Effects of natural and human forcing on mesoscale shoreline dynamics of Saint-Michel-en-Grève bay (Brittany, France)

Serge S. Suanez, Pierre Stéphan

Effects of natural and human forcing on mesoscale shoreline dynamics of Saint-Michel-en-Grève Bay (Brittany, France)

By

Serge Suanez and Pierre Stéphan

GEOMER – UMR 6554 CNRS LETG, Université de Bretagne Occidentale
Institut Universitaire Européen de la Mer, Technopôle Brest-Iroise
Place Nicolas Copernic, 29280 Plouzané, France
serge.suanez@univ-brest.fr

ABSTRACT

By monitoring shoreline changes and subaerial beach volume in Saint-Michel-en-Grève bay in northern Brittany over the past 20 years, the mesoscale shoreline dynamics were assessed. Previous work has shown that both natural and human forcing have played an important role in the long-term changes of the bay, but the respective causes of each type of forcing have not previously been studied in detail. This study shows that between 1990 and 2009, a large volume of sediment input resulted in rapid accretion of dunes in the bay. Sedimentation rates reached an average of $0.1 m^3/m^2/yr$ over the whole study period. This positive sediment budget confirms the trend of sediment accumulation noted since the end of the 19th century. Nevertheless, temporal variation in the shoreline dynamics can be related to changes in the frequency and magnitude of storm surges and resulting high tides. Shoreline erosion/accretion records dating from 1990 were compared with extreme water levels. Relatively high shoreline retreat rates during periods of 1999-2002 and 2006-2008 were associated with a relatively large number of storm surges. Slower erosion and relatively rapid accretion occurred between 1990 and 1999 and during a more recent period, when there have been relatively few major storm surges. Erosion phases were related to the occurrence of extreme spring high tides and wave action associated with storms. Storms and surges in the northern Brittany Channel are associated with Atlantic depressions whose direction and rate of movement have a strong influence on wind speeds, wave energy and the height of tides. However, sediment budget of Saint-Michel-en-Grève bay upper beach, in terms of shoreline erosion/accretion changes, is not directly related to the North Atlantic Oscillation index. Tide condition leading to high or low water level plays a major role by controlling erosion or accretion processes. Human forcing was identified as feedback processes due to the modification of morphological and hydrodynamic conditions. These modifications occurred after coastal engineering works had been carried out on the foreshore to eliminate the confluence of two rivers. West-east longshore sediment transport induced the erosion of the dune of Grand Rocher, while the removed sand contributed to the growth of the dune of Tréduder.

ADDITIONAL KEYWORDS: Sediment budget, monitoring; shoreline changes; dune erosion, storm surges, human forcing.

Manuscript submitted 2 June 2010, revised and accepted 8 February 2011.

Shoreline dynamics are always difficult to determine precisely because the processes by which shores accrete or erode frequently result from a combination of natural and anthropogenic forcing. For instance, erosion on a popular tourist beach at St. Queen's Bay in Jersey (Channel Islands) has been associated with natural forcing via the cessation of sediment input from finite offshore sources as well as with anthropogenic forcing via construction of a seawall and mining of beach sand that has exacerbated erosion (Cooper and Pethick 2005). Similarly, shoreline change analysis carried out along the California coast showed that 40% of beaches are undergoing long-term erosion even if a long-term accretional signal in some parts of the state is probably related to coastal engineering projects and/or large sediment input from rivers (Hapke *et al.* 2009). Morphological dune and beach monitoring at Cabo Falso (Baja California peninsula) also showed morphodynamic processes were the response to natural, Hurricane Juliette (2001), and anthropogenic influence (Camacho-Valdéz *et al.* 2008). Several case studies shown anthropogenic activity was the most influential factor in the long-term sediment budget and shoreline dynamic, making very complex the evaluation of natural forcing on these morphological changes (Lorenzo *et al.* 2007; Martínez del Pozo and Anfuso 2008; Pandian *et al.* 2004; Anthony and Dolique 2001).

In this study, we analyzed the respective roles of natural and anthropogenic forcing in the variation in the sediment budget of Saint-Michel-en-Grève Bay over the past 20 years. With the development of tourism in Brittany since the middle of the 19th century, this remarkable coastline has undergone significant anthropogenic pressures (construction of hotels, coastal defense, coastal roads, etc.) (Goulhen 2004). Over the same time period, natural dynamics, which mainly involve massive inputs of sand, have caused great morphological changes (Pinot 1987, 1995). Analysis of natural forcing thus depends primarily on identifying the high intensity morphogenetic events that have generated important morphosedimentary modifications. These morphogenetic events are short-term impacts, but are nevertheless part of a long-term process that is essentially characterized by a positive sediment budget. On the other hand, anthropogenic forcing involves coastal engineering solutions that have been implemented

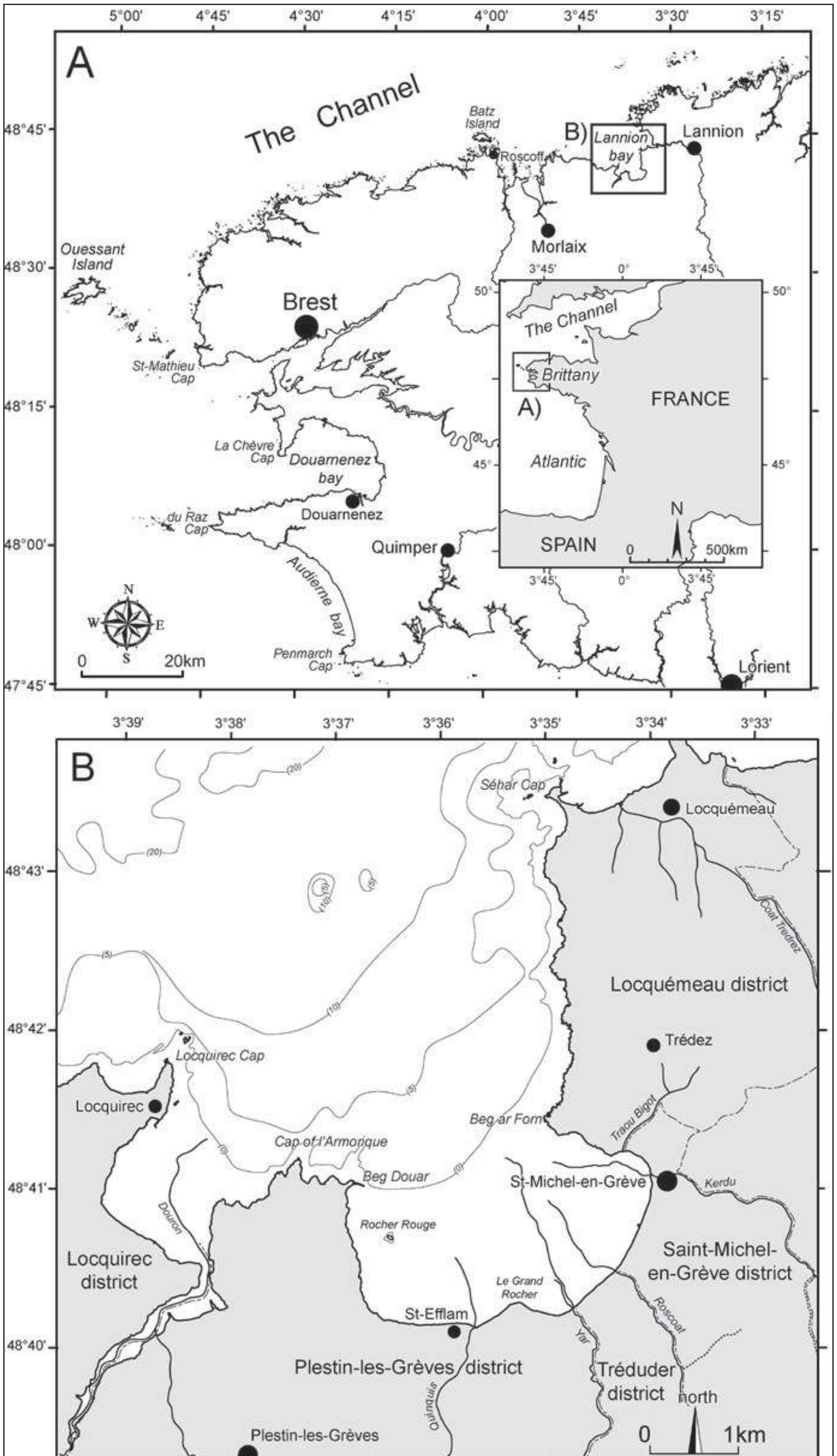


Figure 1. Maps show (A) the general location of Saint-Michel-en-Grève Bay at the end of Bay of Lannion, and an inset (B) giving a more detailed view of the studied bay head.

since the end of the 19th century, including coastal defense structures or, more recently, modifications of river mouth profiles on the shore. In addition, sand had been removed for agricultural purposes for several decades. After a brief presentation of the geomorphological and hydrodynamic setting of the study site, a quantitative analysis of shoreline dynamics is given based on a morphological survey carried out from 1986 to 2010 over two decades. The results are then discussed in light of forcing factors that have played a major role.

STUDY AREA

Saint-Michel-en-Grève Bay is located on north Brittany, at the end of Bay of Lannion (Figure 1). It is a bay head beach surrounded by high cliffs whose height decreases, east to west, from 80 m to 50 m. The bay is exposed to oceanic fluxes from westerly to northwesterly directions. However, the headlands of Berg ar Forn in the east and Beg Douar in the west shelter the bay somewhat and limit the morphogenetic impact of storms. The high tidal range (9.3 m at Locquirec) is responsible for the large beach surface area (7 km^2), which can be exposed over more than 2 km at low tide. The foredunes occupy very little surface area (roughly 27,000 m^2, or 0.04% of the coastal system) This is mainly because the coastal system is "locked in" against bay head cliffs, which prevent the development of a wide supratidal zone. In addition, the construction of a coastal road (*départemental* road D786) also limits the development of the upper beach/dune system. This road has "artificially" pushed the coastline seaward, leading to more frequent submersion of the upper part of the shore, and with it, the destruction of foredunes (Gad *et al.* 2003). Only Holocene dunes are located in the embayments formed by the mouths of the river valleys on either side of Grand Rocher promontory (Figure 2). The dunes are completely dissimulated by anthropogenic structures that were built on them (houses, buildings to accommodate seaside tourism, etc.).

The steep rocky cliffs located on either side of the bay are topped by Quaternary deposits roughly 10 m thick; only the base of the cliff — up to about 1 m in elevation — is actually rocky. This layer of rock may correspond to an ancient abrasion platform shaped by marine erosion when sea level was 1-2 m higher. This platform has been dated from the coarse rounded deposits that correspond to remnants of Eemian beach deposits that fossilized in rocky interstices (Briand and Quéméneur 1973). In general, the cliffs are receding at a relatively moderate rate, especially those that have been protected by defense structures, as in the Toul ar Vilin embayment or the Beg Douar headlands.

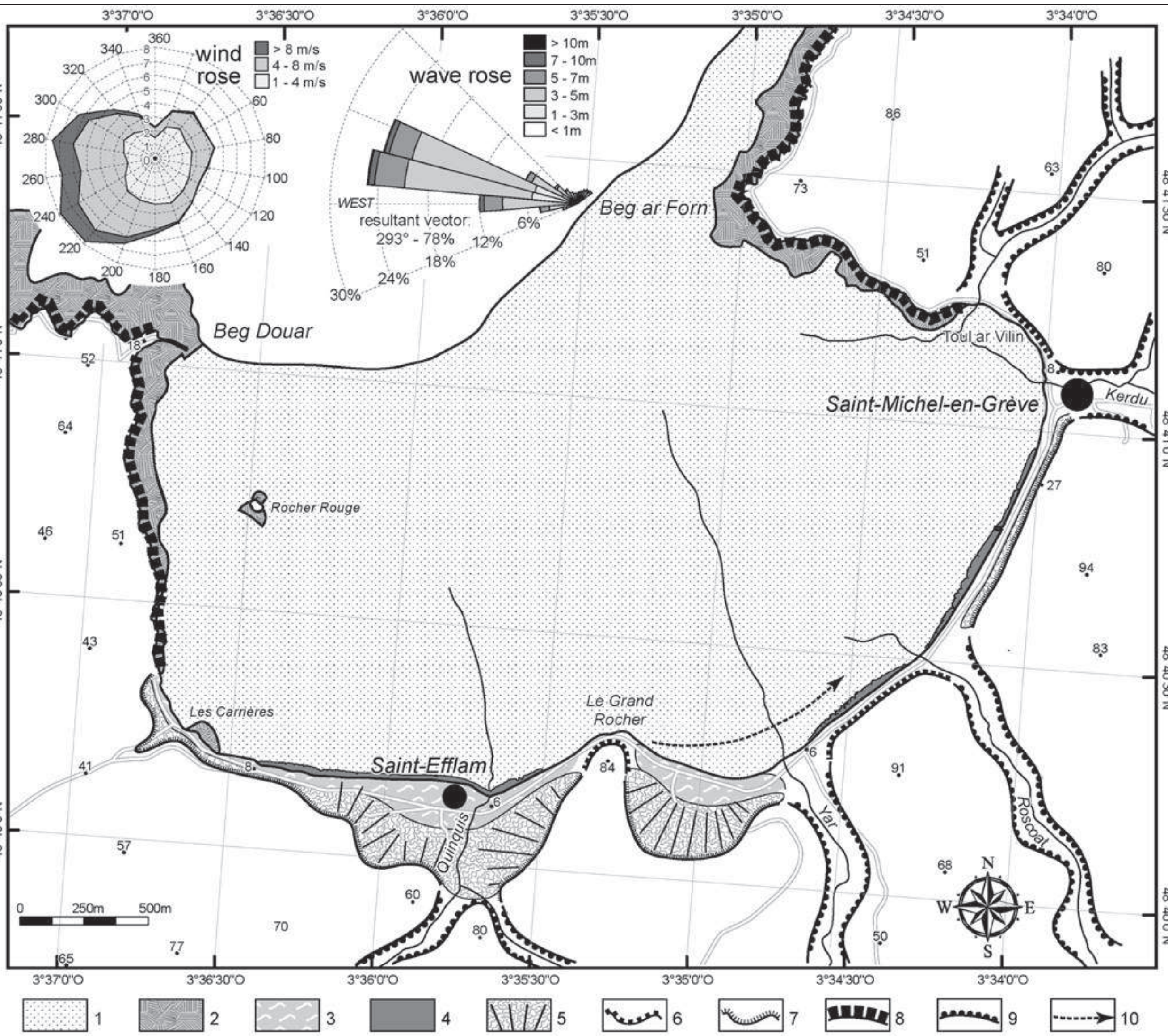


Figure 2. Map shows the geomorphological setting of Saint-Michel-en-Grève Bay. Legend: 1: foreshore; 2: wave-cut platform; 3: Holocene dune; 4: active dune; 5: periglacial deposit (head); 6: rocky abandoned cliff; 7: periglacial abandoned cliff; 8: active cliff; 9: fluvial valley; 10: longshore drift. Wind rose is based on wind measurements from the Lannion meteorological station (Météo France).

Local marine meteorology and hydrodynamic setting

Wind dynamics are, for the most part, conditioned by westerly meteorological and ocean fluxes. The strongest winds come from the westerly to southwesterly direction (220° to 260°) (Figure 2). These winds accompany the Atlantic depressions that cause storms on the coast between October and March (from 18% to 20% of the annual wind regime ranging from 4 m/s to 8 m/s; 14% >8 m/s. These strong winds are often associated with high water levels on the coast, which can lead to the erosion of dunes (Suanez and Stéphan 2006). Winds from the northeast (40°) are the second most frequent strong winds in the annual wind regime (from 5% to 6% of the annual wind regime from 4 m/s to 8 m/s; 6%, >8 m/s). These northeasterly winds are characterized by lower wind speeds than the westerly winds and occur mainly from spring to the end of summer (April to September). These northeasterly winds favor dune growth.

With a maximum tidal range of approximately 9.85 m measured at the port of Locquirec, the Saint-Michel-en-Grève Bay is a megatidal bay (tidal range >8 m). The NGF (IGN 69) [French datum] zero datum line is located at 4.981 m above (zero) chart datum. Thus, the highest astronomical tides reach approximately 5.08 m NGF. As demonstrated below, this level corresponds roughly to dune toe heights, comprised between 5 m and 5.40 m NGF.

The offshore wave climate analysis was based on data acquired from a sea state model (with a resolution of 20 km) developed by the French Naval Hydrographic and Oceanographic Service (SHOM), at point γ located at the entrance of the Bay of Lannion (3.7368°W, 48.9294°N; 50 m depth), over the 1990-2009 study period. The wind data entered in the model correspond to data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The resulting vector shows that 78% of the waves from the annual wave regime are west-northwesterly (293°;

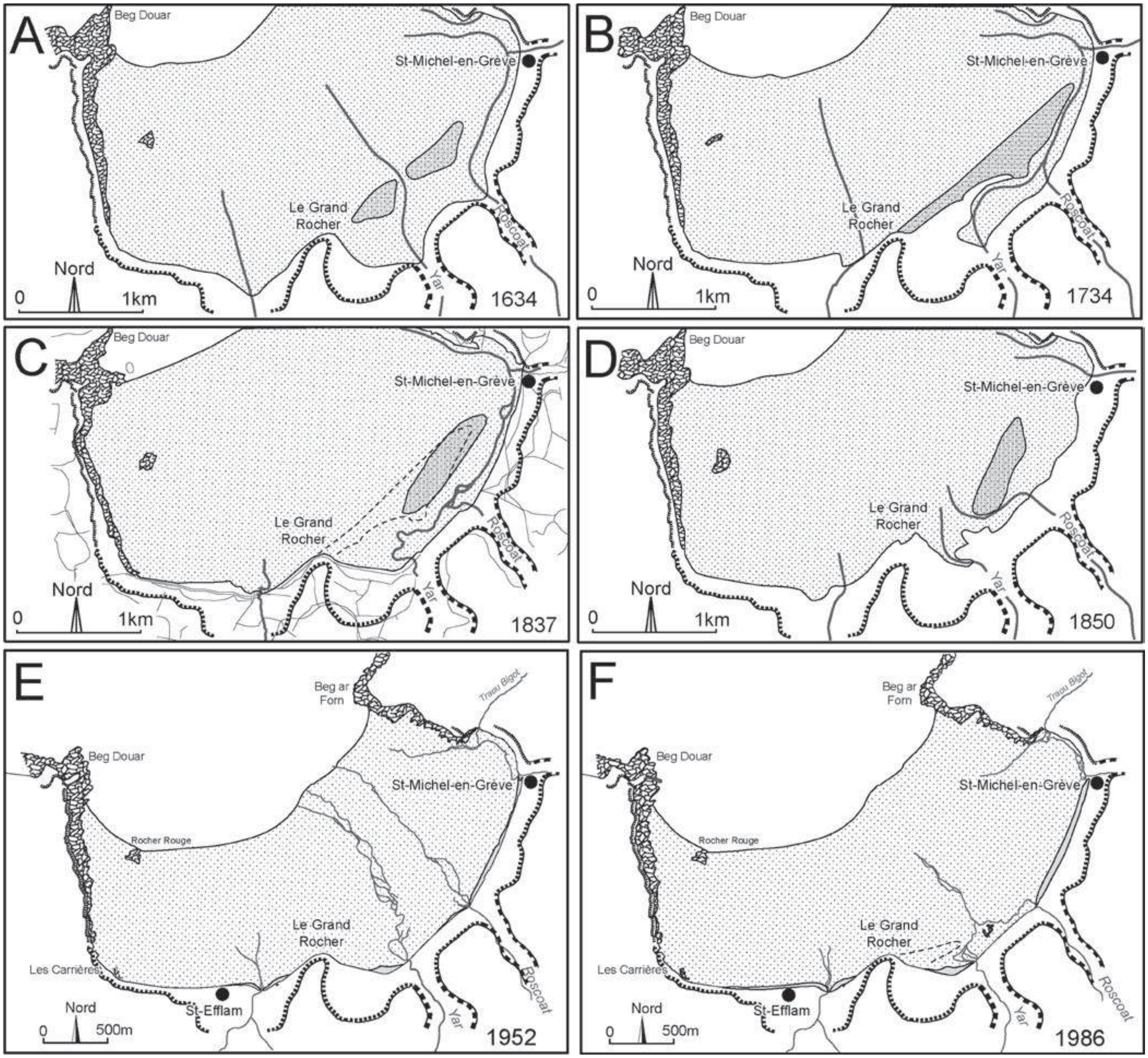


Figure 3. The study of the morphological changes in Saint-Michel-en-Grève Bay since the 17th century was carried out using old maps (source: maps from 1634, 1734, and 1850, Pinot 1987; map from 1837, Gad 1999) and recent aerial photographs from the French National Geographic Institute (IGN) (1952 and 1986).

Figure 2). More than 30% and 10% of these waves are characterized by a wave height comprised between 1-3 m and 3-5 m, respectively. The highest waves (>5 m) represent only 4% of the annual wave regime.

Long-term morphosedimentary dynamics

The precise geomorphological history of Saint-Michel-en-Grève over four centuries has been reconstituted using old documents dating from the 17th century and earlier (Pinot 1987, 1993). The map established by an engineer, Tassin, in 1634 indicates the presence of two "islands" located to the east of the Grand Rocher promontory (Figure 3A). In the 18th century, these sand formations appear to have grown and developed into a coastal spit anchored at the foot of the Grand Rocher promontory and formed by east-trending longshore drift (Figure 3B). This sand edifice pushed the mouth of the Yar River to the east, which then was captured by the Roscoat River and flowed at the foot of the Saint-Michel-en-Grève town proper. This configuration lasted until the 1840s when the Yar cut through the spit near its root and changed course, flowing directly into the sea, perpendicular to the shore. During the second half of the 19th century, the uprooted coastal spit gradually retreated to the shoreline. During the 20th century, an incipient coastal spit formed several times at the foot of the Grand Rocher promontory, deviating the mouth of the Yar River to the east (Figure 3E). By the late 1980s, the Yar River was again deviated to the east, and was captured by the Roscoat River (Figure 3F). Channels were thus dug to straighten the Yar and Roscoat River mouths in 1998 and 1999, as presented below. Several studies on the morphosedimentary changes of the bay head beach have revealed that the shore has undergone accretion since the end of the 19th century (Pinot 1987, 1995; Suanez *et al.* 2002; Gad *et al.* 2003; Stéphan and Suanez 2004). As shown in Figure 4, at the beginning of the 20th

Figure 4. Accretion occurs in the bay head at Saint-Michel-en-Grève Bay as seen in this aerial view dating from the beginning of the 20th century, (A) showing a shingle barrier and part of the wave-cut platform exposed at the foot the town proper. An aerial view (B), taken between 1990 and 1995, shows that the shingle barrier and the wave-cut platform have been covered by sand. The dunes that developed in the bay head are also visible. An old postcard (C) from the early 20th century showing a rocky outcrop called the "Rocher Rose" located on the upper shore of Saint-Michel-en-Grève area. By 2003 (D), the rocky outcrop of "Rocher Rose" was completely covered by the dunes that formed in the late 1980s (photo: S. Suanez, 26 June 2003).

century, the bay head — particularly in the Saint-Michel-en-Grève sector — was composed of shingle beaches and rock outcrops. Now, 100 years later, these morphological features have disappeared under a thick layer of sand.

Since 1990, the influx of sandy sediment has led to enough accretion on the upper part of the shore for foredunes to form (Bouvier 1994; Stéphan and Suanez 2004). These foredunes are found in three sectors of the bay (Figure 2). As shown below, a fourth dune was also found near the Grand Rocher promontory, but has now completely disappeared due to marine erosion. From a morphological point of view, these dunes are low-lying aeolian accumulations whose external surface forms a small dune ridge of less than 1 m in elevation with respect to the highest tide. The grain size of these foredunes is very uniform across the bay. Measurements taken on sand sampled from the dunes in the bay head show very low variation, with values comprised between 163 µm and 142 µm and a mean grain size of 155 µm. In general, the sediment is well sorted, as indicated by the sorting index of 0.41 and an asymmetry index (skewness) close to zero.

Anthropogenic forcing

During the second half of the 19th century, in the towns of Saint-Michel-en-Grève and Tréduder, a coastal road called the "*chemin de promenade*" or "*Chemin de Grande Communication*" was built at the base of the cliff, which was thereby cut off from the sea. This road, which for most of its length runs alongside the coastline, connected the towns of Saint-Efflam and Saint-Michel-en-Grève (Figure 5). It was initially naturally protected from storm flooding by small dunes that had built up in the bay head. However, repeated sand mining for agricultural purposes — to improve the poor, acidic soil in farming fields — led to complete removal of these dunes which had previously provided natural coastal protection. No longer protected from storms, the now-exposed coastal road was progressively deteriorated by erosion. Confronted with this problem, the port admiral promulgated an order on 31 July 1856 to prohibit sand mining at less than 100 m from the shoreline. This ban was renewed on 31 October 1873. These measures were not enforced and sand mining continued, leading to substantial sediment loss at the upper part of the shore and increasing erosion of the shoreline. The first coastal defense structures were erected during this pe-

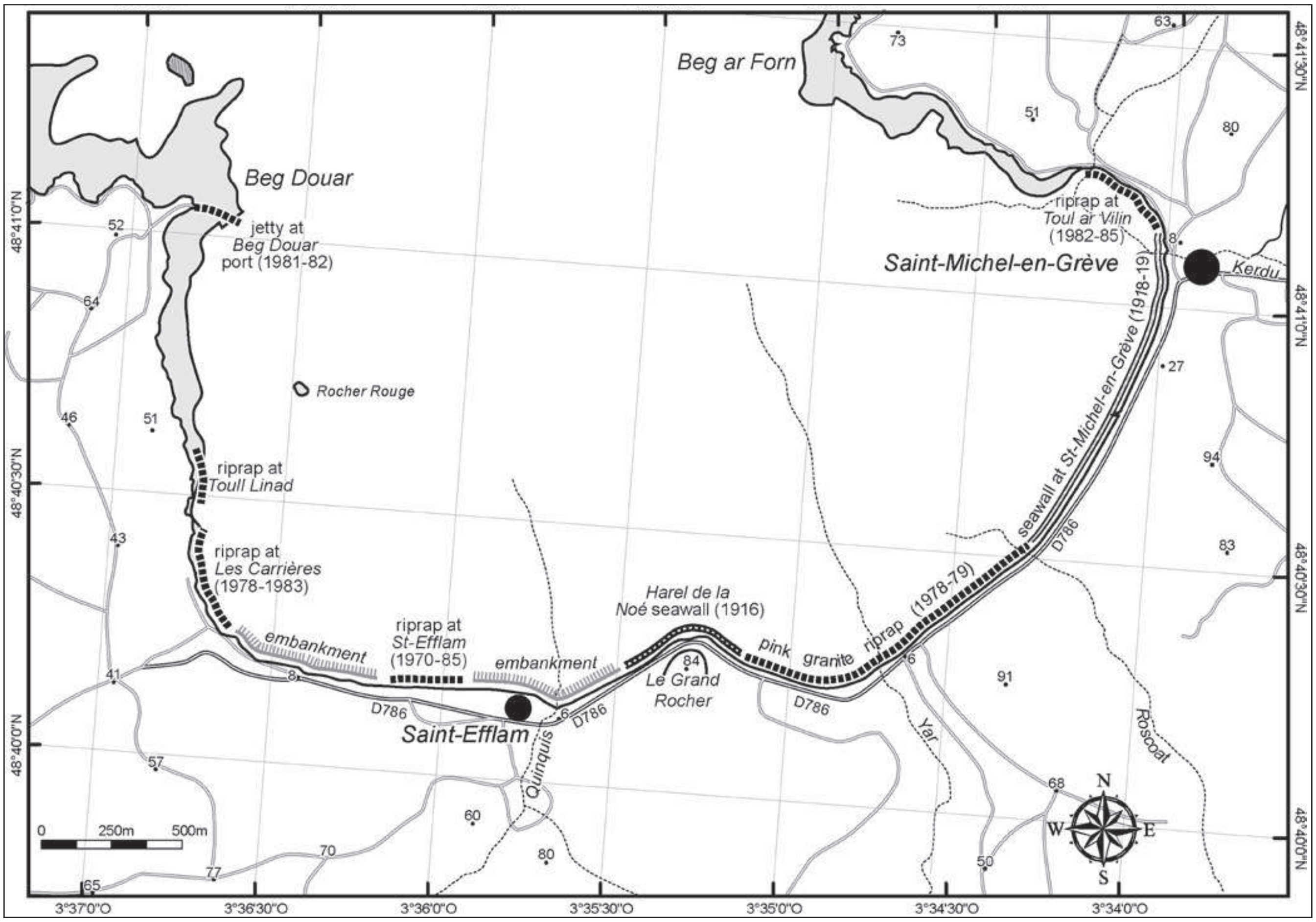
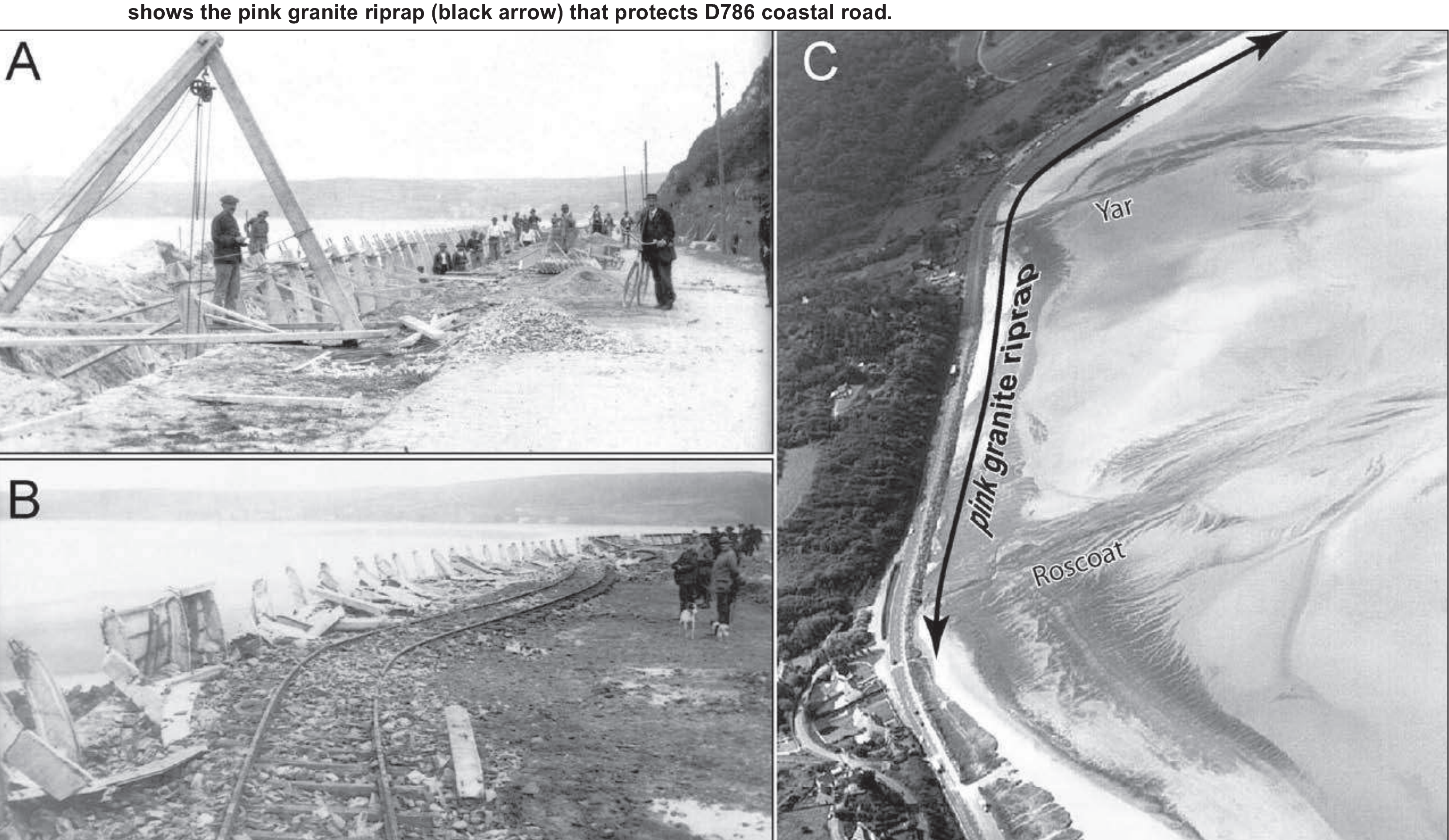


Figure 5. The location and period when the various coastal engineering structures were implemented in the bay head at Saint-Michel-en-Grève.

Figure 6. Photograph (A) shows the construction of the the Harel de La Noë seawall in 1916 in the Grand Rocher promontory sector to protect the future railway line between Plestin-les-Grèves and Lannion. Photograph (B) shows the destruction of the seawall and deterioration of the railway line during the 22 September 1918 storm in the same sector (source: Goulhen 2004). This aerial view (C) of the bay head on either side of the Yar and Roscoat Rivers shows the pink granite riprap (black arrow) that protects D786 coastal road.



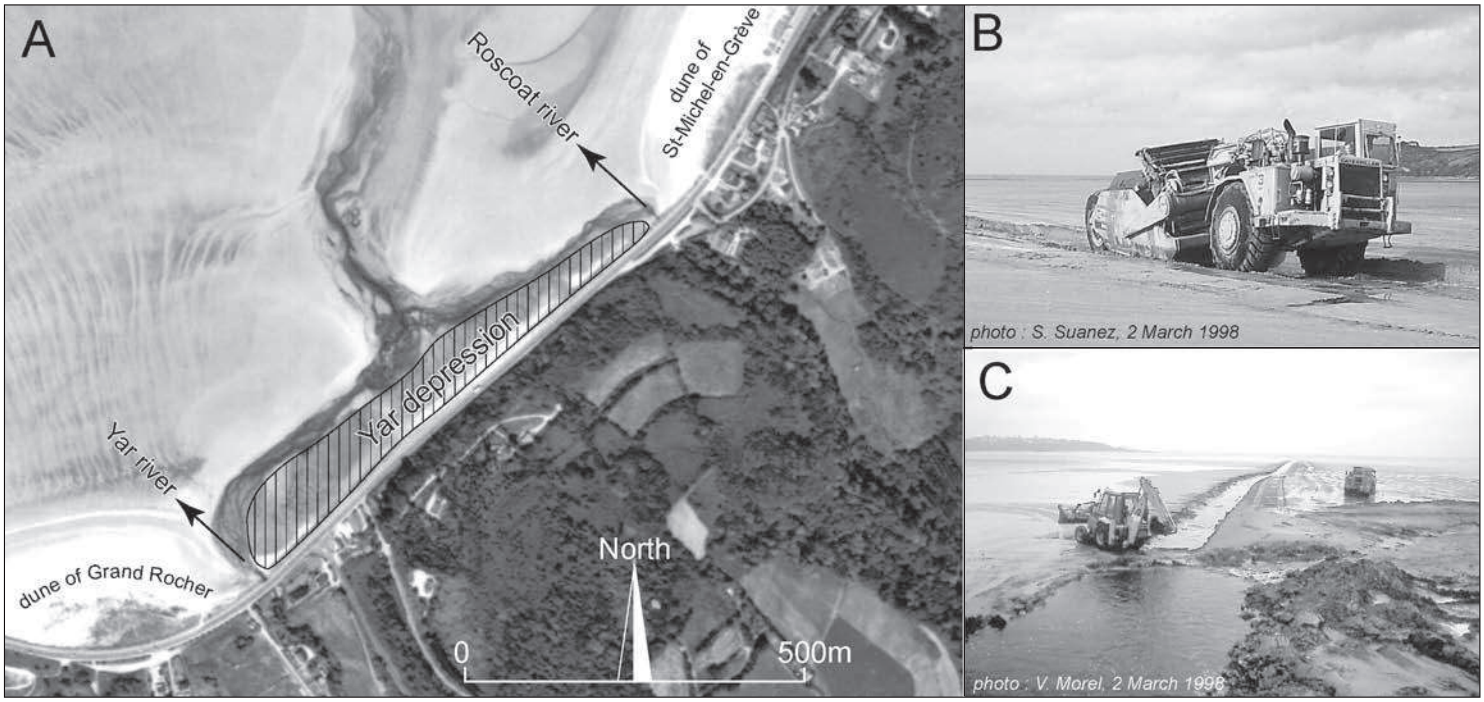


Figure 7. (A) Yar depression located on the upper beach, directly behind the confluence of the Yar and the Roscoat Rivers (source: 1996 aerial photo from Institut Géographique National [IGN]). This depression appeared during the 1980s and it was mainly due to erosion phenomenon induced by the confluence of both rivers.

Table 1. Inventory of aerial photographs and field measurements used for the whole morphological survey.

Shoreline kinematics				Topographical-morphological survey of the shore	
Date	**Mission IGN**	**Scale**	**Photograph no.**	**Date**	**Field survey method**
05/09/1986	F0 715-1315	1:30000	157 and 158	27/02/1998	tachymeter (Géomer)
04/05/1990	FR 8297	1:25000	24	30/03/1998	tachymeter (Géomer)
17/05/1992	FR 8505	1:25000	155 and 156	27/05/1998	tachymeter (Géomer)
17/08/1993	FD 22-56	1:30000	286 and 287	11/03/1999	tachymeter (Géomer)
08/08/1994	FR 5030	1:20000	04	05/05/1999	tachymeter (Géomer)
11/08/1995	FR 5108	1:20000	04	12/06/1999	tachymeter (Géomer)
19/07/1996	FR 5155	1:20000	14	29/06/2000	tachymeter (Géomer)
21/08/1997	FR 5234	1:20000	45	07/08/2000	tachymeter (Géomer)
24/07/1998	FR 5285	1:20000	03	15/09/2000	tachymeter (Géomer)
01/09/1999	FR 5333	1:20000	11	16/11/2000	tachymeter (Géomer)
21/08/2001	FR 5486	1:20000	02 and 03		
12/09/2002	tachymeter survey (Géomer)			14/01/2001	tachymeter (Géomer)
12-15-17/09/2003	tachymeter survey (Géomer)			15/02/2001	tachymeter (Géomer)
10/03/2004	tachymeter survey (Géomer)			24/05/2001	tachymeter (Géomer)
24/03/2005	DGPS survey (Géomer)			18/01/2002	tachymeter (Géomer)
12/04/2006	DGPS survey (Géomer)			13/06/2002	tachymeter (Géomer)
03/04/2007	DGPS survey (Géomer)			12/09/2002	tachymeter (Géomer)
24/03/2008	DGPS survey (Géomer)			06/03/2003	DGPS survey (Géomer)
17/03/2009	DGPS survey (Géomer)			17/09/2003	DGPS survey (Géomer)
				26/03/2004	DGPS survey (Géomer)
				23/09/2004	DGPS survey (Géomer)
				24/03/2005	DGPS survey (Géomer)
				12/04/2006	DGPS survey (Géomer)
				03/04/2007	DGPS survey (Géomer)
				24/03/2008	DGPS survey (Géomer)
				17/03/2009	DGPS survey (Géomer)

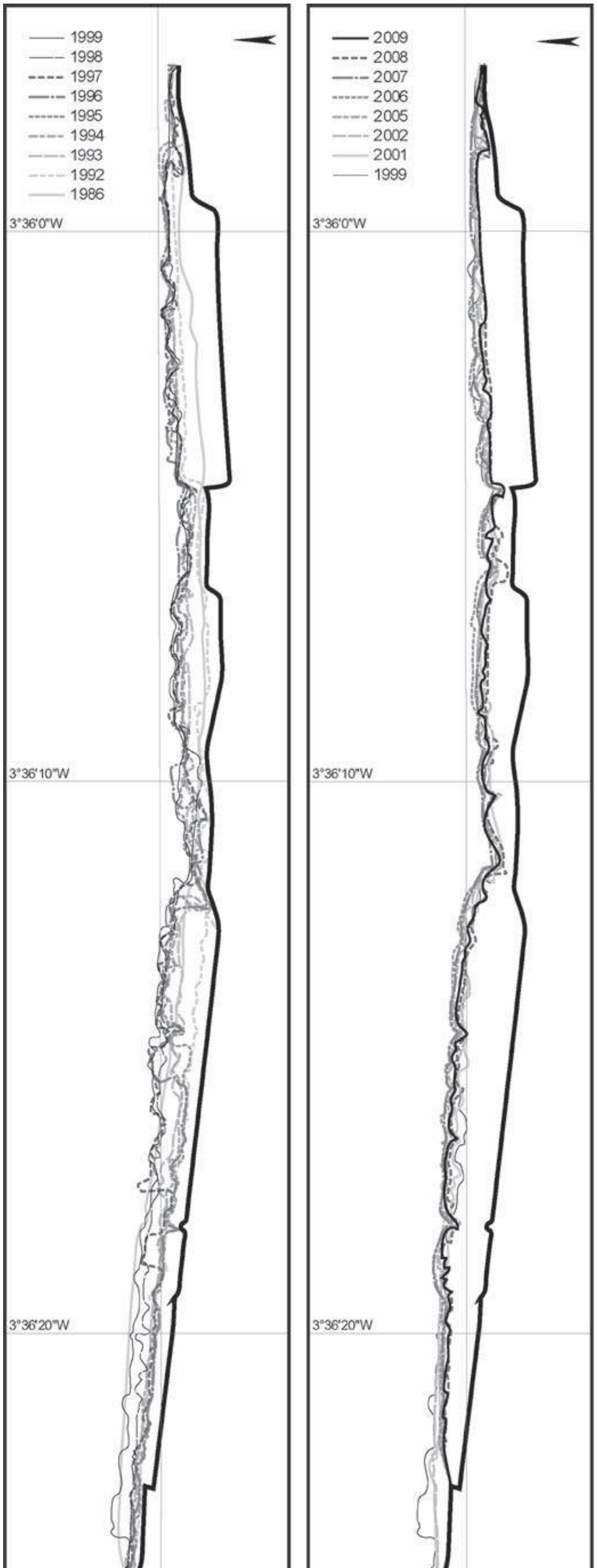
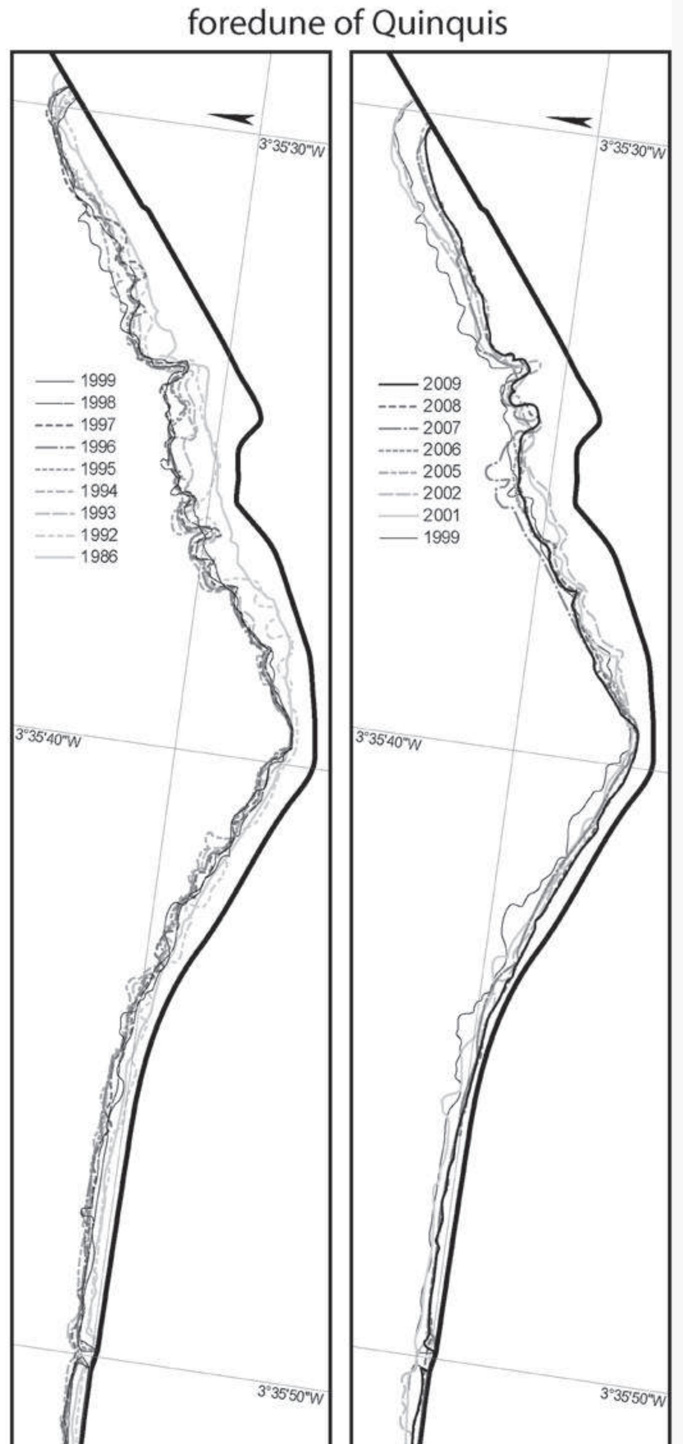
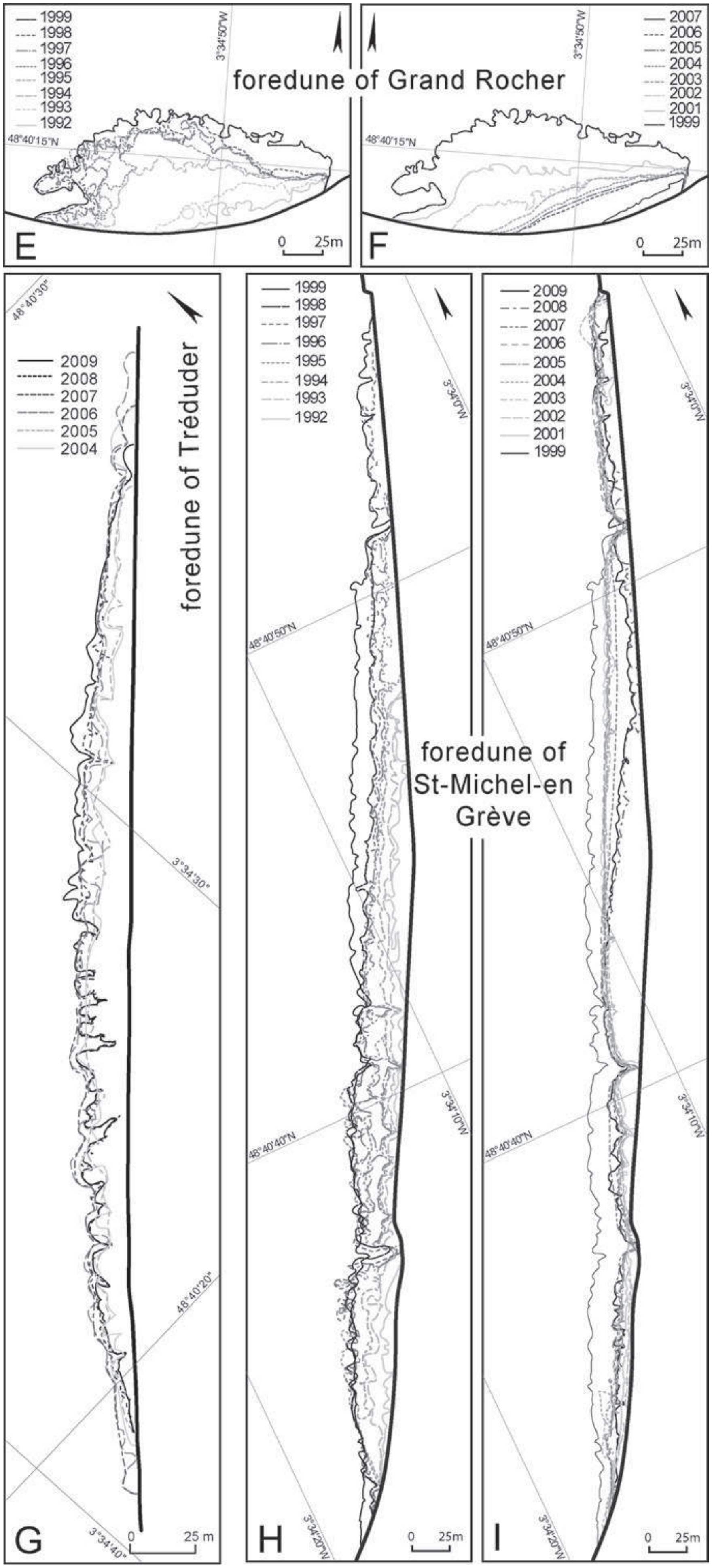


Figure 8 (this and opposite page). Shoreline changes as deduced from measurement of foredune changes at Saint-Efflam (A and B), Quinquis (C and D), Grand Rocher (E and F), Tréduder (G), and Saint-Michel-en-Grève (H and I) between 1986 and 2009.





riod (1870-1880) to artificially protect the coastal road. They were also built to protect the first hotel buildings that were erected in Saint-Efflam and Saint-Michel-en-Grève. After a strong storm on 22 September 1918, these defense structures, originally simple embankments of stone and mud, were rebuilt as low masonry stone seawalls, such as those found in Saint-Michel-en-Grève.

In 1913, the local railway line connecting the towns of Plestin-les-Grèves and Lannion were built on the coastal road, which was also widened. The coastal defense was then extended to other "exposed" areas of the bay to protect the railway line, such as the shore at the foot of the Grand Rocher promontory (Figure 6A). However, these coastal engineering solutions quickly proved to be insufficient to resist to the storm wave attacks (Figure 6B). Between 1937 and 1938, the railway line was shut down. The railroad was torn up and replaced by a roadway that was widened to become the D786 *départemental* road in the late 1970s. During this period, pink granite riprap was installed to protect the coast, and thereby turning the whole bay head shoreline into a hard stabilization structure. The pink granite riprap perfectly illustrates this major phase of coastal defense: installed primarily to protect the D786 *départemental* road, it stretches for 1,500 m between the eastern flank of the Grand Rocher promontory and the Saint-Michel-en-Grève town proper (Figure 6C). All these coastal defense structures were installed on the existing dunes, artificially pushing the shoreline towards the sea. In the late 1980s, there were practically no dunes, and, as shown below, "new" foredunes began to form in the early 1990s.

The most recent human interventions at Saint-Michel-en-Grève Bay involved artificially reopening two coastal rivers, the Yar and the Roscoat, into the shore, in March 1998 and again in March 1999. Channels were cut to fill naturally a depression called "Yar depression" that had been gouged in the upper part of the shore, behind the confluence of the two rivers (Figure 7). The depression had been eroded into the shore by water flow from the Yar and the Roscoat Rivers (Suanez *et al.* 2002; Gad *et al.* 2003). As mentioned above, the deviation of the Yar River had been caused by the incipient sand spit that was anchored at the east

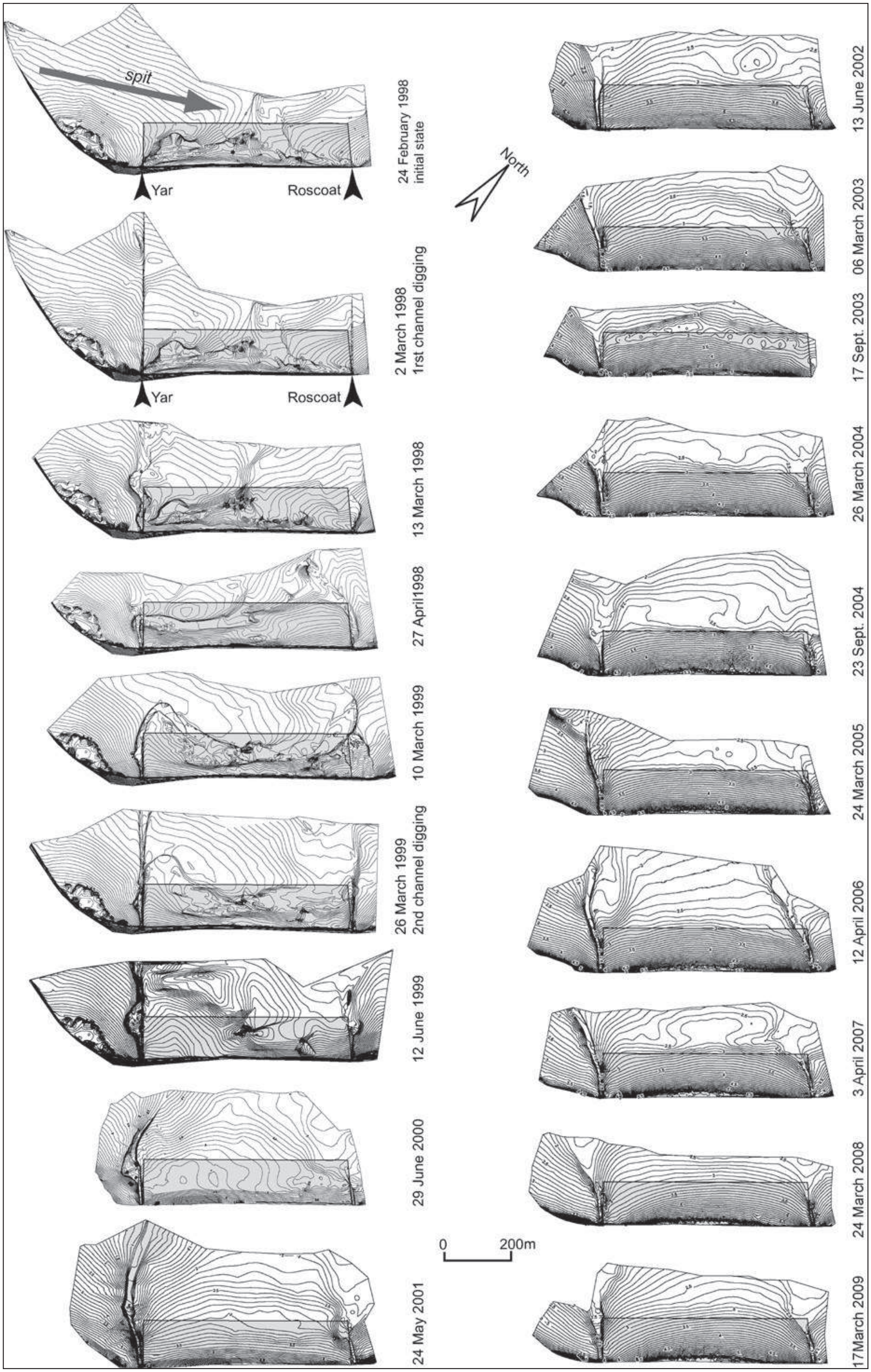


Figure 9. Digital elevation model showing medium-term morpho-sedimentary evolution of the beach situated between Yar and Roscoat Rivers (the shaded area delimits the surface from which the sediment budget was calculated).

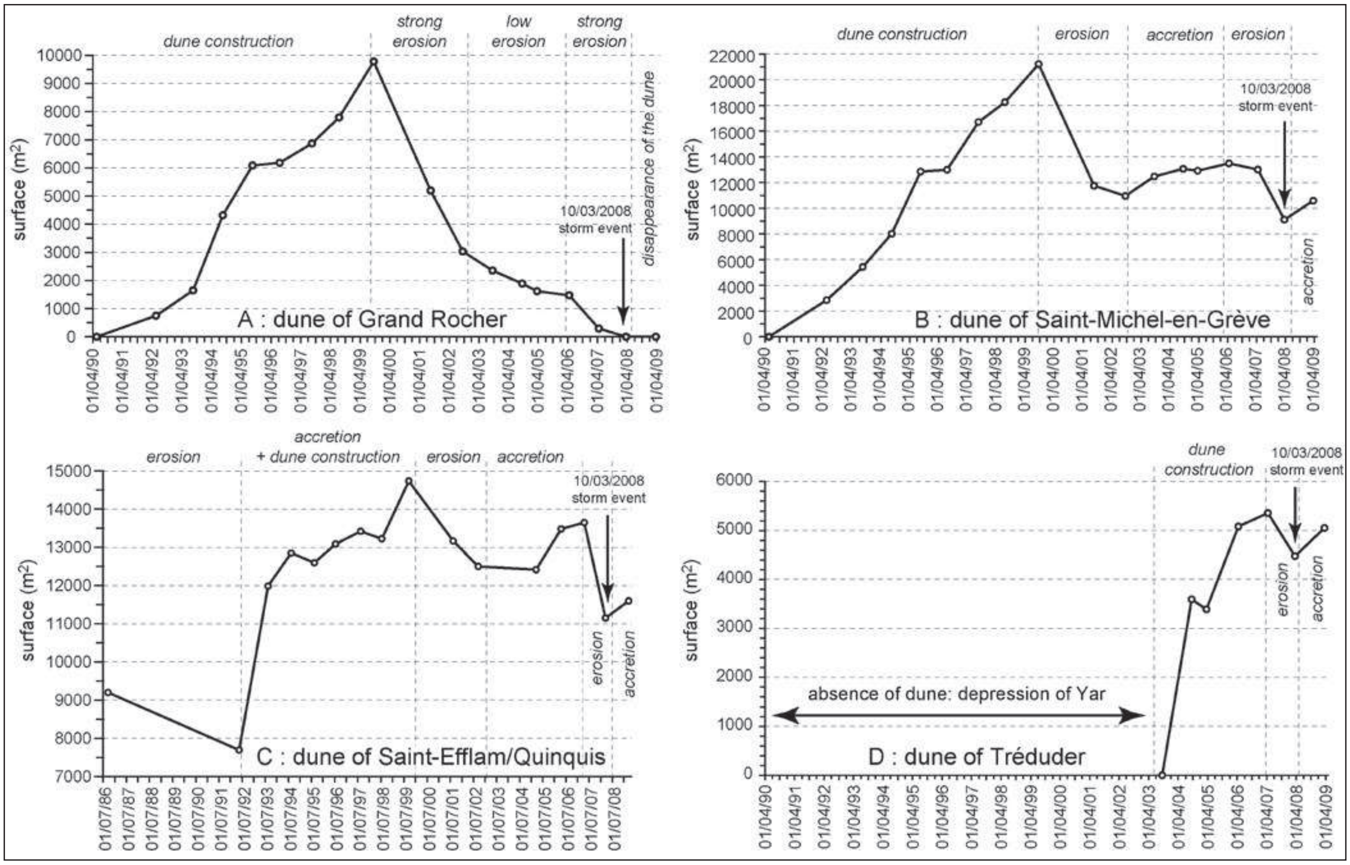


Figure 10. Medium-term variation in the sediment budget based on dune surface calculation using shoreline changes between 1986/1990 and 2009 (results of the Saint-Efflam and Quinquis dune surface changes were added).

side of the Grand Rocher promontory. As a consequence, green seaweed (*Ulva armoricana*) was trapped in this depression on the upper part of the shore and could not be evacuated to the lower part of the foreshore during ebb tide. Accumulation of seaweed caused two problems that the *Côtes-d'Armor* administrative council needed to resolve: first, rotting organic matter gave off nauseous odors and was an eyesore during the summer; second, erosion of the beach revealed outcrops of rocky substrate making removal of the seaweed with heavy equipment difficult.

To fill the Yar depression, the adopted technical solution was to straighten the course of the two rivers so that they would flow parallel to the slope of the shore. An artificial channel with a constant slope of 3‰ was thus cut into the shore (Figures 7B-7C). The long-period winter swells could thus transport sediment to the upper part of the shore to naturally fill the depression and reshape the slope there so that the ebb tide could export seaward the trapped green seaweed.

DATA ACQUISITION AND ANALYSIS

Morphological survey

The morphological survey was based on two types of data. First, the kinematics of the shoreline corresponding to the dune front limit were analyzed (Figure 8), and using this analysis, the variation in dune surface area was assessed for each year of the survey. As shown by Burroughs and Tebbens (2008), monitoring dunes provides the best significant indicator of shoreline changes. In addition, analyses of shoreline changes are frequently employed as a useful proxy to assess subaerial beach volume and morphological changes (Saye *et al.,* 2005; Farris and List 2007; Vespremeanu-Stroe and Preoteasa 2007). In this study, the limit of the shoreline was defined using the limit of vegetated dune edge as the erosion reference feature (ERF). Between 1990 to 2001, these data were obtained by analyzing aerial photographs; from 2002, data were obtained by surveying with a laser tachymeter and DGPS (Table 1).

The second type of data corresponds to surface morphological surveys on part of the upper shore between the Yar and Roscoat Rivers (Figure 9). This survey was set up in 1998 to determine if the artificial reopening of both Yar and Roscoat Rivers was effective. The frequency of the surveys varied with the study period, being more frequent in the beginning of the study and carried out only once a year as of 2005 (Table 1). Using these data, the variation in the sediment budget over a decade was assessed based on the calculation of sediment volumes over a specific surface systematically measured during each survey (Figure 9).

Analysis of hydrodynamic conditions

This analysis was based on processing the wave data obtained via a model developed by the French engineering laboratory of LNHE-EDF (*Laboratoire National d'Hydraulique et Environnement de l'EDF*). The data were produced from an ocean sea state model (resolution, 20 km) in a point located at the entrance of the Bay of Lannion (3.7368°W, 48.9294°N) at a depth of 50 m. Tide data come from the tide gauge located at Roscoff for the 1990-2009 period. In addition, wind and barometric pressure data recorded at the Météo France meteorological station in Lannion between 1993 and 2009 were used.

At the same time, extreme water levels on the coast were estimated by combining the observed tide and wave run-up ac-

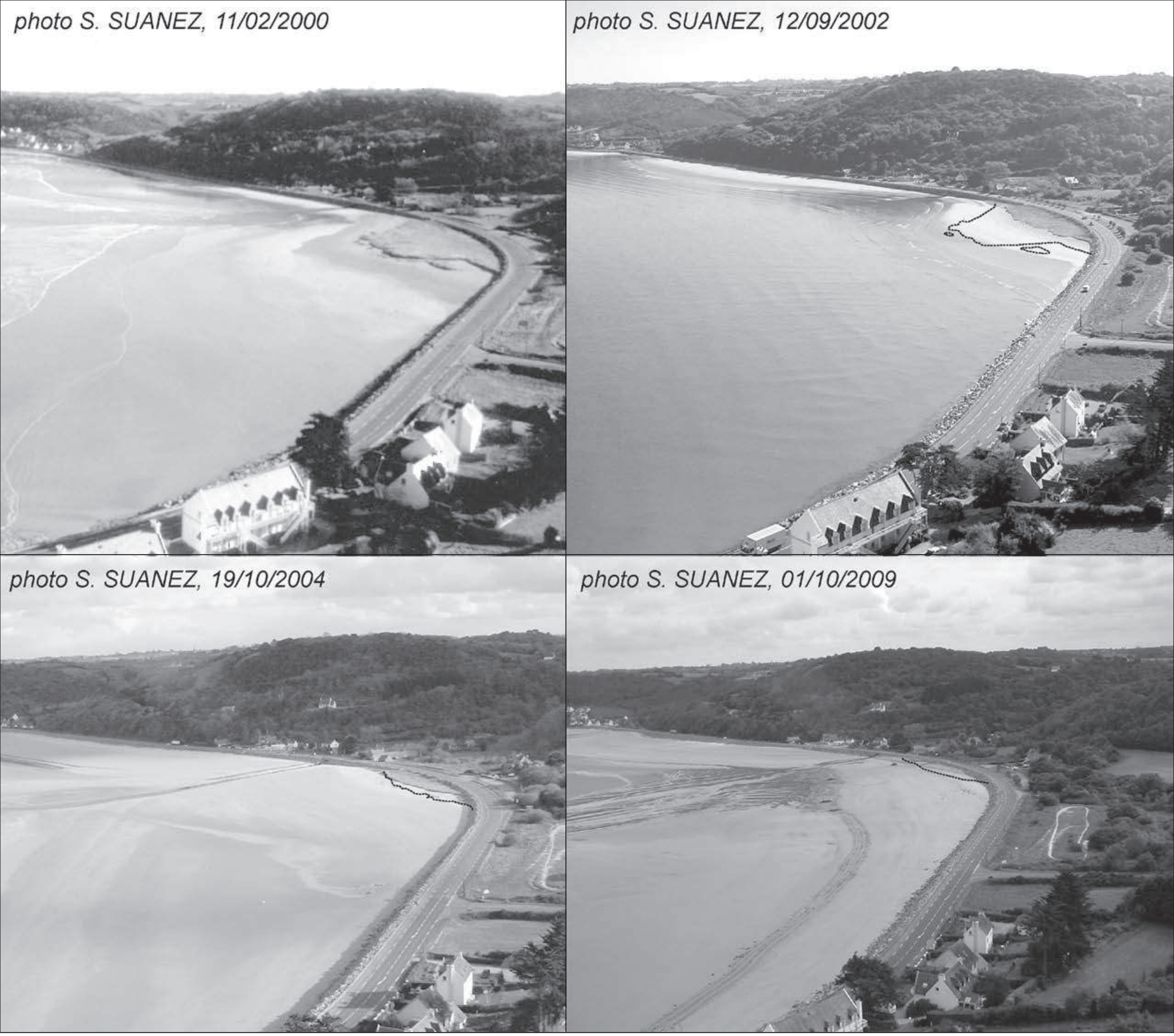


Figure 11. Surface changes of the Grand Rocher foredune due to shoreline erosion between 2000 and 2009. Dashed line corresponds to the former shoreline limit; in 2008, the dune totally disappeared.

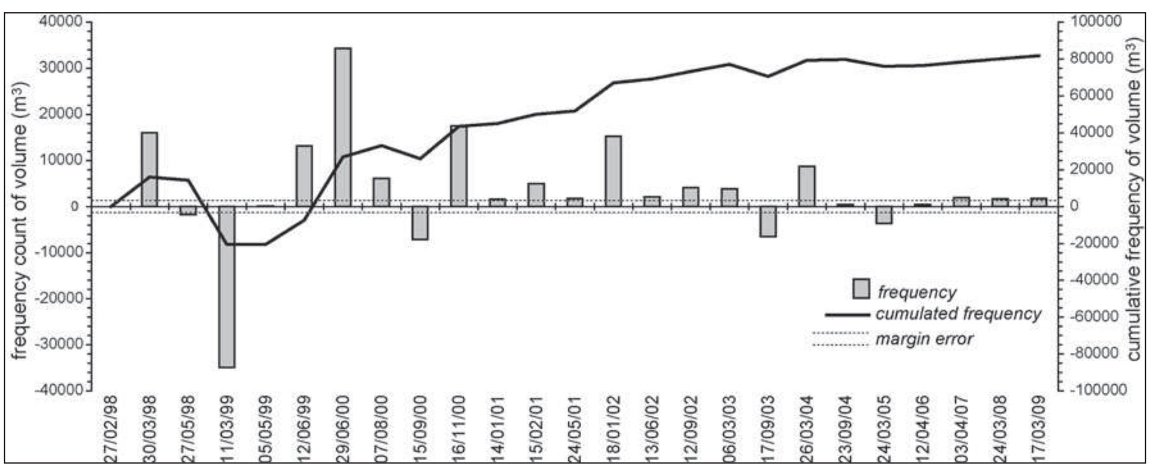


Figure 12. Medium-term sediment budget of the upper beach located between the Yar and Roscoat Rivers from 1998 to 2009. Volume calculation is based on a beach surface of 77,900 m², see Figure 9.

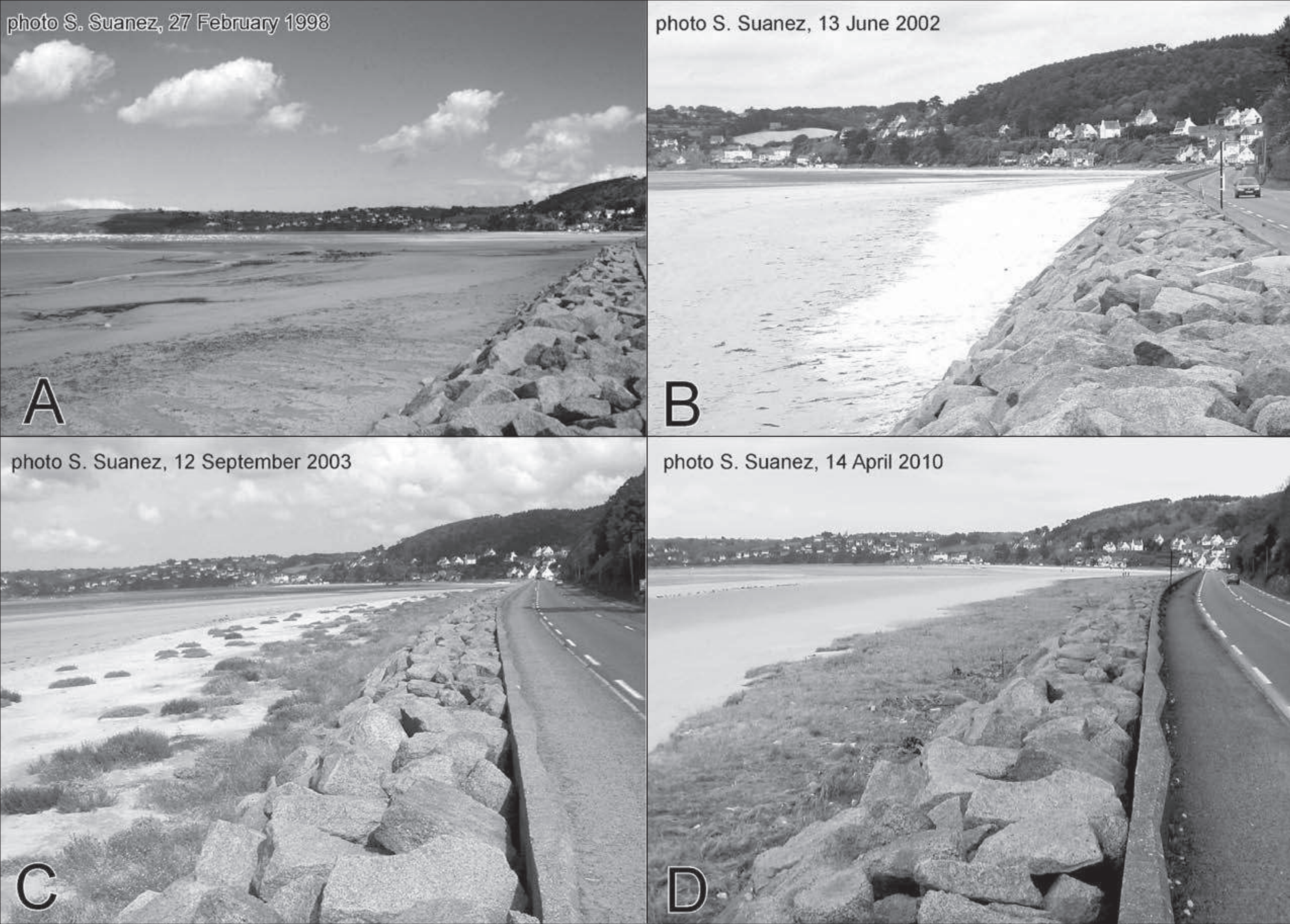


Figure 13. Photographs illustrate the various stages of Tréduder dune construction between 1998 and 2010.

cording to the "property erosion model" developed by Ruggiero *et al.* (2001). As in the analysis carried out by Pye and Blott (2008) on the coast of Sefton (northwest England), the objective was to measure the impact of water levels on dune erosion. Given the mean slope of the foreshore ($tan\beta$: 0.005), run-up was calculated from the equation given by Ruggiero *et al.* (2001) for dissipative to hyper-dissipative beaches:

$$R^{T}_{2\%} = 0.27\sqrt{SH_0L_0} \quad (1)$$

where S is the slope of the beach ($tan\beta$), H_o, the offshore wave height (H_{mo}), L_o, wavelength or $gT^2/2\pi = 1.561T^2$ (g acceleration due to gravity, 9.81 m/s²; T is T_{pic} or wave period in seconds).

RESULTS

Twenty years of shoreline changes

The results indicate rapid progradation of the shoreline between 1990 and 1999 that resulted in the formation of foredune at four of the five sections of coast studied: the Saint-Efflam, Quinquis, Grand Rocher and Saint-Michel-en-Grève sectors (Figures 8A-8C-8E-8H). The highest progradation rates reached between 24 m/yr and 50 m/yr. In 1999, the trend was reversed. Erosion affected the entire bay at variable shoreline retreat rates (Figures 8F-8I). From 2002, the shoreline underwent a new episode of progradation, except in the Grand Rocher sector. Simultaneously, a dune began to form in the fifth sector called Tréduder, located between the Yar and Roscoat Rivers, at the right place where the former Yar depression was located (Figure 8G).

Variation in the sediment budget was reconstituted using the calculation of dune surfaces gained or lost in four sectors Saint-Efflam/Quinquis, Grand Rocher, Tréduder and Saint-Michel-en-Grève (Figure 10). The results showed that the first phase of dune formation, particularly rapid between 1986/1990 and 1999, resulted in a net sediment gain, reaching from 10,000 m² to 22,000 m² depending on the sector (Figures 10A-10B-10C). A second phase of shoreline changes between 1999 and 2002 was characterized by a decrease in dune surfaces. For the Grand Rocher dune, this erosive phase continued after 2002, causing the complete disappearance of the dune in 2008 (Figure 11).

For the Saint-Michel-en-Grève sector, this erosive phase was followed by a new phase (from 2003 to 2006) of dune growth characterized by important shoreline progradation in the south-southwestern part of the sector (Figure 10B). As of winter 2006-2007, a new erosive phase, particularly strong in 2008, occurred. It ended in late 2008, as indicated by dune growth that was observed in 2009. A similar pattern was observed in the Saint-Efflam/Quinquis sector (Figure 10C). After a first erosive phase occurring between 1986 and 1992,

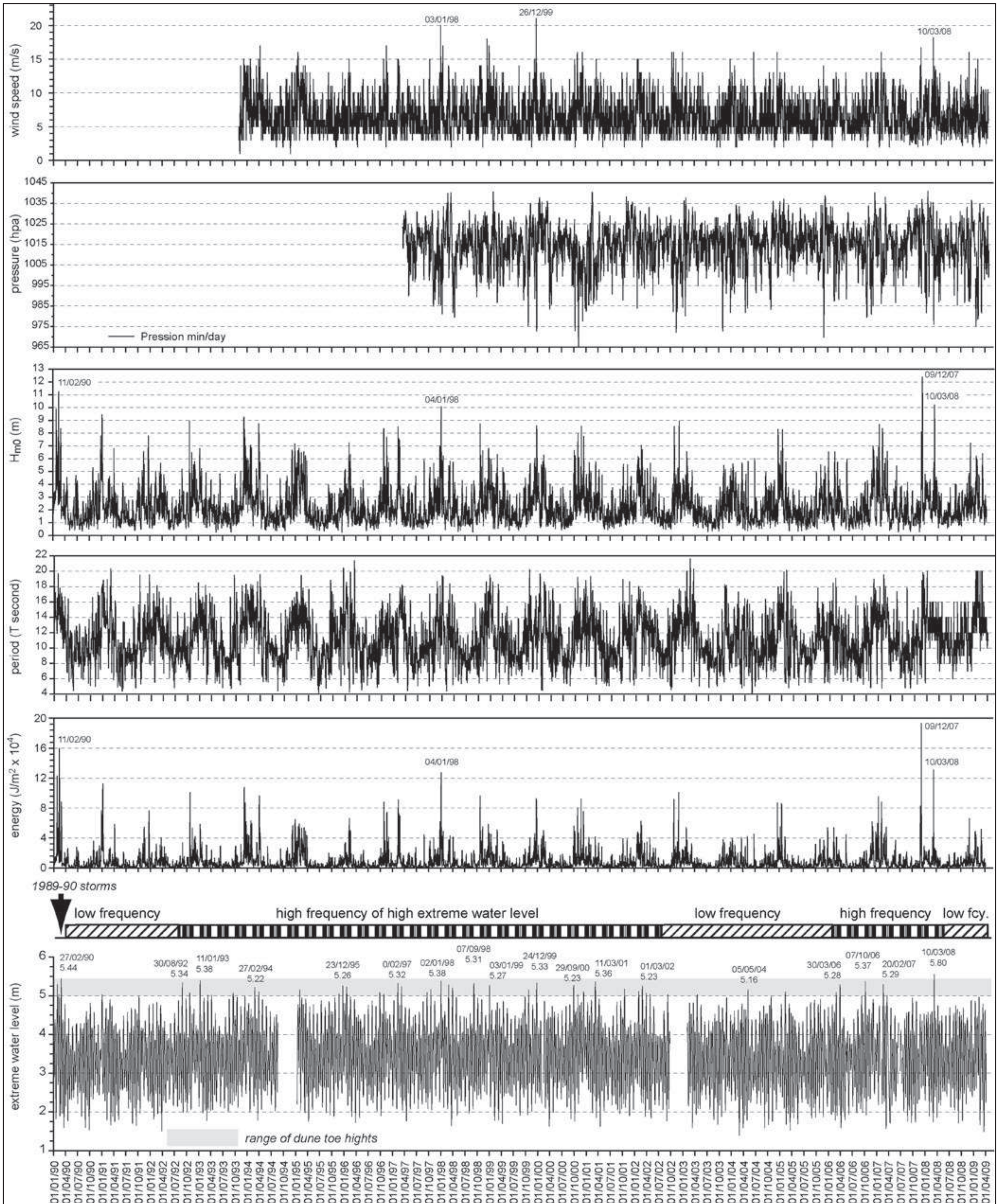


Figure 14. Graphs show the hydrodynamic and marine meteorological conditions during the survey period (1990-2009).

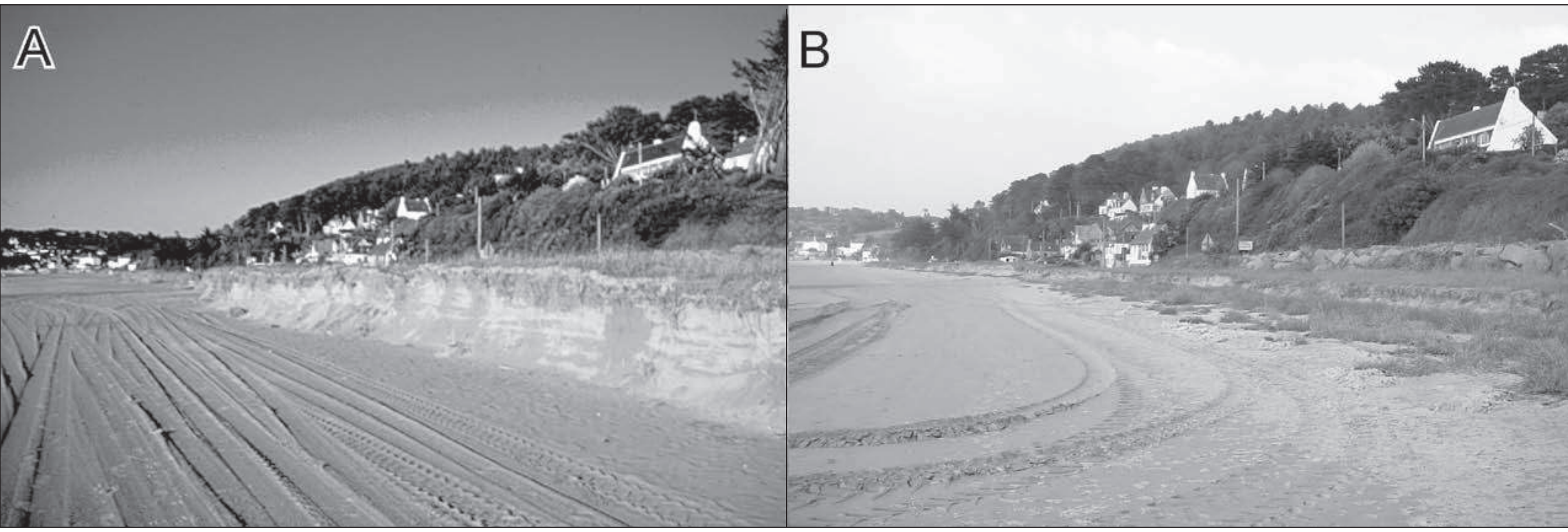


Figure 15. Photographs show the foredune of Saint-Michel-en-Grève on 15 September 2000 (A), when the dunes had eroding bluff forms, and on 12 September 2002 (B), when the erosion forms have disappeared and halonitrophilous plant species have colonized the dune, promoting the formation of embryo dunes (photos: S. Suanez).

dune accretion and/or dune construction occurred until 1999. Then, between 1999 and 2002, the shoreline again retreated. As of 2005, an overall trend of net growth was recorded, interrupted by a major erosive phase between 2006 and 2008. Winter 2008/09 was marked by shoreline progradation.

Finally, in the Tréduder sector, the dune construction phase mentioned above continued until 2007. From 2003, perennial vegetation clearly delimited the shoreline, which prograded until 2007. In 2008, a second erosive phase began, before giving way to a new growth phase during 2009 (Figure 10D).

Quantification of sediment input on the Yar depression area

The second approach aimed to quantify the importance of sediment input in the bay head at Saint-Michel-en-Grève. It was based on analyzing field surveys performed since 1998 on a portion of the Tréduder sector: the beach between the Yar and Roscoat Rivers (Figure 9). The changes in the calculated volume of sediment in this specific area showed that in 10 yr, 82,000 ± 1,600 m^3 of sediment had accumulated (Figure 12). When this value is scaled to the surface area of the sector (77,900 m^2), the accretion rate was determined to be approximately 0.1 $m^3/m^2/yr$. The upper part of the beach was thus elevated 3 m to 3.5 m at the foot of the bay head riprap. This change also resulted in the formation of a dune in the Tréduder sector in the upper shore. According to models established by various authors (Hesp 1981; Hallégouët 1981; Carter *et al.* 1990; Psuty 1992), dunes were formed in three phases: formation of a pre-dune accumulation (Figure 13B), establishment of embryo dunes (Figure 13C), development of vegetation-covered dunes (Figure 13D).

Analysis of hydrodynamic and marine meteorological conditions

To determine the role of natural forcing in the variation in the sediment budget, the morphosedimentary analysis of foredune in Saint-Michel-en-Grève Bay was supplemented with a study of the marine and meteorological conditions recorded over the same study period. Extreme water levels were compared with dune toe heights, reaching 5 m to 5.4 m NGF for all of the dunes found in the bay head. This approach, based primarily on a theoretical model, provides rough estimates that indicate the order of magnitude of extreme water levels. This approach is thus useful for comparing morphogenetic events by combining two essential parameters on water elevation on the coast: predicted tide + surge (observed tide) and waves, represented in this case by runup (Ruggiero *et al.* 2001).

Our results show five distinct phases (Figure 14). The first phase began after the heavy storms of winter 1989/90 and ended in 1992. This phase was marked by low morphogenetic activity. As of winter 1992-1993, an opposite-trending phase occurred. It was characterized by very frequent morphogenetic episodes and ended in winter 2002. During this period, a January 1998 storm was the most violent storm, generating high water levels of nearly 5.40 m. The third phase, covering the period from 2002 to 2006, returned to a lower morphogenetic period, except for one episode in May 2004. Nevertheless, the water level during this storm was generated by low-energy waves. From winter 2006-2007, the frequency of extreme water levels associated with big storms was higher. The 10 March 2008 storm was the biggest. However, wave data indicated that this episode had had relatively low energy compared to the December 2007 storm. The exceptional water levels of the 10 March 2008 storm (approximately 5.80 m) were above all due to the fact that this storm occurred during a spring high tide (tide coefficient equal to 106). Winter 2008-2009 made up the fifth phase and was highly less morphogenetic.

DISCUSSION

The quantitative analysis of mophosedimentary shoreline changes in Saint-Michel-en-Grève Bay showed that, on the whole, the beach has built up since the beginning of the 1990s. This study confirmed the qualitative observations made by Pinot (1995), who noted that several beaches had built up in the Lannion region since the 18^{th} century. The study also confirmed the long-term process of sediment supply in the bay head identified in old postcards dating from the turn of the century (19^{th} to 20^{th} century). We attribute these accretion processes to the hyper-dissipative morphodynamic

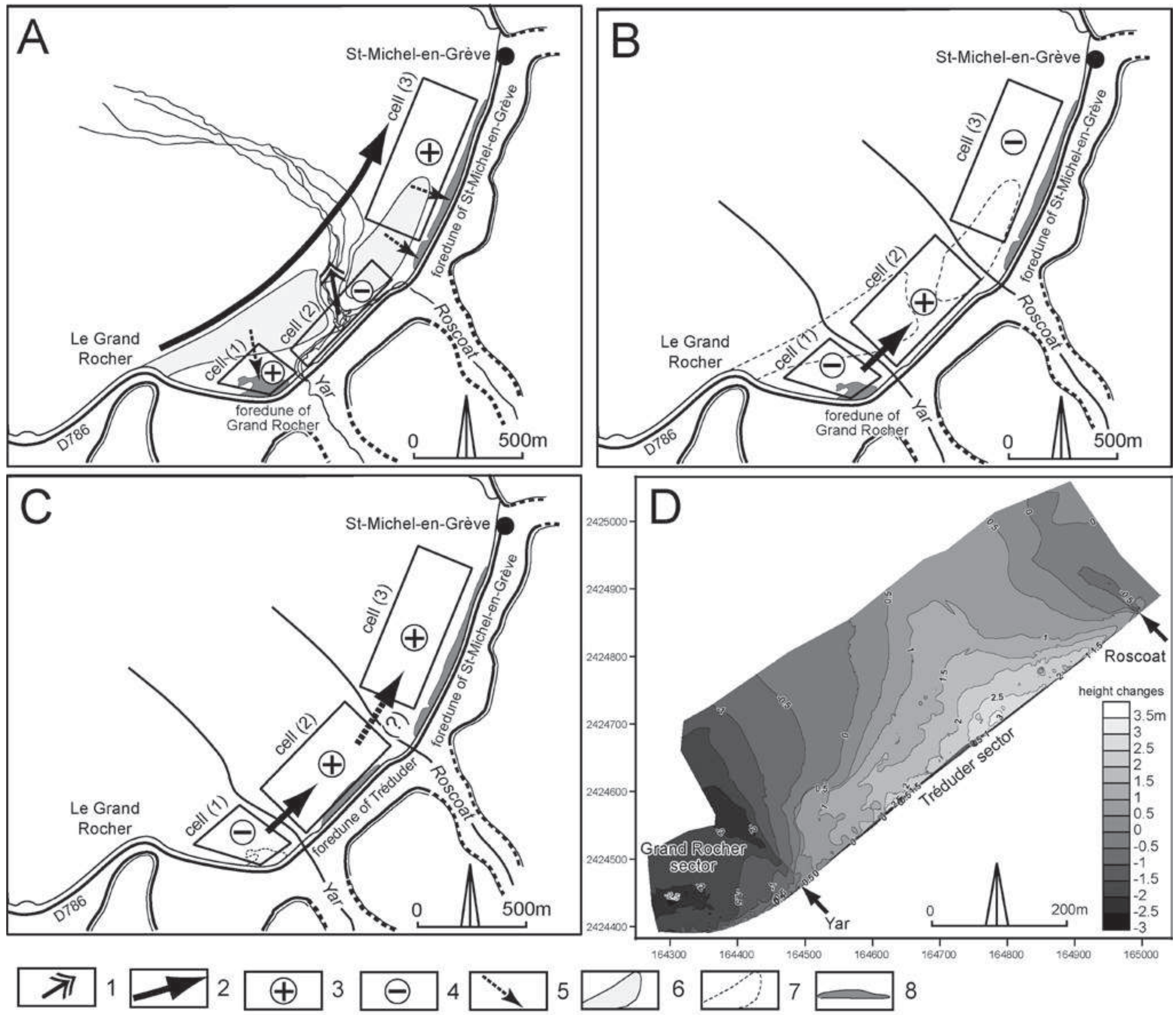


Figure 16. Diagrams show different scenarios of morphosedimentary changes due to the channels that were dug at the mouths of the Yar and Roscoat Rivers. (A) This diagram shows morphosedimentary functioning before the channels were cut in March 1999. (B) This diagram shows morphosedimentary functioning between March 1999 and late 2002. (C) This diagram show morphosedimentary functioning since winter 2002/03. Legend: 1: Course of water flow at the river's mouth, causing the formation of the Yar depression; 2: longshore drift inducing sediment transport; 3: positive sediment budget; 4: negative sediment budget; 5: cross-shore aeolian sediment transport; 6: sandy spit forming an intertidal bar; 7: location of the "former" sandy spit; 8: foredune. (D) Digital elevation model map shows altimetry differences between the 1998 and 2009 for the Grand Rocher and Tréduder sectors.

context of Saint-Michel-en-Grève Bay, which makes it favorable to sediment accumulation. Regarding the source of these sediments, an analysis of heavy metals carried out in the Bay of Lannion (Chauris 1989) shows that sediment inputs come primarily from the continual erosion of the Quaternary periglacial cliff deposits (alterites, head solifluction deposits) surrounding the bay. Chauris (1989) concluded that the contribution of submarine sources was weak, although no reason was given. Pinot (1995) suggested that due to the submarine morphology of the North Armorican shelf, which is strewn with submerged rocks and shoals, little sand from the central plain of the English Channel can be transported onto the shore. In addition to the relatively proximal source of sediment, biogenic production represents a non-negligible source of sediment. A study of the distribution of carbonate sands showed that they represent 47% to 78% of the sediment material in Saint-Michel-en-Grève Bay (Gad 1999). Nevertheless, the actual volume of sediment input since the 19th century is very difficult to quantify because sand was removed for agricultural purposes until 1995, when the regulations prohibiting this practice were strictly enforced.

The relative roles of natural and human forcing in the morphosedimentary changes, and thereby the variation in shoreline dynamics, are difficult to determine. The heavy storms in the winter of 1989-1990 led to significant coastal erosion, as demonstrated by the decrease in dune surface at Saint-Efflam between 1986 and 1992. Moreover, the erosive action of these storms affected most coasts in Brittany (Bodéré *et al.* 1993; Hallégouët and Hénaff 1993; Fichaut

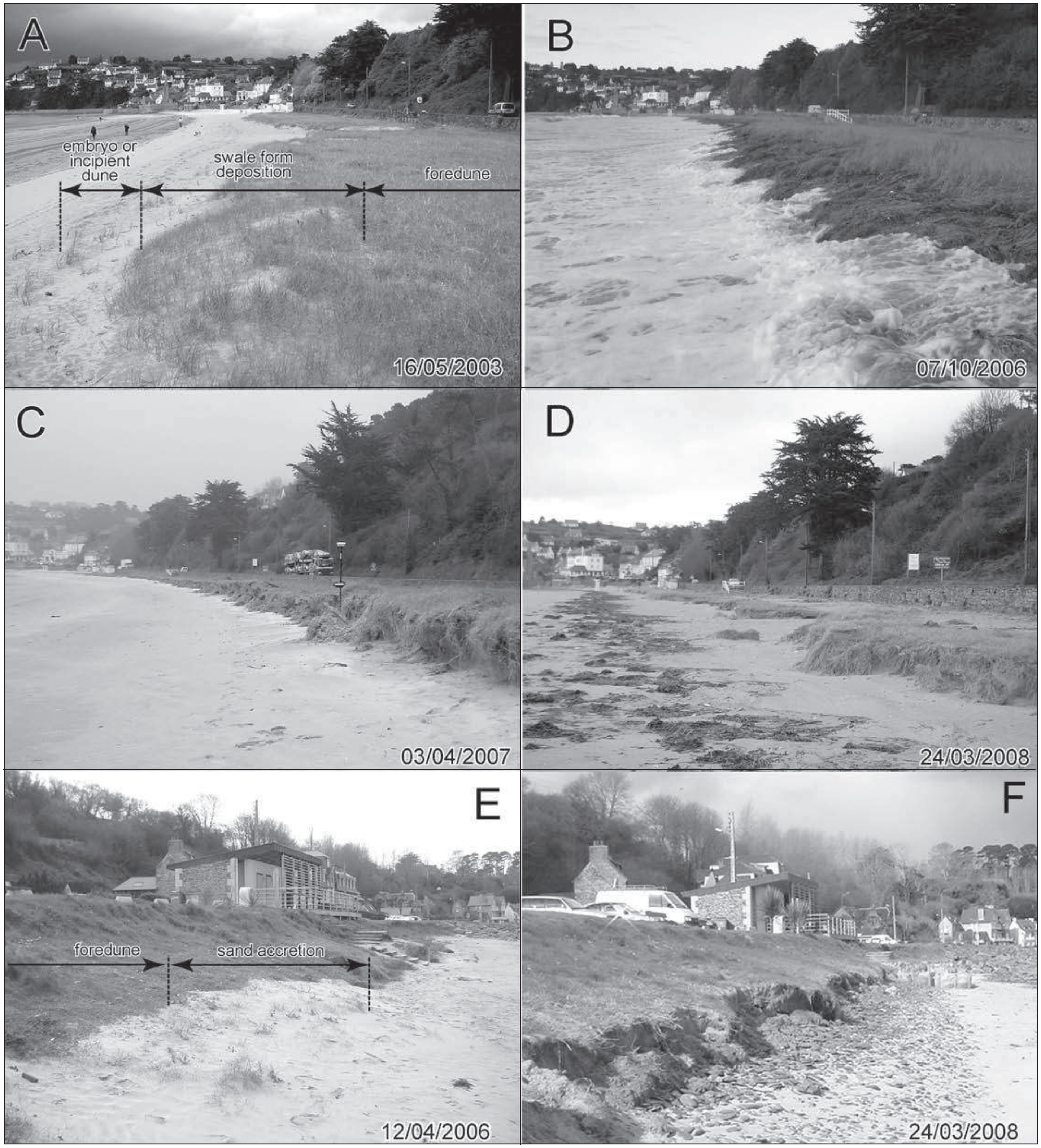


Figure 17. Shoreline changes between 2003 and 2008 were analyzed from the changes in the morphology of the foredunes at Saint-Michel-en-Grève (A, B, C and D) and Saint-Efflam (E and F). (A) Photograph taken in 2003 shows an incipient foredune and swale that appeared following relatively rapid beach accretion. The swale forms a low deposition zone following ridge formation at the seaward edge. (B) On 7 October 2006, run-up processes induced shoreline erosion during the morphogenetic event on that day. (C) During the 20 February 2007 morphogenetic event, a dune bluff was generated by high water levels. (D) The 10 March 2008 storm event caused dune erosion. (E) Taken on 12 April 2006, this photograph shows sand accretion at the seaward edge. This sand accumulation was particularly efficient during the 2002-2006 period, which was characterized by low frequency of morphogenetic events. (F) The 10 March 2008 storm event caused dune erosion, which remains the most significant event of the 2006-2008 morphogenetic period (photos: S. Suanez and P. Stéphan).

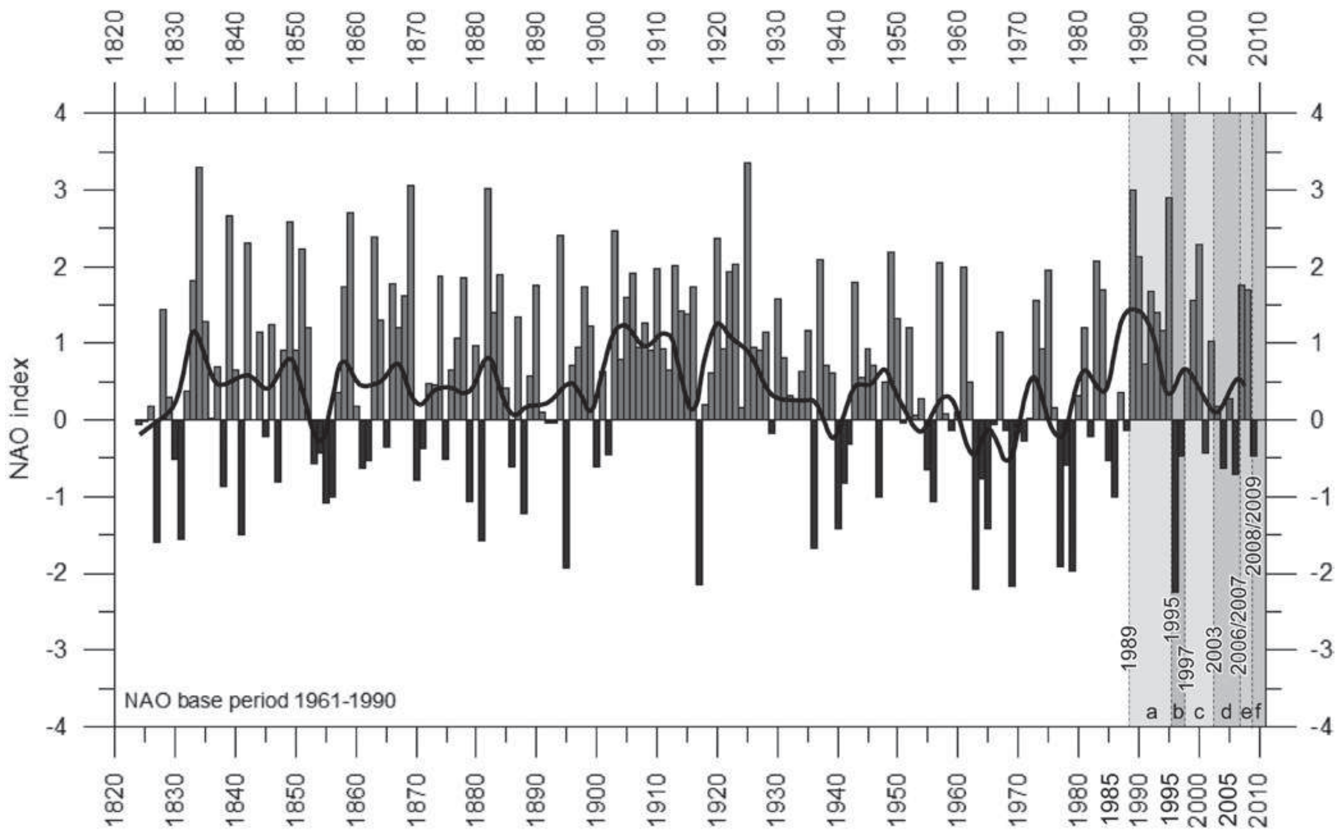


Figure 18. North Atlantic Oscillation (NAO) index over the period from 1825 to 2009 (source: http://www.climate4you.com/).

and Hallégouët 1989; Guilcher and Hallégouët 1991; Hallégouët and Hénaff 2006). There is no sign of these storms on other dunes in Saint-Michel-en-Grève Bay, because there were no dunes at that time. During the calm period that followed, supply of the bay head beach was considerable. Accordingly, the dune of the Grand Rocher began to form in the early 1990s. The formation of the foredunes continued until 1999, despite many morphogenetic episodes during winter 1992-1993 and later. During this period, the volume of sediment input may have compensated for the erosive action of these morphogenetic episodes. However, as shown in Figure 10, the variation in dune surface was practically nil, or dune surfaces were even decreasing, such as at Saint-Efflam, most probably due to erosion during some storm events. As of 1999, all dunes retreated considerably in conjunction with the strong storms of December 1999 and March 2001, or at the end of 2000 (Figure 15).

This erosive phase can also be attributed to human forcing linked to the artificial channels cut at the mouths of the Yar and Roscoat Rivers in March 1999. These human interventions affected the hydrosedimentary dynamics of the area, inducing feedback processes which had led to dune erosion (Suanez 2004). As shown in Figure 16, there are three littoral cells, from west to east following the general direction of longshore transport: the western cell (1), bordered on its western side by the Grand Rocher promontory and on the east by the Yar channel; the central cell (2) corresponding to the "former" Yar depression between both Yar and Roscoat Rivers; the eastern cell (3) that stretches from the right bank of the Roscoat River to the town proper of Saint-Michel-en-Grève. Before human intervention, the hydrosedimentary dynamics, governed by longshore drift, explain the presence of an east-trending spit (Figure 9). While the spit caused the confluence of the two rivers, it nevertheless ensured the continuity of longitudinal sediment transport from cell (1) to cell (3) and protected the dune at Grand Rocher and, to a lesser extent, the one at Saint-Michel-en-Grève from storm surges. Finally, the spit also functioned as a sediment storage area, from where the wind could redistribute marine sediment inputs to foredunes. In this context, cells (1) and (3) accreted, while cell (2) was eroded by river currents. After cutting the channels for the Yar and Roscoat Rivers, the spit disappeared, leading to sediment loss at the upper end of the shore in cell (1) and then retreat of the dune front, now more vulnerable to coastal flooding. Transported by longshore drift, sediments filled the Yar depression and contributed to the accretion of cell (2). By the same mechanism, cell (3) was deprived of considerable input, resulting in the erosion of the dunes at Saint-Michel-en-Grève (Figure 16B). Consequently, cells (1) and (3) eroded while unit (2) accreted. As of the end of 2002, this erosive phase ended. These foredunes even accreted again, such as at Saint-Michel-en-Grève where the erosion forms observed in September 2000 (Figure 15A) began to disappear due to sediment input (Figure 15B). This phase was marked by a positive sediment budget and occurred, as mentioned above, during a period when morphogenetic episodes were decreasing in frequency and intensity. This phase continued until winter 2006-2007. It was during this period that the dune of Tréduder began to be built from removal material coming from the erosion of the dune of the Grand Rocher and transported from west to east. Thus, as of late 2002 and early 2003, cell (1) continued to erode, leading to the complete disappearance of the dune of the

Grand Rocher by late 2007. At the same time, cells (2) and (3) continued to grow, partly from material supplied by cell (1) (Figure 16C). The calculation of the sediment budget between 1998 and 2009 for this sector shows that the erosion of the beach-dune system at the Grand Rocher sector reached between -2.5 m and -3 m. In contrast, accretion at Tréduder reached +3.5 m (Figure 16D).

As of winter 2006-2007, the shoreline retreated again due to erosion generated by more frequent and stronger morphogenetic events (Figure 17). Figures 17B, 17C, and 17D illustrate erosion generated by the high water levels on the coast on 7 October 2006, 20 February 2007 and 10 March 2008, respectively (see Figure 14). The 10 March 2008 storm was the most morphogenetic event recorded over the past 20 years. This storm-generated erosion affected all the dunes in the bay, as demonstrated by the shoreline retreat at Saint-Efflam (Figures 17E and 17F). Finally, as described above, the mild winter of 2008-2009 resulted in a recovery of the dune systems, which continued during 2009-2010.

The succession of these particularly morphogenetic phases and subsequent recovery was also noted by Hallégouët and Hénaff (2006) for several sandy beaches in western Cornouaille (southwestern Brittany). Hallégouët and Hénaff (2006) showed that the 1990-2000 period was marked by many energetic winter storms that occurred over short time intervals, with the biggest storms occurring during winter 1989-1990. In contrast, during the 2000-2006 period, major storm events were less frequent. The succession of these phases may be related to the alternation between positive and negative phases of the North Atlantic Oscillation (NAO). As shown in Figure 18, when looking at the studied period (1989-2009), there are six alternating phases of positive and negative NAO indices that can be related to the morphogenetic periods (NAO+) and calm periods (NAO-) identified here. Thus, phases "a" (1989-1995), "c" (1997-2003) and "e" (2006-2008) were characterized by an increase in the frequency of storms that were particularly damaging for coastal dunes. The high positive index around 1990 appears to be concordant with the energetic storms of winter 1989-1990. On the contrary, phases "b" (1995-1997), "d" (2003-2006), and "f" (2008-2009), during which the NAO index is relatively negative, appear to correspond well with the calmer morphogenetic conditions observed and associated with dune recovery and/or stability. The role of the NAO in the changing wind conditions in Brittany has been highlighted (Pirazzoli *et al.* 2004). However, a study of the meteorological and atmospheric conditions responsible for the storm surges recorded in Brest between 1950 and 1992 shows that the NAO contributes little to the processes behind the occurrence of these surges (Betts *et al.* 2004). The absence of a relationship between storm surges and the NAO can be explained by the fact that the calculation of the NAO for the winter months of January, February, and March effectively smoothes the high variability of the dynamic parameters that act on the water elevation during a storm event. Thus, the particularly morphogenetic impact of a storm event lasting a few hours may not be discernable from an index averaged over three winter months.

Table 2. Number of spring tides with a coefficient ≥ 100.

2002	2003	2004	2005	2006	2007	2008	2009
59	51	27	45	55	54	36	42

A second parameter seems to play a major role in explaining morphogenetic episodes: tide conditions. As shown in Table 2, the years of 2002, 2006, and 2007 were marked by many spring tides with coefficients greater than 100.

Thus, the frequency of high spring tides increases the probability of the joint occurrence of high spring tides and storms. The storm event on 10 March 2008, which occurred during a tide with a coefficient of 106, is a good example of this coupling of high tide and storm conditions. In a contrary, as shown for 2003, despite the high frequency of high spring tides with coefficients greater than 100 (Table 2), morphogenetic episodes were very rare because there were no major storms associated with them. Therefore, as also attested by Pye and Blott (2008), these results could indicate only a modest relationship between shoreline dynamics and the NAO index. More generally, coastal erosion due to morphogenetic events may be more related to occurrences of extreme high water levels. This relationship has also been demonstrated along the northern coast of France (Chaverot *et al.* 2008) and on the Suffolk coast in southeastern England (Pye and Blott 2006).

CONCLUSION

Based on the results of both the shoreline change analyses and the sediment budget calculation of the upper beach of the bay, we identified fundamental geomorphological factors that influence the sedimentary and morphological dynamics of Saint-Michel-en-Grève Bay. The medium-term shoreline changes in Saint-Michel-en-Grève Bay show considerable annual variation, depending on storm event frequency and intensity (e.g. storm events of the end of 2,000 years or the 10 March 2008 storm event, inducing strong shoreline retreat). However, this variation occurs on a backdrop of a general long-term trend of beach accretion.

Changes can be attributed to high sediment inputs that have been clearly observed since the end of the 19th century. These inputs may be even older, considering the morphosedimentary dynamics that can be deduced from maps drawn in the 17th century and later. The measurements taken in the 1990s and later demonstrate that accretion on the upper beach of the bay reaches 0.1 $m^3/m^2/yr$. The positive sediment budget is responsible for the construction of foredunes whose current state is governed by the combined action of natural and human forcing.

Natural forcing, represented primarily by storms' erosive action, induces considerable shoreline retreat that can reach around 50 m/yr, depending on the sector (e.g. dune of Grand Rocher between 1999 and 2001). Nonetheless, years when the frequency of morphogenetic events of high intensity decrease, the dunes are rapidly recovered, which can be attributed to high sediment input that occurs at a rapid rate. We explain this by the fact that the sand volumes eroded from the upper beach-dune system during erosive phases are never completely lost for the whole littoral cell. These subaerial beach volumes are displaced over short distances, between the upper and middle part of the tidal beach, before being brought back up the upper beach-dune system by both low energetic swells and wind action.

Human forcing perturbs the natural morphosedimentary dynamics in a localized manner (e.g. erosion of the dune of

Grand Rocher between 1999 and 2007, the resulting sediments filled the Yar depression during the same period and contributed to the formation of the dune ridge at Tréduder as of 2003). These processes correspond to feedback processes that occur when the morphodynamic equilibrium of the coastal system had been modified by coastal engineering (outlet channels for the Yar and Roscoat Rivers on the shore).

While a great part of the sandy beaches in Brittany is eroding, Saint-Michel-en-Grève Bay appears as an exception because it is one of the only areas where the net sediment budget is positive. We hypothesize this specificity is due to the fact that this bay head beach is hyper-dissapative. The determining factor is the significant sand supply for the coastal system. Given these morphosedimentary dynamics, the usefulness and adequacy of coastal engineering solutions for protecting the shoreline may be called into question because many are nowadays complete disassociated from marine dynamics.

REFERENCES

Anthony, E.J., and F. Doplique 2001. "Natural and human influences on the contemporary evolution of gravel shorelines in Northern France between the Seine Estuary and Belgium." In: *Ecology & Geomorphology of Coastal Shingle*, Packham, J.R., R.E. Randall, R.S.K. Barnes and A. Neal, (eds.), Westbury Academic and Scientific Publishing, 132-148.

Betts N.L., J.D. Orford, D. White, and C.J. Graham 2004. "Storminess and surges in the southwestern approaches of the eastern North Atlantic: the synoptic climatology of recent extreme coastal storms," *Marine Geology*, 210(1-4), 227-246.

Bodéré J.-C, B. Hallégouët, and C. Yoni 1993. "Erosion et protection des côtes entre Penmarc'h et l'Odet. Le Pays Bigouden à la croisée des chemins," *Cap Caval, suppl.*, 17, 295-306.

Bouvier, P., 1994. *Morphogenèse et morphosédimentologie des vastes estrans plans en Bretagne septentrionale*, Thèse de doctorat, Université de Bretagne Occidentale, 395 p.

Briand, M., and E. Quéméneur 1973. "Formations littorales en Trégor occidental," *Penn ar Bed*, 73, 117-125.

Burroughs, S.M., and S.F. Tebbens 2008. "Dune retreat and shoreline change on the Outer Banks of North Carolina," *J. Coastal Res.*, 24(2B), 104-112.

Camacho-Valdéz, V., J.M. Murillo-Jiménez, E.H. Nava-Sánchez, and C. Turrent-Thompson 2008. "Dune and beach morphodynamics at Cabo Falso, Baja California Sur, Mexico: response to natural, Hurricane Juliette (2001) and anthropogenic influence," *J. Coastal Res.*, 24(3), 553-560.

Carter, R.G.W., P.A. Hesp, and K.F. Nordstrom 1990. "Erosional landforms in coastal dunes", in Nordstrom K., N. Psuty, and B. Carter (Eds.), *Coastal dunes. Form and process*, Edit. John Wiley & Sons, England, 217-250.

Chauris, L., 1989. "Origine des sables terrigènes des plages: intérêt de la représentation cartographique des pourcentages en différents minéraux lourds. L'exemple de la baie de Lannion (Bretagne septentrionale)," *Norois*, 144, 391-406.

Chaverot, S., A. Héquette, and O. Cohen 2008. "Changes in storminess and shoreline evolution along the northern coast of France during the second half of the 20th century," *Z. Geomorph. N.F.,* 52(3), 1-3.

Clayton, K.M., 1980. "Beach sediment budgets and coastal modification," *Progress in Physical Geography*, 4(4), 471-486.

Cooper, N.J., and J.S. Pethick 2005. "Sediment budget approach to addressing coastal erosion problems in St. Ouen's Bay, Jersey, Channel Islands," *J. Coastal Res.,* 21(1), 112-122.

Farris, A.S., and J.H. List 2007. "Shoreline change as a proxy for subaerial beach volume change," *J. Coastal Res.*, 23(3), 740-748.

Fichaut, B., and B. Hallégouët 1989. "Banneg : une île dans la tempête," *Penn ar Bed*, 135, 36-43.

Gad, L., 1999. *Dynamique morphosédimentaire de la baie de Saint-Michel-en-Grève. Eléments d'analyse pour le suivi d'aménagements dans un espace littoral sous influence fluvio-marine: la poche du Yar*, Mémoire de maîtrise, Université de Bretagne Occidentale, 186 p.

Gad, L., S. Suanez, A. Hénaff, F. Lidou, and V. Morel 2003. "Apport de la géomorphologie à une problématique environnementale : comment faciliter le ramassage des algues vertes (*Ulva armoricana*) en baie de Saint-Michel-en-Grève (Côtes-d'Armor)?," *Les Cahiers Nantais*, 59, 89-102.

Goulhen, L., 2004. *Petits trains du Trégor. Ligne Lannion – Plestin*, Skol Vreizh, Morlaix, 133 p.

Guilcher, A., and B. Hallégouët 1991. "Coastal dunes in Brittany and their management," *J. Coastal Res.,* 7(2), 517-533.

Hallégouët B., 1981. Les crêtes littorales dunifiées du massif Armoricain: formation et évolution, *Géographie Physique et Quaternaire,* 35(2), 205-218.

Hallégouët, B., and A. Hénaff 1993. "Evolution du littoral septentrional du pays bigouden entre Penhors et Pors Poulhan," *Cap Caval, suppl*, 17, 273- 280.

Hallégouët, B., and A. Hénaff 2006. *Evolution récente et gestion des espaces littoraux de l'ouest Cornouaille*, Les Actes des rencontres de l'ouest Cornouaille «Quelles pistes de développement pour le territoire?», Mai–juin 2005, Association Ouest Cornouaille Promotion (AOCP), Pont-L'Abbé, 20-34.

Hapke, C.J., D. Reid, and B. Richmond 2009. "Rates and trends of coastal change in California and the regional behavior of the beach and cliff system," *J. Coastal Res.*, 25(3), 603-615.

Hesp, P.A., 1981. "The formation of shadow dunes", *J. Sed. Pet.*, 51(1), 101-112.

Lorenzo, F., A. Alonso, and J.L. Pagés 2007. "Erosion and accretion of beach and spit systems in northwest Spain: A response to human activity," *J. Coastal Res.*, 23(4), 834-845.

Martínez del Pozo J.Á., and G. Anfuso 2008. "Spatial approach to medium-term coastal evolution in south Sicily (Italy): implications for coastal erosion management," *J. Coastal Res.*, 24(1), 33-42.

Pandrian, P.K., S. Ramesh, M.V.R. Murthy, S. Ramachandran, and S. Thayumanavan 2004. "Shoreline changes and near shore processes along Ennore Coast, East Coast of South India," *J. Coastal Res.*, 20(3), 828–845.

Pinot, J.-P., 1987. "Des îles disparues sur la Lieue de Grève," *Iles du Trégor*, 2, 17-21.

Pinot, J.-P., 1993. *Rapport sur l'évolution du littoral autour de la baie de Lannion et sur la Côte de Granit Rose, Rapport présenté pour le Schéma de Mise en Valeur de la Mer (SMVM)*, Université de Bretagne Occidentale, 115 p. (non publié).

Pinot, J.-P., 1995. "Quelques plages en voie d'accrétion dans la région de Lannion," *Norois*, 165, 99-117.

Pirazzoli P.A., H. Regnauld, and L. Lemasson 2004. "Changes in storminess and surges in western France during the last century," *Marine Geol.*, 210(1-4), 307-323.

Psuty, N.P., 1992. "Spatial variation in coastal Foredune development," in Carter, R.W.G., T.G.F. Curtis, and M.J. Sheehy-Skeffington (Eds.), *Coastal dunes. Geomorphology, Ecology and Management for Conservation*, Proc. 3rd European Dune Congress, Balkema, Rotterdam, 3-13.

Pye, K., and S.J. Blott 2006. "Coastal processes and morphological change in the Dunwich-Sizewell area, Suffolk, UK," *J. Coastal Res.*, 22(3), 453-473.

Pye, K., and S.J. Blott 2008 "Decadal-scale variation in dune erosion and accretion rates: an investigation of the significance of changing storm tide frequency and magnitude on the Sefton coast, UK," *Geomorphology*, 102(3-4), 652-666.

Ruggiero, P., P.D. Komar, W.G. McDouglas, J.J. Marra, and R.A. Beach 2001. "Wave runup, extreme water levels and erosion of properties backing beaches," *J. Coastal Res.*, 17(2), 407-419.

Saye S.E., D. van der Wal, K. Pye, and S.J. Blott 2005. "Beach-dune morphological relationships and erosion/accretion at five sites in England and Wales using LIDAR data," *Geomorphology*, 72(1-4), 128-155.

Stéphan, P., and S. Suanez 2004. "Dynamique morphosédimentaire des cordons dunaires de Tréduder et de Saint-Michel-en-Grève (baie de Saint-Michel-en-Grève - Côtes d'Armor) entre 1990 et 2003," *Bulletin de l'Association des Géographes Français*, 3, 438-448.

Suanez, S., L. Gad, A. Hénaff, and F. Lidou 2002. "Géomorphologie appliquée et algues vertes : l'exemple en baie de Saint-Michel-en-Grève," *Penn ar Bed*, 187, 1-13.

Suanez, S., 2004. "Modifications morphodynamiques et phénomènes rétroactifs en baie de Saint-Michel-en-Grève (Côtes-d'Armor)," *Bulletin de l'Association des Géographes Français*, 3, 334-345.

Suanez, S., and P. Stéphan 2006. "Forçages météo-marins et dynamique morphosédimentaire saisonnière des cordons dunaires. Exemple de la baie de Saint-Michel-en-Grève (Côtes d'Armor, Bretagne)," *Géomorphologie : relief, processus, environnement,* 2, 91-110.

Vespremeanu-Stroe A., and L. Preoteasa 2007. "Beach–dune interactions on the dry–temperate Danube delta coast," *Geomorphology*, 86(3-4), 267-282.