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The Shaping of the French-Belgian North Sea Coast throughout Recent Geology and History

R. Houthuys[1], G. De Moor[2], J. Sommé[3]

Abstract

The present-day French-Belgian North Sea coastal barrier and coastal plain were shaped after the last Ice Age, when especially between 10,000 and 5,000 years ago the global sea level underwent a rapid rise and the gently sloping northern part of the Flemish plain and the incised river mouths were flooded. The present paper brings an integrated overview of the French-Belgian coastal plain's recent geological and historical evolution, such as it is documented by the sedimentary record as well as by historical sources. The geologic approach provides indirect and environmental evidence for the coastal barrier dynamics. Also, some implications on present-day coastal management are given.

Introduction

The French-Belgian North Sea coast is a 120 km long, almost rectilinear sand beach barrier stretching from the Cap Blanc Nez chalk cliffs (France) to the mouth of the Westerschelde (Belgium/the Netherlands). East of Calais, the shoreline consists of a gently sloping sandy beach backed by coastal dunes. The morphology of this part of the southern North Sea coast is described in more detail in this volume by De Putter *et al.* (this volume).

These sandy beaches have been built up through thousands of years by the action of wind, waves and tides on a supply of loose sand grains at the seaward side of a complex coastal barrier, perhaps an island barrier, whose location changed with time. At the same time, in the more sheltered area landward of the coastal barrier, an intertidal flat developed by deposition of mainly fine-grained material and by intermittent peat formation.

The French-Belgian coastal plain extends some 10 to 20 km landward from the beach barrier. Most of the plain's present-day elevation is between mean and high tide sea level. As such, the plain would be inundated by the sea twice a day, should it not be protected by a continuous system of beaches, dunes and dikes.

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[1] Project Engineer, Eurosense, Nerviërslaan 54, B-1780 Wemmel (Belgium)

[2] Professor, Laboratory of Physical Geography, Ghent University, Krijgslaan 281, B-9000 Gent (Belgium)

[3] Professor, Science and Technology University of Lille, Geomorphology and Quaternary Laboratory and UPR 7559 CNRS, F-59655 Villeneuve d'Ascq Cédex (France)

The first geologic studies of the coastal plain date back to the 19th century (Belpaire, 1855; Rutot, 1897). Later pioneer work included the definition of nowadays well-known stratigraphic units such as the Calais and the Dunkerque Formations (Dubois, 1924; Briquet, 1930; Halet, 1931). In most of the coastal plain the Calais deposits and their cover of Dunkerquian sediments are separated by the Upper Peat complex (fig. 2), also called surface peat, at least where this latter unit is not eroded by tidal gullies. Modern geological and morphological research in the Belgian coastal plain was initiated by Tavernier & Ameryckx (1947), and by Tavernier & Moorman (1954), while Stockmans *et al.* (1948) introduced pollen analysis as a dating tool and Verhulst (1959) started historical research on the Dunkerque transgressions and on the impact of man. Their results are summarized by Tavernier *et al.* (1970). An overview of more recent research can be found in De Moor & Pissart (1992a), in Maréchal (1992) and in Sommé (1988). In the Belgian coastal plain recent geological work has especially been carried out by Baeteman (1981, 1991) in the western part, by Mostaert (1985) and by De Moor *et al.* (1992b) in the eastern part, while De Ceunynck (1985) studied the dunes and Thoen (1978) and Augustijn (1992) resumed the historical approach.

The present description of the Holocene coastal evolution is mainly based on published data relating to the coastal plain's sedimentary record and historical sources, without presenting new evidence. This paper for the first time synthesizes data from both the French and the Belgian parts of the coastal plain.

The present-day coastal barrier and coastal plain, whose position and shape were conditioned by the pre-existing topography, have been shaped in a very recent and short time, at least geologically speaking, known as the Holocene (table 1). Since the end of the last Ice Age, especially between 10,000 and 5,000 years ago, the global sea level underwent a rapid rise. As a result of this, the gently sloping northern part of the coastal plain

Geological time	**standard classification of marine deposists**
Subatlantic (from -900 on)	Dunkerque III (from 12th century on)
	Dunkerque II (+250 to +800)
	Dunkerque I (-500 to -200)
Subboreal (-3000 to -900)	Dunkerque O (?) (-1500 to -1000)
	Calais IV (?) (-2700 to -1800)
Atlantic (-6000 to -3000)	Calais III (-3300 to -2700)
	Calais II (-4300 to -3300)
	Calais I (-6000 to -4300)
Boreal (-7000 to -6000)	
Preboreal (-8000 to -7000)	

Table 1: Subdivision of the Holocene (-8000 to present) and transgressive periods. Time is given in years AD (positive numbers) and BC (negative numbers). Based on Van Staalduinen (1979) for the Rotterdam area.

and the incised river mouths were flooded. The local rate of the Holocene sea level rise is illustrated in fig. 1.

The sea level rise still goes on today. Over the period 1927-1990, an increase of mean sea level of approximately 1.5 mm/year was measured in Oostende. In the same period, the tidal range increased by approximately 0.9 mm/year[4].

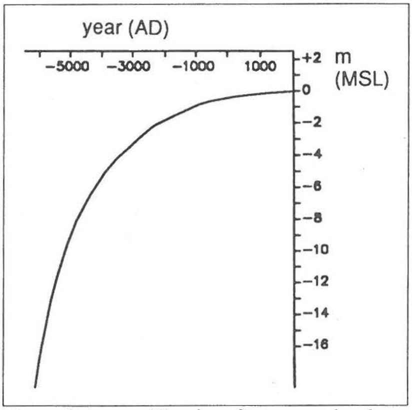

Figure 1: The rise of mean sea level, as documented by sediments in the coastal plain (after Köhn, 1989).

The causes of the sea level rise are complex and will not be discussed in detail in this paper. The main components of the experienced rise are generally agreed to be the melting of the Weichselian ice caps and the corresponding increase of seawater volume, the thermal expansion of sea water due to higher temperatures, and, locally in north-western Europe, a relative subsidence of the land surface to compensate for the glacio-isostatic rebound of Scandinavia after the end of the glaciation when the pressure of the ice cap was taken away. Other reasons for a local relative sea level rise include compaction of unconsolidated sediments such as clay and peat, and the continuation of restricted tectonic movements such as those related to the North Sea - Rhine graben system. Land movements during the Holocene due to tectonics and glacio-isostatics appear to be negligible in the Belgian part of the coastal plain (De Moor & De Breuck, 1973).

Though the rate of sea-level rise decreases with time (fig. 1), many scientists nowadays believe that rates may increase again as a result of the global warming, attributed to the greenhouse effect. Apart from the interesting scientific aspects, the study of the origin and development of the coastal barrier and plain is relevant to predict long-term responses of the coastal system to a possible further rise in sea level.

Another very important factor in the evolution of the coastal barrier and the coastal plain is the frequency and intensity of storms. All major breachings and inundations documented since the Middle Ages, are related to storm events. This holds true for the episodes of severe erosion in our time as well (De Wolf *et al.*, this volume).

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[4] Source: Hydrographic Service, Oostende, Belgium.

The formation of a coastal barrier and the development of a coastal plain

The French-Belgian coastal barrier is essentially a long, almost rectilinear sandbody whose geomorphological units are the dunes, the beach, and the nearshore (the latter being sometimes called the underwater part of the beach). In cross section, this sandbody is typically a few hundreds of metres to a maximum of about 2 km wide, while its surface may reach heights of 15 to 20 m (fig. 2). At irregular distances the coastal barrier was interrupted by tidal inlets and river mouths, most of which are nowadays transformed to harbour access or drainage channels.

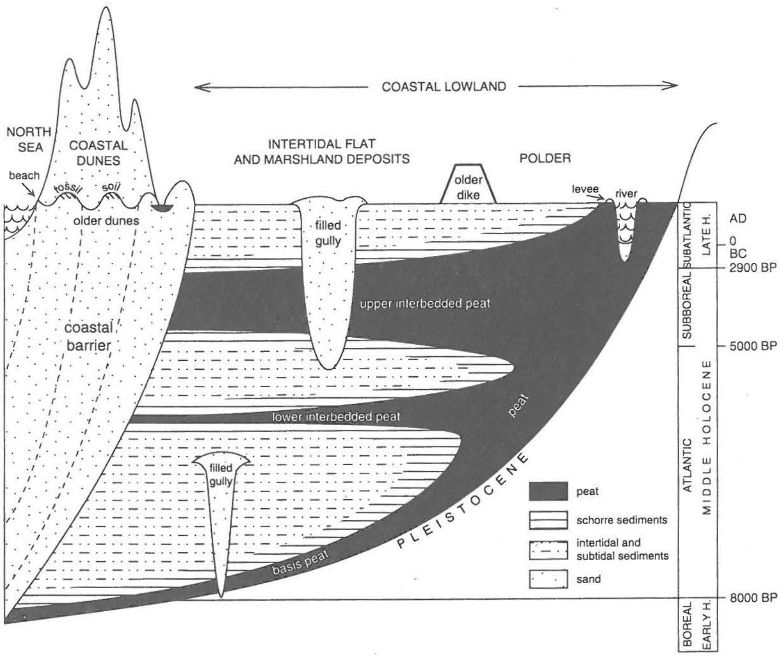
The present-day position of the coastal barrier is the result of a dynamic equilibrium between coast-building and coast-destructing forces, acting on loose grains of sand. These are supplied by coastal currents, winds and waves. Position and shape of the coastal barrier has changed significantly throughout geological and historical time. The main factor triggering these changes appears to be the changes in sea level, i.e. both the Holocene sea level rise and the changes in tidal range. Sea level strongly determines the impact of the forces acting directly on the coast : waves, wave driven currents, tidal currents, and winds. Most of these factors have a dual action, i.e. they can both be constructive and destructive forces, depending on their magnitude, frequency, direction, etc.

It is not the purpose of this paper to review the action of these natural forces, although their impact on coastal barrier formation is still a major topic in present-day coastal research.

The variability in position of the coastal barrier is illustrated in fig. 4. It is believed that, after the last Ice Age, no coastal barrier was present at the French-Belgian coast until the rate of sea level rise slowed down during the Atlantic. The reasons for sediment accretion at the southeast side of the southern North Sea, including the formation of a coastal barrier, an inshore sediment accumulation, and the development of offshore sand banks, are complex. According to Eisma (1980), the following conditions explain the trend of accretion during the Holocene :

- the presence of large amounts of unconsolidated material, predominantly sand, deposited on the emerged shelf surface during the Ice Age low stand;
- the continuing supply of sand and mud by the rivers;
- the easterly, net coastward direction of coastal transport.

During the Holocene sea level rise, the coastal barrier formed at some distance seaward within the newly inundated area. The flat area between the coastal barrier and the elevated inland was regularly flooded by tide and storm water through tidal inlets, river mouths and occasional overwash events. These tidal flats, sheltered by the coastal barrier, were subject to differential sedimentation, sand being deposited in tidal channels and on tidal flats, and clayey sediments on higher marshes. The different facies of the coastal plain Holocene sediments testify of the changes in landscape that occurred throughout time. Fig. 2 is a schematic overview of the different sedimentary facies and their geographical relationship, representative of the coastal plain in the IJzer river area.



H = Holocene; BP = before present, i.e. before 1950.

Figure 2: Simplified cross-profile representative of the coastal plain sedimentary system near Nieuwpoort and the IJzer river. Shown with strong vertical exaggeration. Modified after Köhn, 1989.

Peat layers developed in predominantly freshwater bogs, which possibly reflect a rise in ground water level induced by the rising sea level. The intervals between the peat layers consist of a complex succession of compact clays, units of interlayered sand and mud, and metres thick masses of either subhorizontally bedded or cross-bedded sand. These sediments reflect environments of coastal lagoons, salt marshes, intertidal flats, shorefaces, and tidal channels, respectively.

The succession of the Dunkerque III deposits (table 1) is probably not due to fluctuations in sea level but rather reflects fluctuations in sediment availability and supply and in hydrodynamic characteristics. Important factors in this are the geometry of the coastal barrier and the occurrence and intensity of storms, but also the growing interference of man. The more recent inundations of the coastal plain often have a differing geographical extent, due to the network of dikes gradually being established.

Geographical distribution and thickness of the Holocene sediments

The Holocene deposits in the French-Belgian coastal plain consist of two successive units, named Calais and Dunkerque deposits, which are described below. The total thickness of the Holocene sediment body may locally exceed 50 m, more particularly in the coastal dune belt. In most of the coastal plain however, the top surface of the Holocene is so flat that the relief of the Holocene base provides a good image of its thickness.

Fig. 3 is a contour line map of the Holocene deposits' base surface in the coastal plain. It shows essentially a surface dipping towards the present-day coastline and cut by the paleo-thalwegs of Aa (north of Watten), IJzer (north of Diksmuide) and Zwin (near Cadzand). Note the striking difference in thickness of the deposits between the eastern and western parts.

In the coastal plain east of Diksmuide, the Holocene base is mostly above −5 m and has a very gentle slope towards the coast. In most places, the Holocene deposits cover a basal peat that overlies Pleistocene sediments. Near the coast, the base surface slope increases and thicknesses exceed 20 m.

West of Diksmuide, the slope of the Holocene base is steeper. Thicknesses are mostly between 10 and 20 m, while in the very coastal zone the surface is incised to depths of over 25 m below mean sea level. In this western part, the contour lines suggest a more pronounced embayment during the Flandrian sea level rise than that formed by the present-day coastline.
Here also the Holocene base fossilizes an erosional relief developed in Pleistocene and locally Tertiary sediments, and west of Calais even in Cretaceous sedimentary rocks. The fossilized relief of the westernmost area shows some control by tectonics and lithology of the substratum (Sommé, 1988b). Elsewhere in the coastal plain however, there is no clear evidence for a lithological or tectonic control. The Pleistocene substratum shows no significant lithological differentiation. Neither is there any important change in substratum lithology at the transition from the thick western to the thin eastern part.
In the coastal plain few outcrops of Pleistocene sediments exist. South of Calais, the elevated remains of marine Pleistocene spits pierce the Holocene tidal flat deposits at Coulogne and Les Attaques (Sommé, 1977, 1988a, b). Near Bergues and Gistel are outcrops of the Tertiary substratum. North of Gistel, at Oudenburg, a low Tardiglacial (late Pleistocene) sand ridge was high enough to escape immersion in Holocene time.

Evolution during the Atlantic (Calais Transgression)

Calais deposits are found in most of the French-Belgian coastal plain, especially where the base of the Holocene is deeper than −5 m with respect to mean sea level: the large embayment-like area between Calais and Oostende, and some deeper seaward parts of the area east of Oostende (fig. 3). As they are overlain by the younger Dunkerque deposits, they crop out only in areas such as De Moeren at the French-Belgian border, where peat has been dug during the Middle Ages.

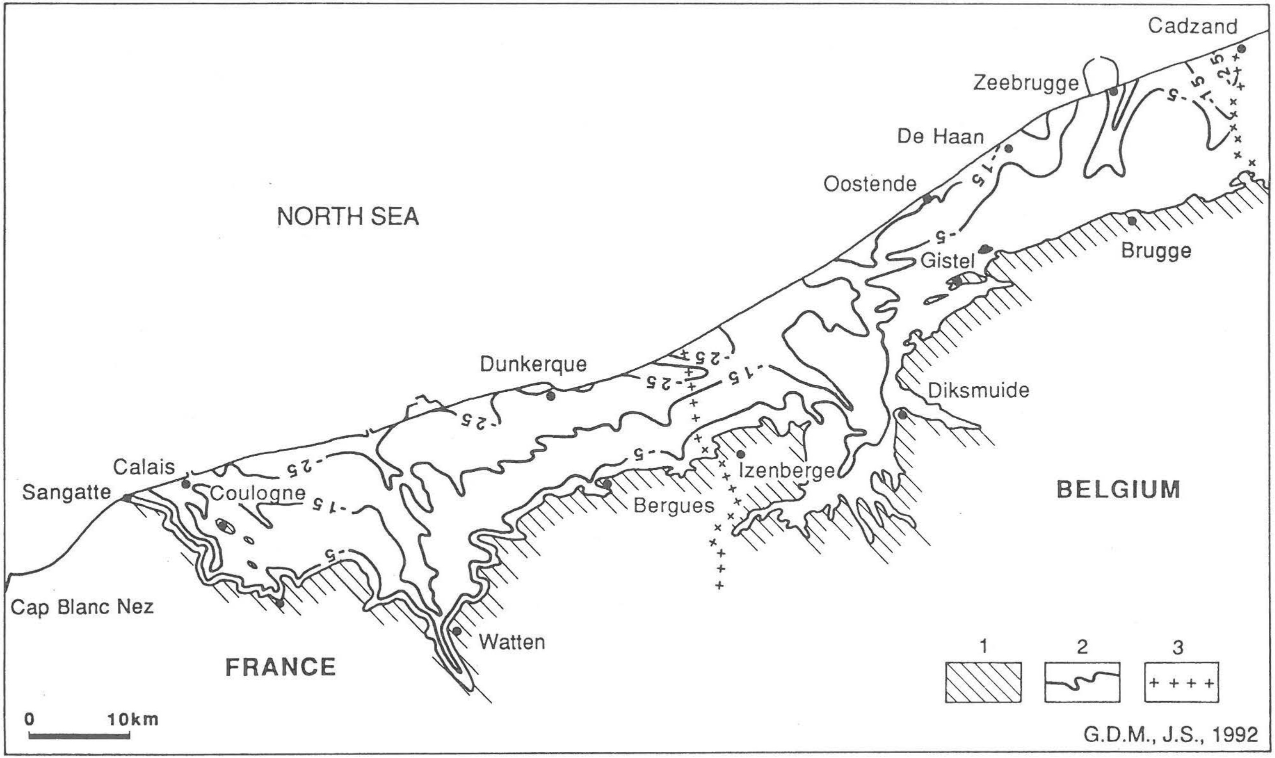


Figure 3: Base of the Holecene deposists in the French-Belgian coastal plain.
Key: 1. Outcrop of pre-Holocene; 2. Depth contour lines of the base of the Holocene (in metres below mean sea level); 3. State boundary.

The depth and facies of dated sediments and their position in relation to the present-day coastline allow to retrace the successive locations of the coastline during the postglacial sea level rise. They show that already during the earlier stages of the Flandrian transgression the sea entered the deeper parts of the Early Holocene French-Belgian coastal zone, especially the large Aa embayment west of Dunkerque and a few smaller channels northwest of Diksmuide (Baeteman, 1981; fig. 3).

At about 8,000 years BP, at the end of the Boreal, the sea already reached Watten in the Aa estuary, 20 km from the present-day coastline, where marine sediments have been found at a depth of −17 m (Sommé *et al.*, 1992).

A more generalized marine inundation of the Atlantic marine embayment took place around 7,000 years BP reaching a depth of −10 m. Around 6,600 years BP a larger part of the IJzer area was flooded, the sea level reaching −7 m.

A temporary outcrop in that area, described by De Moor *et al.* (unpublished), showed the base of the Calais deposits over a postglacial podsolic soil developed in the top of the Pleistocene sediments at a level of about −7 m. The Calais deposits probably did not develop above 0 m.

West of Dunkerque, the Calais deposits are mainly composed of tidal flat and beach sediments, deposited in the Early and Middle Atlantic. The sediments are predominantly sandy ("*sables pissards*"), though the upper part may consist of more silty or clayey intertidal deposits. In the inner reaches of the coastal plain, the deposits are significantly more silty and clayey and contain peaty horizons which possibly indicate transgressive and regressive oscillations (Sommé, 1979, 1988a, 1992; Van der Woude & Roeleveld, 1985).

More to the east the Calais deposits consist mostly of fine sands, with clayey and peaty intercalations becoming more abundant upward.

The coarser facies of the Early Atlantic Calais deposits suggests that initially no coastal barrier was present, and this was probably so up to 6,800 years BP (Baeteman, 1978). Afterwards finer-grained sediments indicate a more or less sheltered intertidal flat environment, where tidal channels supplied sediment. In this sheltered environment, lagoonal deposits, brackish reed swamps and even moors could develop when conditions were favourable.

In Atlantic times, the coastal barrier, locally covered with dunes, was less rectilinear than the present coast. East of Nieuwpoort, it had a much more seaward position than the later Dunkerque shores, while at the French-Belgian border it had a more landward position, such as indicated by the Ghyvelde Atlantic dune ridge (fig. 4). Near Calais, a remarkable remainder of the Atlantic coastal barrier is formed by the "Banc des Pierrettes", a shingle spit complex (fig. 4). This sediment body contains a lot of flint and chalk pebbles, derived by erosion from the chalk cliffs of Cap Blanc Nez. The complex spit shows a permanent vertical growth at a constant position (Dubois, 1924; Sommé, 1977, 1979).

During the Late Atlantic a marked decrease of marine influence is observed in the inner and central parts of the coastal plain, and finally peat growth became dominant at the brink of the Subboreal.

Evolution during the Subboreal

In the French-Belgian coastal plain the Subboreal was a period of decreased marine influence, in which tidal flats silted up and were increasingly sheltered by coastal shoals and barriers. A vegetation cover spreaded over most of the coastal plain. Due to the low and wet conditions, peat formation in coastal moors extended over all the lower grounds behind the coastal barrier system. Towards the end of the Subboreal, the peat grew into a raised bog, the top layers of which consisted of *Sphagnum*. Locally it formed dome-shaped bodies that would not be flooded during the later Dunkerque inundations. Peat was also present and developed to relative high levels in all of the Westerschelde area (fig. 4).

The Subboreal peat of the inner reaches of the coastal plain is mostly a single layer that today, even after important compaction due to sediment load and dewatering, locally still reaches thicknesses of 4 to 6 m. In the outer reaches, especially in the western part of the French-Belgian coastal plain, the peat often splits up into a number of peat beds, separated by sandy, silty or clayey layers. They indicate minor transgressions, due to changes in coastal barrier morphology, storm events, or short transgressive episodes.

The Subboreal peat is generally called surface peat. Where it has not been taken away by tidal channel erosion or exploitation by man, it is at the origin of many stability problems of roads and constructions in the coastal plain.

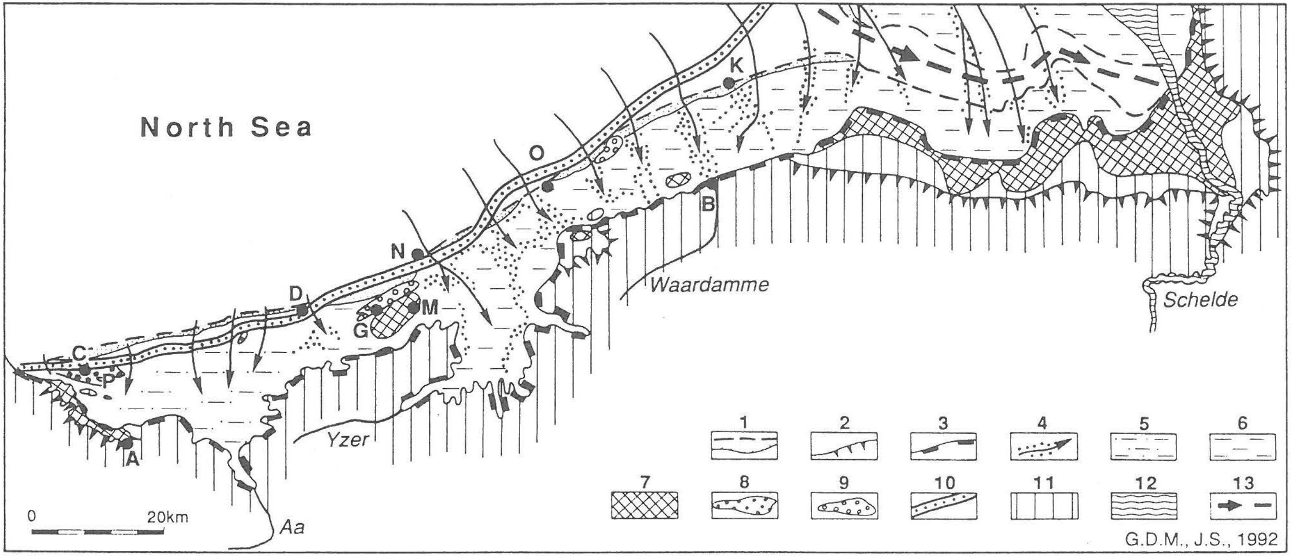
Evolution during the Subatlantic (Dunkerque Inundations)

Successive inundations occurred during the Subatlantic. The three main transgressive phases are referred to as Dunkerque I, II, and III (table 1). The latter is often subdivided in Dunkerque IIIa (12th century) and IIIb (post-12th century inundations). Dunkerque II and III are well documented by both geological and historical sources. The extent of these inundations is shown in fig. 4. In Belgium, their extents were mapped by Tavernier *et al.* (1970) using pedo-morphological characteristics and by Verhulst (1959) using historical data.

The two main regressive stages are known as the Roman and Carolingian regressions. During the regressions the emerging peat surfaces were occupied and the upsilted marshlands reclaimed. At the onset of Dunkerque IIIa, a few defensive dikes were built. Since the first Dunkerque IIIb inundations however, dikes have not only been built to defend but as well to gain land. Drainage after land reclamation has provoked differential setting and relief inversions. The latter refer to sand-filled tidal channels that after dewatering are now slightly higher than the surrounding clay and peat flats. Relief inversions are particularly clear in the area left unaffected by the Dunkerque III inundations.

At the beginning of the Dunkerque inundations, the coastline was more or less that from the Atlantic, remains of which are found in the Pierrettes spit and the Ghyvelde dunes. In the Hem-Aa estuary system, an opening towards the sea continued to exist. The coastal dunes, as relatively safe (high) and interesting (between sea and marshland) locations, are the site of early human settlements (Thoen, 1978; Termote, 1992). Remnants of Neolithic habitation have been found in the older dunes.

During the Dunkerque I transgression, most of the French part of the coastal plain was inundated, with the exception of the very southern edge of the Calais marshes near Ardres, where locally lacustrine marls were deposited. Near Calais, a new system of sandy barrier ridges covered by low stabilized dunes marked a change in the general orientation of the coastline in this area (from W-E to WSW-ENE). This change is thought to reflect erosion in the cliff region west of Sangatte



Key: 1. Present-day coastline with dune belt; 2. Not inundated parts of the coastal plain; 3. Limit of Dunkerque II tidel deposits; 4. Dunkerque II beach barrier breachings and intertidal channels with sandy infill; 5. Intertidal sand flat deposits; 6. Intertidal mud flat deposits; 7. Outcrop of surface peat; 8. Gravelly pre-Dunkerque spits; 9. Older dunes (Mid-Holocene and Early Subatlantic); 10. Beach barrier, breached at the Dunkerque II transgression; 11. Outcrop of Pleistocene deposits; 12. Pre-Dunkerque III Schelde; 13. Westerschelde Estuary, developed during the Dunkerque III transgression.

A = Ardres; B = Brugge; C = Calais; D = Dunkerque; G = Ghyvelde; K = Knokke; M = De Moeren; N = Nieuwpoort; O = Oostende; P = Pierrettes spit.

Figure 4: The French-Belgian coastal plain and the Schelde Estuary at the Dunkerque II transgression.

(Sommé, 1979). In Belgium, the existing shore was strongly attacked and several breachings occurred during Dunkerque I (Tavernier *et al.*, 1970). The landward extension however was rather restricted and a large part of the Belgian coastal plain remained a peat surface.

During the Roman regression, widespread human occupation appeared at the southern margins of the coastal plain. Also in the coastal dunes, remains have been found of Roman occupation.

The Dunkerque II transgression was the largest in extent (fig. 4). At the southern borders of the coastal plain, Dunkerque II tidal flat deposits may directly cover the Tertiary substratum. Particularly in the area south of Dunkerque, Dunkerque II sands overlie Weichselian loess or cover sands (Paepe, 1960; Sommé, 1977).

In some areas bogs grew sufficiently high to escape flooding: fringes of the plain near Ardres and southeast of Oostende, and a wide bog named De Moeren. Also some existing dunes escaped flooding. Numerous breachings of the beach barrier occurred. East of Oostende, the coastline underwent a remarkable landward retreat. A wide gap in the coastal barrier must have existed at the Aa mouth. In this area large sand flats developed; elsewhere, the sedimentation was more clayey (fig. 4).

The origin of the recent dune belt dates back to the late Dunkerque II and the subsequent Carolingian regression. From that time, the coastal plain itself showed a scarce occupation, first for open-range sheepherding and afterwards, using dikes for the first time to protect against spring tide flooding, for growing crops. In the Belgian part of the coastal plain, areas with outcropping Dunkerque II deposits are known as "Oudland".

At the Dunkerque IIIa transgression, the extent of the inundations of the coastal plain was restricted by man-built dikes. Wide open inlets developed at the Aa and IJzer river mouths, and a tidal inlet east of Knokke, named Zwin, was considerably widened. This inlet reached its maximum development in the 12th century. Brugge was connected to the Zwin inlet by the Damme canal and this link to the open sea was fundamental to the city's famous commercial and economic bloom. The inundated areas have gradually been reclaimed, mainly during the 12th century. Areas where Dunkerque IIIa deposits crop out are named "Middelland".

In Belgium, the Dunkerque IIIb transgression primarily affected the area northeast of Brugge, especially in the present-day Westerschelde area, where very rapidly since the 12th century an important complex of tidal channels developed. These would eventually, due to regressive erosion, capture and divert the river Schelde north of Antwerpen. At the same time, the Zwin inlet was subject to rapid upsilting. Areas where Dunkerque IIIb deposits are outcropping are known as "Nieuwland".

During the Dunkerque III transgressive period, which is actually still going on, the main coastline changes can be summarized as follows.

West of Calais, an erosional tendency predominates near the Sangatte cliff. Between Calais and Dunkerque, the sea front of the estuarine zone is marked by a series of low sandy barrier ridges that successively take in more seaward positions. These tend to close the river mouths by easterly accretion. In the Gravelines area (Aa estuary), the shoreline has advanced about 2 km since the end of the Middle Ages. East of Dunkerque, the coast has retreated, but not over substantive distances. Here, older and younger dunes form an elevated single ridge subject to erosion. Also east of Nieuwpoort and Oostende, dune development went on. The major trend in coastline development from Dunkerque to Oostende was rectification through local advances and retreats of the coast. Near Knokke the coastal retreat was more important, related to the development of the Westerschelde estuary.

Well-coordinated attempts to consolidate the coastline at its existing position characterize the 19th but especially the 20th century. They essentially included the construction of sea walls and groynes, and, more recently, the application of beach scraping and beach nourishments (De Wolf *et al.*, this volume).

The coastal barrier nowadays is still the sea-defence for the coastal lowlands, and this fact along with the outstanding economic and touristic significance of the sea front area itself, justifies the French and Belgian governments' efforts for the rational management and better understanding of this dynamic environment.

Conclusion

Information on the Holocene development of the French and Belgian part of the North Sea coastal plain and coastal barrier has been collected and presented in an integrated way in this paper. The reconstruction of their Holocene evolution is mainly based on the sedimentary record present in the coastal plain. The available evidence clearly shows the triggering function of the Holocene sea level rise, especially for the Atlantic Calais transgressions. The most recent coastal barrier breachings were more localized and were, in addition to sea level and tidal-range changes, more heavily related to the occurrence of storm events and the morphological balance of the coastal system.

The geologic approach provides indirect and environmental evidence for the coastal barrier dynamics. A coastal barrier has been present ever since the rate of sea level rise slowed down during the Atlantic. Important changes have occurred in its position, the main trend being a seaward shift in the embayment-like French North Sea coast and a landward movement in Belgium, especially when approaching the present-day Westerschelde estuary.

Some implications on present-day coastal management arise from the geological experience. Even though in the more recent evolution of the coastal barrier sea level rise has not been a dominant factor, it is clear that even a slight change in sea level would occasion significant and rapid morphological adaptations. Equally intense impacts are to be expected if the natural processes of sediment supply and transport are artificially disturbed. The fact that no new deposits are allowed to form in the reclaimed coastal lowlands is another cause of long-term inequilibrium in the natural coastal evolution.

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