

Coastal evolution of a cusped foreland (Flakket, Anholt, Denmark) between 2006 and 2010

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Flakket is a cusped marine foreland on the north coast of Anholt in the Kattegat sea. It is composed of a number of gravel-rich beach ridges typically covered by aeolian sand and intervening swales and wetlands including a relatively large lagoon. The most recent evolution of the coastline of this marine foreland between May 2006 and September 2010 is documented in this paper. Flakket is under erosion on its northwestern side, which has retreated up to 40 m during the observation period. The shoreline of the northeastern side of the beach-ridge plain moved up to 70 m in a seaward direction during the same period.

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Many coastal areas in northern Denmark possess well-developed marine forelands (Jessen 1897; Schou 1945; Hansen 1995; Clemmensen *et al.* 2001; Nielsen *et al.* 2006; Bjørnsen *et al.* 2008). The overall morphology of the marine foreland can take various shapes with the most common types being beach-ridge plains, spits and cusped forelands. The marine forelands are typically characterized by closely situated beach ridges separated by swales (Jessen 1897; Hansen 1995; Nielsen *et al.* 2006; Clemmensen & Nielsen 2010). The marine forelands have developed over the past 7000–8000 years and their long-term development was controlled by isostatic uplift, sea-level change, sediment supply, and wind and wave climate (e.g. Brun 1993; Clemmensen *et al.* 2001, Bjørnsen *et al.* 2008). While some marine forelands such as the northernmost part of the Skagen Odde spit system (Clemmensen *et al.* 2001; Nielsen & Johannessen 2009) and the major part of the Anholt beach-ridge system (Bjørnsen *et al.* 2008; Clemmensen & Nielsen 2010) have been characterized by uninterrupted and simple growth during most of their evolution, other systems such as many of the spit systems on Læsø (Hansen 1995) experienced growth punctuated by erosion phases and associated reorganization of the spit structures. Little is known, however,

on the processes that caused these major changes in coastal evolution in the past, and we also have little knowledge of the rates of coastal change that took place during these events of coastal reorganization. Studies of modern evolution of foreland systems may thus add to a better understanding of past evolution of these complex coastal systems.

Flakket

Anholt is a small island in the middle of the Kattegat sea (Fig. 1). The island is composed of a glacial highland towards the west, a raised beach-ridge plain towards the east, and a lower-lying marine foreland, Flakket, towards the north (Fig. 2; Larsen & Kronborg 1994; Bjørnsen *et al.* 2008; Nielsen & Clemmensen 2009; Clemmensen & Nielsen 2010). Formation and preservation of the beach-ridge deposits are partly due to isostatic land rise which amounts to around 9 m during the past 6600 years (Bjørnsen *et al.* 2008). Flakket forms a rounded protrusion on the north coast of Anholt and can be classified as a cusped foreland (Gulliver 1896; Johnson 1919; Moslow *et al.* 1981; Semeniuk *et al.* 1988;

Park & Wells 2007). Flakket is composed of a number of NW–SE trending gravel-rich beach ridges. The berm and the outermost beach ridge are devoid of aeolian sand cover while most inland ridges are covered by aeolian sand forming typical dune ridges. Intervening depressions, swales, are developed as wetlands with a rich swamp vegetation. One of these wetlands comprises a relatively large coastal lagoon (Figs 3–4). Flakket faces the medium-energy Kattegat sea. Tidal variation is insignificant, with the tidal range reaching no more than 0.4 m; sea-level change related to meteorological conditions, however, is significant and short-term variation may reach 2 m or more (Nielsen & Clemmensen 2009; Clemmensen & Nielsen 2010). Nearshore processes are controlled by wave action and by longshore currents transporting sediment towards the east under the influence of the dominating westerly winds (Cappelen & Jørgensen 1999; Jönsson & Holmquist 1995). Wave energy has been modelled on the basis of measurements from 1979–2007 in an area around 20 km southwest of Anholt. From these analyses the significant wave height is estimated to be 3.0 m and the maximum wave height 5.6 m based on the extreme values for a 5 year return period (Grode & Hansen 2010).

Flakket started to develop around AD 1000 as indicated by optically stimulated luminescence dating of one of the oldest beach ridges on the marine foreland

(Andrew Murray, personal communication 2010). The early stages of foreland evolution are not known from map information, but topographical maps from 1792 to 1991 supplemented by an aerial photo from 2005 indicate that Flakket is a highly dynamic coastal system (Fig. 2; Larsen & Kronborg 1994). Until 1887 Flakket had a linear shoreline over most of its length. Reorganization of the foreland started after 1887 and is most likely linked to construction of the harbour at the northwest corner of the island in 1902. The construction of the harbour seems to have modified the local littoral currents and caused the formation of a cusped foreland. Sediment from distant sources and sediment released by erosion of deposits at the westernmost part of the foreland was transported northeastward by longshore currents and deposited in shallow water under the influence of constructive wave action from different directions. After 1934, erosion on the western side of the foreland continued and the cusped foreland was shifted eastward and grew wider (Fig. 2). This shift in coastal dynamics was probably supported by an enhanced influence of westerly winds after 1920 (Jönsson & Holmquist 1995). Evolution of Flakket after 1934 was linked to continued beach-ridge formation. Beach ridges were fed by material from the eastward moving longshore currents and sand and gravel were deposited high on the beachface during extreme events with elevated sea

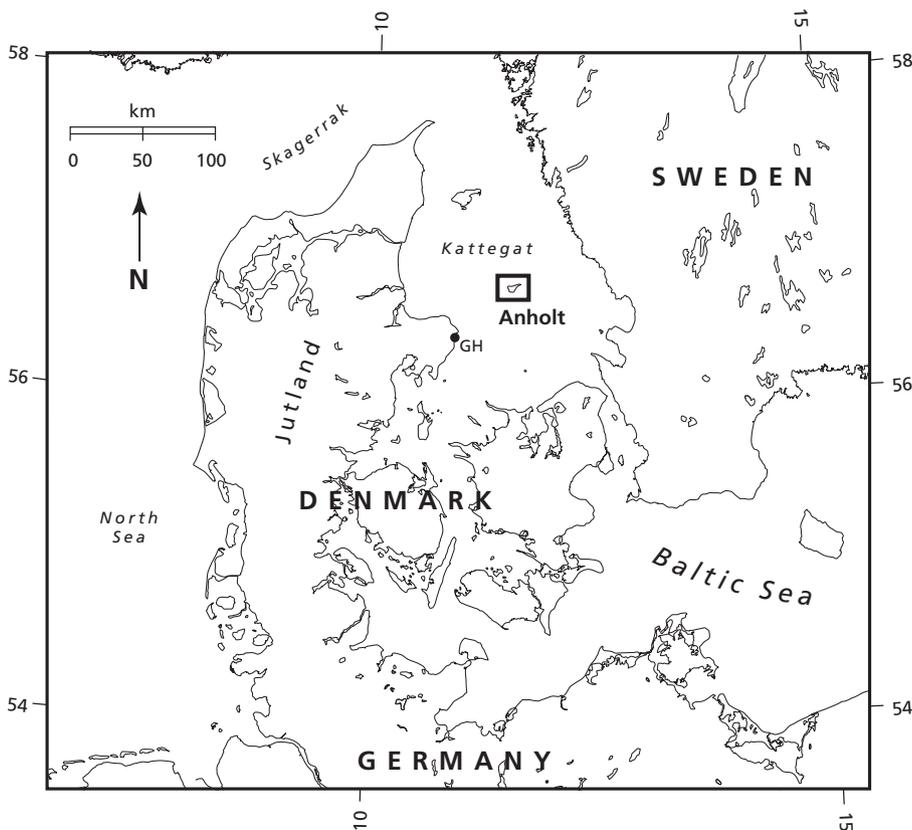


Figure 1. Location map of Anholt. The location of Grenå Havn is given by GH.

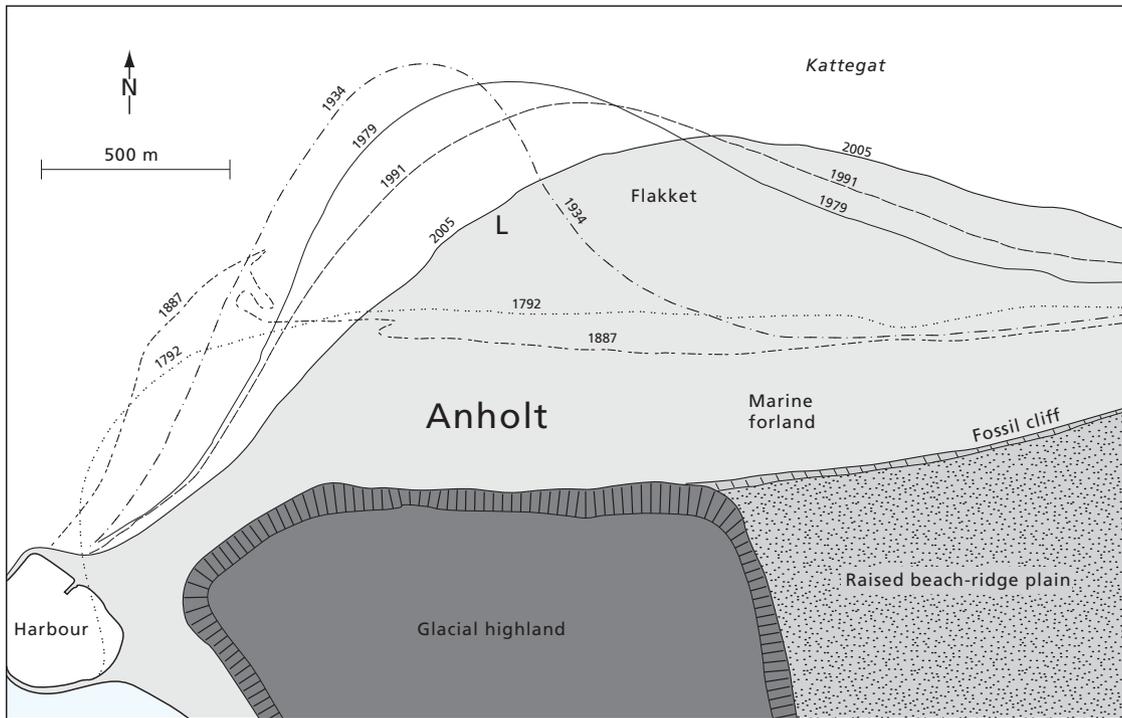


Figure 2. Evolution of the cusate foreland Flakket on the north coast of Anholt. The reconstruction is based on topographical maps measured in AD 1792, 1887, 1934 and 1979/80 and 1991 supplemented by an aerial photo from 2005. The maps were first digitized and later georeferenced in order to integrate the maps in ARCGIS software. The location of the lagoon is given by L.

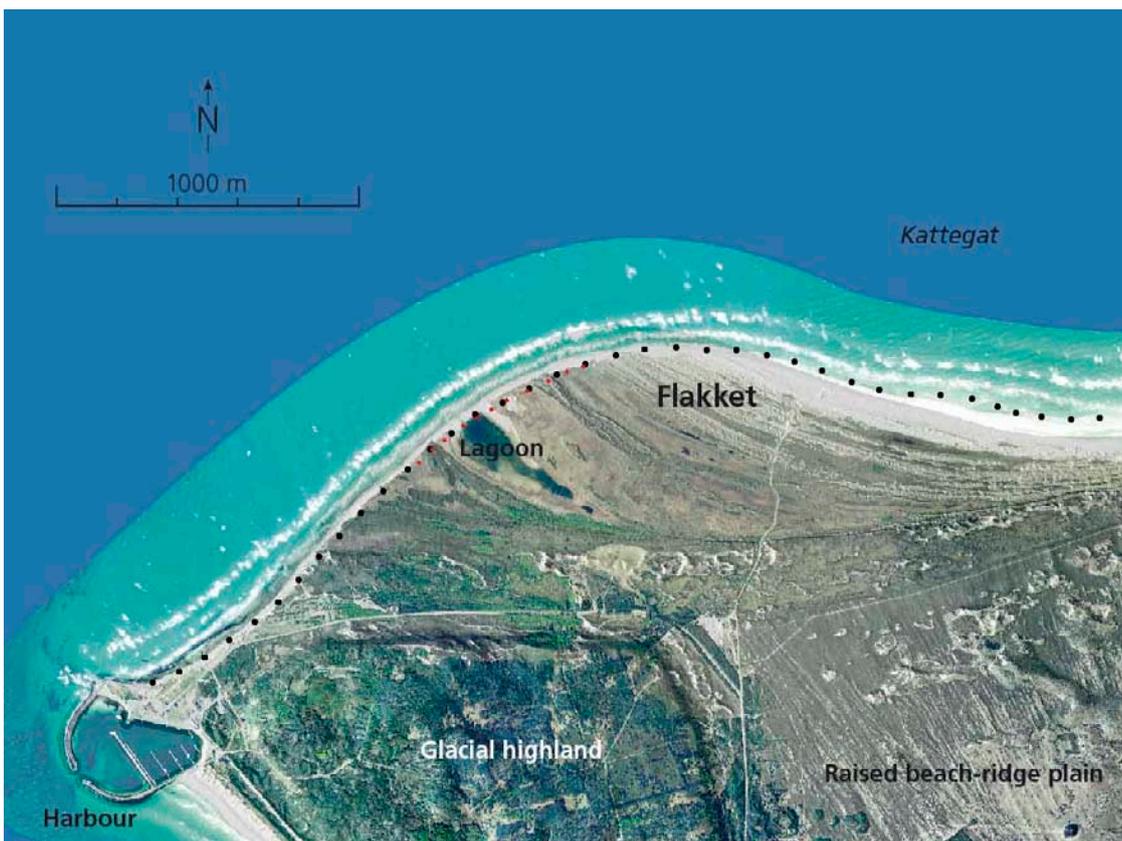


Figure 3. Orthophotograph of Flakket (May 14, 2006) with shoreline positions measured on September 2, 2010 (black dots) and on November 11, 2010 (red dots).

level and strong wave run-up (Nielsen & Clemmensen 2009). Simultaneously with beach-ridge formation and progradation of the northeastern side of the marine foreland, the northwestern side of Flakket was eroded leading to a truncation of the oldest beach ridges (Figs 3–4). This wave erosion has led to rapid coastal retreat, and in the area immediately east of the harbour a short stretch of the shoreline is now not more than about 25 m from the main road on the island (Fig. 3).

We here present new data that documents the most recent shoreline changes on Flakket between May 2006 and September 2010 with supplementary data from November 2010. Our data makes it possible to quantify the rates of coastal change with special emphasis on the scale of erosion that has taken place on the northwestern side of Flakket since May 2006.

Methods and results

Our analysis is based on an aerial photo from May 2006 supplemented by field measurements of shoreline positions in September 2010 and November 2010. Beach morphology was studied in August 2007, June 2008, August 2009, September 2010 and November 2010.

The aerial photo from May 2006 shows the curved shoreline of Flakket (Fig. 3). The beach is relatively narrow and featureless on the northwestern and retreating side of Flakket, and the beach is here commonly backed by eroded swales and beach/dune ridges. The beach on the northeastern and prograding side of Flakket is relatively wide and in August 2007 the beach was here composed of a seaward dipping beachface of sand with a few scattered stones backed by an up to 1.8 m high gravel-rich berm with relatively steep sides. Inland of the gravel-rich berm followed a flat-based swale covered by sand and a few scattered stones, an inactive, gravel-rich beach ridge, a second flat-based swale, and most inland a dune-covered beach ridge (Nielsen & Clemmensen 2009). Due to coastal progradation, however, the characteristics of this system change rapidly and in November 2010 a new, incipient berm had developed in front of the large berm which had become inactive. At the same time, the two swales that were practically devoid of aeolian sand in August 2007 had now been partly covered by low aeolian dunes and vegetation had invaded the swales and the outermost beach ridge.

On May 14, 2006, when the aerial photo was taken, sea level at the nearby Kattegat station Grenå Havn varied between 0.20 m at 08.30 and -0.07 m at 15.40



Figure 4. Orthophotograph of the retreating part of Flakket (May 14, 2006) with shoreline positions on September 2, 2010 (black dots) and on November 11, 2010 (red dots). The diameter of a black dot is around 5 m.

(Farvandsvæsenet, Danish Maritime Safety Administration). With beachface gradients around 6° this means that the observed shoreline changed from 3.0 m landward to 1.0 m seaward of the DVR90 (Danish Vertical Reference 1990) shoreline during the above mentioned period. The aerial photo portrays nicely the beach-ridge plain at Flakket with beach ridges that are curved and roughly trending NW–SE; the truncated nature of the first formed beach ridges is clearly seen (Fig. 3). It can be observed that the lagoon at Flakket is separated from the Kattegat sea by a narrow beach barrier.

During fieldwork in September 2010 the position of the shoreline at Flakket was measured with traditional GPS. The shoreline (here defined as the water's edge, which equals the upper limit of wave uprush; Hughes & Turner, 1999) was tracked from a point near the harbour towards the east for a distance of approximately 3500 m. A total of 37 points with an average distance of 175 m were measured (Figs 3–4). The lateral accuracy of the measured positions provided by this standard GPS system was typically around ± 5 m. The measurements were carried out on September 2 between 11.30 and 12.35. Water levels at the nearby Kattegat station at Grenå Havn rose from 0.01 m to 0.12 m above mean sea level in this time interval (Farvandsvæsenet); it ap-

peared that wave run-up was of minor importance on Anholt in this interval. Thus the measured shoreline was only about 0.15 to 1.7 m more landward than the DVR90 shoreline.

During fieldwork in November 2010 the shoreline position of the central part of Flakket was remeasured with a Trimble R8 DGPS. This was done to acquire supplementary data on the shoreline position near the lagoon. The shoreline (water's edge) was tracked for a distance of approximately 600 m and 11 points were measured (Figs 3–4). These measurements are significantly more accurate than the data from the standard GPS, and points are given with an accuracy of ± 0.03 m. The data were collected between 10.00 and 10.30 on November 11, 2010 and the sea level (at Grenå Havn) was elevated around 0.20 m in this time interval (Farvandsvæsenet); wave runup on Anholt caused the water level at the water's edge to be elevated by an additional 0.30 m. Thus the measured shoreline was about 7 m more landward than the DVR90 shoreline.

We also carried out a DGPS survey of the beach barrier which separates the lagoon at Flakket from the sea. The barrier, which is gravel-rich, consists of two spit segments cut by a narrow inlet (Fig. 5). The western and longest of these spit segments has a length of 140 m and reaches heights of around 1.20 m above

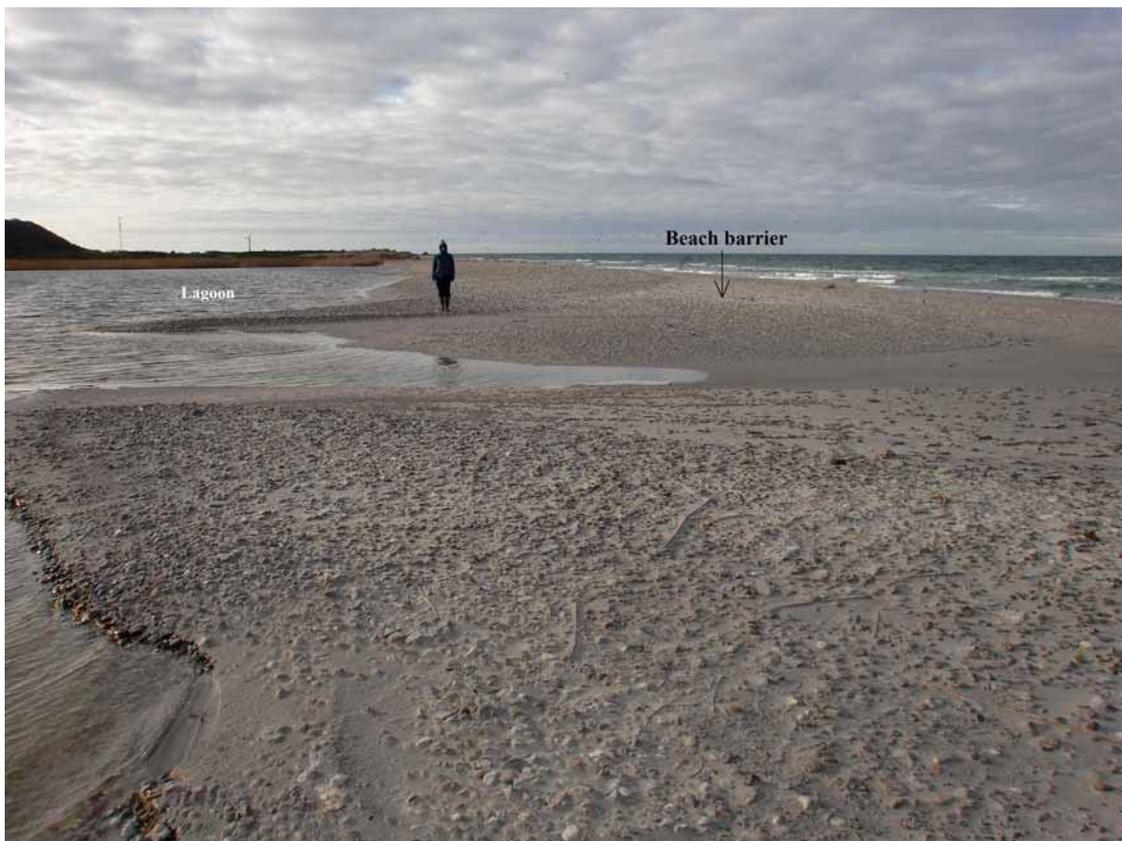


Figure 5. A narrow beach barrier separates the lagoon on Flakket from the Kattegat sea. A partly sand-filled inlet cuts the beach barrier in the foreground of the photo and recurved spits have developed along both sides of the inlet. View towards the southwest.

mean sea level, while the inlet has a threshold value of around 0.50 m above mean sea level. Wash-over tongues of beach material are seen at the back side of the barrier spit.

Discussion and conclusions

The accuracy of the traditional GPS is around ± 5 m under ideal conditions and defining the shoreline from these data may therefore involve a small inaccuracy. When the points as here form a smooth curved line it is believed, however, that our GPS measurements yield a reasonably accurate estimate of the shoreline position in early September 2010 (Fig. 3).

In early September 2010, Flakket formed a rounded cusped marine foreland with its northernmost point approximately 500 m northeast of the lagoon (Fig. 3). The results presented here clearly indicate that the northwestern side of Flakket has retreated between May 2006 and September 2010, while the northeastern side of Flakket has prograded. Coastal retreat appears to have been particularly pronounced close to the lagoon on Flakket, and shoreline retreat here is up to 40 m or almost 10 m per year assuming a constant retreat over

the study period (Fig. 4). Shoreline retreat is linked to a deficit in sediment supply at this side of the foreland. Simultaneously with coastal retreat on the northwestern side of Flakket the northeastern side of the foreland has prograded and the shoreline has here advanced up to 70 m in response to a surplus in sediment supply (Fig. 3).

The shoreline of the northwestern part of Flakket of November 11, 2010 agrees well with that observed on September 2, 2010, although the November shoreline is situated 1 to 9 m more inland than the September shoreline (Fig. 4); these differences in shoreline position can primarily be accounted for by the higher water level in the Kattegat sea during the observation period on November 11.

According to Sørensen *et al.* (2007), water levels of 1.02 m above mean sea level are statistically reached once a year (at Grenå Havn), while levels of 1.63 m above mean sea level are reached every 20 years indicating that the lagoon, which is separated from the sea by a beach barrier reaching heights up to 1.20 m above mean sea level, is likely to be flooded during extreme events with elevated sea level (Fig. 5). The presence of newly formed wash-over tongues at the back side of the beach barrier also indicates that waves frequently overtop the barrier and that sea water during these episodes enters the lagoon.



Figure 6. The retreating coast on the northwest side of Flakket is backed by eroded dune ridges; the dune ridge shown is situated immediately southwest of the lagoon. View towards the northeast.

The northwestern side of Flakket is backed by eroded dune ridges and peat-bearing swales, also indicating that coastal retreat has taken place here in recent years (Fig. 6). Sand from the eroded dune ridges and the uppermost part of the beach is becoming available for aeolian transport and a large part of the old beach-ridge plain at the westernmost edge of Flakket is now being covered by inland transported aeolian sand. Aeolian sand also frequently covers the main road leading to the harbour.

The central part of Flakket including the lagoon is part of an EU habitat on Anholt (Natura 2000), and is of particular interest because of its well-developed wetlands and swales that separate the dune ridges. Our new data indicate that the lagoon at Flakket and the surrounding wetlands are likely to be flooded frequently in coming years. Coastal retreat not only diminishes the area of the beach-ridge plain and the lagoon, but it also leads to an increased inland transport of aeolian sand. Coastal retreat of the northwest side of Flakket may also impact the infrastructure on the island as the main road leading to the harbour is running on a narrow beach-ridge plain between a high inland cliff and the retreating shoreline.

The documented coastal evolution of Flakket between 2006 and 2010 demonstrates that the eastward shift of the cusped foreland that began around 1934 continues. It most likely records a dominance of westerly winds and a related eastward directed longshore drift on the north coast of Anholt. This study of coastal evolution of a cusped foreland shows that coastal changes can be very rapid, and although the changes seen on Flakket probably started due to man-induced processes (harbour construction) they document that local rates of erosion can be very high, and that significant parts of a beach-ridge plain can disappear rapidly. Between 1934 and the present a wedge of beach-ridge sediments up to 500 m wide has disappeared on the northwest side of Flakket amounting to an erosion rate of up to 6.5 m/year; between 2006 and 2010 erosion rates up to 10 m/year are measured. These rates of erosion are indeed high when compared to other Danish coastal systems, where erosion rates along the Danish North Sea coast are up to 3–5 m/year (e.g. Christiansen & Møller 1979–1980; Aagaard *et al.* 2004) and erosion rates along shores in the Kattegat sea are up to 2m/year (e.g. Binderup 1997).

The eastward shift of the cusped foreland leads to the formation of an erosion surface cutting into older beach-ridge and swale deposits along the western part of the system. This erosion surface related to local beach retreat would share many of its characteristics with a transgressive ravinement surface (e.g. Goy *et al.* 2003; Storms & Kroonenberg 2007; Johnston *et al.* 2007). Care should be taken therefore in the analysis

of ancient beach-ridge systems to distinguish between areal extensive erosion surfaces formed during sea-level rise, and erosion surfaces of more local distribution formed during morphodynamic reorganization of the system.

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