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Shoreface sand supply and mid- to late Holocene aeolian dune formation on the storm-dominated macrotidal coast of the southern North Sea

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ABSTRACT

Although pulses of coastal dune development in the course of the Holocene have been attributed to variations in the availability of sand, to modulation of sand supply by sea level change, and to changes in wind conditions, identifying the processes driving such pulses has been rather elusive. The shore deposits bordering the tide- and storm wave-dominated southern North Sea evince complex mid- to late Holocene stratigraphy and sediment heterogeneity. These deposits include a unique 7 km-long, 0.3–0.6 km-wide, and up to 7 m-high aeolian sand unit, the Ghyvelde dune, occurring astride the French–Belgian border in an apparently 'anomalous' inland location. The dune overlies, and is surrounded by, tidal sandy and muddy deposits incorporating freshwater peat. Data from four mechanical cores and eight auger holes, and three radiocarbon ages and one OSL age suggest that this inland dune was part of an ancestral North Sea sand flat and mudflat environment. Confronting the dune stratigraphy with the prevailing tide- and storm-controlled dynamics of shoreline progradation in this area indicates that dune formation occurred under a pulse of abundant sand supply resulting from the attachment, to a mid-Holocene North Sea tidal-flat shore, of a shoreface tidal bank under repeated storms. This mode of onshore sand supply generates extremely rapid progradation (up to 1 km over a century) of the sand flat shore, the surface of which serves as a large aeolian fetch zone for active backshore dune accumulation, while parts of this surface trap, locally, significant amounts of mud that are subsequently fossilised by aeolian sand. The potential influence of sea level and storminess in modulating the timing of shoreface sand supply and late Holocene coastal dune development in the southern North Sea, reported in studies from other areas, remains to be established.

1. Introduction

Research on the mechanisms and environmental implications of mid- to late Holocene coastal change has led to a rising interest in the factors and processes involved in coastal dune development. Phases of active dune development have been linked not only to sand supply, and to modulation of such supply by changes in wave base and storm activity induced by sea level change (e.g., Orford et al., 2000, 2003; Lees, 2006; Aagaard et al., 2007), but also to changes in wind conditions in the presence of available sand (e.g., Chase and Thomas, 2006; Clemmensen et al., 2007). Few studies provide a shore morphodynamic process framework of phases of late Holocene dune construction, notable exceptions being those of Orford et al. (2003) and Aagaard et al. (2004, 2007), and much remains to be known, therefore, of the variety of morphodynamic conditions involved in such phases of past active dune formation.

The coastal plains bordering the eastern English Channel and the southern North Sea (Fig. 1) are characterised by Holocene muddy and sandy tidal-flat and aeolian deposits. In the extreme north of France, former tidal deposits entirely surround, and underlie, a well defined, unique aeolian unit lying astride the French–Belgian border, the Ghyvelde dune, 7 km-long, 0.3–0.6 km-wide, and up to 7 m-high (Fig. 1). The complex stratigraphy and the attendant facies heterogeneity in the vicinity of this 'inland' dune have generated conflicting views of shoreline development patterns, no doubt shrouded in an inadequate understanding of the morphodynamic processes and sediment supply conditions involved in coastal progradation. The earlier interpretations (Paepe, 1960; Sommé, 1969, 1977; De Ceunynck, 1985) basically considered this dune as part of a discontinuous ancestral barrier shoreline. Baeteman (2001) concluded, on the basis of a review of these earlier interpretations of the subsurface facies in front of the dune, and of her own work, that the Ghyvelde dune was not associated with a North Sea shoreline but developed in an inland position, within a mid- to late Holocene sand flat environment, from what she termed a 'surge drift line at the edge of a wide sand flat fronting a mixed (sandy–muddy) flat and a

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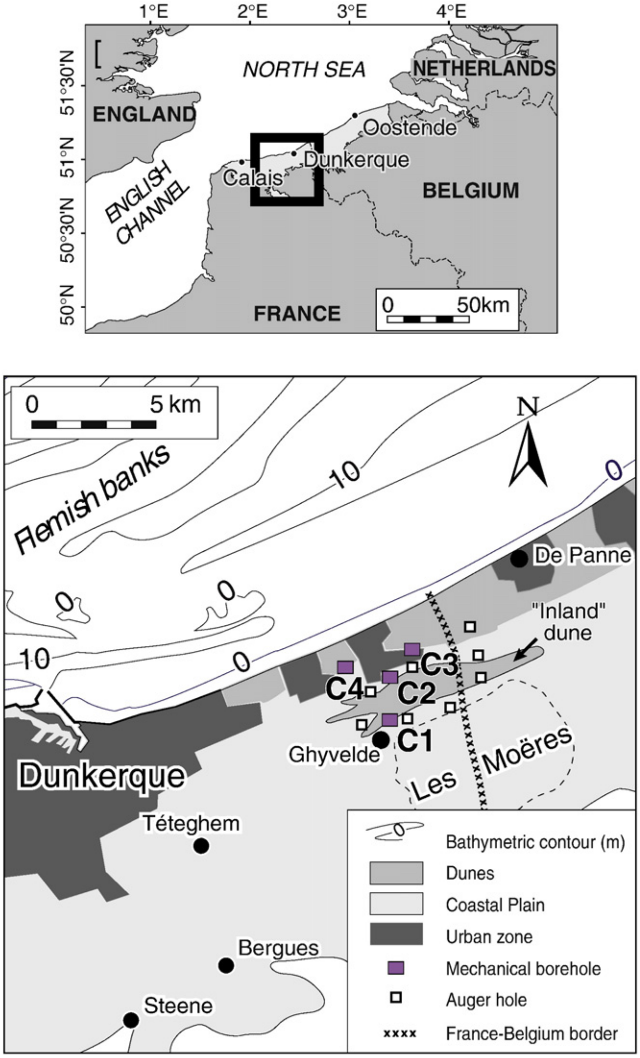

Fig. 1. The North Sea coastal plain in France showing the 'inland' Ghyvelde dune and locations of cores and auger holes.

mudflat'. The apparently 'anomalous' inland location of the Ghyvelde dune offers an opportunity to explain the regional pattern of mid- to late Holocene coastal accretion of this tide- and storm-dominated setting based on dune chronostratigraphy confronted with insight gained from a decade of research on the morphodynamics of shoreline progradation and accretion in this area.

2. The southern North Sea: shoreface and coastal dune accretion

The French part of the southern North Sea coastal plain occupies a 10 to 20 km-wide embayment that stretches from Calais to The Netherlands (Fig. 1). The plain is now completely reclaimed and protected seawards by a continuous 100 to 600 m-wide coastal dune barrier, and by dikes and port defences. The surface of the plain lies at an elevation ranging from −2 to +4 m IGN 69 French ordnance datum, this datum being generally used as a reference for mean sea level. The coast experiences mean spring and neap tidal ranges of about 5.5 and 3.7 m, and much of the plain, therefore, lies below the level of mean high water springs, and is susceptible to marine flooding. The nearshore zone comprises numerous linear sub-shore-parallel sand banks and ridges. The coastal hydrodynamic pattern depends jointly on tides and wind and wave activity. Offshore modal significant wave heights are less than 1.5 m, but may attain up to 3 m during storms that may last 2 to 3 days, with a recurrence interval of days to 1–3 weeks in autumn and winter, and weeks to 1–2 months in spring and summer. Wave periods are in the range of 4 to 6 s, typical of a fetch-limited environment. There are no rivers or streams debouching directly into the study area, which lies between the estuaries of two small river catchments, the Aa (1215 km^2) to the west, and the IJzer (381 km^2) in Belgium.

Disentangling the complex shore stratigraphy in the vicinity of the Ghyvelde dune necessiates a consideration of the specific mode of coastal progradation and attendant dune development characterising this macrotidal storm wave coast. Anthony and Héquette (2007) highlighted, from a detailed analysis of grain parameters, the common marine source of the Holocene to present sandy deposits of the southern North Sea coastal plain. The accumulation of abundant medium to very fine sand on the west-facing inner shoreface of the eastern English Channel and in the southern North Sea bight from France to Belgium is considered as the product of large-scale tide-dominated and wind-enhanced hydrodynamic circulations during the Holocene that gradually sorted out, on the sea bed, heterogeneous terrigenous sediments deposited during the Late Pleistocene low sea level stand by proglacial outwash and by rivers (Anthony, 2002). Medium to very fine sand winnowed out by these large-scale sediment sorting and segregation processes accumulated on the shoreface as tidal ridges and banks, and in coastal embayments as sand flat, tidal channel, and aeolian deposits. Silt and mud were most probably derived from erosion of the Pleistocene basement by tidal channel incision, as well as from the bed of the southern North Sea, where abundant mud accumulation has been reported (Fettweis and Van den Eynde, 2003).

In this southern North Sea context, the mixed tide- and storm-dominated hydrodynamic regime and the abundance of tidal sand banks on the shallow shoreface lead to a unique mode of shoreline accretion. This occurs via the episodic wholesale onshore welding of the tidal banks as they are driven from the shoreface, over a timescale of years, by repeated storm wave activity. Wave and wind redistribution of sand during high spring tides induces accretion of the surface of the welded sand bank over time to high intertidal/supratidal levels. This surface then forms an extensive temporary (at a timescale of decades to centuries) intertidal beach-fronted sand flat that serves as both a basement and a sand source for the subsequent accretion of aeolian dunes, essentially at the dry inner flanks of these flats (Anthony et al., 2006, 2007). A fine recent example of this has been documented from the Calais area (Fig. 1), where, during the 20th century, rapid sand flat accretion and 'inner' dune formation occurred following the onshore welding of a 5 km-long tidal sand bank (Anthony et al., 2006). Héquette and Aernouts (2010) calculated in this area sand flat progradation of more than 300 m between 1949 and 2000, and showed that the welded bank volume grew up to about 100×10^6 m^3 in the course of the 20th century, thus indicating that the bank still acted, following welding, as a sink for shoreface sand, such transport being assured by both onshore-directed wave asymmetry and shore-parallel tidal and wind-induced currents (Héquette et al., 2008). Sustained accretion and progradation of the sand flat is assured by cross-shore wave reworking of sand from this welded shallow subtidal–intertidal sand bank reservoir via an intertidal profile of accretionary beach bars (Reichmüth and Anthony, 2007). Storm waves washing over the upper intertidal sand flat rapidly percolate over this surface, enhancing its accretion. Wind action over the dry parts of the sand flat redistributes sand inland towards embryo dunes that develop over time into a longitudinal dune complex (Anthony et al., 2007). Parts of the accreted sand flat may trap layers of mud up to 1 m-thick during consecutive high spring tides, as Aubry et al. (2009) have shown for the sand flat in the Calais area. Such mud may be colonised by saltmarsh vegetation, which, in places where tidal inundation no longer occurs, evolves into freshwater marsh. These facies may be fossilised rapidly by dune development (Anthony et al., 2007).

Where no further sand bank impinges on the shore, the ultimate fate of the welded bank is progressive recycling of the sand across the beach to the upper intertidal–supratidal sand flat, which, in turn, sources dune enlargement and accretion. Complete recycling may result in the formation of a fully dune-bound shore that may then enter a phase of stability or even erosion (Reichmüth and Anthony, 2008; Ruz and Anthony, 2008) until a new cycle of sand supply from a bank interrupts this phase. The natural cycle of coastal accretion is enhanced where offshore port breakwaters have been emplaced, hastening the onshore welding of such tidal sand banks, as along parts of the Dunkerque (Fig. 1) port breakwaters.

The irregular pattern of shoreline accretion, stability or erosion of the eastern English Channel and southern North Sea coast is thus explained primarily by variations alongshore in sand supply from the shoreface tidal banks. The morphology and proximity of the banks also have a determining influence in modulating incident storm wave energy variations alongshore (Héquette et al., 2009).

3. Methods

The stratigraphy and facies of the dune and surrounding deposits were defined from four mechanical drill cores and eight hand-operated auger borings down to depths of 5 to 10 m (see locations in Fig. 1). These were part of a larger set of cores and auger holes aimed at elucidating the Holocene depositional history of the coastal plain. Bedforms and facies, based on visible changes in bedding, colour, laminations and grain size, were identified after splitting the cores in the laboratory. The auger holes provided additional information on major facies changes. One sample from a thin (<1 cm) palaeosoil horizon and two articulated shells (*Cerastoderma edule* and *Scrobicularia plana*) from finely laminated beds of grey sand were extracted from the mechanical cores for radiocarbon dating. A sample of quartz silt in the 4–15 μm range was also extracted from a core for optically stimulated luminescence (OSL) dating.

4. Results and interpretation

The deposits in the cores (Fig. 2) and from the hand augers consist of homogeneous moderately to well-sorted medium to very fine grey quartz sand interpreted as representing tidal flat facies. They are capped in cores C1, C3 and C4 by structureless brown to yellow dune sand. Grey sand is composed of sandy cross beds, regular laminated beds with occasional thin beds (1–2 cm) of laminated silt or mud, and flaser and lenticular beds. Cross beds contain significant concentrations (up to 30%) of shelly debris, but also abundant intact *S. plana*, *Hydrobia ulva* and *C. edule* shells, and pebbles of mud and peat derived from erosion of mudflats and freshwater marshes. Regular and flaser to lenticular beds comprise 5 to 10% of comminuted *S. plana* and *C. edule* shell debris. These deposits correspond to tidal channel and sand flat environments. Cross-bedded deposits are most abundant in tidal channels. Sand flats are dominated by regularly bedded laminated sand with occasional thin laminated mud beds, and flaser and lenticular beds. These deposits of fine sand also include rare reworked peat debris and thin layers (<0.1 m) of coarse-grained shelly material that appear to express the influence of episodic high-energy storm reworking of the surface of the sand flats during high-

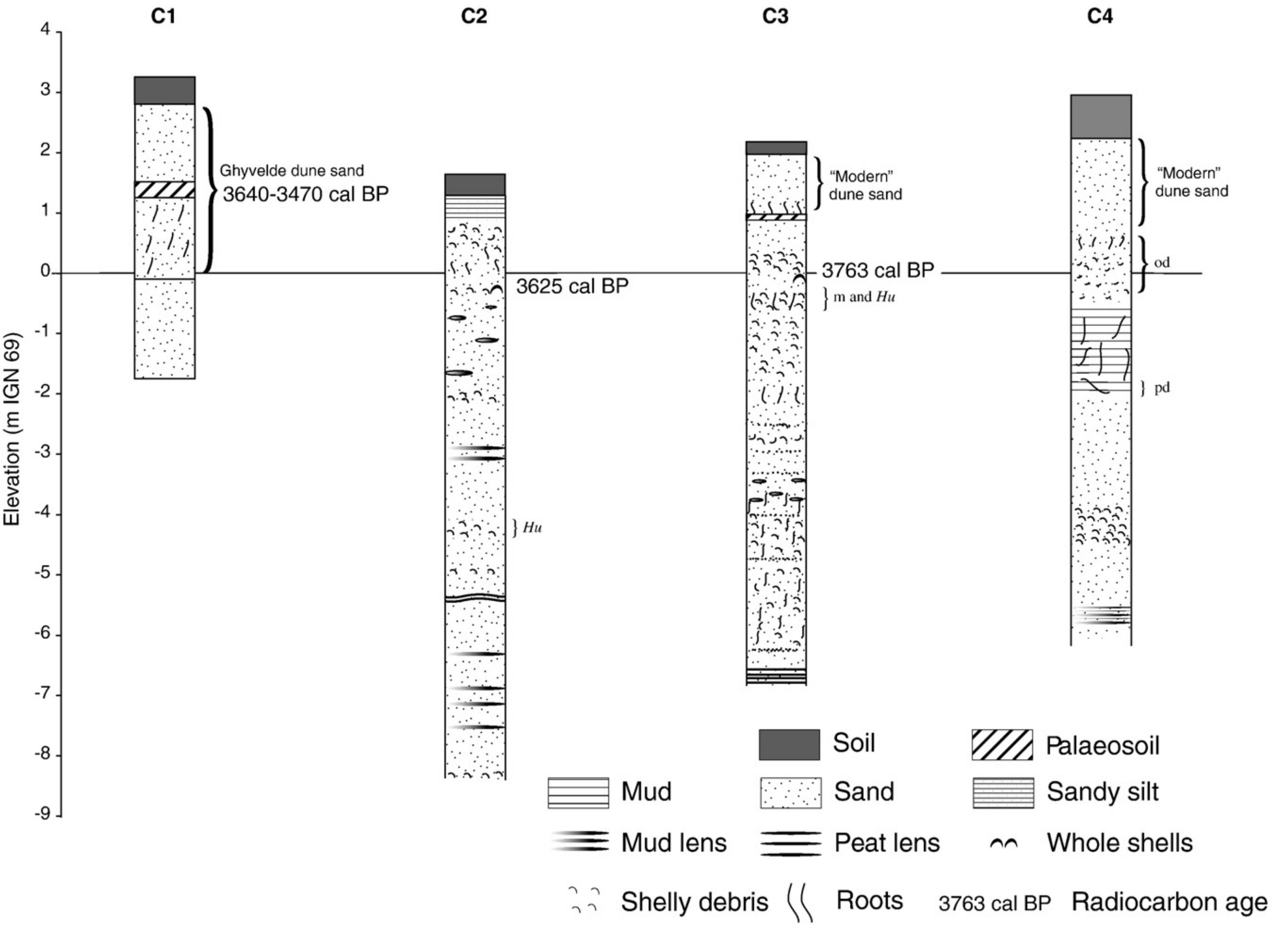

Fig. 2. Synthetic logs of the four mechanical boreholes from the Ghyvelde dune area. Accolades refer to the presence of abundant *Hydrobia ulvae* shells (*Hu*), and thin (<0.1 m) laminated beds of whole peat (p) and peaty debris (pd), mud (m), and organic debris (od) other than peat.

tide stages. The Ghyvelde dune thus overlies, and is fronted by, sand flat deposits that include muddy horizons. Baeteman (2001) identified a similar relationship in neighbouring Belgium.

The three radiocarbon ages have yielded ages that are very similar (Table 1). The palaeosoil underlying the dune has an age of 3640–3470 cal. B.P. (3315 ± 35 yr B.P.), while the ages from shells in living position from grey sand flat deposits are, respectively, 3763 cal. B.P. (3418 ± 50 yr B.P.), and 3625 cal. B.P. (3308 ± 50 yr B.P.). Although shell ages need to be considered with caution because of the strong possibilities of reworking by tidal channels as well as by waves, the two ages show a good age/elevation coherence that suggests that they may, together with the palaeosoil (Fig. 2) and one OSL age (3.04 ka ± 09 yr B.P.), be reliable indicators of the accumulation of at least a part of the Ghyvelde dune. Variations in the age of the dune may be expected. De Ceunynck (1985) dated older freshwater peat (4270 ± 65 yr B.P. and 4300 ± 65 yr B.P.) overlain by Ghyvelde dune sand from the landward dune margin, and Baeteman (2001) surmised, essentially from miscellaneous grey-literature sources, that the dune probably started developing between 5000 and 4500 cal. B.P.

5. Discussion and conclusion

The subsurface sediments from the Ghyvelde dune and from the inner flanks of the 'modern dune' bounding the coastal plain comprise thick beds of sand flat and tidal channel deposits and thin mudflat interbeds (Fig. 2). Hand augering shows that the sand flat deposits fronting the dune incorporate mud and peat layers representative of the mudflat–saltmarsh and freshwater marsh environments that are currently observed on prograded seafront sand flats. Accretion of the Ghyvelde dune occurred after ca. 4000 to 3500 yr. B.P. By this time, the French–Belgian Holocene coastal embayment had accreted (Baeteman and Declercq, 2002) to a stage where an indispensable condition for notable dune formation on this sand-rich coast, an important dry fetch provided by a wide accreted sand flat, was met for the first time. Dune formation occurred under a pulse of abundant sand supply resulting from the attachment, to a mid-Holocene North Sea tidal flat shore, of a shoreface tidal bank under repeated storms. Unfortunately, the age frame of this 1 km-wide sand flat, at the inner confines of which the dune was constructed, is not known. No other 'inland' palaeodune has been identified in the French–Belgian coastal plain. The specific location of the dune would have been hinged on that of the welded sand bank, eventually delimited alongshore by flanking tidal inlets through which sediment was still being supplied to the infilling back-barrier tidal basin. The orientation of the dune is consistent with that of the dominant dune-building synoptic winds from the southwest and secondary shore-normal winds from the north.

A second phase of larger-scale dune formation associated with the present 0.6 to 1 km-wide (modern) dune barrier lining the southern North Sea (Fig. 1) occurred under the same conditions of pulsed onshore transfer of tidal bank sand, followed by relative shoreline stability. If the dates in Table 1 are reliable indicators of the age of the inland dune, then these processes have occurred over the last 3000 years. The formation of the present continuous dune barrier was accompanied by the sealing of extant tidal inlets, progressively rendered underfit by a diminishing tidal prism due to advanced infill of the coastal plain.

The mode of development of the Ghyvelde dune barrier fits with the earlier interpretations of a discontinuous ancestral barrier shoreline by Paepe (1960), Sommé (1969, 1977) and De Ceunynck (1985). The inference by Baeteman (2001) that the dune initially developed landward of a wide sand flat is consistent with the pattern of shoreline evolution identified from a decade of research on this coast summarised in Section 2. The conclusion derived by this author, however, of 'surge drift line' deposits, aimed at comforting the claim that this dune is not related to North Sea beach and sand flat shore processes, does not agree with the dynamics of aeolian dune formation from sand flat shores in this macrotidal setting. A 'surge drift line' interpretation is at variance with the volume of the Ghyvelde dune (ca. $30 \pm 5 \times 10^6$ m^3 of sand). Dune accumulation at this scale would have required sustained sand supply from a large dry aeolian fetch area (Anthony et al., 2009). Interpretation of the origin of the dune should not be guided by its 'anomalous' location relative to the modern dune barrier shoreline (Fig. 1), as shown earlier.

The mode of development of the Ghyvelde dune, and of the dunes bounding this part of the North Sea, suggests the primacy of episodic large-scale sand supply from the shoreface under repeated storm wave action. This 'pulsed' sediment supply criterion has also been advocated in other studies of late Holocene dune development in Northwest Europe using a morphodynamic approach (Orford et al., 2000, 2003; Aagaard et al., 2004, 2007). In these examples, sea level, falling (Orford et al., 2000, 2003), or rising (Aagaard et al., 2007), in conjunction with variability in storm activity, is considered as an important control in modulating shore-incident wave energy levels and shoreward sand supply instrumental in significant dune formation. It remains to be established as to what extent sea level and variability in storminess may have modulated over time the driving of tidal sand banks onshore in the southern North Sea bight, a point that offers scope for future work.

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Table 1

An optically stimulated luminiscence age (a) and three radiocarbon ages from organic matter (b) and shells (c). The OSL dating was carried out following the methodology described by Mauz et al. (2002). The radiocarbon ages which were calibrated following Stuiver et al. (1998), using the programme Calib 5.0.1 (http://www.cali.qub.ac.uk/calib/), are presented in calibrated years before present, and quoted with a 2σ range. Shell dates were corrected for a reservoir age of 400 ± 40 B.P.

Elevation (m IGN 69)	U (μg g^{-1})	Th (μg g^{-1})	K (wt %)	Age (ka)	Laboratory number
a					
0.5	0.92 ± 0.05	1.07 ± 0.02	0.80 ± 0.01	3.04 ± 0.09	BN 50

Elevation (m IGN 69)	Age (yr B.P.)	Calibrated age (cal. B.P.)	Dated material	Laboratory number
b				
1	3315 ± 35	3640–3470	Soil	KIA 19480

Elevation (m IGN 69)	Age (yr BP)	Calibrated age (cal. B.P.)	2δ (cal. B.P.)	δ^{13}C ‰	Dated material	Laboratory number
c						
−0.1	3418 ± 50	3763	3883–3633	−0.48	*Cerastoderma edule*	KIA 19493
−0.2	3308 ± 50	3625	3746–3477	0.17	*Scrobicularia plana*	KIA 19498

for the Study and Conservation of Belgium's Heritage. The OSL dating was carried out by Barbara Mauz at the University of Liverpool. Denis Marin and Patrick Pentsch prepared the figures. This paper is a contribution to IGCP Project 495 “Late Quaternary Land–Ocean Interactions: Driving Mechanisms and Coastal Responses”.

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