Geomorphology 254 (2016) 104–120

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Geomorphology and dynamics of a traveling cuspate foreland, Authie estuary, France

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ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form 11 November 2015
Accepted 21 November 2015
Available online 23 November 2015

Keywords:
Traveling foreland
Salient
Foredunes
Foredune dynamics and geomorphology
Authie estuary
France

ABSTRACT

Cuspate forelands or salients occur all over the world in lakes, estuaries and on ocean shores, yet there have been few studies conducted on traveling cuspate forelands (or salients), that is, forelands that migrate or travel alongshore. This paper presents a study of a traveling foreland in the Authie estuary, France, termed the Bec du Perroquet. Historical shoreline changes may be traced from the 1200's AD and the region has experienced both marked intertidal-subtidal accretion extending from the south, and massive erosion in the north since this period. An analysis of aerial photographs from 1947 until the present shows that the original Bec foreland was established at the mouth of the Authie estuary, but gradually disappeared by the 1960's and a new foreland developed in the middle of the northern-central portion of the bay. This foreland was composed of a suite of foredune ridges which have been successively eroded on the northern margin and initiated on the southern margin as the foreland traveled or migrated southwards. As the foreland traveled south, from 1947 to 2009 the northern part of the bay retreated more than 350 m, while mid-bay, the coastline retreated ~215 m. As the foreland evolves and migrates, incipient foredunes can develop rapidly (e.g. 18 ridges formed in an 11 week period), while at other times the ridges form slowly and may be eroded and disappear. Two or more foredune ridges may blend into a single ridge over time depending on the initial degree of vegetation cover on the ridge and swale set. Aeolian processes in dune swales are much more important in this system than in typical prograding foredune plain systems due to the sometimes marked lack of vegetation colonization in the swales following foredune ridge development, and aeolian deflation of the swales (along with blowout development) is important particularly when they become open conduits to the beach as erosion of the NW foreland proceeds. The ages of each of the surviving ridges on the foreland in 2009 have been determined, and the evolutionary path of the ridges ascertained. Formerly intact, relatively stable, continuous ridges evolve to erosional knobs, turrets and nebkha over time. Foredune ridges (and swales) can be extremely arcuate to semi-circular in form where the foreland and especially the spit extension are exposed to a wide range of wind directions and where the shoreline trends through an arc of at least 270°. This study illustrates a remarkable cycling of the formation, destruction and reformation (travel) of a cuspate foreland over a ~50+ year period.

1. Introduction

Cuspate forelands are formed in accretion zones, and are generally triangular in form (Gulliver, 1896; Craig-Smith, 2005), although they may have a gently convex terminal bow in many cases, and can represent the evolutionary stage between a salient and a tombolo (Horikawa, 1988). They have also been termed a Ness (e.g. Dungeness; Benacre Ness) in Britain (Gulliver, 1887; Bird, 2005; Burningham and French, 2014). Rosen defines a cuspate foreland as "a cuspate projection of a beach on a shoreline with no fetch limitations, representing reorientation of the shoreline to dominant wind/wave approach" (Rosen, 1975, p. 90). They may migrate on one flank and these have been termed traveling forelands by Escoffier (1954) and others (e.g. Russell, 1958), and the direction of migration may also reverse or oscillate (Hardy, 1966). While there have been multiple studies on cuspate forelands and spits, there have been few on traveling cuspate forelands (e.g. Escoffier, 1954).

Cuspate forelands occur all over the world in lakes, estuaries and on ocean shores, and the scale can vary considerably (e.g. Gilbert, 1885; Abbe, 1895; Gulliver, 1896; Pelnard-Considère, 1956; Zenkovich, 1959; Carter, 1980; Moslow and Heron, 1981; Coakley, 1989; Humlum et al., 1995; McNinch and Luettich, 2000; Alcantara-Carrio and Fontan, 2009; Anthony, 2009). Cuspate forelands (and salients) may form due to the operation of two opposing wave directions where one is higher energy than the other (Escoffier, 1954), wave refraction processes behind offshore islands, patch reefs, shallow rocky substrates, and human-made devices (e.g. detached breakwaters) (Johnson, 1919;

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http://dx.doi.org/10.1016/j.geomorph.2015.11.015
0169-555X/

Fisher, 1955; Silvester and Hsu, 1993; Sanderson and Eliot, 1996; Sanderson et al., 2000; Bouchette et al., 2014), but also on straight coasts (Steers, 1964) due to a possible range of processes including high angle wave approach and subsequent shoreline instability (Rosen, 1975; Ashton et al., 2000, 2001; Ashton and Murray, 2006a, 2006b; Coco and Murray, 2007; Serizawa et al., 2012). Cuspate forelands commonly comprise a few to many foredunes or beach ridges, but also occasionally other dune types, and in some cases complexes of two types (e.g. along the Ningaloo coast, parabolic dunes dominate the windward flank, while foredune ridges dominate the leeward, more sheltered flank (Hesp, 1986). Sanderson et al. (2000) noted that cuspate forelands may change or respond to changes in wave climate, tidal currents, longshore currents, and climate variability, including changes in storminess.

There is a considerable literature on the evolution of beach ridge plains, and foredune or relict foredune plains on cuspate forelands, salients and straight and embayed coasts (see e.g. Johnson, 1919; Zenkovich, 1959; Clemmensen et al., 2011; Bendixen et al., 2013). Most of these studies are concerned with (i) Holocene history and dating of the ridges and/or barrier (e.g. Thom and Roy, 1985; Thom et al., 1992; Delcourt et al., 1996; Mason et al., 1997; Murray-Wallace et al., 2002; Bristow and Pucillo, 2006) (ii) ridge and swale morphology (e.g. Davies, 1958), (iii) genesis in terms of waves vs winds or some combination thereof (e.g. Carter, 1986; Thompson, 1992; Lichter, 1995; Otvos, 2000; Hesp, 2006; Hesp et al., 2005; Nott, 2010), and (iv) their value as paleoenvironmental records, and internal stratification and GPR signatures (e.g. Neal et al., 2002; Anthony, 2009; Nielsen and Clemmensen, 2009; Clemmensen and Nielsen, 2009; Scheffers et al., 2012; Clemmensen et al., 2012; Tamura, 2012). While some studies have examined the aerial photographic history of the sites, most rates of development have been obtained via dating of ridges and are mean values, and very few studies have examined seasonal to yearly changes (e.g. Wallen, 1980; Hesp, 1984, 2013; Burningham and French, 2014), and this is particularly so for cuspate forelands which migrate alongshore.

The following presents a study of a cuspate foreland, termed the "Bec du Perroquet", in the mouth of the Authie estuary (Fig. 1). The Authie estuary is one of four macrotidal estuaries located between Boulogne-sur-Mer and Cayeux-sur-Mer along the west facing English Channel coast of northern France (Fig. 1). The mouth of the Liane estuary has been extensively altered by port works, while the other three have been altered or managed to various degrees. Due to the embankment of intertidal saltmarshes, the Canche, Authie and Somme estuaries have extensive polders, and also ponds developed for duck hunting. These three estuaries all display some degree of cuspate foreland or salient development at or near the mouths. This paper, which focuses on the cuspate foreland of the Authie estuary, examines the historical changes in shoreline morphology, the dynamics of the foreland, and the nature of spatio-temporal foredune and relict foredune development on the foreland. Such studies are important in order to better

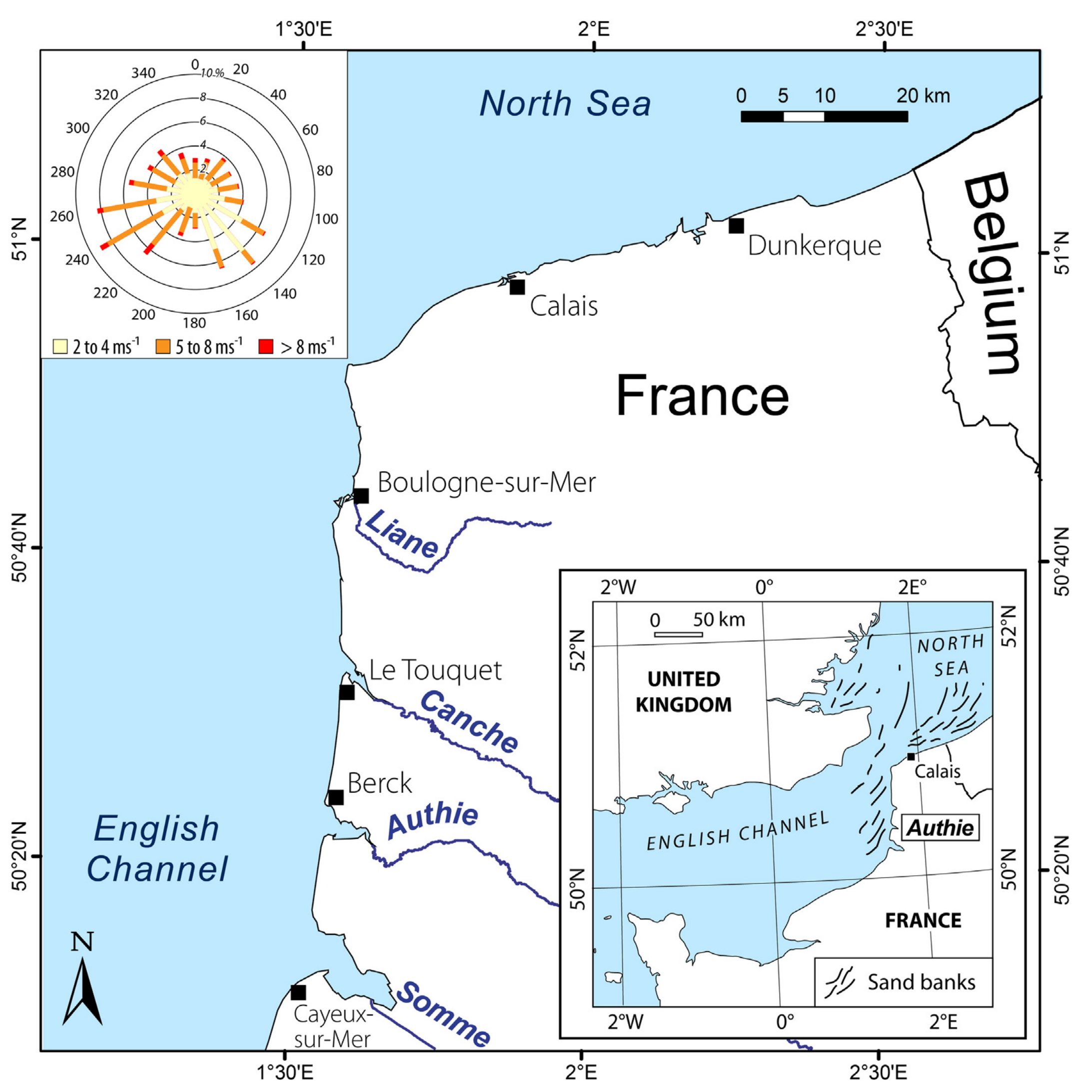

Fig. 1. Location map of the study area and wind rose diagram for Le Touquet.

understand (i) relationships between actual rates of ridge building and shoreline dynamics versus mean rates derived from dating relict ridge and swale sequences, (ii) the temporal dynamics of a foreland system and its attendant ridges and swales versus the net resulting landforms forming the final landscape record, and (iii) the nature of foredune and relict foredune morphological change as forelands move through time and space.

2. Study area

The study area is located at the mouth of the Authie estuary, a small macrotidal estuary at the mouth of a 98 km-long coastal river that debouches on the French coast of the eastern English Channel (Fig. 1). The river drains a low-gradient Mesozoic limestone plateau catchment of approximately 985 km^2 that supplies very limited sediment to the coastal zone due to the nature of the bedrock geology. The mean annual discharge of the Authie River is 10 m^3 s^{-1} and is relatively constant throughout the year, ranging from 4 m^3 s^{-1} in summer to 13 m^3 s^{-1} in spring (Dobroniak, 2005). The estuary mouth is affected by large tides, the mean tidal range being approximately 8.5 m and 4.9 m for spring and neap tides, respectively. This large tidal amplitude is responsible for strong tidal currents that can reach 1 m s^{-1} at the mouth during spring tides and up to 1.5 m s^{-1} seaward of the estuary mouth and in the adjacent coastal zone (Anthony and Dobroniak, 2000; Dobroniak and Anthony, 2002). The coastal/nearshore zone is characterised by a shore-parallel circulation dominated by northward-directed flood currents (Cartier and Héquette, 2011).

The dominant winds in the eastern Channel are from west-southwest, followed by winds from north to northeast (Fig. 1). Storms can be severe and maximum wind gusts up to 155 km/h have been recorded on this coast. The average number of days with maximum instantaneous winds above 57.6 km/h is 16.4 days (http://www.infoclimat.fr/climatologie-07002-boulogne.html). Average temperatures range from 3 °C (December and January) to 18 °C (July and August) (http://www.climate-zone.com/climate/france/celsius/lille.htm). Snow occurs on occasions, with an average of 2 snow days per year.

The wave regime is dominated by short period, southwesterly, waves generated in the English Channel. Offshore significant wave heights are generally less than 1.5 m, but may periodically exceed heights of 4 m during major storms (Héquette et al., 2008). Wave heights are much lower at the coast, however, due to significant refraction and shoaling over the sand banks of the eastern Channel (Fig. 1), resulting in modal inshore wave heights less than 0.5 m high (Sedrati and Anthony, 2007).

The Authie estuary forms a shallow elongated embayment that shows rapid infilling by sand from the English Channel (Anthony and Dobroniak, 2000; Marion et al., 2009). The coast to the south has both prograded seawards and northwards over time, and the northward progradation has been accompanied by the development of a very extensive intertidal and subtidal platform and spit (Fig. 2). The progressive extension of this major accumulation feature that protects the inner estuary from wave action favored the development of mudflats and saltmarshes (Deloffre et al., 2007). The estuary mouth is largely blocked by the prominent sand spit and intertidal/subtidal platform, and this has forced the main channel of the estuary to flow along the northern shore of the estuary mouth and adjacent shoreline (Fig. 2). Large portions of the inner estuary have been empoldered during the last centuries, which resulted in increased sedimentation and seaward saltmarsh progression (Anthony and Dobroniak, 2000; Dobroniak, 2005).

During low tide, most of the estuary, except the main channel, is sub-aerially exposed, exhibiting extensive sand flats and sand bars that represent potential sediment sources of wind-blown sand for the coastal dunes that developed along the estuarine shore (Fig. 2). The northern, west facing shoreline extending from Berck Plage to the southern shore of the Bec du Perroquet foreland has been eroding for several decades (Dobroniak and Anthony, 2002). Coastal erosion primarily occurs during southwesterly to westerly storms that can induce water level set-up in excess of 1 m at the coast in the study area (Chaverot et al., 2008). Waves easily overtop the partially submerged breakwater extending across the first northern bay from Berck to approximately half way down the coast (Fig. 2). That coastal strip is characterised by active and stabilised (mostly artificially stabilised) parabolic dunes in the north to central region, and the cuspate foreland in the southern region. *Elymus farctus* dominates the vegetation growing on the foreshore and incipient foredunes while *Ammophila arenaria* (marram grass) is dominant on established foredunes.

3. Methodology

Historical evolution of the Authie estuary and adjacent area was analyzed from maps published in Briquet (1930) dating from the 1200's AD, and the "map of Cassini", the first general maps of the French territory based on geodetic triangulation. The latter were made by the Cassini family during the 18th century on a scale of 1:86,400 (see Fig. 3). This was the first comprehensive, detailed map of France,

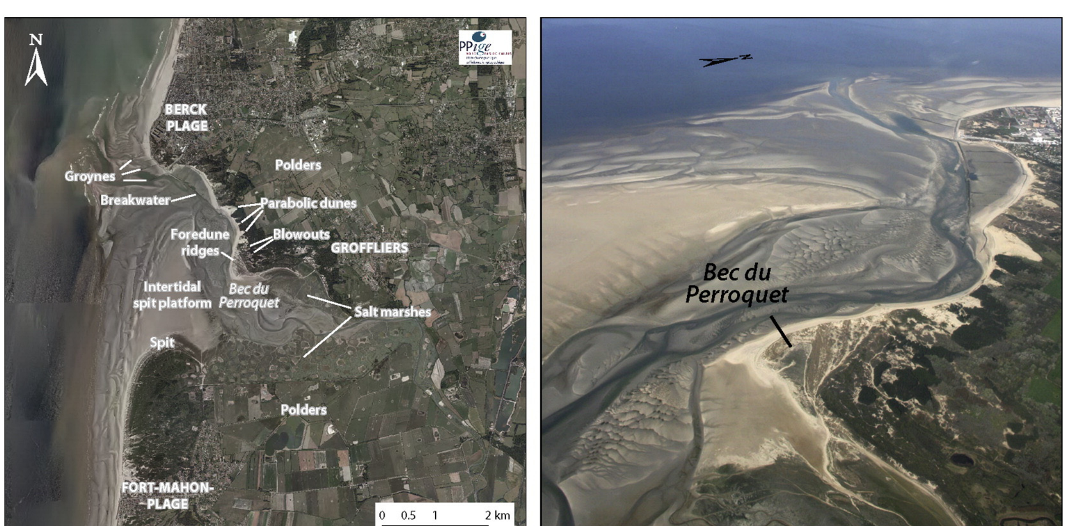

Fig. 2. Vertical and oblique aerial photographs of the Authie estuary. The oblique photograph was taken looking from the SE. Sources: vertical aerial photograph © Institut Géographique National, 2009; oblique photograph © Association de Défense Contre la Mer en Baie d'Authie, 2013.

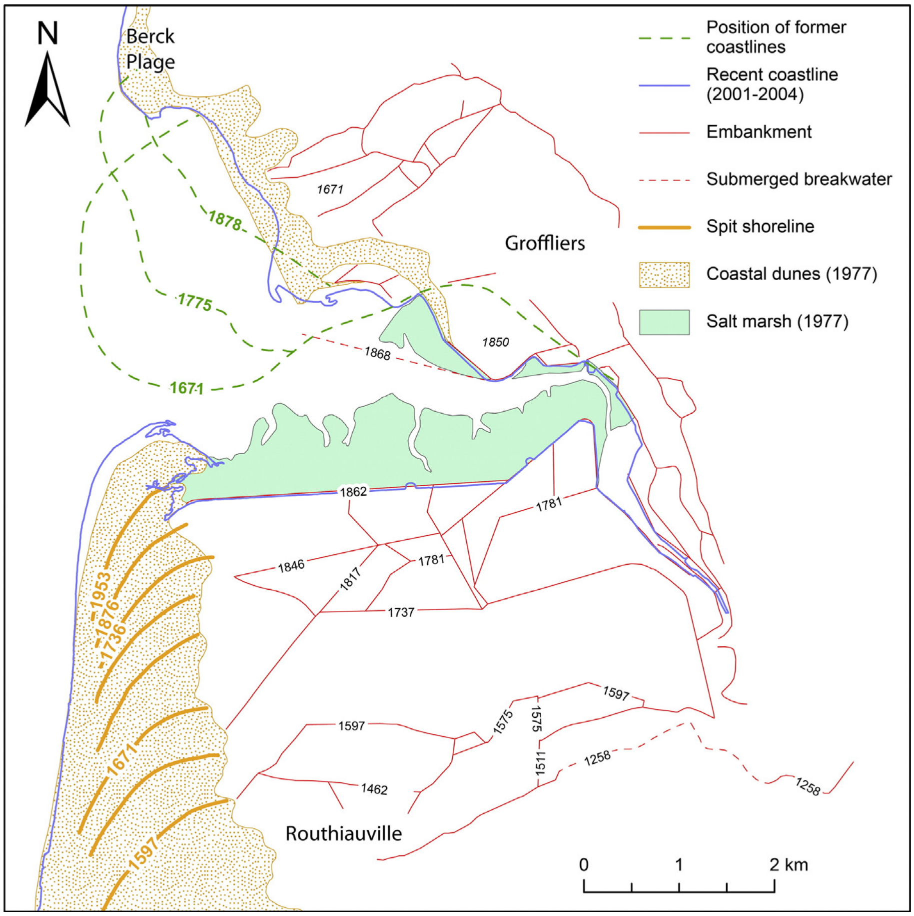

Fig. 3. Historical evolution of the Authie estuary (modified from BRGM, 1981; Briquet, 1930, 2001–2004 shoreline from IGN).

compiled following survey work carried out between the 1740s and 1780's AD. Georeferenced military maps, called "cartes d'Etat Major" published in 1833 at a scale of 1:80,000, were also used.

Vertical stereo aerial photographs were examined for the years 1947, 1949, 1955, 1962, 1965, 1971, 1974, 1975, 1976, 1977, 1981, 1982, 1983, 1991, 1994, 1997 (May and August), 2002, 2004 and 2005. Detailed geomorphological maps and tracings of foredune ridge lines were created in stereo from these photographs. In addition, georeferenced and rectified aerial photographs (1947, 1991), orthorectified aerial photographs (1983, 1991) and high resolution orthophotographs (2000, 2009 and 2013) were used to analyze recent shoreline evolution, where the shoreline corresponds to the upper tide/storm wave limit/base of a scarp or limit of vegetation, and for the LiDAR it is the uppermost tide limit.

The error margin of the orthorectified aerial photographs is ± 2 m but an empirically-derived error margin of approximately ± 6.5 m was calculated for shoreline position based on the comparison of the shoreline position on the orthorectified aerial photographs (of 2013) with shoreline position determined from high-resolution LiDAR data obtained the same year (see below). Oblique aerial photographs from 2011 to 2014 were also used for evaluating recent shoreline change.

Detailed topographic data of the coastal zone were obtained from airborne LiDAR surveys carried out in 2006, 2008, 2011 and 2013. The data were collected using different LiDAR operating systems that were all coupled with real time kinematic DGPS and inertial motion unit, ensuring a planimetric position accuracy lower than 0.5 m in all cases. The 2006 LiDAR data were collected using a Falcon II LiDAR system (manufactured by Toposys) operated by Eurosense. The average data point density during this survey was about 4 points/m^2 with an estimated elevation accuracy of ± 0.15 m over bare surface areas. The 2008 survey was carried out with an Optech ALTM 1020 LiDAR system operated by TerraImaging. Data point density was about 1.3 points/m^2 with a planimetric position accuracy on the order of ± 25 cm and a vertical error range of approximately ± 0.10 m. The 2011 and 2013 LiDAR data were obtained using a Leica ALS60 LiDAR system. The planimetric position accuracy of the data points during these two surveys ranged from ± 0.10 to 0.17 m with a vertical accuracy $< \pm 0.10$ m as verified by several ground control points. These vertical error ranges can easily increases to ± 0.25 m or more in areas covered by dense vegetation however (Saye et al., 2005).The LiDAR topographic data were filtered to remove vegetation, buildings and other objects. Filtered data were then used to create contour Digital Terrain Models (DTM) using Golden Software Surfer™ and calculate volume changes between each LiDAR survey. The DTMs were obtained by linear interpolation using a Delaunay triangulation resulting in a grid with a 1 m resolution, a grid cell resolution of 1 m^2 appearing to provide reliable representation of topography and accurate volumetric measurements in coastal dunes using LiDAR data (Woolard and Colby, 2002; Grohmann and Sawakuchi, 2013).

In addition to the LiDAR elevation data, in situ topographic profiles of the dune ridges and beach were measured in October 2010 using a DGPS (Leica TPS Syst1200) with vertical and horizontal accuracy of ± 2.5 cm and ± 1.5 cm respectively. Multiple surface sediment samples were collected across the ridges and beach-face during the same field survey. Grain-size analyses were carried out using a Beckman Coulter LS 230 laser granulometer and grain-size parameters were calculated according to the Folk and Ward (1957) method.

Wind data were analyzed (in m s^{-1}) to obtain a wind rose and sand rose for the study area. Wind roses were built via WRPLOT software (http://www.weblakes.com/lakewrpl). The Fryberger and Dean

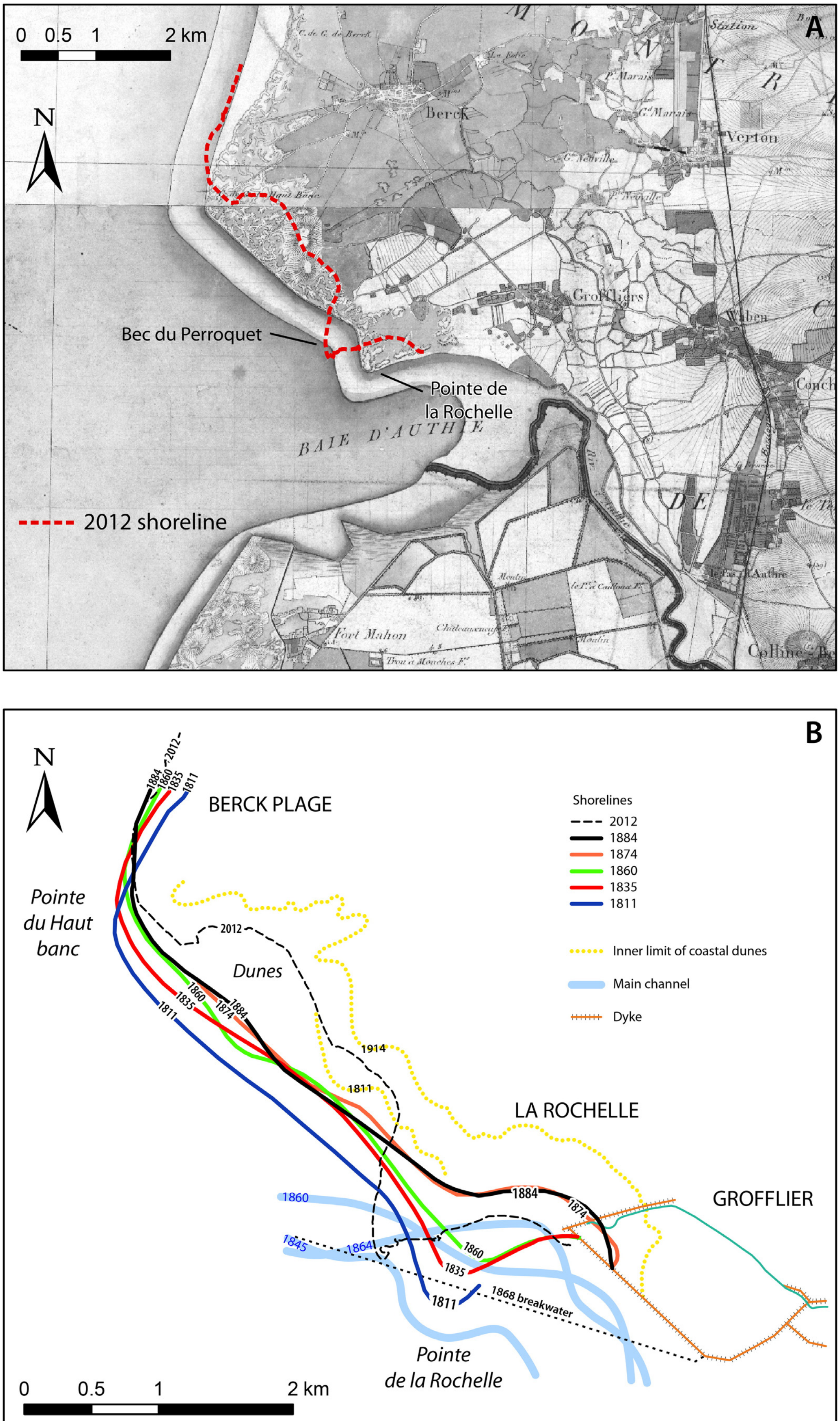

Fig. 4. Evolution of the north shore of the Authie estuary during the 19th century. A) Etat Major map of 1833; B) Shoreline evolution and changes in the position of the main channel of the Authie river (modified from Briquet, 1930). The location of the shoreline in 2012 is shown on both maps.

Fig. 5. Series of vertical aerial photographs showing the evolution of the north shore of the Authie estuary from 1947 to 2009 (© IGN). The Bec du Perroquet is present near the mouth of the Authie in 1947, but largely gone by 1965. The small traveling foreland (arrowed) present in 1947 mid-bay has grown significantly by 1965 and then travels south over time, although the rate of travel slows post-1990. Note the significant extension of the western intertidal/subtidal platform into the bay over time.

(1979) method was used to determine potential sediment transport (Bullard, 1997; Pearce and Walker, 2005; Miot da Silva and Hesp, 2010). The method uses wind data (speed and direction) to calculate the potential for sand drift and is based on the determination of the Drift Potentials (DPs) for each class of velocity and direction. Potential errors associated with using this method are discussed by Fryberger and Dean (1979); Arens (1997); Bullard (1997) and Pearce and Walker (2005). In the Fryberger and Dean (1979) model, a grain size with an average diameter of 0.25–0.30 mm and a threshold velocity of 6 m s^{-1} (measured at 10 m height) is assumed. Many regard this threshold velocity as too low, and so in this present study, a threshold velocity (Vt) was calculated following methods in Zingg (1953) and Belly (1964). A mean grain size of 0.23 mm was determined from multiple sediment samples taken from the beach and dunes around the Authie beach-dune system, and the threshold velocity was calculated as 6.68 m s^{-1}.

Sand roses were constructed for all winds for the period Jan 1961 to May 2012. The data are three hourly observations from 1961 to Nov 1992, and hourly after that. The data were observed at Le Touquet (see Fig. 1) and provided by Meteo-France. Drift potentials were calculated for these data. The Fryberger and Dean (1979) method is a widely used method to determine potential sediment transport in aeolian environments (Bullard, 1997; Pearce and Walker, 2005). The method uses wind data (speed and direction) to calculate the potential for sand drift and is based on the determination of the Drift Potentials (DPs) for each class of velocity and direction. Potential errors associated with using this method are discussed by Fryberger and Dean (1979); Bullard (1997), and Pearce and Walker (2005). The direction classes used were 16 equal 22.5° sectors, as proposed by Pearce and Walker (2005) as more appropriate to conform to the original Fryberger and Dean (1979) method, and to minimize the influence of systematic frequency and magnitude biases. The speed classes are modified from Pearce and Walker (2005), converted to m/s and with two speed classes added (5.6 to 7 m s^{-1} and 7 to 8.7 m s^{-1}). These have to be included, otherwise the weighting factor calculated for the 5.7–8.8 m s^{-1} class would be negative and not included in the DP calculations (Miot da Silva and Hesp, 2010). This would result in exclusion of the first class of wind speed that is considered by many authors the minimum speed required to transport sand, and consequently would have created a potential underestimation of the total DP.

4. Historical shoreline changes

In 1930, Abel Briquet produced a superb book documenting the shoreline changes for several areas along the French English Channel coast, including the Authie estuary (Briquet, 1930). His historical maps plot the shorelines from before 1200 AD, and are quite detailed from the late 1600's onwards. In around 1200 AD, the southern spit tip shoreline was approximately 4.5 km to the south, approximately near Routhiauville (Fig. 3). Over the period from at least the 1200's onwards, as the southern spit gradually prograded northwards, polders or dams were built along the estuary and marsh shores to stabilize the land and provide farming areas (Fig. 3). Reclamation was pronounced from the 18th century onwards (Dallery, 1955; Anthony and Dobroniak, 2000). To the north, the shoreline described a pronounced arc 2 km seawards of the present shoreline, clearly visible on the Cassini map (1671 AD). As the southern spit prograded northwards, this northern shoreline eroded rapidly and retreated landwards at a maximum rate of ~10 myr^{-1} between 1671 and 1775 AD (Fig. 3).

4.1. 19th and early 20th century evolution

On the Etat Major map of 1833 AD, a cuspate foreland, called “Pointe de la Rochelle” appears on the north shore, west of Groffliers (Fig. 4A). This foreland was 1 km wide in 1811 AD and was rapidly eroded due to the Authie main channel wandering. Briquet (1930) depicted a detailed evolution of the coastline, from Berck Plage to Groffliers between 1811 and 1884 AD (Fig. 4B). According to Briquet (1930, p.151), the

Fig. 6. Photographs of the Authie area in 1975 and 1986 showing the significant northward migration of the intertidal-subtidal platform across the bay, the shoreline erosion, migration of the foreland, and destabilization of the adjacent dune field.

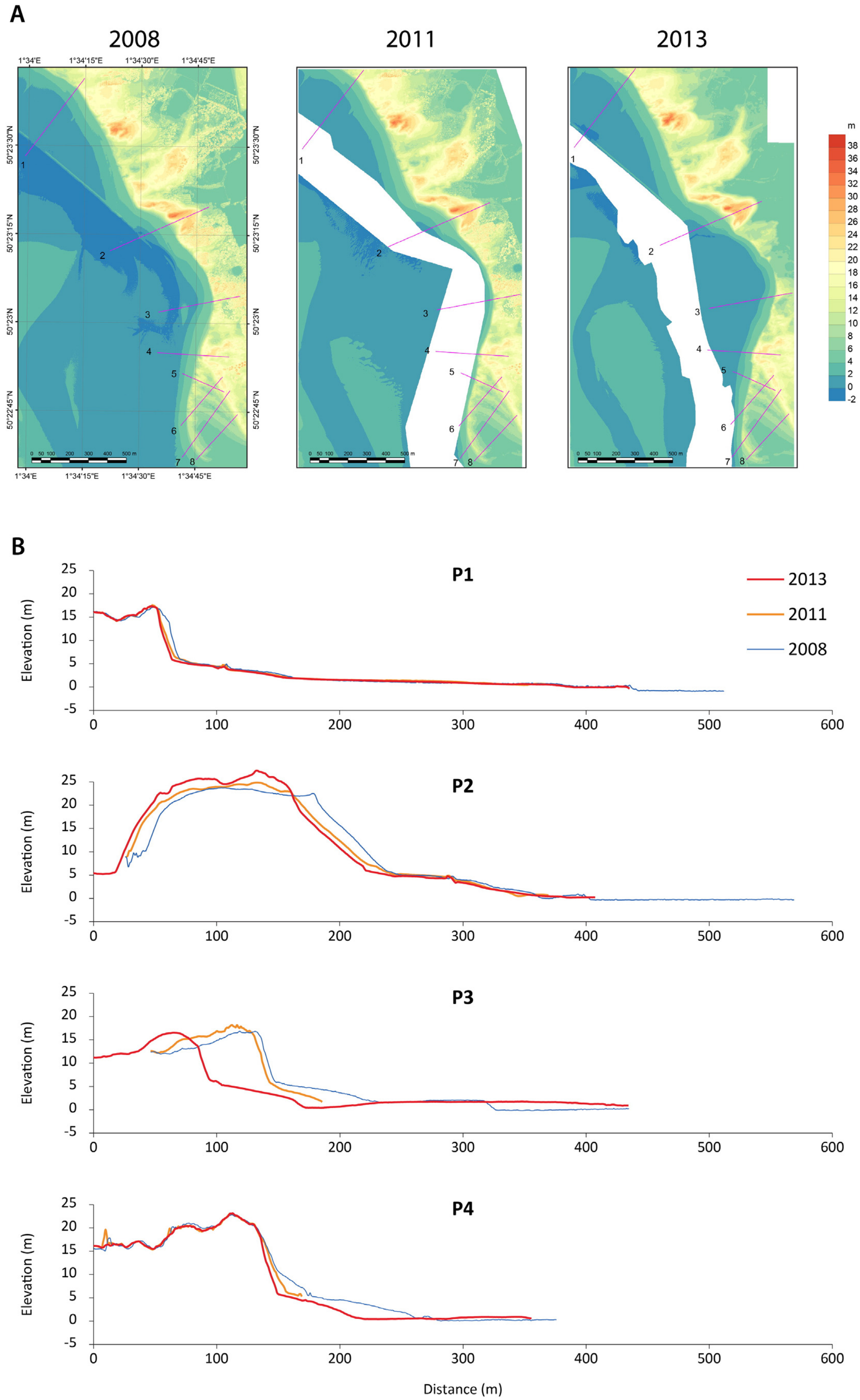

Fig. 7. A) Surface elevation maps of the north shore of the Authie estuary in 2008, 2011 and 2013 from LiDAR data; B) Selected cross-shore profiles along the north shore of the estuary showing coastal evolution from 2008 to 2013 (the location of the profiles is shown on the elevation maps).

erosion of the foreland was on the order of 400 m between 1824 and 1854 AD and 600 m between 1835 and 1878 AD. This foreland completely disappeared by the end of the 19th century as the Authie main channel was deflected to the north (Fig. 4B), as a result of the southern spit northward progradation (Fig. 3). In 1868 AD, the Barrois embankment, a submersible breakwater, was constructed along the estuary margin in the Authie mouth in order to reduce the impacts of channel migration and erosion towards the Groffliers shore and town. This embankment was partially buried by accretion of the southern spit by the 1920's. The northern shore continued to erode at substantial rates, while the southern spit continued to prograde northwards. According to Briquet (1930), the “Pointe du Haut Banc” to the north (Fig. 4B), retreated by 170 m between 1835 and 1878 AD and 75 m between 1897 and 1921 AD and, in order to protect Berck Plage, four wooden groins were installed in 1875. With shoreline retreat, active coastal dunes migrated landward, invading meadows.

Overall in the historical period from the beginning of the 19th century to 1920's, very significant and large scale erosion has taken place along the northern shore of the Authie estuary. During the 19th century, a large cuspate foreland (Pointe de la Rochelle) developed eastward of the present day foreland (Bec du Perroquet) and was completely destroyed by the beginning of the 20th century (Fig. 4B).

4.2. 1947–2009 shoreline evolution

Fig. 5 illustrates six photographs from the area covering the period 1947 to 2009. Prior to 1947, there was significant WWII activity along this coast, and massive German bunkers were built along the shore and under the dunes, so some of the dune mobility may be due to WWII influences. However, rates of shoreline erosion have been severe so the dunes may have been highly erosional and mobile in any case. The 1947 photograph depicts a largely active suite of parabolic dunes fronted by a high, steep scarp, a slight cuspate foreland (or salient) positioned roughly in the middle of the bay and a prominent cuspate foreland at the mouth of the Authie (Fig. 5). According to Briquet (1930), after the destruction of the Pointe de la Rochelle, a salient started to form in the early 20th century (1914–1921) westward of the former foreland. On the aerial photo of 1947 this foreland comprises a suite of foredune ridges and a small spit is extending south into the estuary mouth. By 1965, the Bec du Perroquet foreland has suffered significant erosion on its seaward face, as well as the shoreline south of Berck Plage. In order to delay erosion, a partially submerged breakwater was constructed to the south of Berck in the early 1960's (Anthony and Dobroniak, 2000). The parabolic dunes had largely been stabilised by human agencies, although a high scarp was still present along the

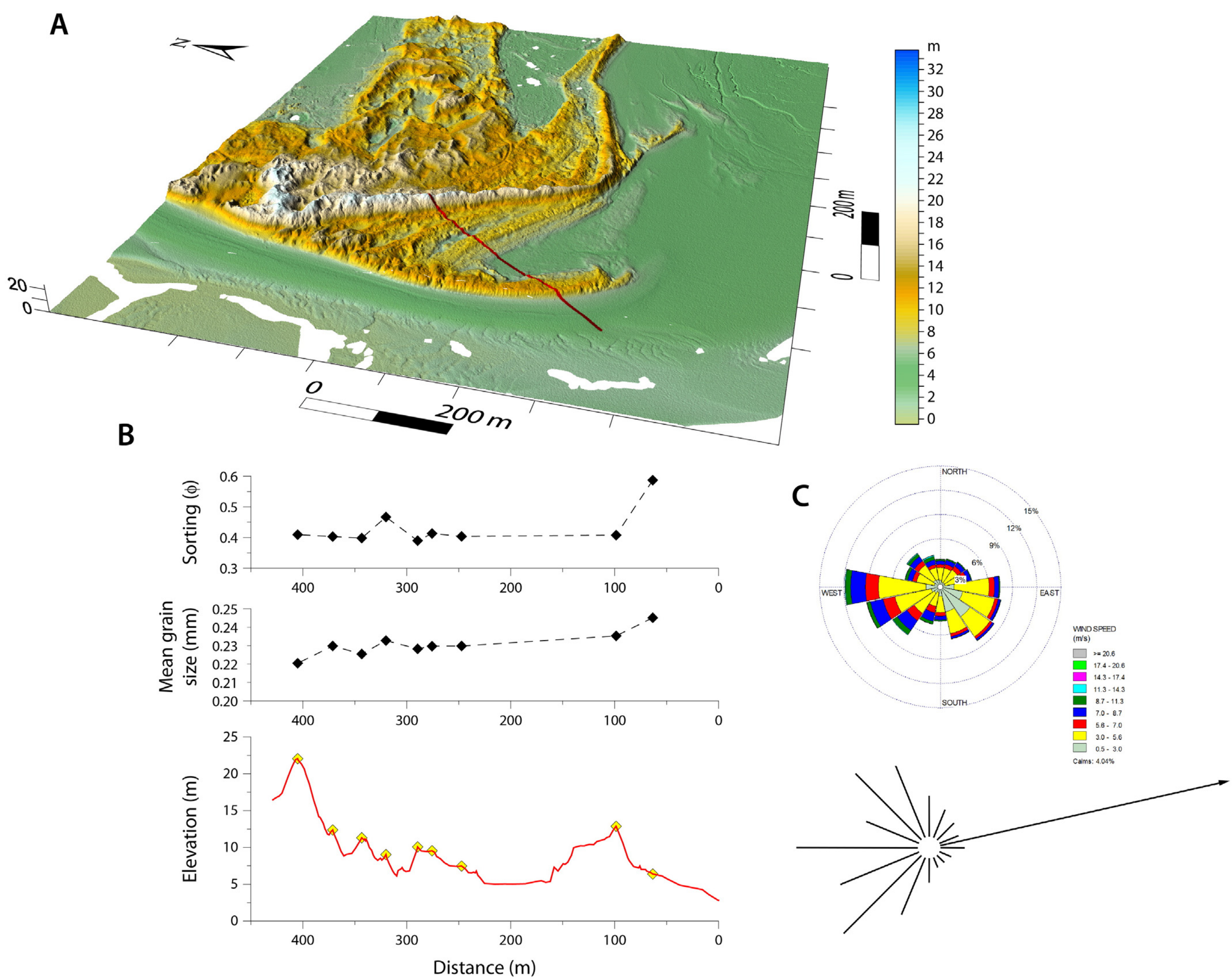

Fig. 8. A) 3D diagram of the cuspate foreland based on LiDAR data obtained in 2008; B) Mean grain-size and sorting of surface sediment samples collected along a topographic profile surveyed across the dune ridges in October 2010 (line on the 3D diagram shows the location of the topographic profile); C) Wind rose from Le Touquet (1961 to 2010) and corresponding sand rose diagram for mean sand size of 0.23 mm.

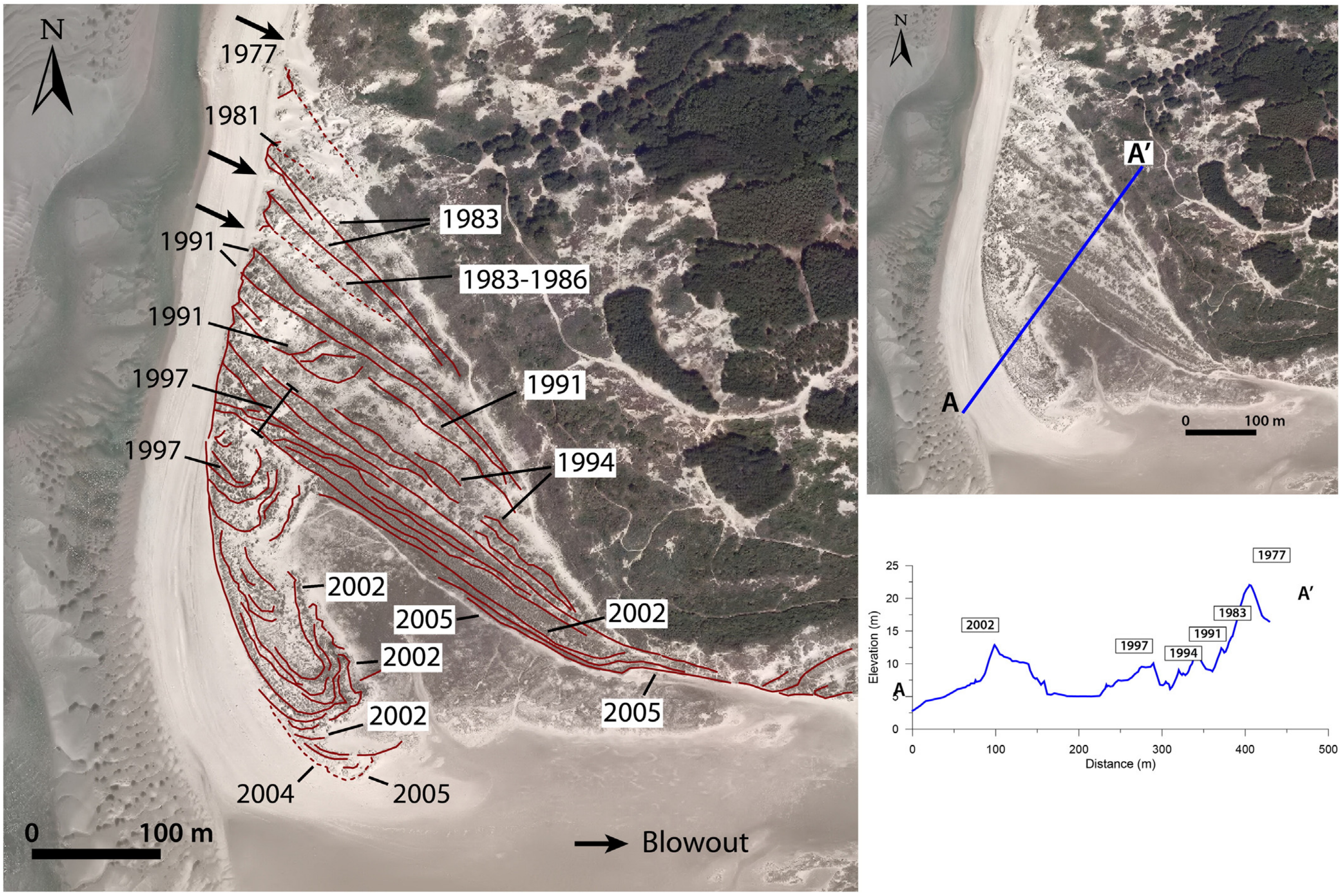

Fig. 9. Age of aeolian foredune ridges of the cuspate foreland visible on the 2009 vertical aerial photograph (© IGN). Ridge ages were determined from mapping of individual ridge lines on all vertical stereo aerial photographs. The age of some of the ridges is also indicated on the topographic profile surveyed in October 2010.

dune margin in 1965. The foreland/salient feature in the mid-bay shows considerable extension to the south, and several foredune ridges have been formed past the knick-point in the shallow bay (Fig. 5).

In 1974 the foreland had moved further south and filled the seaward arc of the erosional bay situated to the immediate south of the 1960's foreland. A few foredune ridges and a spit extension existed at this time but by 1975 the intertidal low (wide runnel) formed between these two features had infilled and the foreland had broadened seawards. This trend continued into 1976, and at least 7 new foredune ridges were formed between 1974 and 1976. By 1977, updrift erosion resulted in scarping of the northern portions of the oldest foredunes, and a southward extension of the foreland.

By 1983, the submerged breakwater has been developed further, and dune front armoring emplaced along the shoreline in the lee of the breakwater. The northern half of the bay has eroded further, while the mid-bay foreland has progressed further to the south. The original Bec du Perroquet foreland has largely retreated and pine plantations were carried out on the parabolic and active dunes in order to stabilize them. At its southern tip a small recurved spit developed.

The northern shore continued to erode into the 1990's and the 1991 aerial photograph (Fig. 5) shows that the parabolic dunes were reactivated and new blowouts developed in the central portion of the bay. Erosion was probably concentrated in the mid-bay region due perhaps to wave focusing forced by the presence of the semi-submerged breakwater, and the eastwards migration of the Authie main channel. An analysis of water levels at Boulogne-sur-Mer revealed that in 1990, a series of major storm events induced a high frequency of high water levels (Chaverot et al., 2008) that resulted in significant erosion along the region's shoreline, which may explain the rapid erosion in the mid-bay. In the 8 years between 1981 and 1991, the cuspate foreland moved a significant distance to the south, and multiple foredune ridges were formed. This process continued through 1994 and 1997 with the foreland becoming more triangular in morphology over time (Fig. 5). Further shoreline armoring was also emplaced along the bay immediately to the north of the cuspate foreland between 1991 and 1994.

From the late 1990's until the present, the Bec du Perroquet cuspate foreland continued to migrate or travel to the south, although at a slower rate and also experienced gross morphological change. In 1991, the cuspate foreland outline described an asymmetrical, roughly Gaussian, smoothly convex shape, but by August 1997 a spit extension had developed on the southern tip thereby creating a more asymmetric, pointed form. This extension had an intertidal portion that extended in a slight arc across the mouth of the Authie, which is visible on the 2000 aerial photograph (Fig. 5). Dobroniak and Anthony (2002) showed that in a short period between April 1998 and May 1999, the spit extension projecting southwards from the cuspate foreland grew rapidly out into the Authie mouth.

From the 1940's onwards, the original Bec du Perroquet foreland, well developed in 1947, was eroded and a new foreland began in the upper central portion of the bay and then migrated to the south, close to the position of the former (1947) foreland. The cuspate foreland has migrated or traveled from near the middle of the bay to now be extending across and into the Authie mouth, and occupying a similar position to the Bec du Perroquet which existed in 1947 (the first photograph available). This illustrates a remarkable cycling of the formation, destruction and reformation of a cuspate foreland over a ~50+ year period. The north shore meanwhile underwent major erosion. From 1947 to 2009 the northern part of the bay retreated more

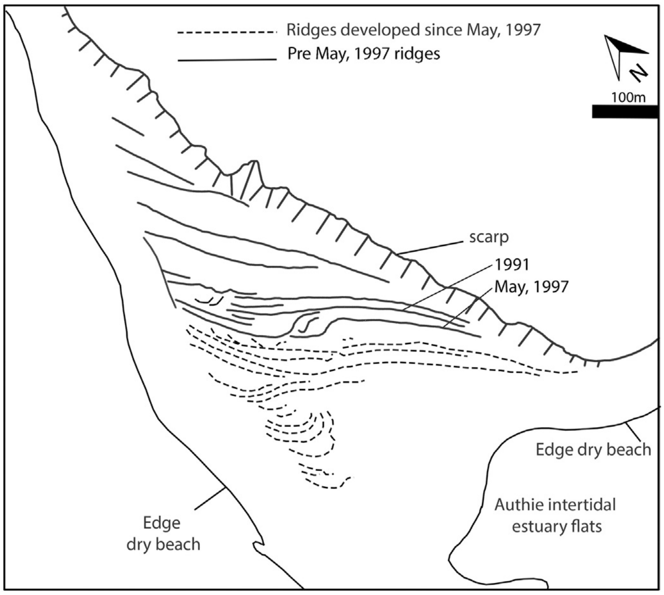

Fig. 10. Sketch map showing the evolution of distal dune ridges between May and August 1997 based on photo-interpretation of aerial photographs.

than 350 m, while mid-bay, the coastline retreat was about 215 m. The Bec du Perroquet prograded 120 m seaward during the same period.

The retreat has largely been induced by the migration of the main channel to the east (shorewards). This channel shift is due to the northward progradation of the prominent subtidal/intertidal spit platform across the bay and estuary mouth. Fig. 5 illustrates the northwards progression of the subtidal/intertidal platform, and the migration of the Authie main channel. Fig. 6 shows in greater detail the significant expansion of the intertidal/subtidal spit platform across the bay mouth between 1975 and 1986.

Fig. 11. Ground photographs of dune ridges in 1998 (photograph: M.H. Ruz) and in 2010 (photograph: P. Hesp).

5. Recent shoreline and dune changes

While the spit extension on the tip of the cuspate foreland continued to extend in a S-SSE direction, the remainder of the shoreline continued to erode into the present day. Fig. 7A illustrates three LiDAR elevation maps obtained in 2008, 2011 and 2013, and from these 4 topographic lines have been extracted (Fig. 7B). Line 1 in the northern portion of the bay shows that the shoreline has suffered slight erosion (<5 m), and is probably protected by the semi-submerged breakwater and armoring. Line 2 which cuts through the largest active parabolic dune in the north central zone, has experienced more erosion and has retreated almost 20 m landwards and built 3.5 m upwards in the ~5 year period. The coastal dunes in this area have behaved as classic shorewards translating dunes, and whilst experiencing cliff face retreat, also experienced dune crest and lee slope accretion (cf. Psuty, 1989; McCann and Byrne, 1994; Ruz and Allard, 1994; Davidson-Arnott, 2010; Hesp and Walker, 2013; Hesp et al., 2013). The maximum landward retreat is observed on line 3, with erosion up to 50 m occurring between 2008 and 2013, which was accompanied by a significant lowering of the upper beach (>2 m). This major erosion occurred mainly between 2011 and 2013. Line 4 also shows a significant loss of volume on the upper beach and an erosion of 20 m of the dune toe between 2011 and 2013 (Fig. 7B).

In terms of historical development since 1947, a period of ~68 years for which there is excellent aerial photographic cover, the foreland is now (in 2015) back to roughly where it was located in 1947 (Fig. 5).

6. Cuspate foreland foredune geomorphology and dynamics

Fig. 8 illustrates the foredune and swale morphology across the foreland from airborne LiDAR data collected in 2008 and a topographic profile surveyed in 2010. The present day cuspate foreland of the Bec du Perroquet consists of a series of foredune ridges approximately 3 to 7 m high that are composed of fine sand (mean grain-size: 0.22 to 0.24 mm) (Fig. 8). The foredune ridge sediments are well sorted while the upper beach sediment is moderately well sorted. *E. farctus* and *A. arenaria* dominate the incipient and established dunes (respectively) foreland environment, but the innermost dune ridges are also extensively covered by *Hippophae rhamnoides*. Most of these ridges developed under the action of dominant westerly winds and face WSW to SW (see wind and sand rose in Fig. 8C). Some ridges, however, developed under the influence of winds from the SW, south and east, predominantly once the foreland switched from operating as a triangular salient to a more southerly extending spit (post-1997). Some of the dune ridges which developed post-May, 1997 wrap around the foreland spit terminal arc and are therefore semi-circular in form. A few ridges have also developed on the inside margin of the spit with a north–south trend as these face into the estuary on an east facing beach line (see later Fig. 10).

An analysis of all available aerial photographs from 1947 to 2009 has enabled the authors to fairly accurately date either the initiation of, or period of development of most of the foredune ridges on the 2009-foreland. Fig. 9 illustrates the foreland in August 2009 and includes the ages of the foredune ridges at their time of creation. The oldest existing highly erosional nebkha chain which originally formed a continuous ridge was initiated in 1977. Relatively intact ridges are present from the 1983 initiation period onwards (Fig. 9). Fig. 9 shows that as the ridges become older, they begin to lose their ridge continuity, structure, stability and vegetation cover. This occurs for a number of reasons. First, adjacent shoreline erosion on the NW-facing portion of the foreland destabilizes the seaward-facing northern terminal end of the ridge, and it becomes highly scarped, and destabilizes. Second, the swales on both

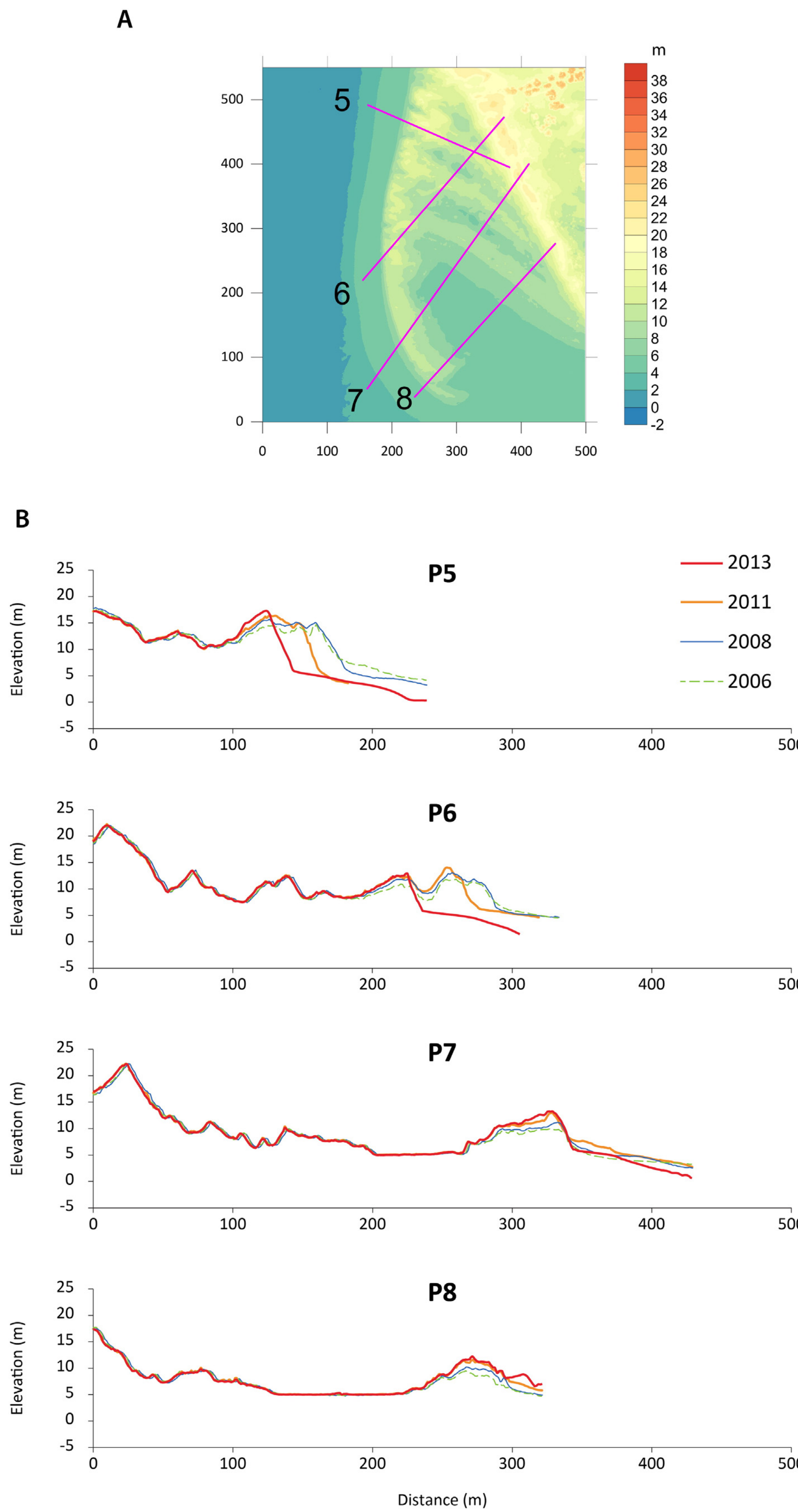

Fig. 12. A) Surface elevation map of the cuspate foreland of the north shore of the Authie estuary in 2008 from LiDAR data showing the position of selected cross-shore profiles; B) Cross-shore profiles evolution along the cuspate foreland from 2006 to 2013 based on LiDAR data.

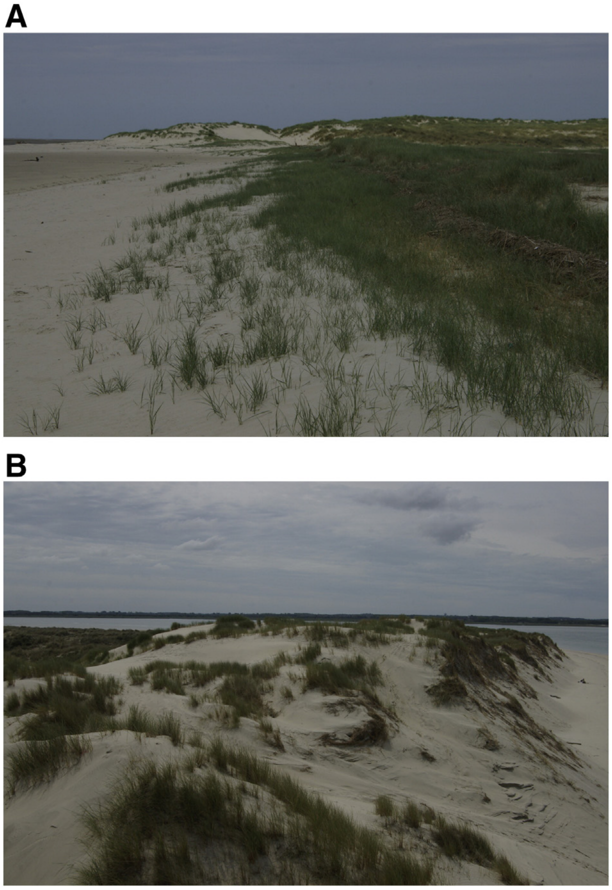

Fig. 13. 2010 photographs of incipient foredunes near the terminus of the foreland (A), and the highly erosional foredune-blowout complex at the updrift erosional portion of the foreland (B).

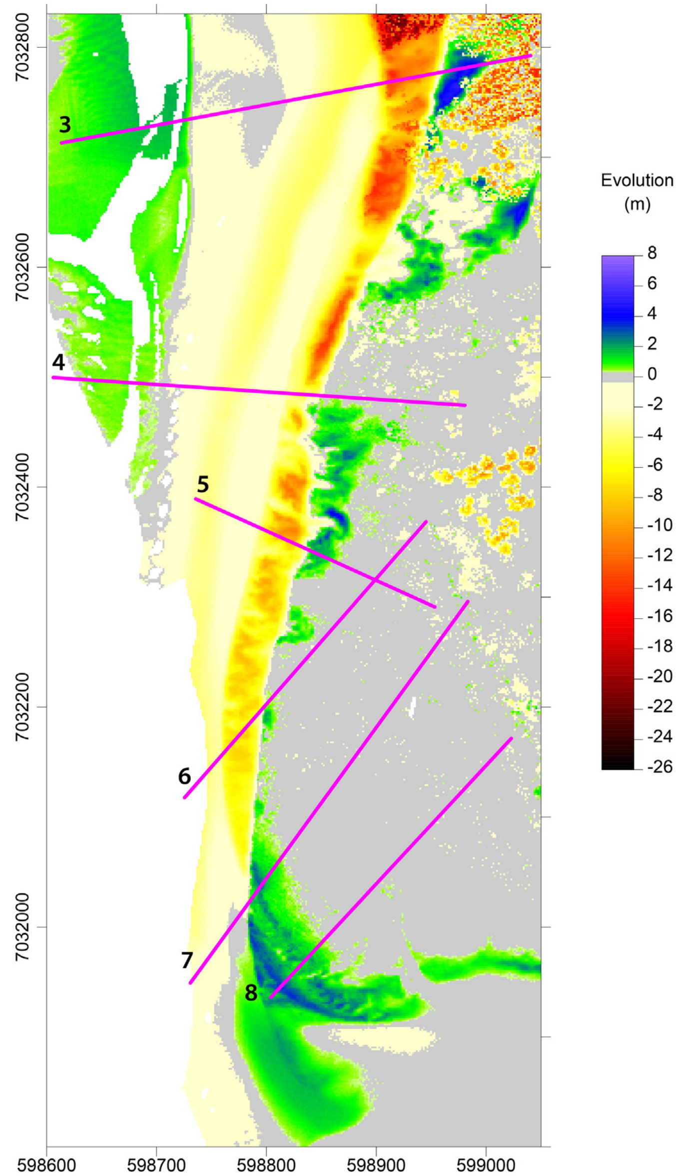

Fig. 14. Net changes in surface elevation over the cuspate foreland and along the shore north of the foreland between 2008 and 2013 based on LiDAR topographic data.

sides of a ridge are often poorly vegetated. Exceptions are the 1991 and 2002 sets of ridges. Sand is removed by aeolian processes from the swales onto the ridges, causing accretion but also burial and upper stoss slope and crestal destabilization. Third, once the modern foredune on the northwest facing portion of the foreland (arrowed in Fig. 9), is removed from along the front of the ridge and swale suite (as downdrift erosion proceeds), the ends of the swales facing the sea are open to the beach and blowouts develop within or up the swale margins (arrowed in Fig. 9). These blowouts operate as conduits for beach sand to be transported into the swales and onto the adjacent ridges, and also enlarge over time into the swales and undermine the stoss and lee slopes of adjacent ridges. Fourth, small blowouts develop in the ridge crests eventually leading to a break-up of the crests, and the creation of a more nebkha-like or turret-like erosional topography. The wind and sand roses (Fig. 8) indicate strong onshore sand transporting winds which line-up very well with the axis of the blowouts. Depending on the initial degree of vegetation cover on the ridge and swale set, this process can occur out of temporal order. For example, Fig. 9 illustrates that a younger aged ridge can be more erosional than an older ridge (the 1983–86 ridge is less stable and continuous than the 1983 double ridge line).

6.1. Temporal variations in foredune evolution

There are noteworthy differences in the rate of development and temporal changes in both foreland and foredune ridge and swale morphology over time. For example, five incipient foredunes formed in 1983 but only the landwardmost ridge remained intact in 1986, and one ridge 'remained' as a zone of scattered erosional nebkhas (i.e. discrete clumps of vegetation and associated dune mounds) or remnant knobs. Seven new ridges formed in the 1974 to 1976 period. Four main ridges and 3 short arcuate ridges formed in 1991 (Fig. 9). In 1994, the 1991 seawardmost incipient dune was scarped and had built upwards to become a more prominent ridge, but all ridges remained in subsequent years and through to present. Obviously there are single to multiple storm events, especially in winter (Chaverot et al., 2008), which result in scarping through to complete removal of one or more ridges as seen elsewhere on foredune plains (Davidson-Arnott, 2005, 2010; McLean and Shen, 2006; Hesp, 2013).

In 1997 the spit extension trending southwards from the cuspate foreland, while still an intertidal feature, clearly dried out at times and provided a significant sand source for aeolian processes. Fig. 10 provides a geomorphological map of the ridge trends in August, 1997 and illustrates the rapidity with which ridges build during one spring between the 25th of May, 1997 and the 15th August 1997 (11 weeks). During this short period, 18 new dune ridges were formed (Fig. 11). Eight of these continued the ridge trend of those formed earlier along the southern base of the foreland, and another eight formed short, arcuate and curling, semi-circular ridges out onto the spit extension mimicking the

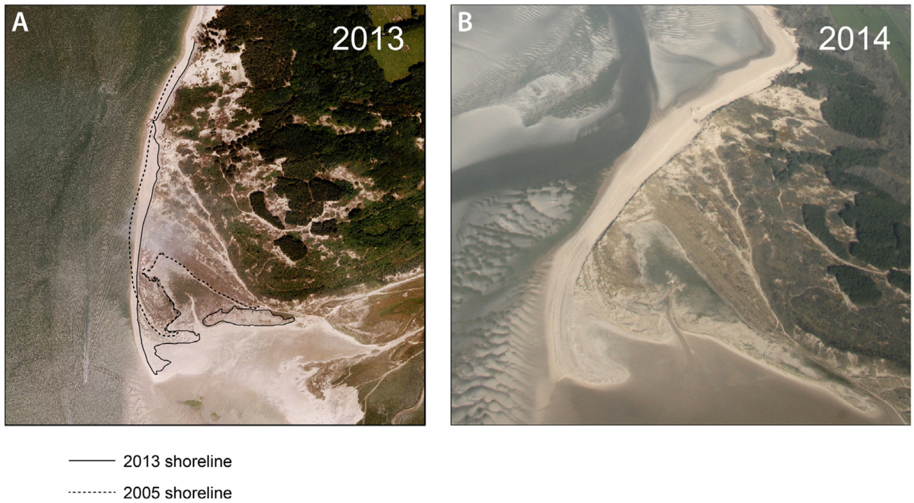

Fig. 15. A) 2013 vertical aerial photograph of the cuspate foreland showing the shoreline position in 2005 and 2013 (© IGN); B) Oblique aerial photograph of the cuspate foreland in 2014 (© Association de Défense Contre la Mer en Baie d'Authie).

terminal spit shape. This section of the foreland has exposure to winds in an arc from the NNW around to the east and, thus, incipient foredunes can be formed in a semi-circle mirroring the arc of the foreland-spit. In 2015, these ridges are still present (see Fig. 9). This provides ample evidence that at times it is possible to have multiple incipient foredunes formed almost at once, or within a few days of each other, since 18 ridges developed in a seawards progression in 11 weeks. This also testifies to the robustness and vigor of *E. farctus* and *A. arenaria* in colonizing the backshore and very rapidly creating and stabilizing a ridge line (Fig. 11).

Some ridges are formed very close to each other and fairly rapidly, while in other examples the ridges are more widely separated, presumably as a result of the rate of progradation (Hesp, 1984, 2002; Ruz and Allard, 1994). In 1983 and 1991, double ridges were formed and these are, or were quite prominent (Fig. 9). The 1983 'double foredunes' were clearly defined in stereo imagery as two close, but separate ridges, but by 2009 the ridges had coalesced due to aeolian processes, while the 1991 ridges were still clearly separate ridges. The 1986 ridge displayed a distinct ridge line in the year during its formation and up until ~1991. By 2009, the ridge had been degraded by aeolian processes. Blowouts had formed along, and through the ridge crests, and sand from the largely unvegetated swale to seawards had blown onto the ridge. Thus, the ridge line is now much more irregular and less apparent.

LiDAR surveys and recent aerial photographs provide additional information about the evolution of the cuspate foreland up to 2014 (Fig. 12A). Fig. 12B illustrates 4 topographic profiles across the foreland-spit between 2006 and 2013 based on LiDAR data. Line 5 trends NW-SE (Fig. 12A) and illustrates how three initial ridges present in 2006 are merged into one ridge as erosion (~40 m horizontal retreat between 2006 and 2013) of the northern portion of the cuspate foreland proceeds over time (Fig. 12B). This landward retreat was accompanied by dune crest accretion on the order of 1 m. This profile also demonstrates "RD-A's" or 'Robin's Rule' (Davidson-Arnott, 2005) in operation as the foredune translates landwards and upwards during shoreline erosion and retreat. Lines 6 to 8 are progressively more south of each other and lie on a NE–SW orientation. On line 6, the dunes suffered major erosion, with a landward retreat of ~55 m, resulting in the successive destruction of two ridges between 2008 and 2011 and between 2011 and 2013 respectively. Conversely, the seaward most foredune at Line 7 was fairly stable between 2006 and 2013, and underwent vertical accretion, especially between 2008 and 2011. At line 8, the shoreline was relatively stable to slightly progradational through the period 2006–2008. Then, between 2008 and 2013, the foredune built upwards over time and an incipient foredune developed seawards in 2013. In this area, the foredune built upwards and outwards as the spit extension to the cuspate foreland prograded southwards and slightly seawards. This progression of foredune morphodynamics from line 5 through to line 8 demonstrates a sequential evolutionary trend of how the foredunes evolve on the traveling foreland: (i) a foredune is initiated, builds vertically and seawards during progradation, (ii) then vertically as approximate stability occurs (aggradation), (iii) then upwards with attendant aeolian accretion of more landward dunes as minor retreat occurs, (iv) then upwards and landwards with a significant increase in dune height, and, (v) large scale cliff/scarp development as major retreat sets in. The final evolutionary stage is complete removal of the ridge. Fig. 13 illustrates photographs of parts of this sequence.

Volume change calculations based on the LiDAR data revealed that almost 186,000 m^3 of sand was eroded between 2008 and 2013 between line 3 and line 6 to the south (Fig. 14), Most of this sediment loss (approximately 131,000 m^3) occurred between 2011 and 2013. Erosion took place northward of the foreland, but since 2008, erosion also affected the northern part of the cuspate foreland resulting in the destruction of the seaward dune ridges (Lines 5 and 6, Fig. 12B). Some sediment accumulation occurred downdrift to the south, but only took place at the tip of the southern spit (Lines 7 and 8, Fig. 12B), with a net volume gain of 27,200 m^3 between 2008 and 2013. This large discrepancy between erosion and accumulation volumes indicates that most of the eroded sediment was dispersed into the bay, presumably contributing to the infilling of the estuary and adjacent bay.

The erosion of the northern part of the cuspate foreland during the last few years is obvious when the 2005 shoreline is overlain on the 2013 aerial photograph, also showing the southward progression of the tip of the spit (Fig. 15A). A 2014 oblique aerial photograph of the same area (Fig. 15B) reveals that the spit is now extending eastward rather than southward, resulting in a progressive enclosure of a saltmarsh that was visible on the 2009 aerial photograph (Fig. 9). The growth of the cuspate foreland seems to now operate through the formation of a sand spit (i.e. it is less a cuspate foreland or salient and more spit-like) over which aeolian transport can result in a landward transfer of sand towards the saltmarsh rather than continued foredune formation along the open shoreline. Note that foredunes can form in the marginal saltmarsh vegetation, however.

7. Discussion

The exact reason(s) for the development and migration of the traveling foreland and the ridges contained thereon are unknown, and further research is required to link the relationship(s) between foreland position and migration and subtidal/intertidal spit and bay dynamics. In this region it is likely that the northward progradation of the subtidal/ intertidal spit platform is strongly influencing the wave refraction patterns and ebb tidal channel location, but this remains unproven as yet.

In general, the morphodynamics of this traveling foreland and the foredune ridges contained thereon are both similar and quite different to many of the cuspate forelands, salients and beach ridge/foredune plains in the world. In similarity to some, perhaps most, foredunes and foredune plains, there are periods when there is rapid to very rapid accretion (Figs. 11, 13), periods of relative quiescence and stability, and periods of small to moderate accretion, punctuated by erosion events and loss of foredune ridges on occasion. At times, all ridges are preserved from a progradation phase, although such preservation is limited; eventually if the foreland continues to migrate or travel, all ridges are lost. At other times, one to several ridges are reworked by aeolian processes into one more landward ridge, and sometimes only one, or no ridges developed during a progradation phase are preserved in the record over a decade or less. The details of individual ridge development and change shown here provide a guide to how foredunes might be viewed elsewhere, even in more stable, non-traveling sites. Many foredunes, especially larger ones, represent a combination of progradation, erosion and aggradation to various degrees, depending on the site and site characteristics.

What is surprising is the fact that there is sometimes relatively little spread of vegetation and plant colonization of swales and originally non-vegetated dune ridge segments, especially in the first few years after ridge formation. Thus, as the foreland has evolved, portions of the older dune ridges have been significantly wind eroded and modified.

Blending or coalescence of formerly discrete dune ridges occurs as the traveling foreland evolves and migrates, a process which has not been commonly observed. Where the rate of progradation varies alongshore, it is common for one dune ridge to build in place (essentially aggrade) on a foredune plain while in another section of the plain several foredune ridges are formed (progradation) at the same time (e.g. Dominguez et al., 2009). In the case of the Authie foreland system, aeolian processes and reactivation of ridges leads to merging or coalescence of formerly completely discrete ridges. Such blending has implications for later age determination if the system were to stabilize in place, and the foreland become part of the Holocene geological record. In particular, estimates of the average rates of development of ridges as is commonly done (e.g. Murray-Wallace et al., 2002; Hesp, 2013) would have little meaning at this site.

8. Conclusion

The following conclusions may be made from this study:

(i) The Berck Plage to Baie d'Authie coast and Authie estuary have suffered very extensive erosion with the shoreline experiencing 100's of meters of retreat at least since the 1600's. The Bec du Perroquet foreland existent in 1947 disappeared and a new traveling foreland developed mid-north bay and traveled south over the next 30 years, forming foredune suites as it migrated;

(ii) Incipient foredunes develop very rapidly, and then at times disappear (e.g. the 1983 incipient foredunes). On occasions (e.g. in an 11 week period in 1997) there is phenomenal multiple development of foredunes, indicating multiple plant seedling lines or wrack lines of rhizome fragments germinating on, or across the backshore;

(iii) Discrete foredune ridges may blend into a single ridge over time in this highly dynamic traveling foreland system (e.g. the 1983 double foredunes blended into one ridge by 2009 due to aeolian processes). In addition, depending on the initial degree of vegetation cover on the ridge and swale set, younger foredune ridges may become more erosional than older ones due to the lower plant cover. Aeolian processes in swales are much more important in this system than in typical prograding foredune plain-prograding barrier systems due to (a) the sometimes marked lack of, or very slow, vegetation colonization in the swales following foredune ridge development, and (b) deflation of the swales particularly when they become open conduits for beach sediment delivery following erosion of the W-NW facing foreland margin;

(iv) The 1977 oldest surviving ridge line (actually now erosional knobs, turrets and nebkha) will soon disappear. These traveling forelands therefore are singularly different from many beach ridge-foredune ridge plains which typically preserve many of the ridges formed throughout the mid- to very late Holocene;

(v) Foredune ridges (and swales) can be extremely arcuate to semicircular in form where the foreland and especially the spit extension portion of the foreland has exposure to a wide range of wind directions and where the shoreline trends through an arc of at least 270°. On two occasions at least, dunes have formed semicircular arcs as the foreland has developed. Between 1986 and 1991, three short, arcuate ridges were formed with orientations facing S-SE, and again in 1997, multiple foredunes were formed with strongly arcuate to semi-circular ridge trends;

(vi) As updrift erosion of the NW-facing margin of the foreland takes place, old foredune ridges are reactivated, and may accrete considerably, at least initially by scarping, scarp fill and crestal deposition, but also via sediment delivery through adjacent swales (both from the beach and unvegetated swale margins), and by blowout development. They then get broken up into erosional nebkha and remnants as erosion continues until complete ridge breakdown and removal occurs as the foreland migrates or travels southwards. Terming older foredunes 'relict foredunes' as has been done elsewhere for foredune plains (e.g. Hesp, 1999), is not appropriate here since old foredunes may be reactivated on traveling forelands. In addition, since the ridges forming a traveling foreland are here often moderately to poorly vegetated, many of the ridges throughout the foredune ridge system can still undergo some accretion and/or erosion and are never therefore, truly relict; and

(vii) This study is believed to be the first observation of blowout initiation and development up dune swales which face transversely or obliquely onto the beach.

Acknowledgments

This study was partly funded by a Université du Littoral Côte d'Opale Visiting Fellowship to P. Hesp. The LiDAR data were obtained through the interregional program CLAREC funded by the Regional Councils of Normandy, Picardie and Nord-Pas de Calais and by the French Centre National de la Recherche Scientifique (CNRS). F. Levoy and P. Bretel of the CLAREC program are thanked for the acquisition and processing of the LiDAR data. Vertical aerial photographs were obtained from the French Institut de Géographie Nationale. Oblique aerial photographs were kindly provided by the Association de Défense Contre la Mer en Baie d'Authie. Wind data were obtained by courtesy of Météo-France though a research agreement with the Université du Littoral Côte d'Opale. The authors would like to thank V. Sipka for his help during the field measurements, our respective universities for support, Peter Rosen and Edward Anthony for their assistance with literature, and the reviewers and editorial assistance of Andrew Plater for their assistance in making this a (hopefully) better paper.

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