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By

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ABSTRACT

The Sillon de Talbert is the largest gravel barrier spit in Brittany and forms a swash-aligned formation exposed to swell that enters the English Channel from the west. It partially protects the islands of the Bréhat Archipelago against coastal erosion and marine flooding of low-lying land. The main morphological changes to the Sillon de Talbert have been studied since the 17th century, and were accurately quantified between 1930 and 2010, based on early marine maps, aerial photographs and topographic surveys recently conducted by DGPS. The examination of early maps shows this barrier was attached to the Olone Islands until the end of the 17th century. Towards the mid-18th century, a breach that had formed in the north of the barrier resulted in its transformation into a trailing spit. A gradual change in its general direction towards a more drift-aligned position promoted longshore sediment drift towards the distal end. A slow cannibalization processes began, dividing the spit into a source area at the proximal section, a transit zone in the median section and an accumulation zone at the distal section of the spit. Long-term analysis of shoreline changes over the past decades highlights the mobility of the Sillon de Talbert, which is characterized by rapid landward retreat by rollover. This trend is mainly due to a sediment supply deficit, which can be explained above all by sediment depletion on the continental shelf and, to a lesser extent, by anthropogenic activities, particularly gravel extraction. The results obtained show that for the entire period (1930-2010), the mean migration rate was 1.1 m/yr. Upon closer investigation, the rate of retreat and the main morphological changes proves to differ between the morphosedimentary units of the spit and illustrates cannibalization processes. Thus, the proximal section shows very high retreat rates (1.35 m/yr) due to a sediment budget deficit, which can be explained by gravel migration towards the north-east section of the spit. For these sections, this evolution results in greater sensitivity to erosion and breaching during severe storms, as was the case in April 1962 and during winter 1989-90. Its median section corresponding to the transit zone shows lower retreat rates than the proximal section (1.05 m/yr) and a relatively balanced sediment budget, as illustrated by the high resilience of this section of the spit submitted to sluicing overwash. Finally, the distal section has undergone retreat by rollover of its exposed outer face and progradation of its inner face which benefited from sediment supply from proximal section. From the 1970s, several human interventions based on coastal defense strategy attempted to slow the spit's retreat due to rollover. The failure of these interventions led to the definition of a new coastal management policy. Since the 2000s, the national organization in charge of the acquisition of coastal land for its preservation (*Conservatoire du Littoral*) has been implementing an acquisition policy geared towards urbanized areas sensitive to coastal erosion and marine flooding in the back-barrier area of the Sillon de Talbert. This policy enables the organization of strategic withdrawal and leaves natural processes to gradually take their course.

ADDITIONAL KEYWORDS: Brittany, France; coastal morphology; barrier spit evolution.

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Gravel spits generally have a high mobility potential (Carter *et al.* 1989; Héquette and Ruz 1991; Forbes *et al.* 1991, 1995; Fox *et al.* 1995; Jolicoeur *et al.* 2010; Stéphan 2011a, 2011b). Landward retreat by rollover is caused by overwash (Carter and Orford 1984). The morphological impact of overwashing is determined by (i) storm frequency and intensity, (ii) the joint occurrence of such storms and high spring tides on macro-tidal coasts, (iii) the sediment budget of the spit and its inertia (volume and height), as defined by Orford and Carter (1984). A cannibalistic trend is also observed when sediment input is lower than sediment removed by longshore drift. In this case, the cannibalistic process leads to the gradual appearance of an eroding proximal source area, a

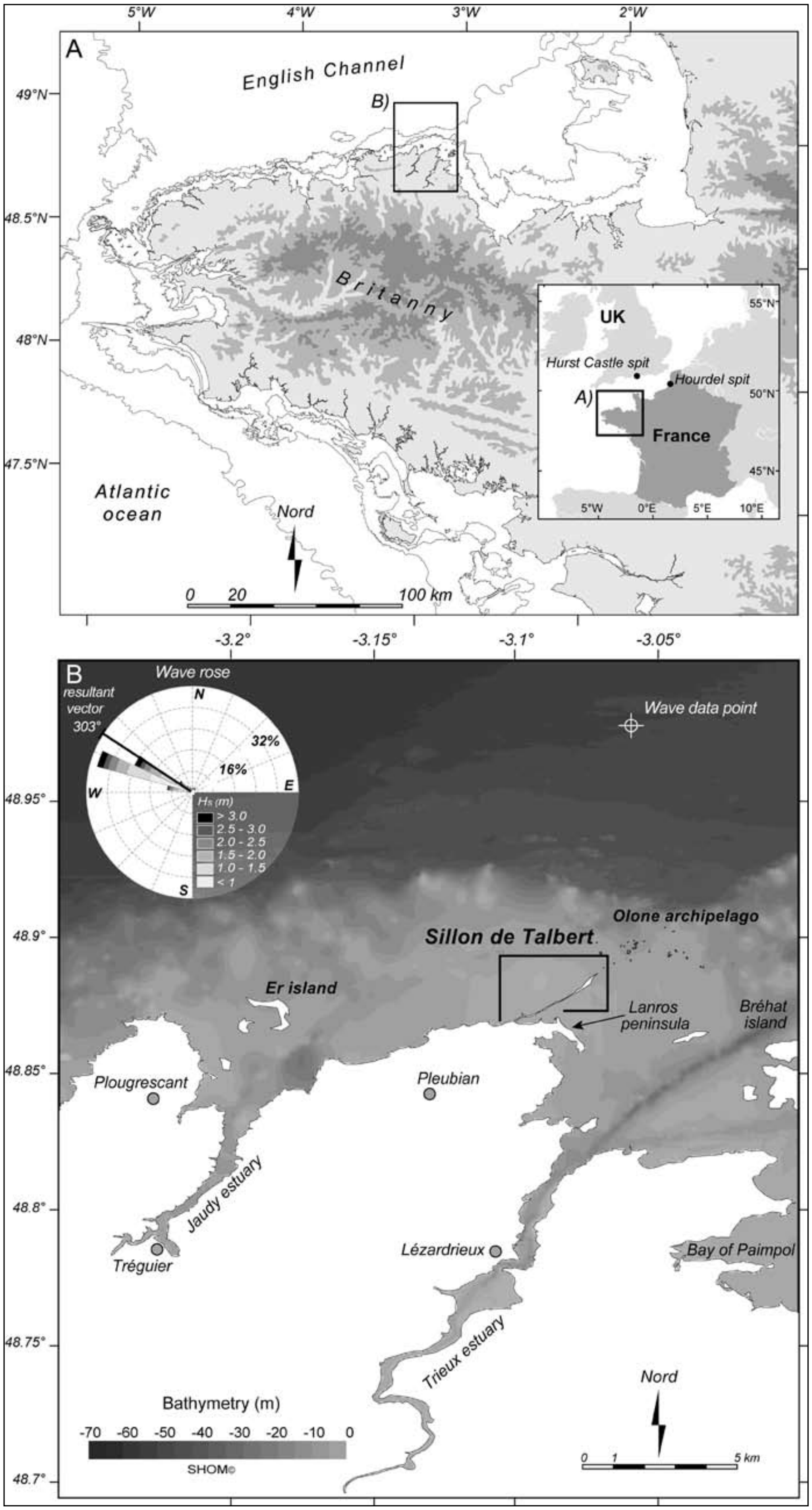

Figure 1. Maps (A) of the general location of Sillon de Talbert on the northern part of Brittany, and an inset (B) giving a more detailed view of the area.

transport corridor with a balanced sediment budget and a distal accumulation area with a positive sediment budget, according to a process described in detail by Orford *et al*. (1996).

The coasts of the English Channel feature many large gravel barriers (Kidson 1963; Carter *et al.* 1987; Firth *et al.* 1995). Several of these barriers have a negative sediment budget that results in particularly rapid retreat by rollover during storms. In urban areas, the recent evolution of these gravel barriers has been particularly well studied due to their protective function against wave erosion and coastal lowland flooding. For instance, in the south of England, Hurst Castle Spit, which is 2.5 km long and located in the southern part of Christchurch Bay (Hampshire, UK), is currently undergoing cannibalization. The rate of retreat by rollover recorded at the proximal end was estimated at 3.5 m/yr between 1968 and 1982 (Nicholls and Webber 1987a; 1987b). This erosion is mainly of anthropogenic origin. Initially, the spit was supplied with sediment from the low cliffs located to the west of the bay. The natural shingle input was severely reduced when coastal urbanization required the construction of coastal protection works farther to the west. From the 1950s, many defense structures (groins, seawalls, rock armoring) were installed progressively on the spit to attempt to stop its erosion. Nevertheless, the storms of November 1954, February 1979, and December 1989 caused several breaches. In 1996-1997, the New Forest District Council decided to implement a £5 million long-term stabilization scheme based on a regular sediment recharge strategy.

On the French coasts of the Channel, the 18-km-long Hourdel gravel spit, fed by gravel delivered by the chalk cliffs, also shows a cannibalization trend that has led to a negative sediment budget at the proximal end. The retreat of the spit by rollover was estimated at between 0.5 and 1.5 m/yr between 1939 and 1991 (Costa 1997; Dolique and Anthony 1999). In the 19th century, many port jetties were built in the sediment transit area, reducing the volume of gravel moving toward the spit. Then, in 1882, the construction of a large jetty at Le Tréport put a definitive end to supply to the spit by blocking sediment in transit (Briquet 1930; Regrain 1992; Costa and Davidson 2004; Costa *et al.* 2007). Since 1966, 80

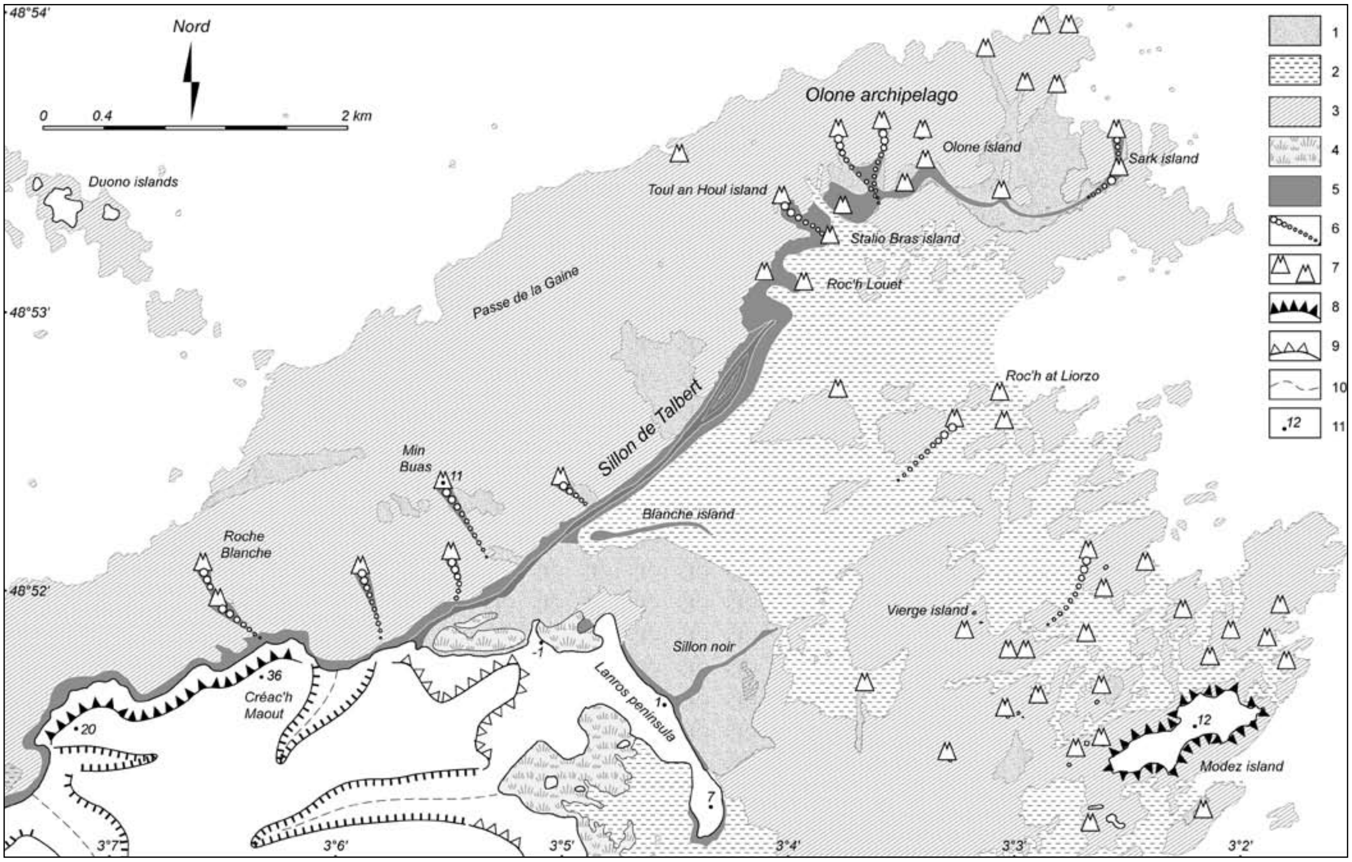

Figure 2. Geomorphological setting of Sillon de Talbert. Legend: (1) sandy foreshore; (2) muddy foreshore; (3) rocky platform; (4) salt marsh; (5) gravel accumulation; (6) trailing spit; (7) skerries; (8) active cliff; (9) abandoned cliff; (10) stream; (11) elevation (m a.s.l.).

cross-shore groins have been successively installed over a distance of 9 km, from Ault to Cayeux-sur-Mer (Dolique and Anthony 1999) in an attempt to stop erosion of the proximal section. During the storm of February 1990, breaching led to the flooding of 3,000 ha of partially urbanised land. Between 1990 and 1994, around 660,000 m^3 of shingle was supplied to repair the damage caused by this storm (Morel 1997). From 1995, the spit management policy involved a regular supply of about 20,000 m^3/yr to feed the spit (Dolique 1998; Dolique and Anthony 1999).

The present study focuses on the Sillon de Talbert, a trailing gravel spit 3.2 km long located on the northern coast of Brittany, in the Côtes d'Armor area (Figure 1a). No doubt due to its large size and its importance in terms of regional tourism, the Sillon de Talbert has been the subject of several observations by Chanson (2004, 2006). It is exposed to swell that enters the Channel from the west, and partially protects the Bréhat Archipelago from coastal erosion. It also protects the Lanros peninsula, an urbanized lowland area, against marine flooding. The retreat rates recorded for the Sillon de Talbert over the past decades are among the highest for the coasts of Brittany (Stéphan 2011a). In order to determine the spit's sediment budget, the evolution of the Sillon de Talbert since the 17th century was reconstructed qualitatively from several early marine maps. Between 1930 and 2010, the mobility of the spit was quantified by the digital processing of aerial photographs and DGPS recordings. The cause of this retreat was then examined through anthropogenic and natural forcings, and in particular among the latter the morphological impact of overwash.

DESCRIPTION OF THE STUDY AREA

The spit lies in a north-east/south-west direction and presents a single crest, except at the distal end where it spreads into a series of skerries (Figures 2 and 3a). The spit is flooded at extreme water levels by storm waves (Figure 3f). The spit's sediment volume is estimated to be 1.23 x 10^6 m^3. Beyond its tip, the Olone Archipelago forms a set of granite islets interlinked by several gravel accumulations that are submereged at high tide (Figures 2 and 3c).

FORMATION OF THE SILLON DE TALBERT

Chanson (2006) dates the establishment of the Sillon de Talbert to over 100,000 yrs ago and explains its formation by the convergence of two tidal currents from the estuaries of the Trieux and Jaudy rivers. These explanations are inaccurate. Like most spits on the coasts of the Channel, the Sillon de Talbert began to form around 6,000 cal BP when relative sea-level rise began to slow (Pinot 1963; Morzadec-Kerfourn 1995). This accumulation was facilitated by the presence of many reefs scattered across the wide seaward-inclined abrasion platform, which blocked the sediment materials transported shoreward during the post-glacial transgression. These materials came from various sources. During the last glacial period (Weichselian), the wide rocky platform that extends in front of the Sillon de Talbert was subject to severe frost shattering (gelifraction) under periglacial conditions, thus providing large quantities of coarse material that supplied periglacial head deposits. These deposits were then eroded and moved shoreward during the Holocene sea level

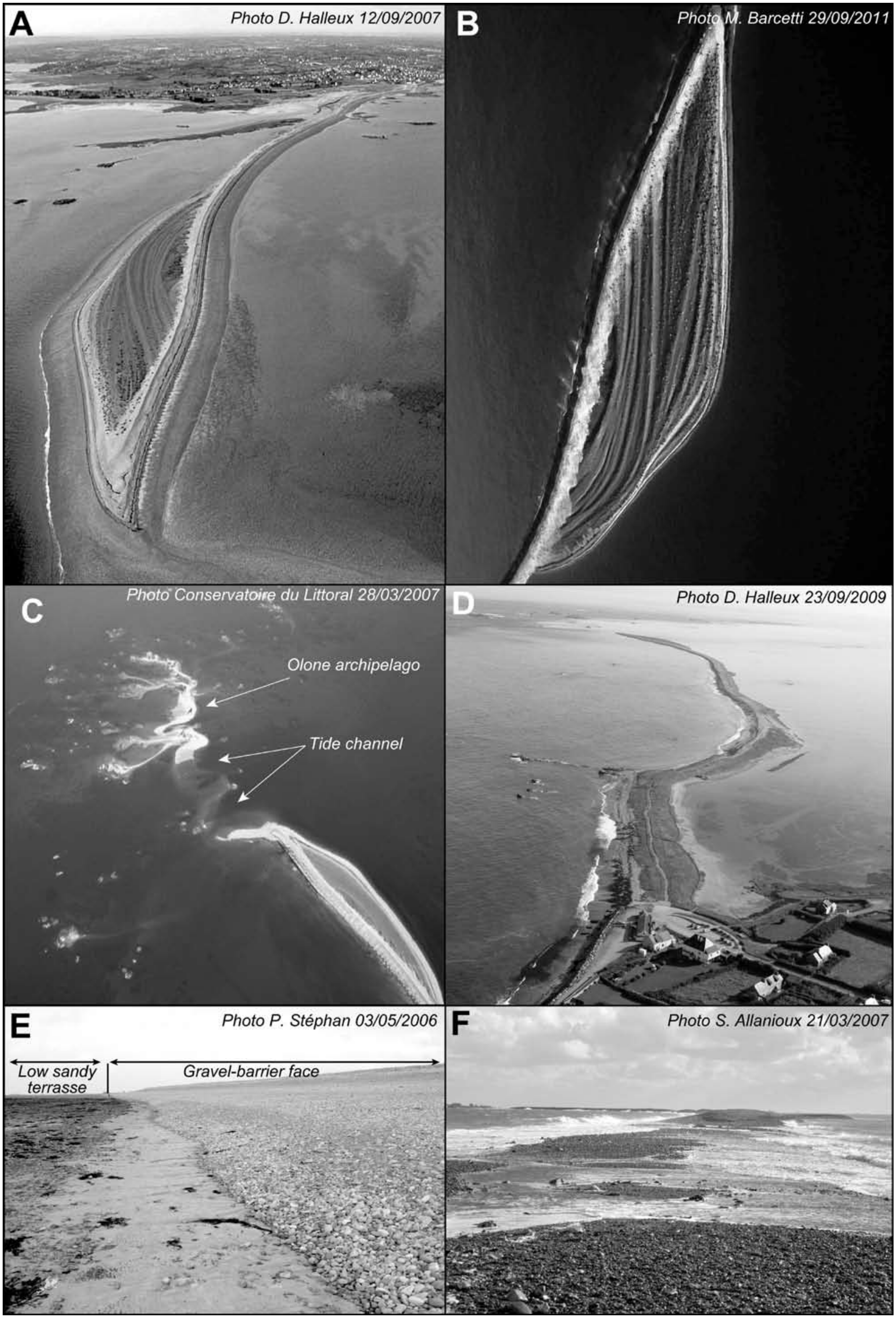

Photo D. Halleux 12/09/2007

Photo M. Barcetti 29/09/2011

Photo Conservatoire du Littoral 28/03/2007

Photo D. Halleux 23/09/2009

Photo P. Stéphan 03/05/2006

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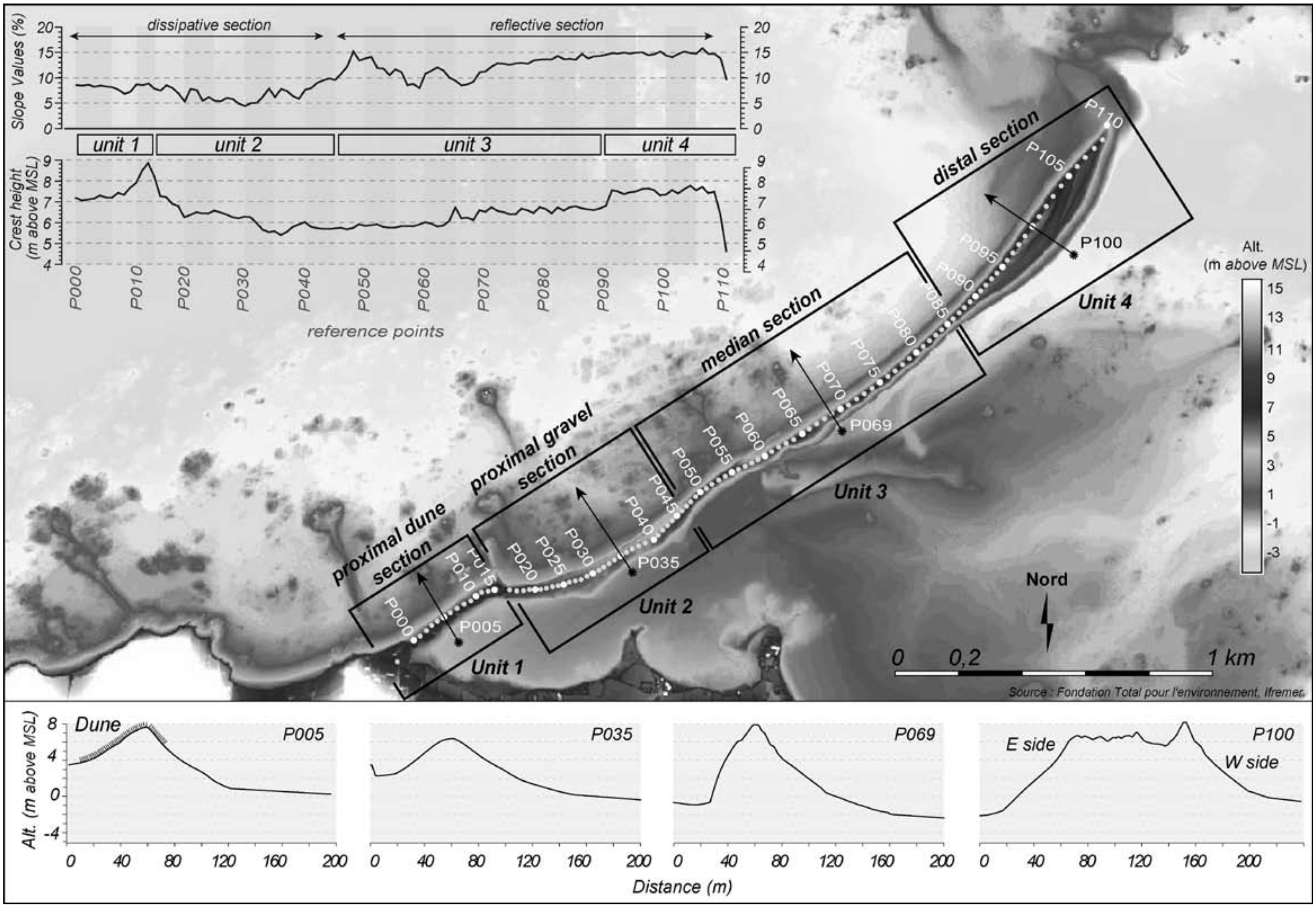

Figure 3 (opposite page). Photographs of: (A and B) the distal part of the spit. (C) Ollone Archipelago separated of Sillon de Talbert by a large tidal channel. (D) The proximal dune section. (E) Slope and sediment characteristics of the gravel barrier face and the low sandy terrace. (F) Overwash event on the median section of Sillon de Talbert.

Figure 4 (above). Morphological characteristics of Sillon de Talbert (Stéphan *et al.* 2010, modified).

rise. The second source of sediment that made up the Sillon de Talbert was the alluvial terraces of the Trieux and Jaudy rivers, constructed during low sea level phases on the continental shelf. These deposits were also moved shoreward during the Holocene sea level rise (Le Page 1967). All these sediment sources contributed to the gradual formation of the current gravel spit, at a location where incident wave energy was too weak to transport the mainly coarse sediment to the coastline. A few hundred meters seaward from the spit, a peat deposit shows at the surface, in which a Final Neolithic archaeological site was uncovered, dating from around 2800 BC (Giot 1972). This human settlement, then located in the sheltered back-barrier area, bears witness to the considerable movement of the sediment accumulation due to sea level rise during the past millennia.

MORPHOSEDIMENTARY ASPECTS

The Sillon de Talbert belongs to the "composite gravel beach" type (Jennings and Shulmeister 2002). The beach face is characterized by a break in slope at mid-tide level (Figure 3e). The lower part of the beach face has a low slope (0.01%), and takes the form of a rocky platform. The upper part of the beach face shows steeper slopes, of between 5% and 15% according to the different types of sediment assemblages that make up the barrier.

Four distinct morphosedimentary units can be distinguished along the spit (Figure 4). Unit 1 is the proximal dune section that stretches over a distance of 500 m. This section is mainly sandy (pebbles < 30%) and has a low slope (between 5% and 8%). The crest of the accumulation is topped with a dune (Figures 3d and 4) whose height exceeds 8.5 m MSL (mean sea level) in places. This section is protected by many reefs located in front on the rocky platform. In the north-east part of this unit, the spit is protected by riprap for a distance of 120 m. Unit 2 is the proximal gravel section and is made up of a heterometric mixture of poorly sorted sand and pebbles (pebbles < 40%). The spit has a low slope (between 5% and 7%) and a low elevation of around 6 m MSL. Unit 3 is the median section. The sediment material is mainly composed of pebbles (> 70%). The beach slopes are steeper and the crest is higher (7 m MSL). Finally, Unit 4 forms the distal section of the Sillon de Talbert. The external edge, exposed to waves, is the most reflective part of the spit (Figure 3a and 3b). The slope averages 15% and the crest elevation is 7.5 m MSL (Figure 4). The proportion of pebbles is greater than 80%.

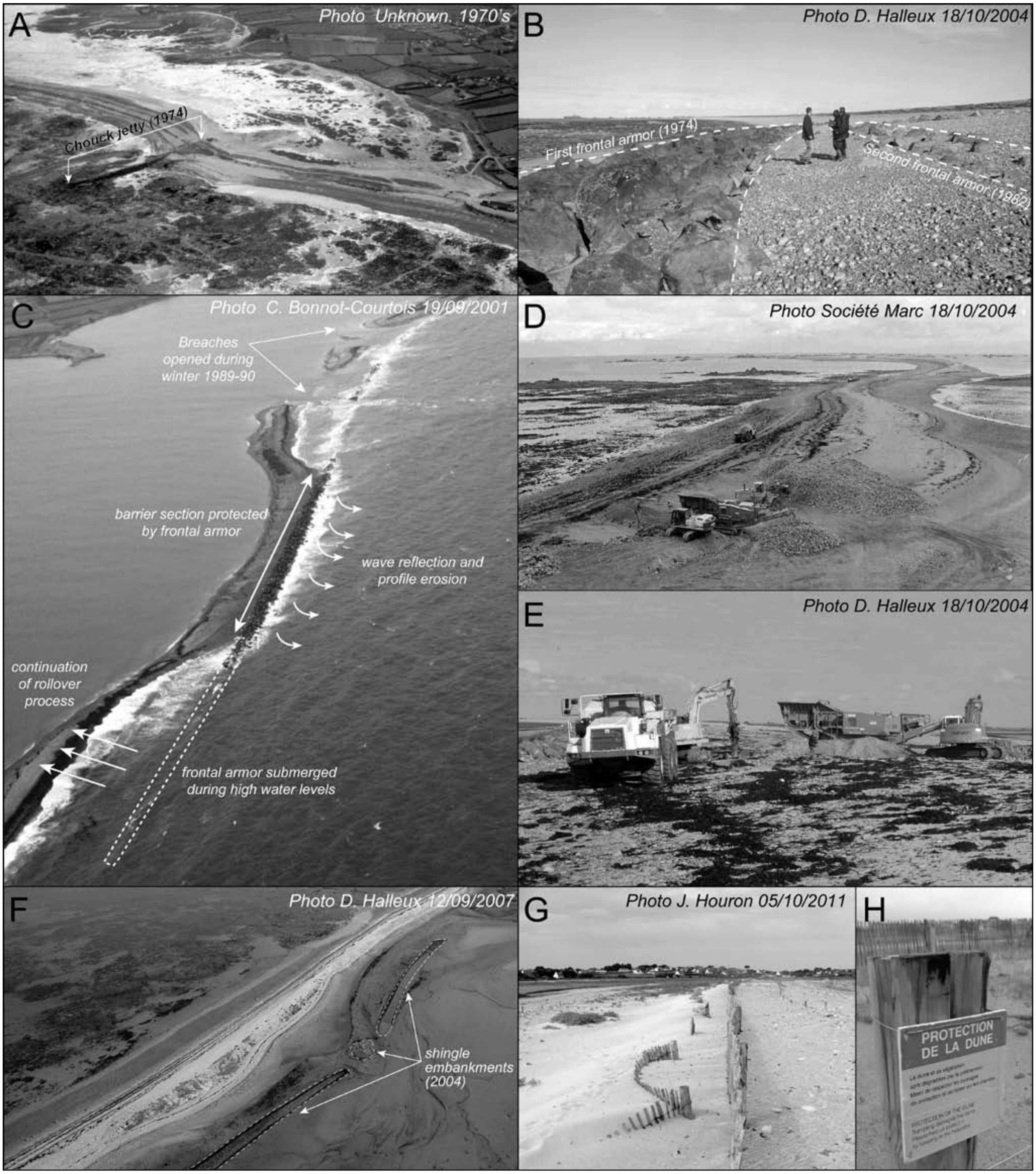

Figure 5 (above). Coastal structures used to protect and restore Sillon de Talbert. (A) Chouck Jetty constructed in 1964 to stabilize the proximal dune section. (B) First and second frontal armor constructed respectively in 1974 and 1982 on the crest of the barrier and located at mid- and low part of the profile in 2004. (C) Median section and proximal gravel section of Sillon de Talbert during a high water level event, illustrating the inefficiency of the frontal armor to stop the barrier rollover. (D and E) Destruction of frontal armor in October 2004. (F) Shingle embankments constructed in October 2004 on the back side of the barrier. (G and H) New policy of coastal management based on dune restoration.

Figure 6 (opposite page). Morphological impacts of the storm Johanna (10 March 2007). (A) Proximal dune section overwashing. (B) Washover runnels during the storm Johanna. (C) Same runnel after the storm. (D) Shingle deposits projected by waves on the top of the proximal dune section. (E) Breach opened during Johanna in the proximal gravel section. (F) Sandy washover fan stopped by shingle embankment on the rear of the proximal gravel section. (G) Crest morphology after sluicing overwash of the median section.

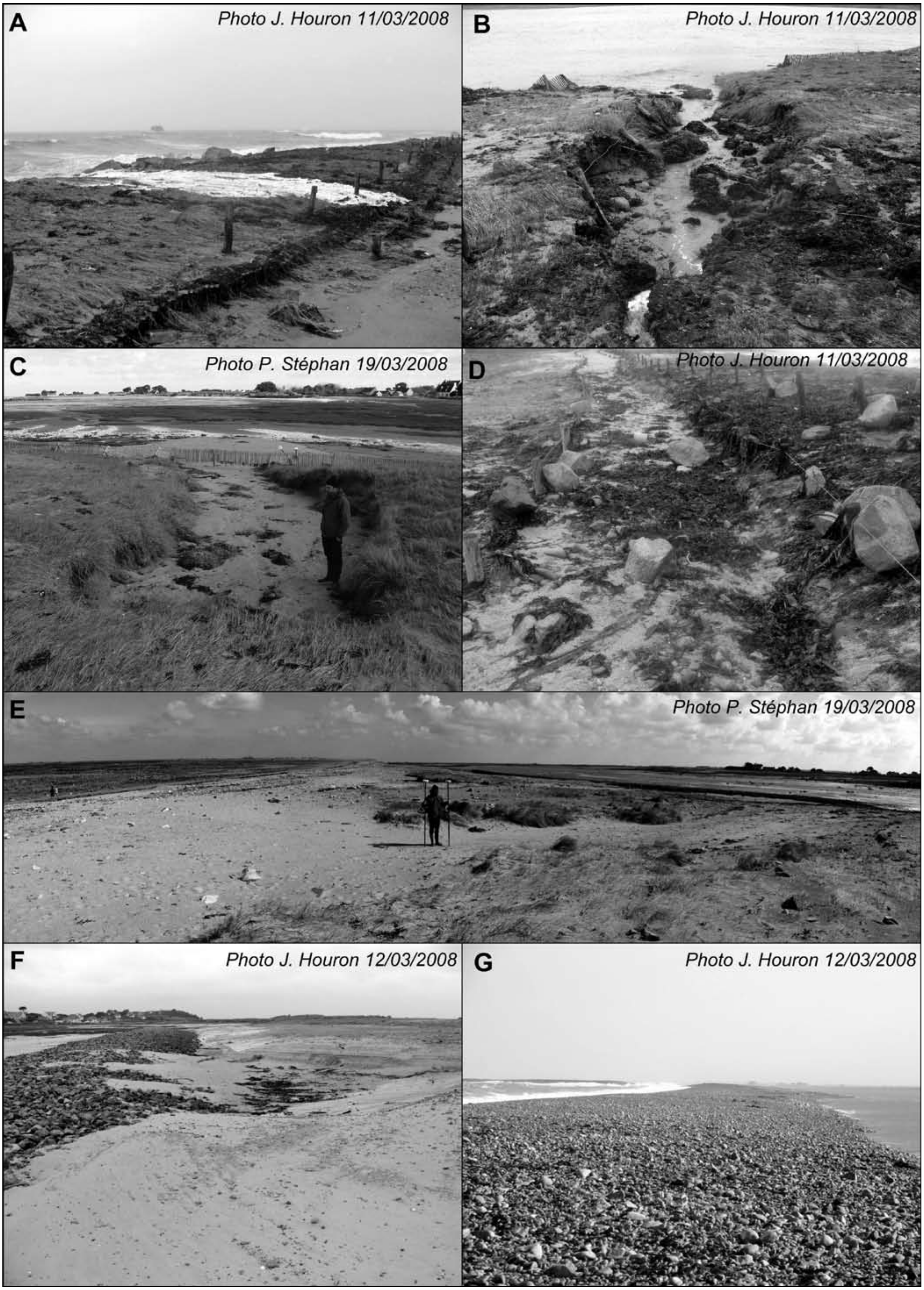
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Table 1. Inventory of ancient maps, aerial photographs and field measurements used to reconstruct the historical evolution of Sillon de Talbert.

Ancient maps:

Title	Date of publication	Date of survey	Authors	Scale	Source
Plan de l'Isle de Bréhat	1666		P. Collin		Bibliothèque Nationale de France
Carte de l'Isle de Bréhat (avec les mouillages et les costes roches et isles voisines)	1764	1675	J.-N. Brellin	30 000	Bibliothèque Nationale de France
Partie de la coste de Bretagne (depuis les isles de Bréhat jusqu'aux sept isles)	1764	1675	J.-N. Beillin	61 000	Bibliothèque Nationale de France
La carte de l'Academie	1751-1815	1747-1789	C.F. Cassini (de Thury)	86 400	Bibliothèque Nationale de France
Cadastra de Pleubian	1829	1829	M. Barré	20 000	Archives départementales des Côtes d'Amor
Plan des passes de la rivière de Tréguier	1843	1837-1838	C. Beautemps-Beaupré (de)	20 000	Service Hydrographique et Océanographique de la Marine

Shoreline kinematics:

Date	Mission IGN	Scale	Photograph no.
29/08/1830	ALG N°6	9 000	74-75-76
22/05/1952	F 07 14-0814	25 000	24
20/06/1961	F 07 14-08-14	25 000	16-17-18
02/05/1966	F 07 14-08-14	25 000	36-37
14/08/1978	FR-3012P	20 000	60-61
04/05/1990	FR 8297	25 000	105-106
09/08/1998	FD 22	25 000	1718-1728
18/09/2002	LIDAR survey (Ifremer)		
01/05/2006	DGPS survey (Géomer)		
20/09/2010	DGPS survey (Géomer)		

HYDRODYNAMIC ASPECTS

The area is macrotidal, with a maximum tidal range of 10.85 m, locally generating relatively strong tidal currents. At the northern tip of the Sillon de Talbert, a vast ebb-tidal lobe has formed, where the currents are channeled into a tidal creek. The current speeds have been estimated at 0.3 m/s (Saur 1974) in this area. The dominant swell comes mainly from the west-northwest (Figure 1B). The significant height (Hs) is between 1 and 1.5 m, and the modal period (Tpic) between 9 and 10 seconds. During storm events, the wave height can sometimes reach up to 9 m and the period up to 20 seconds. In these conditions, the Sillon de Talbert acts as a natural barrier against marine erosion, offering a sheltered environment for the Bréhat Archipelago to the east and preventing flooding by storm waves of the Lanros peninsula to the south, of which a large part is low-lying. Furthermore, the general direction of the spit in relation to the dominant swell induces longshore sediment transport to the distal end, estimated at 3,700 m^3/yr (Stéphan *et al.* 2010).

OVERVIEW OF HUMAN INTERVENTION

The retreat of the Sillon de Talbert observed since the 18th century has led, over time, to the idea that action must be taken to stabilize and/or protect it. This notion was reinforced from the 1960s as the lowland areas behind the spit were beginning to be urbanized. After each erosive stormy event, humans have intervened (or attempted to intervene) when it appeared necessary. The storm of 5 April 1962, which resulted in two large breaches in the proximal dune section, marked the beginning of major stabilization work on the spit. In 1967, the breaches in the dune were artificially plugged and it was from this period that the first coastal defense structures began to be built (Pinot 1994). A riprap jetty, nicknamed "*Chouck Jetty,*" was built in 1974, 400 m from the root of the spit, in order to protect the dune section and to stop eastward sediment transit (Figure 5a). A first riprap longshore defense structure, or frontal armor, was also built at the crest of the spit over a distance of 1100 m (Figure 5b). The purpose of this structure was to prevent overwash of the spit by storm waves to the extent possible in order to stop rollover processes. In 1982, this riprap was extended by a second frontal armor structure toward the tip of the spit over a 300 m section.

However, the armors hindered the spit's natural self-organization processes. While the structure absorbs a lot of the energy of the waves that break on the spit, it also prevents the rise of the crest by overtopping. Furthermore, the presence of riprap leads to strong reflection of swell, which leads to the erosion of the low-lying areas of the beach face (Figure 5c). During winter 1989-90, a series of storms caused considerable subsidence of the Sillon de Talbert, the formation of new breaches and the retreat of the spit despite the protective structures (Pinot 1994). From this date, the main part of the frontal armor became located mid-slope on the beach (Figure 5c).

In 2001, management of the Sillon de Talbert was transferred to a public body (*Conservatoire du Littoral*), which adopted a different coastal erosion

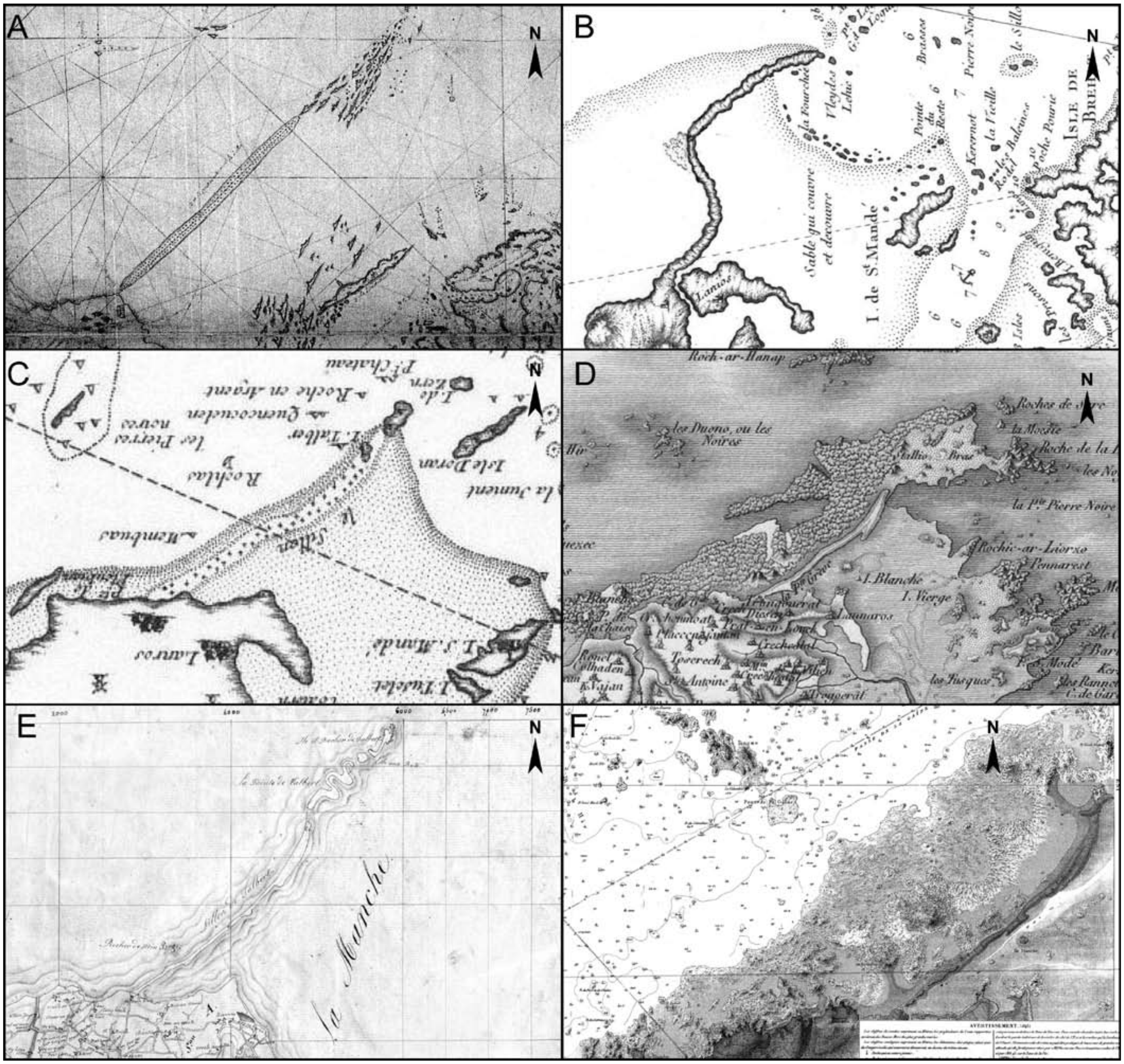

Figure 7. Ancient maps of Sillon de Talbert. (A) Map drawn by P. Collin in 1666. (B and C) Maps of J.-P. Belin based on field surveys of 1675. (D) Map drawn by C.F. Cassini based on field surveys between 1747 and 1789. (E) Cadastral map drawn by Barré in 1829. (F) Marine chart drawn by C. Beautemps-Beaupré based on field surveys between 1837 and 1838.

management strategy. This involved the restoration of the site and some small-scale occasional sediment recharge and barrier reprofiling. The aim was to let the spit retreat while attempting to prevent its complete dislocation. In October 2004, a large part of the frontal armor was removed. The boulders that made up the riprap were crushed (Figures 5d and 5e). The material was then deposited a few dozen meters from the lee edge of the Sillon de Talbert in the form of three shingle embankments intended to slow down its retreat (Figure 5f). Meanwhile, the breaches that had formed during winter 1989-90 in the proximal gravel section were artificially plugged. In this section, dune vegetation restoration measures were also taken at the summit of the spit in order to route pedestrians and promote the growth of the crest by trapping aeolian sediment (Figure 5g).

The last major erosive episode to date was that of storm Johanna, which occurred on 10 March 2008 (Cariolet *et al.* 2010). As shown below, this particularly morphogenic event combined strong storm swell with high spring tides, resulting in major retreat by rollover. Over 10% of the sediment volume of the gravel spit was moved from the outer edge to the inner edge in the median section. Meanwhile, many breaches were formed in the dunes in the proximal section (Stéphan *et al.* 2010) (Figures 6a to 6e). Concurrently with the decision to leave the spit to natural processes, human intervention was restricted to plugging breaches in the dune, and setting up new rows of fencing to trap aeolian transport so as to reinforce dune stabilization (Figure 5h).

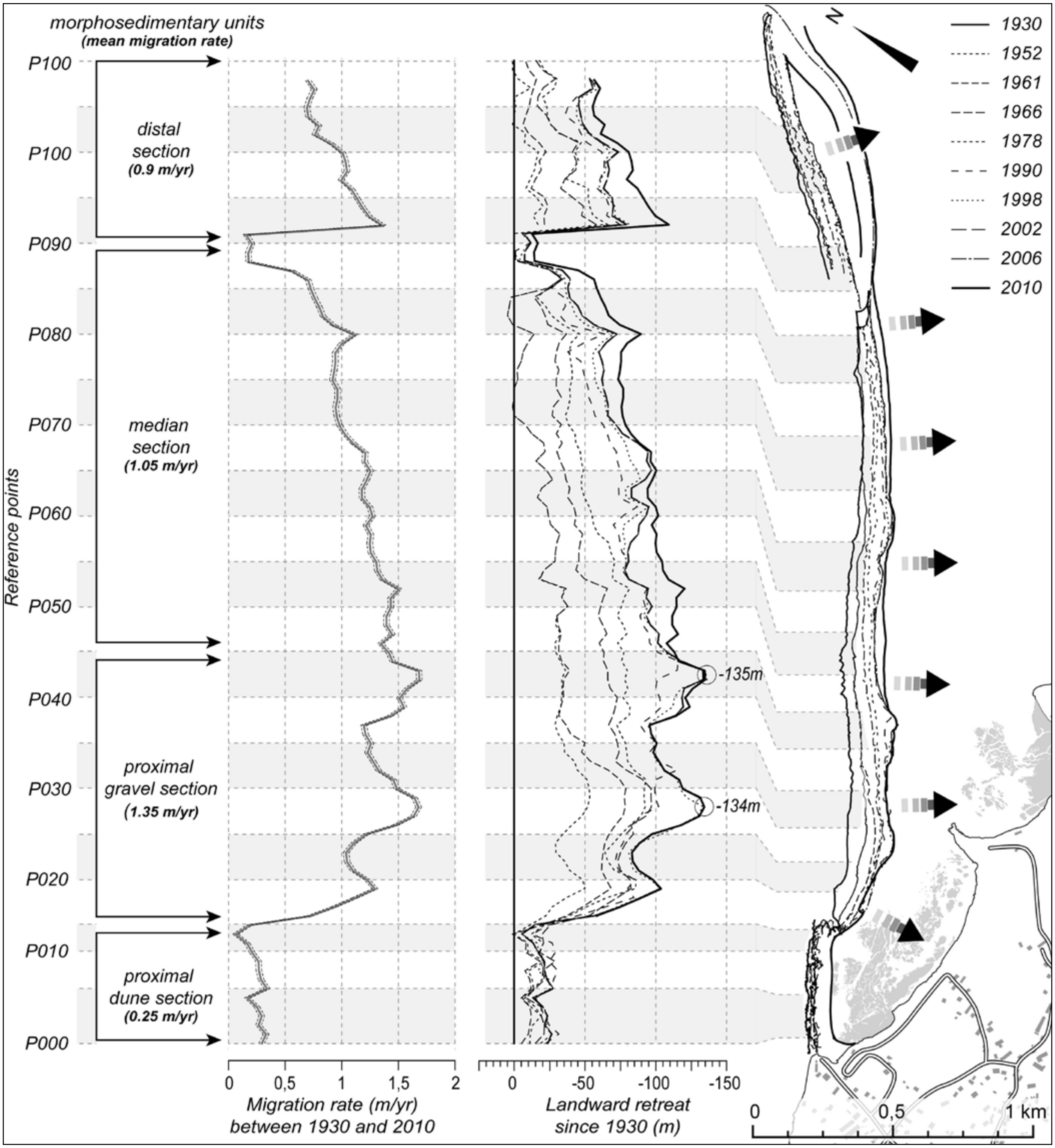

Figure 8. Mobility of Sillon de Talbert between 1930 and 2010.

DATA ACQUISITION AND ANALYSIS

The historical evolution of the Sillon de Talbert was reconstructed from three types of data. First, a series of early maps and cadastral documents were examined (Table 1). The problems related to the use of early maps have been discussed by many authors (Carr 1980, 1962; De Boer and Carr 1969; Anders and Byrnes 1991; Fox *et al*. 1995; Cohen 1997). Until 1750, most maps were inaccurate and aesthetics took precedence over cartographic accuracy. They were often produced for military purposes and many of these maps were simply reproductions of older cartographic documents. No matter how such maps are processed to reduce uncertainty, their use implies considerable error (Thieler and Danforth 1994). The examination of these documents only enabled a qualitative assessment of the main morphological changes that occurred over the last four centuries on the Sillon de Talbert.

Thereafter, various aerial surveys conducted by the French National Geographic Institute (IGN) between 1930 and 2002 were used to quantify the mobility of the Sillon de Talbert (Table 1). Photographs were scanned, geometrically corrected and georeferenced according to a well-known procedure described by

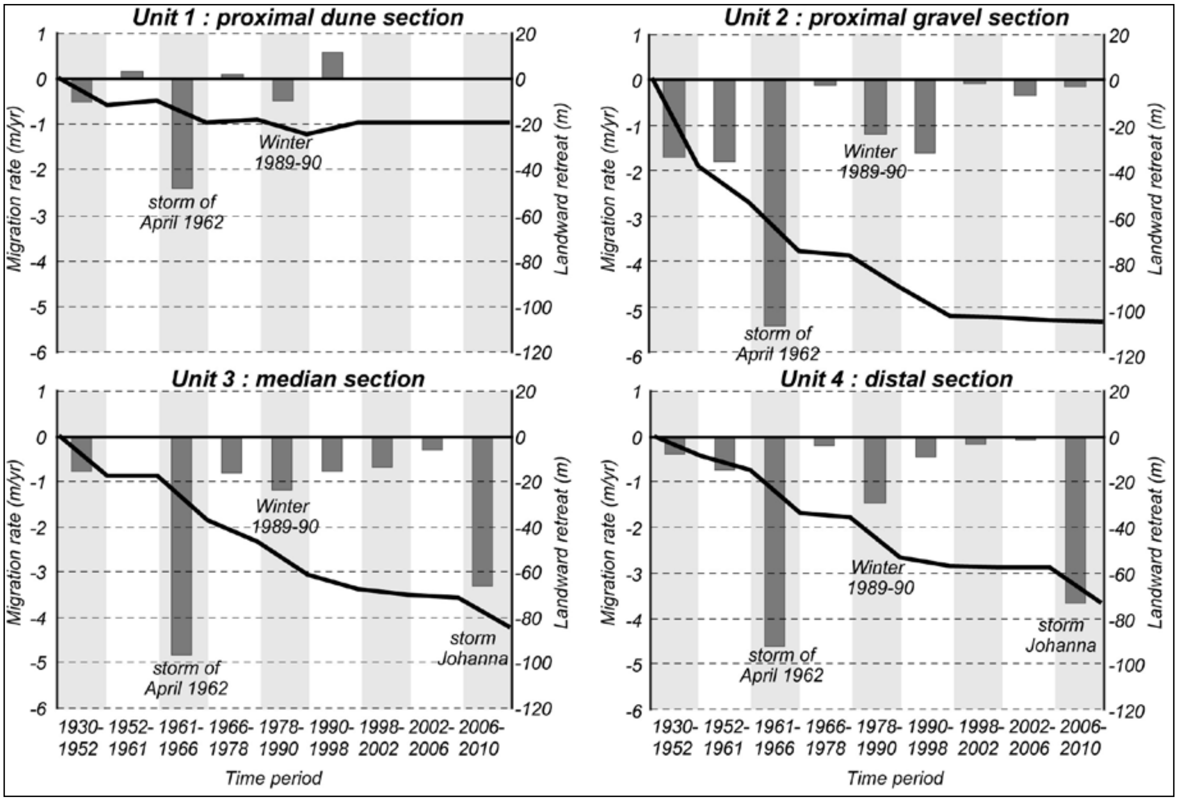

Figure 9. Migration rates (bars) and landward retreat (curves) of the different morpho-sedimentary units of Sillon de Talbert.

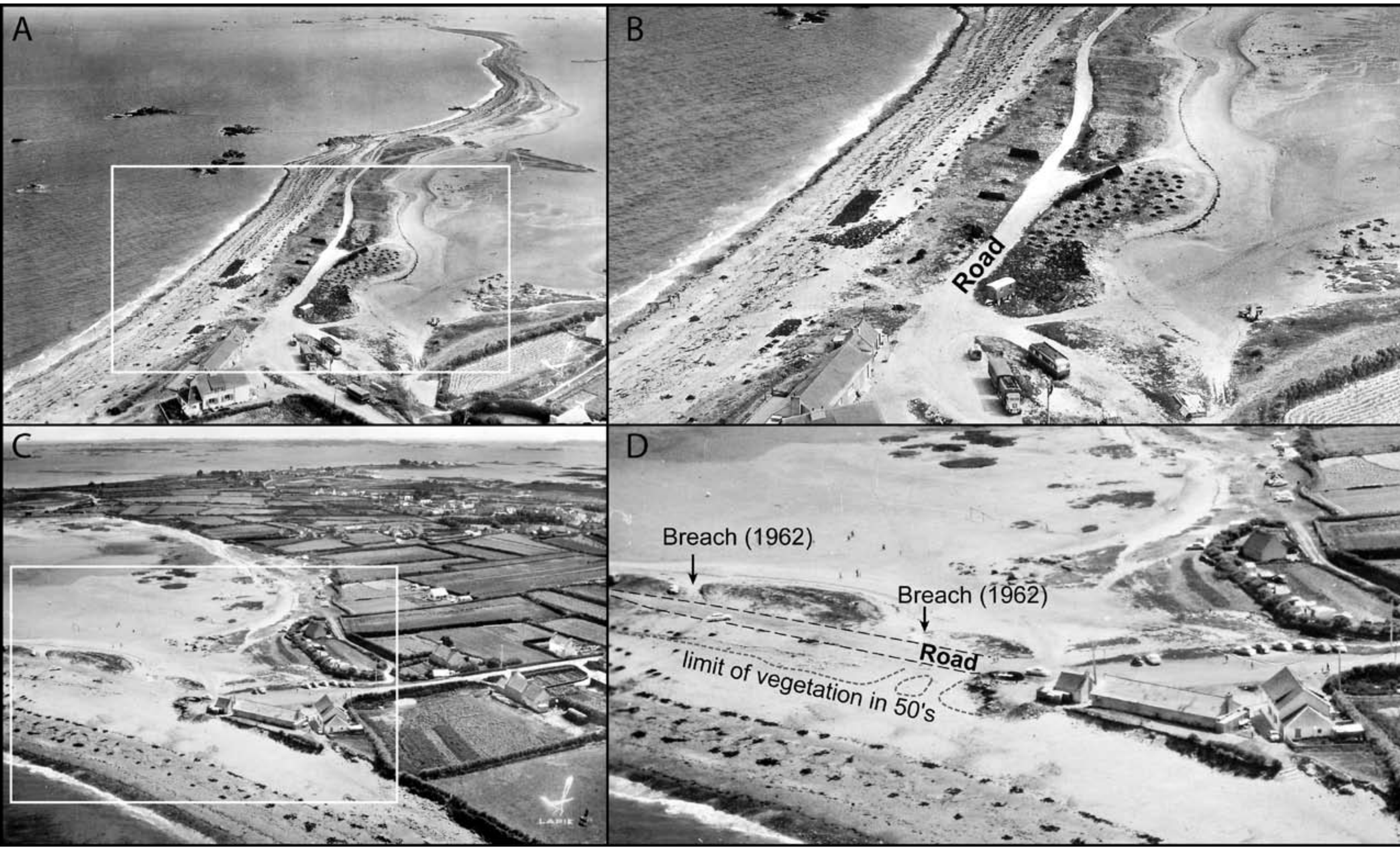

Figure 10. Photographs (A and B) of the proximal dune section of Sillon de Talbert in the 1950s and (C and D) the same section in the mid-1960s, illustrating the morphological impact of the storm of April 1962.

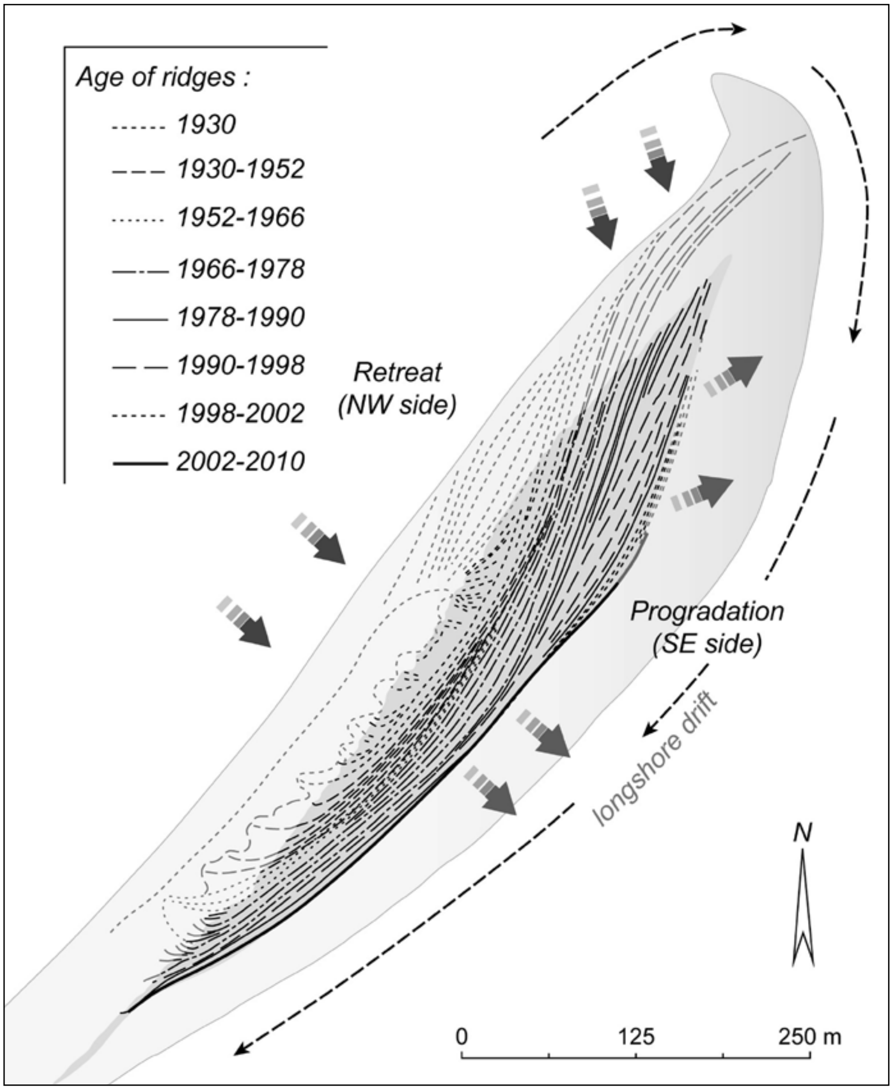

Figure 11. Morphological evolution of the distal part of Sillon de Talbert and historical formation of multi-ridge morphology on the crest.

many authors (Crowell *et al.* 1991; Dolan *et al.* 1980; Douglas and Crowell 2000). The supra-tidal vegetation line was used as the coastline in areas where the spit crest was vegetated (proximal dune section). For the other sections, the base of the lee face was taken as the coastline and was used to quantify retreat rates by rollover. Following the digitization of the coastline on these images, the spit's mobility was measured along 110 reference points, each around 30 m apart. Finally, the errors were estimated using the same procedure as Moore and Griggs (2002) and were found to be less than ±1 m in the areas studied.

A topographic survey was also conducted between 2002 and 2010 based on DGPS measurements (Table 1). The data focused on the position of the vegetation line in the dune section and the position of the lee face base for the rest of the gravel spit. The measurements were taken in RTK mode with a horizontal accuracy of less than 5 cm, and less than 2 cm vertically.

HISTORICAL MORPHOSEDIMENTARY EVOLUTION OF THE GRAVEL SPIT

Analysis of ancient maps: initial dislocation of the spit

The first detailed map of the area of study was drawn in 1666 by P. Collin (Figure 7a). The Sillon de Talbert was represented as a relatively straight line and it appears to be longer than it is today. The spit was attached to the islands of the Olone Archipelago. The maps by J.-N. Bellin (Figures 7b and 7c), published in 1764 but recorded in 1675, are more realistic and also show the barrier as being connected to the islets of Roc'h Louet and Stalio Bras in the Olone Archipelago. A major morphological change can be seen on the map by C.F. Cassini, recorded in the second half of the 18th century. Here, the Sillon de Talbert is no longer attached to the Olone Archipelago (Figure 7d). It was separated by a 200-300 m long breach, probably formed during a storm and maintained thereafter by tidal currents. The Sillon de Talbert is represented here as a trailing spit. The distal end is recurved in the opposite direction to give it a hook-like shape, which suggests that wave diffraction at the tip of the spit was no doubt as strong as it is today and generated longshore drift towards the southwest on the inner edge. The Napoleonic cadastre (Figure 7e) and the hydrographic maps by C. Beautemps-Beaupré (Figure 7f) confirm this morphological modifications during the 19th century. After this date, the main morphological changes were landward retreat and a progressive shift in the orientation of the spit to a more drift-aligned position (Pinot 1994). The proximal section retreated at a lower rate that the rest of the spit, which caused it to pivot towards a position increasingly parallel to incident waves.

Analysis of aerial photographs: retreat of the Sillon de Talbert between 1930 and 2010

Between 1930 and 2010, the mobility of the Sillon de Talbert was dominated by landward retreat by rollover (Figure 8). However, the migration rates and the periods of retreat are distinct between the different morphosedimentary units that make up the spit (Figure 9). During the observation period, the proximal dune section (Unit 1) retreated by around 20 m. This retreat took place mainly between 1930 and 1966. A rapid spit retreat phase was observed between 1961 and 1966 (retreat rate > 2 m/yr), caused by an episode of very intense overwash dated to 5 April 1962, creating two large breaches in this section of the spit (Figure 10). From 1966 onward, Unit 1 showed high stability, due to the construction of the Chouck Jetty restricting sediment transport from this section towards the north-east (Figure 5a).

The proximal gravel section (Unit 2) showed the fastest migration rates for the Sillon de Talbert (an average of 1.35 m/yr). In this section, migration rates exceeded 5 m/yr between 1961 and 1966 (Figure 9). Like for Unit 1, retreat was caused here by the storm event of 5 April 1962. A period of stability was then

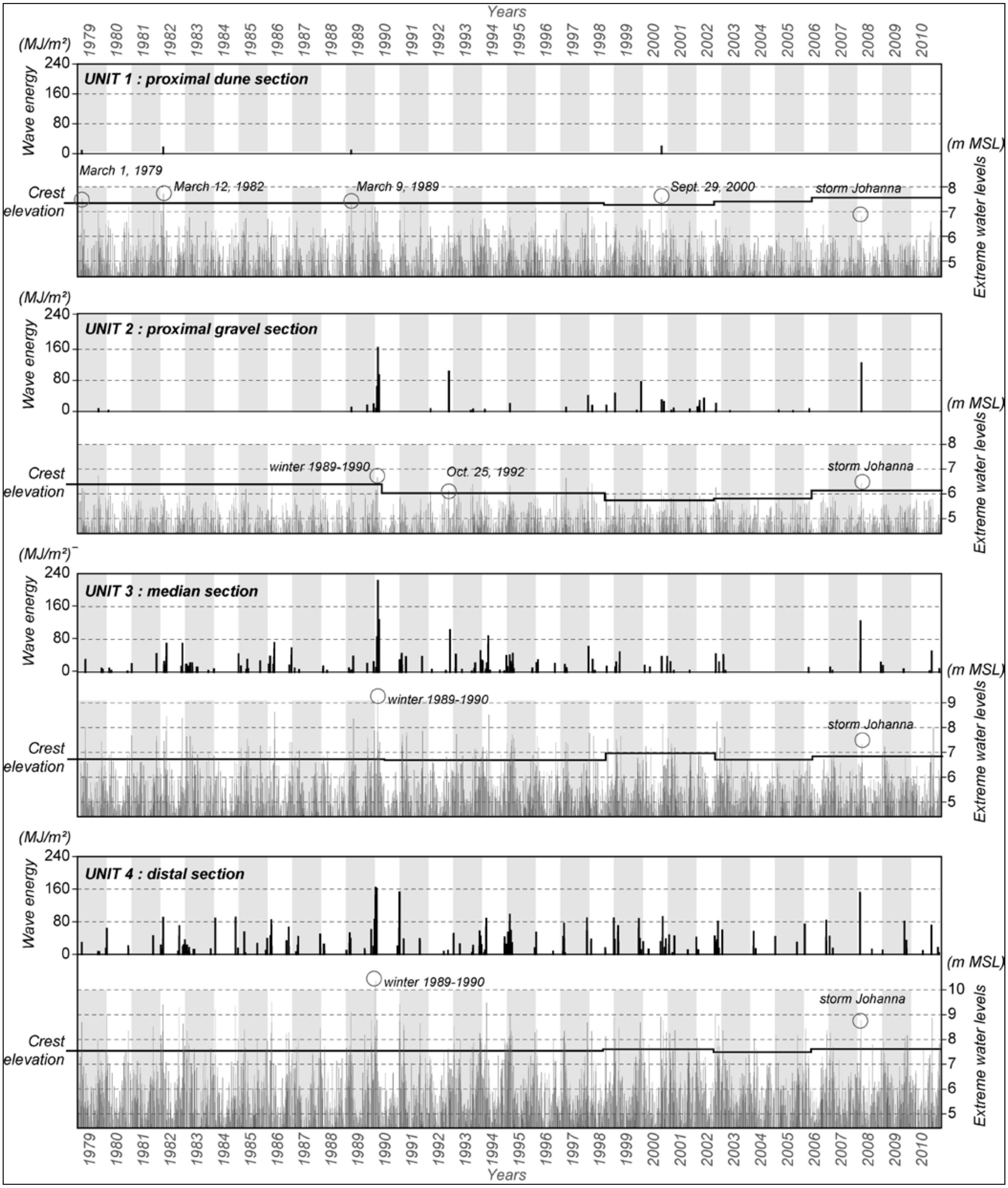

Figure 12. Chronology of extreme water levels and intensity of overwash events between 1979 and 2010 on the different morphosedimentary units of Sillon de Talbert.

observed between 1970 and 1980. During winter 1989-90, a series of storms caused two breaches to form between P025 and P030 and between P040 and P045. In these two areas, retreat was about 135 m between 1930 and 2010 and migration rates exceeded 1.7 m/yr. Since the end of the 1990s, retreat in this section of the spit has slowed, which can be explained, as seen previously, by a series of dune maintenance and restoration efforts on the crest.

The median and distal sections (Unit 3 and Unit 4) showed apparently regular retreat between 1930 and 2010. The migration rate by rollover was on average 1.05 m/yr for Unit 3 and 0.9 m/yr for Unit 4 (Figure 8). However when we take a

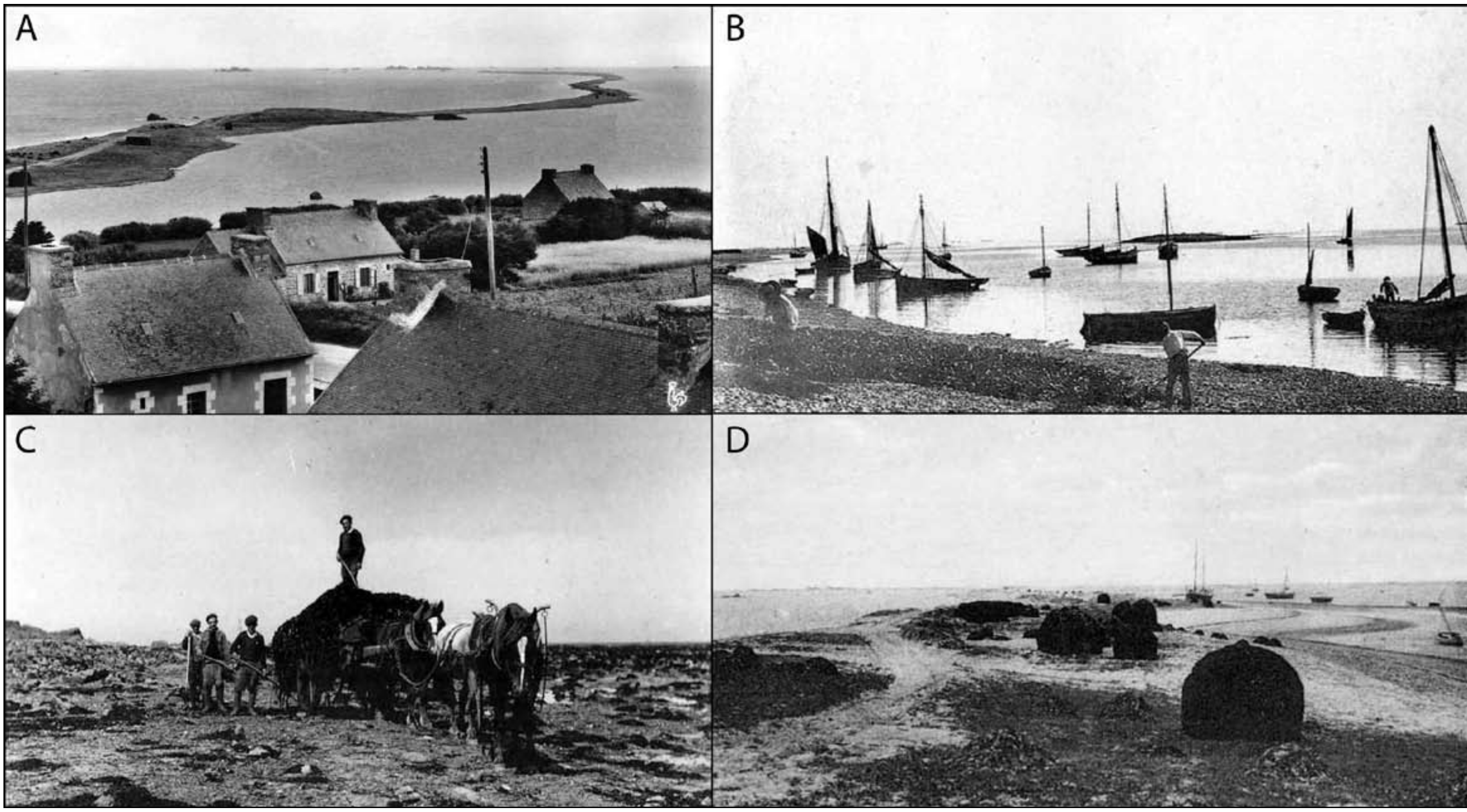

Figure 13. Photographs taken at the beginning of the 20th century illustrating traditional seaweed exploitation and pebble collection around Sillon de Talbert.

closer look, it appears that the mobility of these two sections showed high temporal variability and was characterized by a succession of long phases of stability interspersed with short periods of retreat by rollover associated with episodes of intense overwash. Between 1961 and 1966, the spit's retreat rate was close to 5 m/yr and was largely influenced by the storm event of 5 April 1962, which caused the spit to retreat by around 19 m at its median and distal sections. The period from 1978 to 1990 was a period of stability, but ended with a series of storms during winter 1989-90 that led to a retreat of between -15 m (Unit 3) and -17 m (Unit 4). The most recent retreat phase dates back to the 2006-2010 period, when the retreat rates exceeded 3 m/yr. The majority of this retreat (13.2 m for Unit 3 and 14.7 m for Unit 4) occurred during storm Johanna on 10 March 2008. Although this overwashing was severe, it did not result in breaches in these sections on the spit. The crest was eroded all along the spit. Its elevation decreased, promoting rollover. Inversely, the periods of stability were marked by the rebuilding of the crest by overtopping. The altitude of the spit increased once again, gradually reducing the frequency of overwash.

In addition to retreat by rollover, the distal section underwent major morphological changes between 1930 and 2010, associated with the successive construction of a series of ridges on its inner side (Figure 11). This progradation trend suggests there was a good sediment supply. The majority of longshore drift was redistributed in this section. These evolutions were also the result of an inversion of sediment transfer, from west to east along the outer edge of the spit and in the opposite direction along the inner edge. This inversion of sediment transport was caused by wave diffraction at the tip and the action of secondary swell from the north-east.

ANALYSIS OF OVERWASH EPISODES

In a recent paper, Stéphan *et al.* (2010) described in detail the methodology used to determine the chronology of episodes of overwash along the Sillon de Talbert between 2002 and 2008. All the processing techniques used were applied in this study and extended to the period 1979-2010. This chronology is based on the analysis of extreme water levels that draws upon: (i) the predicted tide defined by the SHOM (French Naval Hydrographic and Oceanographic Service) near to the Sillon de Talbert, (ii) surges and drops calculated at the port of Roscoff, 50 km from the study site, (iii) extreme run-up values defined by the equations of Stockdon *et al.* (2006).

Figure 12 illustrates the chronology of overwash events for the four morphosedimentary units of the Sillon de Talbert. Unit 1 was affected by very few overwash episodes between 1979 and 2010 (Figure 12). These episodes occurred during equinox tides (spring and autumn) and were accompanied by low wave energy, which explains the stability of this spit section from the 1970s. Unit 2 was more frequently affected by overwash events (Figure 12), in particular after the series of storms in winter 1989-90 during which two breaches appeared in this section of the spit. The increase in the number of overwash events in the 1990s can be explained by the lowering of the crest. From 2004, dune vegetation restoration measures implemented on the crest by the *Conservatoire du Littoral* resulted in an increase in the spit crest height. These measures probably prevented breaching during storm Johanna on 10 March 2008. The presence of back-barrier shingle embankments also prevented spit retreat by rollover. Units 3 and 4 showed more frequent overwash events between 1979 and 2010. The most severe of these events were associated with the storms of winter 1989-90 and storm Johanna on 10 March 2008 (Figure 12). These two major sluicing overwash events caused respectively a landward retreat of 15 m and 13.2 m for unit 3 and of 17 m and 14.7 m for Unit 4. Several secondary discrete overwash events were also recorded during the spit's low mobility phases.

DISCUSSION

As shown by the early maps, the Sillon de Talbert was a gravel barrier attached to land at both ends (welded barrier) until the end of the 17th century, before being transformed into a spit due to a breach in the northern part of the barrier during the 18th century. This transformation marked the beginning of a slow cannibalistic process throughout the 19th and 20th centuries accompanied by continuous landward retreat of the spit by rollover. The cannibalistic trend on the Sillon de Talbert is linked to a gradual change in its general direction in relation to incident waves, from a swash-aligned to a more drift-aligned position, leading to an increase in longshore drift. The topographic surveys conducted between 2002 and 2008 enabled an estimation of current longshore drift at an average of 3,700 m³/yr in a north-easterly direction (Stéphan *et al.* 2010). This sediment transport fed the distal end, which widened out through the formation of successive accretion ridges (Figure 3B). In return, the proximal end experienced a sediment deficit due to sediment loss by drift. This situation explains the appearance of many breaches at the root of the spit and the need to build the Chouck Jetty in 1974 to put a stop to erosion. The sediment shortage was deferred to areas downdrift of the jetty, where breaches formed during the 1990s and where the highest retreat rates were recorded over the last decades.

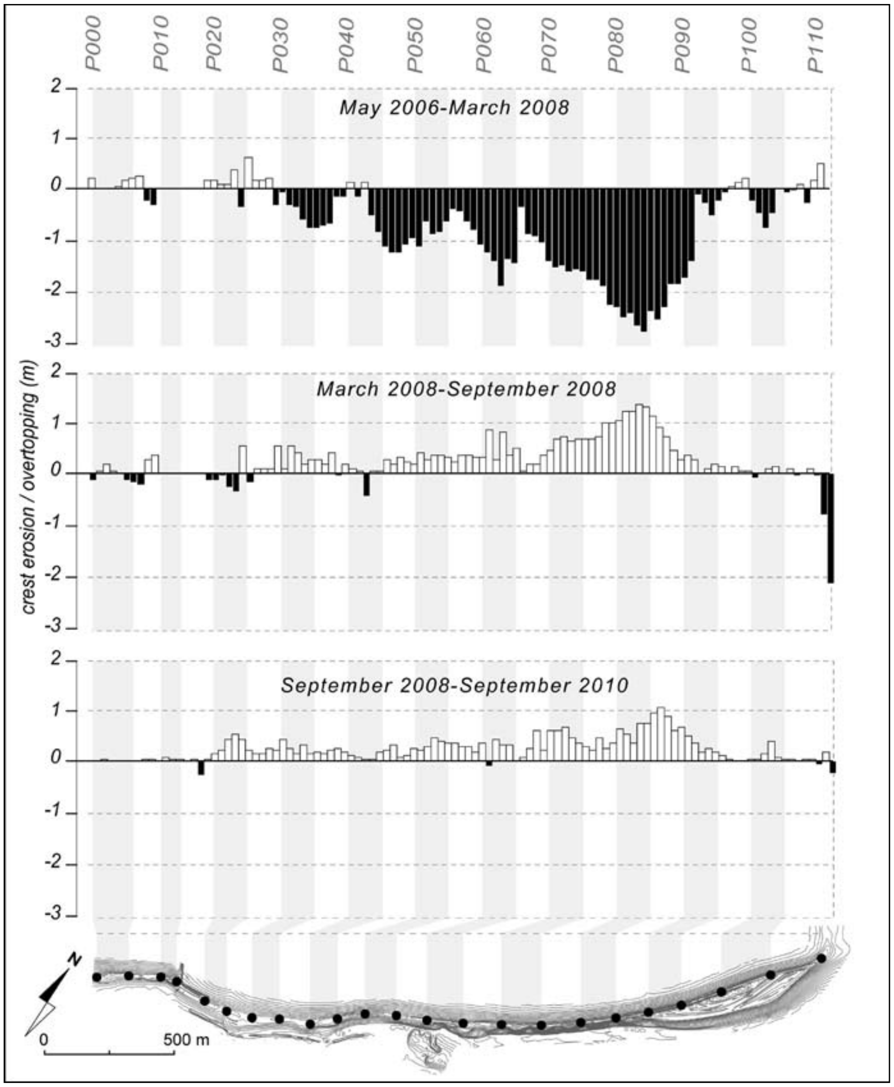

Figure 14. Crest erosion of median and distal sections between May 2006 and March 2008 illustrating the morphological impact of the storm Johanna (10 March 2008). The great resilience of the barrier is illustrated by crest overtopping between March 2008 and September 2010 (modified from Stéphan *et al.* 2010).

This cannibalistic trend is consistent with the processes observed on Hurst Castle Spit and Hourdel spit. However, for these two examples, this cannibalization is mainly of anthropogenic origin. On Hurst Spit, longshore sediment drift was reduced by artificial cliff stabilization in the sediment source area (Nicholls and Webber 1987a; 1987b). On Hourdel spit, the sediment shortage was linked to the construction of harbor jetties, which blocked drift and stopped sediment supply to the spit (Regrain 1992; Costa 1997; Dolique and Anthony 1999). The cannibalistic process was all the more rapid as these were drift-aligned spits and their stability was only maintained by a constant longshore sediment supply from adjacent coastal areas. On the Sillon de Talbert, on the other hand, cannibalization is the result of natural evolution, triggered by the dislocation of the original barrier at the north end. Pinot (1994) dates this dislocation to the mid-18th century. However a breach may have formed before this time, in the early 18th century, due to the violent storm on 26 November 1703. This storm hit the British Isles and western France and is believed to have cost the lives of between 8,000 and 15,000 people. In England, this storm alone is thought to have killed 1,700 men and to have sunk 12 Royal Navy vessels. It was the subject of a novelized description by Daniel Defoe in his book entitled "The Storm." It remains one of the most violent storms in history (Lamb and Frydendahl 2005).

The cannibalization of the Sillon de Talbert highlights the lack of significant sediment input during the recent period in this area. Gravel barriers are deposits of fossil sediment which have formed over long periods of time within a context of sediment abundance and rapid sea level rise during the early and mid-Holocene (before 6,000 yrs BP). In the eastern part of the Channel, authors have shown that much of the gravel present on the coast originated from the alteration by the sea of a peri-glacial head deposits present on the continental shelf during post-glacial transgression (Giot 1962; Bray *et al.* 1995; Morel 1997; Costa 1997). This sediment source gradually became exhausted during the last millennia because of the decrease of the rate of sea-level rise. Studies conducted in Brittany have shown that gravel input from shallows is now limited (Morel 1997; Suanez *et al.* 2011). This sediment depletion is considered by many authors as a major cause of worldwide beach erosion (Bird 1985, 1996). It is explained by the fact that, in areas where sea level over the past 5,000-6,000 yrs has been relatively stable, accumulations formed by sediment were derived from available materials accumulated on the inner continental shelf. The morphosedimentary dynamics of the Sillon de Tabert gravel barrier therefore suggest that these drowned nearshore deposits were totally reworked by waves and driven onshore during the Holocene transgression.

In terms of sediment supply to gravel barriers in western France, the soft cliffs of head deposits, composed largely of coarse sediment, have gradually become the main, or even only, sediment sources (Guilcher 1949; Guilcher *et al.* 1957, 1990; Chauris 1989). Coastal rivers in no way contribute to this input as they transport fine grain sediments in suspension (Laignel *et al.* 2008). However, these soft cliffs are currently experiencing extremely slow retreat rates and supply low sediment volumes to the coast (Stéphan 2011b). This may be explained by the absence of transgressive pulses in the sea level in Brittany over the last millennia. On the coasts of Nova Scotia in Canada, the authors have explained gravel barrier and spit erosion by the absence of major fluctuations in sea level during the past millennia, therefore not promoting the release of large quantities of sediment on the foreshore by acute cliff erosion by waves (Forbes *et al.* 1995; Orford *et al.* 2002). In Brittany, the rate of relative sea-level rise was estimated at 1 mm/yr during the last three millennia (Morzadec-Kerfourn 1995). Stéphan (2011c) showed that in western Brittany (Bay of Brest), rates of relative sea-level rise have not been regular, but have gradually declined since 2,700 BP and are below 1 mm/yr for the last millennium. These rates of relative sea-level rise are not sufficient to enable a widespread release of sediment by cliffs of head deposits. Field observations indicate that the base of soft cliffs is rarely reached by waves (Stéphan 2011a). Coastal slopes tend to gradually become regularized and most landslides become vegetated. Furthermore, the almost complete stripping of peri-glacial material from cliffs has led to the gradual appearance of subjacent bedrock, often very resistant, that it is difficult for waves to erode. The presence of a large platform in front of the current cliffs promotes the dissipation of wave energy before it reaches the foot of the cliff, limiting erosion by the sea.

Furthermore, on the coasts of the Channel, the gravel shortage has been exacerbated by major sediment removal. On the coasts of Normandy, sediment removal halved the sedimentary stock of beaches between the beginning and end of the 20th century (Morel 1995). From 1840, flint pebbles were exported to Great Britain to make pottery (earthenware and porcelain). In 1875, a pebble extraction and sorting plant was set up in Dieppe. In 1900, the volume of pebbles extracted for export reached 10^5 m^3. Along the Brittany coastline, pebbles were only extracted for industrial use in the Bay of Audierne. Pebbles were mainly extracted during the Second World War by the "Todt Organisation," an auxiliary body of the Wehrmacht, to supply the construction of fortifications forming the Atlantic Wall (Desquesnes 1992; Chanson 2004). In this area, sediment extraction represented a volume of around 10^6 m^3 (Morel 1995).

For the Sillon de Talbert, no data is available to estimate the volumes extracted, but historical documents indicate that during the 18th and 19th centuries, the barrier was home to major human activity that revolved around seaweed exploitation and pebble collection (Figure 13). Most sediment removal was by local populations for construction purposes. Pebbles were also used as ballast for many sailing ships that benefited from the sheltered waters on the leeward side of the barrier. Sediment removal was not prohibited until the early 20th century. During the Second World War, the German army also tapped into the Sillon de Talbert, but most sediment removal occurred on the Eemian barrier on Ile Blanche (Pinot 1994). The Sillon de Talbert was therefore never an industrial pebble source and the spit's current sediment shortage mainly reflects the regional context of diminishing sediment, mainly coarse sediment, on the continental shelf.

Morphological analysis combining the coastline kinetics and the study of extreme water levels provides a distinction between two rollover dynamics along the spit, according to the different morphosedimentary units. In the proximal sections (Units 1 and 2), the spit comprises a high proportion of sand. Its summit is vegetated. The slopes are less steep and the crest lower. The rollover processes are similar to those described for barrier island sand spits (Leatherman 1979, 1983; Stockdon *et al.* 2007). Episodes of overwash give rise to breaching, erosion channels through the crest (Figure 6e), and washover fans on the inland side. This type of morphology was observed after storm Johanna (Figure 6f) in Units 1 and 2 of the Sillon de Talbert. In these sections, the natural plugging of breaches is slow. The high proportion of sand makes sediment accumulation at the crest by overtopping difficult. Breaches are plugged by trapping aeolian sediment by summit vegetation and dune reformation.

On the other hand, the median and distal sections (Units 3 and 4) are mainly composed of gravel and pebbles. The sandy fraction is almost nonexistent. The beach slope is steep and the crest altitude high. During overwash events, the spit's response is characterized by that described by Orford and Carter (1982) on gravel barriers. Only major events combining a high tide level and storm conditions lead to major landward gravel transfer and general retreat by rollover, defined as "sluicing overwash" by Orford *et al.* (1991). Minor events lead to discrete overwash or an overtopping process that promotes crest reformation and a return to the initial situation following a period of erosion. From this point of view, gravel barriers therefore show strong resilience to extreme events (Orford 2011). Through annual topographic monitoring conducted following storm Johanna, this resilience was quantified (Stéphan *et al.* 2010). Post-storm measurements taken on 19 March 2008 showed the complete remobilization of the crest by waves, resulting in an average 1 m reduction, promoting overwash processes at high tide levels (Figure 14). The retreat by rollover measured in the median and distal sections reached an average of 10 m. Similarly, the volume transported was estimated at 100,000 m^3, *i.e.* 10% of the overall volume of the Sillon de Talbert (Stéphan *et al.* 2010). From September 2008, the measurements showed a rise in the crest due to overtopping processes. This post-storm trend continued until September 2010, at which point the crest reached its pre-storm elevation (Figure 14). Thereafter, the last measurement, taken in September 2011, which is not presented in this study, shows the continuity of these resilience processes.

This study shows there are no coastal engineering solutions to limit rollover processes on gravel barriers. The overview of human intervention on the Sillon de Talbert highlights the inefficiency of riprap defense structures in the face of the rollover process. The frontal armor set up in 1974 on the crest was unable to reduce overwash. The same conclusion was drawn for Hourdel Spit and Hurst Castle Spit, where the local authorities have now opted for a regular sediment recharge scheme on the proximal sections. On the Sillon de Talbert, the frontal armor was almost entirely destroyed in 2004 due to its negative effects on barrier profile and due to its inefficiency to stop barrier retreat. This is a unique initiative for the French coastline since the Sillon de Talbert is the only example of the deliberate removal of a coastal defense structure. It denotes a radical shift in the coastal erosion and coastline retreat management strategy in France. It was led by the *Conservatoire du Littoral*, the national organization in charge of the acquisition of coastal land for its preservation. Since the 2000s, the *Conservatoire du Littoral* has also been implementing an acquisition policy geared towards urbanized areas sensitive to coastal erosion and marine flooding in the back-barrier area of the Sillon de Talbert. This policy enables the organization of strategic withdrawal and leaves natural processes to gradually take their course.

CONCLUSION

The study of early maps showed that, until the end of the 17th century, the Sillon de Talbert was connected to the islets of the Olone Archipelago, forming a 4-km-long swash-aligned gravel barrier. The dislocation of this original barrier gave rise to a gravel spit, whose distal end gradually became recurved, and which became more drift-aligned. This morphological change gradually reinforced sediment transit toward the north-east and a cannibalistic process over the past centuries. The absence of significant sediment input over the recent period exacerbated this sediment shortage. Indeed, the Sillon de Talbert was formed by the remobilization of the abundant sediment stock present on the continental shelf during the Holocene sea level rise. Yet, this stock has been entirely remobilized over the past 5,000-6,000 yrs. The cannibalistic process affecting the spit has resulted in the weakening of its proximal section and its erosion during the heavy storm of 5 April 1962. On the other hand, the distal end has benefited from a sediment supply by longshore drift. The spit has widened out and a series of successive ridges has formed.

Alongside this cannibalistic trend, the analysis of coastline evolution has shown that the mobility of the Sillon de Talbert has led to rapid retreat by rollover over the past decades. Between 1930 and 2010, the average retreat rate was 1.1 m/yr for the whole of the spit. Upon closer investigation, the evolution is shown to differ between morphosedimentary units. The proximal dune section has been stable since 1966 thanks to the construction of a jetty in 1974 which restricts sediment drift towards the north-east. The proximal gravel section shows a negative sediment budget and recorded the highest retreat rates (1.35 m/yr between 1930 and 2010). Locally, retreat reached -135 m between 1930 and 2010, where breaching during the 1989-90 winter storms promoted leeward sediment transfer. In this section, the rollover dynamics appear similar to those of barrier islands, due to the high proportion of sand in the spit sediment. Dune restoration measures on the crest and the construction of artificial embankments on the back-barrier now limit the retreat of this section. The median section is the transport corridor and has a balanced sediment budget. The average retreat rate was 1.05 m/yr between 1930 and 2010. However, the mobility of this section shows high temporal variability and is characterized by long phases of stability, interspersed with short periods of retreat. Retreat occurs when a high tide level coincides with storm waves. Sluicing overwash affects the whole of the upper part of the spit profile. Retreat occurs in only a few hours, without local breaching. Following such episodes of overwash, the crest may be reformed rapidly by overtopping, as shown by the topographic surveys conducted in the aftermath of storm Johanna on 10 March 2008 (Stéphan *et al.* 2010). The distal section also has a balanced sediment budget. The retreat rate was 0.9 m/yr between 1930 and 2010 and the mobility was similar to that of the median section. The eastern side of the hook has a positive sediment budget and shows a progradation trend through the construction of successive ridges. Sediment supply to this part of the spit is estimated at 3000 m^3/yr.

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