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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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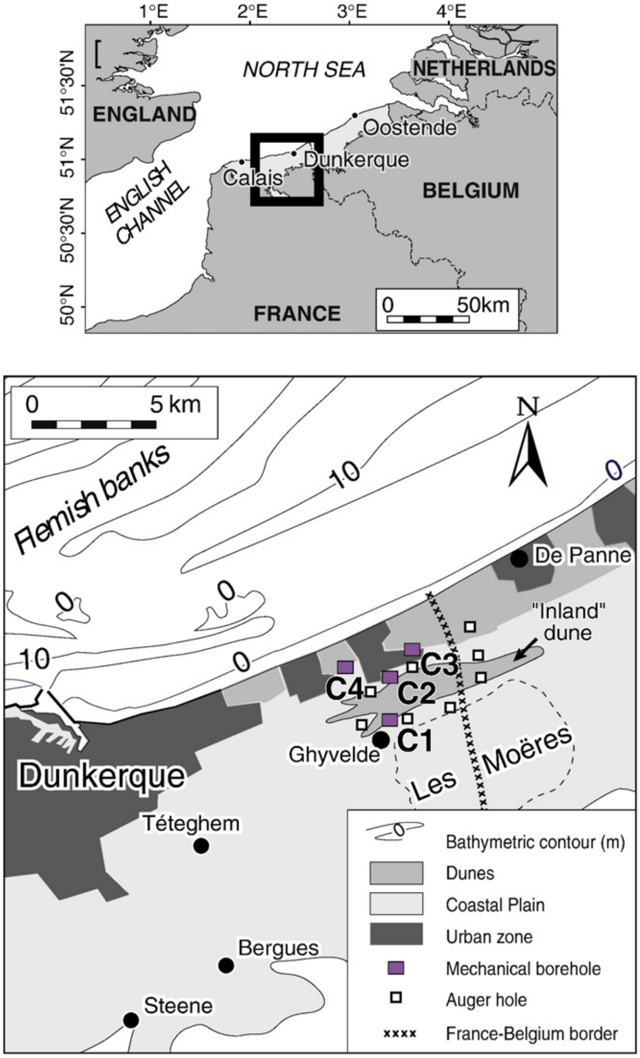

Fig. 1. The North Sea coastal plain in France showing the 'inland' Ghyvelde dune and locations of cores and auger holes.

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 km²) to the west, and the IJzer (381 km²) 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).