa (1990) the spit fulfilled an important protective function for the backing lagoon and human settlements (the small village of Amanzaguapos) until the beginnings of the 1950s. In the 1947–1954 period, erosion processes produced 300 m of coastal retreat (Correa 1990). Spit erosion and narrowing weakened spit protection function and erosion threatened human settlements that were relocated landward. The new village, named Pueblo Nuevo, was founded in 1954 northeast of the previous one.

The spit experienced narrowing in **1964** and **1974** and the south part was totally eroded in **1984**, with the loss of 0.45 km^2; as a consequence Pueblo Nuevo was exposed to erosion processes and the settlement was relocated 100 m eastward in 1985 (Correa 1990).

In following years sandy supplies from alongshore drift favoured spit accretion and southward migration of c. 500 m, with an associated growth of 1.0 km^2 (**1991**, Fig. 1.6).

Southward migration in the following years allowed the free edge to merge with the coastline (**1997**, Fig. 1.6). In successive steps it then disintegrated (**2,000** images) because of the loss of 0.7 km^2, increasing erosion processes at Pueblo Nuevo. In **2013** the spit accreted of c. 0.7 km^2 and migrated down drift about 80 m.

1.4.1.3 Isla Cascajo Sector

Isla Cascajo was a calcareous Plio-pleistocene reef rocky island about 2 km from the mainland as recorded in **1935** photograms (Fig. 1.7). Its distance from the shoreline gradually reduced from 1935 onward because of coastline accretion of

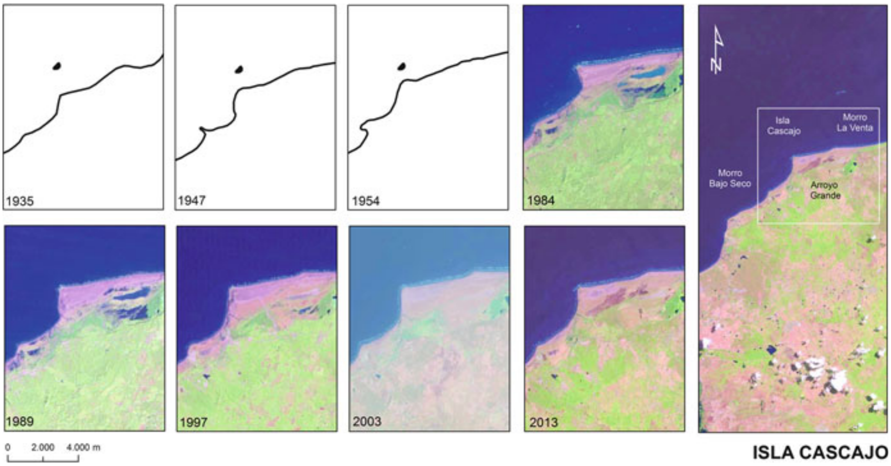

Fig. 1.7 Evolution of Isla Cascajo sector between 1935 and 2013

0.7 and 2.5 km^2 in **1947** and **1954** (Fig. 1.7). Such behaviour was linked to the formation and progressive accretion of a tombolo originated in the shadow area of the island (Fig. 1.7). Accretion processes determined the connection of the tombolo with the mainland in 1981 and an increase of 0.95 km^2 of beach surface in **1984** (Fig. 1.7).

Such accumulative processes continued in following decades and favoured seaward shoreline migration with an increase of 0.53 and 0.54 km^2 respectively in **1989** and **1997** (Fig. 1.7). Accumulation rates diminished in following years and produced an increase of beach surface of 0.24 and 0.03 km^2 in **2003** and **2013.** Further, as evidenced in 1954 photograms, a secondary spit enclosing small lagoons developed landward of a small rocky headland, south of Isla Cascajo. This spit migrated to the SW and merged with the shoreline (1984). Coastal lagoons protected by the tombolo and the spit progressively disappeared because they were artificially drained and naturally infilled by landward migrating dunes.

Martinez et al. (1990) affirmed that sediments accumulated in this coastal sector in recent decades derived from the breaking up of the Galerazamba large spit that was observed in old maps until 1864. It is a plausible hypothesis but hard to confirm. Indeed the lapse time between the dismantlement of ancient Galerazamba spit (1864) and the formation of the tombolo is quite large considering the dynamism of the study area. Alternatively, sediments deposited at Isla Cascajo might have been gradually eroded from updrift areas.

1.4.1.4 Punta Canoas

According to Correa (1990) and Martinez et al. (1990) the spit, not visible in **1947** photograms (Fig. 1.8), was formed at some time before 1961. In **1974** and **1984** photographs it presented a similar form and a length of c. 2 km. In the period between 1984 and **1989** the spit widened, increasing 0.1 km^2, and migrated down drift enclosing new small water bodies (Fig. 1.8). In **1991** a small amount of erosion affected the free (southern) edge of the feature that, in the following years, continued its southward migration until it joined the coastline in **1997** with an accretion of 0.49 km^2. Successively, the northern spit area recorded erosion (-0.59 km^2, in **2003**) and presently (**2013**) a new small spit is reforming (Fig. 1.8).

1.4.2 Morphodynamic Model

A conceptual model of spit and sandbody evolution was presented in Fig. 1.9. It deals with Puerto Colombia spit study case but can be applied to other investigated sectors. The model is broadly based on the works of Forbes et al. (1990, 1995a) y Orford et al. (1991) which described barrier evolution in paraglacial coasts. Such environments are characterised by gravel (and gravel/sand) barriers which size is typically of the order of 10^2–10^4 m in length – depending on the

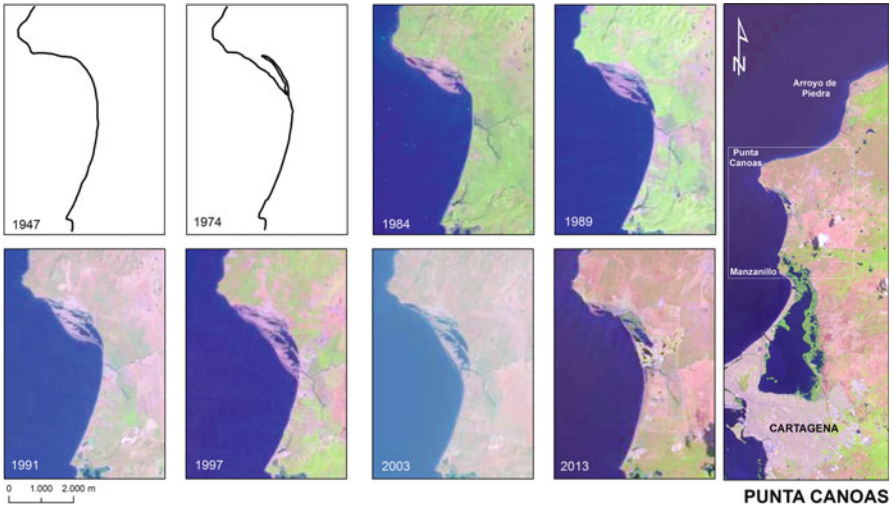

Fig. 1.8 Evolution of Punta Canoas sector between 1947 and 2013

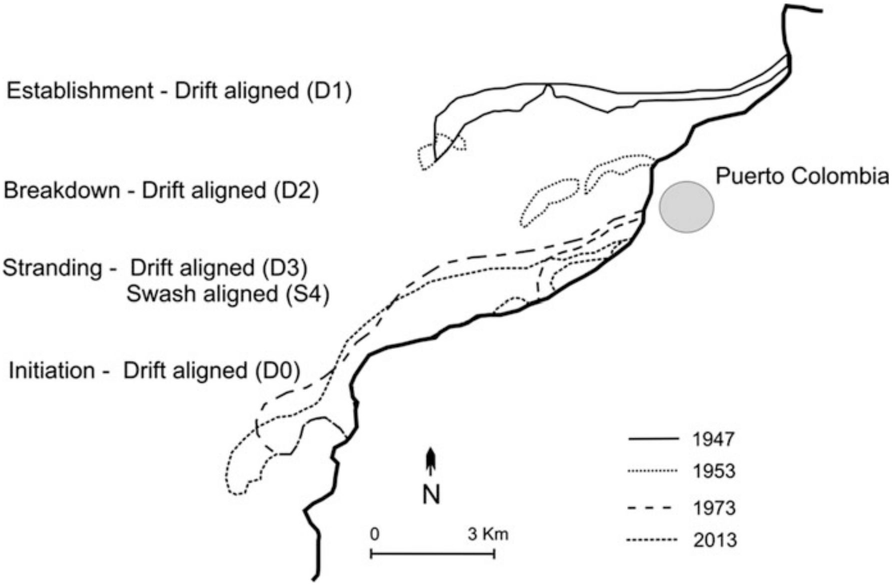

Fig. 1.9 Morphodynamic sketch of investigated sandbody behaviour

rock-irregularities distinctive of many paraglacial coasts, and their origin is linked to the erosion of glacial deposits. Systems formation and evolution take place over time scales of decades to centuries, the lifespan depending in large part on the volume and endurance of the sediment source (Forbes et al. 1995b). Specifically, according to Carter et al. (1989, 1990) and Forbes et al. (1995a), the long-term evolution of coastal systems in paraglacial environments is controlled by several external factors: (i) the geological and physiographic setting; (ii) relative sea-level changes resulting from long-term glacial-eustatic and isostatic adjustments; (iii) time-varying sediment supply, primarily from glacigenic or related deposits; (iv) the climate system, i.e. wave climate and secular changes in related energy inputs and also (v) tides and river discharges.

Sandbody systems analysed in this work presents similar dimensions to the features described by Forbes et al. (1995a) but essentially consisted of sand deposits which give rise to smooth dissipative environments strongly contrasting with the reflective beaches observed in gravel barriers (Carter et al. 1989, 1990). The formation of investigated sandbody and gravel barriers is in both cases linked to the erosion of large sedimentary deposits, respectively coastal sediments of fluvial origin (in this study case from the western arm of the Magdalena River delta) and gravel deposits of glacial origin – as an exempla Carter et al. (1990) in a study case from Nova Scotia, recorded a total sediment release in the order of 10^6–10^7 m^3. Formation of investigated sand bodies takes place at decadal scale so, in contrast to gravel barriers of glacial origin cases, sea level variations are not important in their formation and evolution, achieving major importance sediment supplies and wave climate factors.

Despite mentioned differences in origin and sedimentological characteristics, sandbody systems formation and migration follow the self-organisation, cannibalization and transformation processes close to the ones observed for gravel barriers of glacial origin. The investigated sand bodies (Fig. 1.9) followed the conceptual model presented by Forbes et al. (1990, 1995a) y Orford et al. (1991) which describes as a barrier is initiated, become established, and may eventually range through different stages (transition, stranding, or breakdown), depending on the external conditions (energy and mass inputs) and internal response (morphodynamic feedback) of the system. According to the model, barriers may be initiated from discrete or line sources, and give rise to drift- or swash-aligned embryos (D0 and S0, Forbes et al. 1995a), depending on the local topography (coastline, nearshore bathymetry, and backbarrier accommodation space). In the study case presented in Fig. 1.9 there is no record of the "initiation" stage and it is only possible to presume that the sandbody was originated at some point after jetties construction probably from several minor sand bodies located at river mouth that merged together and migrated downdrift (Fig. 1.2). Later, under conditions of large and increasing sediment supplies from the river delta dismantlement, the sandbody formed a drift-aligned structure ("establishment" stage, D1, Fig. 1.9). Following Ruz et al. (1992), such structures can extend very rapidly in shallow water and this was the case of the investigated spit which rapidly migrated downdrift. According to the model, as supply declines, drift-aligned barriers may experience severe sediment budget deficits, leading to alongshore cell accentuation, barrier breaching, self-adjustment, and breakup. The "breakdown" stage (D2, Fig. 1.9) took place in between 1947 and 1953, when the spit experienced fragmentation and started to migrate landward, i.e. started the transition from a drift-aligned to a swash aligned feature.

In the following stage, “stranding” (D3 and S4, Fig. 1.9), both drift-aligned and swash features are observed. Following to Forbes et al. (1995a), stranded barriers may evolve from swash- or drift-aligned barriers which have lost their seaward anchor or they may develop in place. In such kind of situations, interactions between basement control and longshore cell development can produce a complex pattern of morphodynamic variation alongshore. The volume of sediment remobilised and the degree of self-organization depend on the amount of sediment available and on the erosion and transport potential at a given coastal site. Deficient supplies of material may prevent the development of coherent structures and favour the breakdown of existing forms as well as exaggerated amounts of supplies my alter the self-organisation mechanism in the system because saturate the transport potential. This is often observed because cells develop in long spits in case of sediment starvation (Carter and Orford 1991). As a result, cell formation produces the subdivision of the shoreline into segments wherein the longshore transport potential successively accelerates and decelerates, leading to updrift erosion, downdrift deposition, and the growth of shoreline irregularities. The nearshore wave field is affected by such irregularities and, as a consequence, the wave approaching direction and surf dynamics change creating energy gradients associated with drift- to swash-alignment conditions that reinforce the cell growth. Such self-organization mechanism produces barrier fragmentation, cannibalization of the proximal sections and breakup in drift-aligned features where alongshore sediment exchange represents the main sedimentary process but may give rise to thinning and total feature failure in swash-aligned barriers which are dominated by cross-shore sediment movement (Carter et al. 1990; Forbes et al. 1990, 1995a; Orford and Antony 2011).

Last, at Puerto Colombia (Fig. 1.9), an “initiation” stage (D0) was observed because the drift-aligned (D3) barrier in the “stranding” stage formed an initial, small spit which is growing and migrating to the southwest. All described stages for Puerto Colombia sandbody evolution take also place at other investigated places.

1.5 Conclusions

The investigated coastal sectors show great variability in the form and behaviour of large sand bodies linked to important sediment supplies from Magdalena River, that are transported toward Cartagena de Indias, about 120 km downdrift.

Until the construction in 1935 of two jetties at Bocas de Ceniza (Magdalena River mouth), such sedimentary supplies formed sand spits and shoals and maintained wide beaches in down drift areas. Huge sand spits were observed at Galerazamba in the 1800s and at Puerto Colombia in 1935. Formation of these features – at a high angle with shoreline was determined by bathymetric contours patterns to be linked to structural control.

After the emplacement of jetties, fluvial sediment supply to the littoral system was channelled offshore by structures. Huge volumes of sand were presumably lost to deeper areas by the occurrence of at least, three submarine slumps related to delta front instability. Hence, sedimentary inputs to down drift areas were reduced to those associated with erosion of the western delta arm. Hundreds of meters of retreat were recorded in a few decades. Such supplies were not continuous in time and spits started to migrate down drift, e.g. toward the SW, working as "free" sand bodies. As a result, the spit at Puerto Colombia progressively diminished in size and merged with the coastline between 1953 and 1959. South of this location, a new spit formed before 2000 which now shelters a marina at Puerto Velero.

Sediment supply from coastal retreat at Magdalena River mouth also favoured the formation of a spit at Galerazamba, much smaller than the one that had existed until 1864, great accretion at Isla Cascajo, a rocky island that produced the development of a rapidly growing tombolo, and the formation of a spit at Punta Canoas. Sandbodies evolution recorded self-organisation, cannibalization and transformation processes close to the ones observed for gravel barriers of glacial origin by different authors.

Migration of fixed spit edges and the lack of natural replacement of eroded sediments produced great erosion at several places of important tourist interest, e.g. Punta Sabanilla, Puerto Colombia, etc. Such erosive processes were counteracted by the progressive emplacement of protective structures, essentially groins and seawalls. Structures partially interrupted alongshore transport and favoured the deposition of fine suspended sediments that generated – in few years – large sandy beaches, but created erosion in down drift areas.

Acknowledgments This work is a contribution to the Andalusia Research PAI group n° 328 and was carried out under the framework of the convention between the University of Cadiz (Spain) and the Department of Ciencias de la Tierra, Faculty of Science, EAFIT University of Medellin (Colombia).

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Chapter 2
Patterns of Sand Spit Development and Their Management Implications on Deltaic, Drift-Aligned Coasts: The Cases of the Senegal and Volta River Delta Spits, West Africa

Edward J. Anthony

Abstract The sand spits associated with the Volta and Senegal River deltas, the two largest river deltas in West Africa, after that of the Niger River, show complex patterns of morphodynamic development while also strongly reflecting the recent impacts of human activities. The large spit of the Volta delta seems to be a direct outgrowth of a natural change in the location of the mouth of the Volta and of a marked reduction in sand supply on the eastern coast of Ghana that largely predated the construction of the Akosombo dam, but which has been strongly aggravated since this dam was completed in 1961. Spit formation has led, in particular, to segmentation of the unique sand drift cell that prevailed on the Bight of Benin coast between the Volta delta mouth and the western confines of the Niger delta. These changes have been associated with strong gradients in longshore drift and fundamental modifications in the dynamics of sand barriers on the Bight of Benin coast and hitherto fed by sand supplied by the Volta River. The spit has prograded massively by the adjunction, in situ, of new individual beach ridges, rather than by undergoing elongation, a pattern of growth that has entailed sand sequestering within the confines of the delta. The distal tip of the spit has recently welded to the shoreline, creating a new barrier-lagoon system, and assuring the resumption of integral sand drift from the mouth of the Volta towards the rest of the hitherto sand-starved Bight of Benin coast. The process should also offer limited respite from erosion to the beleaguered town of Keta, located just downdrift of the former distal tip of the now welded spit.

The Langue de Barbarie spit at the mouth of the Senegal River delta is an outgrowth of strong longshore drift affecting one of the finest examples of a wave-dominated delta. The spit developed jointly with the delta and appears to have inexorably extended downdrift in conjunction with river-mouth diversion and

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G. Randazzo et al. (eds.), *Sand and Gravel Spits*, Coastal Research Library 12,
DOI 10.1007/978-3-319-13716-2_2