Geological history of the area off Walcheren and Zeeuwsch-Vlaanderen (southwestern Netherlands), since the start of the Eemian

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Abstract

Compilation of existing and new data from boreholes and seismic surveys in the area off Walcheren and Zeeuwsch-Vlaanderen (southwestern Netherlands) has led to a new insight into the geological evolution of that area since Eemian times. During the Eemian, several terrace like levels linked to Tertiary escarpments were formed in this area, at least three of them in the offshore part. At the end of the Weichselian and at the onset of the Holocene, a system of Belgian rivers (the Waardamme and Leie) eroded into Weichselian predominantly aeolian and Eemian marine deposits in that area. During Atlantic and Subboreal times these rivers were probably located partly behind barriers or coastal dunes, where tidal flats and/or peat could only develop to a small extent. This is in contradiction with earlier views, mostly based on data from the land area, in which a large tidal flat or peat area was postulated (cf. Zagwijn, 1986). During the Early Subboreal, the old river system was used as a starting point for erosion. This erosion created an outer delta environment.
On top of deposits belonging to that environment, outer ebb-tidal-delta sediments were deposited until recent times. In the youngest sediments a medieval erosional phase is recognized, which can be linked to the final breakthrough of the river Scheldt to the present Western Scheldt.
Recent pollen analyses enabled us to produce a correlation diagram of the lithostratigraphic systems used in the studied offshore and adjacent onshore areas.

1 Introduction

In 1965, the geological mapping by the Geological Survey (Rijks Geologische Dienst: RGD) of Zeeuwsch-Vlaanderen (the Netherlands), in the 1:50,000 series, was completed (Van Rummelen, 1965), and gives a fairly good understanding of the geology of that area. The same holds true for Walcheren in 1972 (Van Rummelen, 1972). Until recently, this was not the case for the offshore area of Walcheren and Zeeuws-Vlaanderen. Data acquisition in that area only started around 1968, and a systematic collection of geological data started in the second half of the 1980s. This yielded maps in the 1:250,000 series: the Ostend sheets (Laban & Schüttenhelm, 1991; Balson et al., 1991) and a map in the 1:100,000 series: the Rabsbank sheet (Ebbing et al., 1993).

The evaluation of this ample set of data on the area around the mouth of the Western Scheldt highlighted the complexity of the geological setting. This region differs from the northern part of the Dutch coast by the high elevation of the Tertiary strata, which are in places outcropping. This part of the southern North Sea is situated at the margin of the slowly subsiding North Sea basin and, unlike it, is stable or even rising. This led to a somewhat divergent behaviour of the area during sea-level changes in the Quaternary.

Since Tertiary deposits occur near the surface, they have exerted a strong influence on the development of this part of the coast. A palaeoreconstruction should therefore start at the end of the Tertiary. However, apart from a few small spots in the study area, with an early-Pleistocene erosional residue, the deposits from the Eemian form the base of the Quaternary (Laban & Schüttenhelm, 1991: Ebbing et al., 1993). It is therefore appropriate to start with the "Saalian Palaeorelief" for a reconstruction of the geological history of the area.

The remnants of the morphology at the end of the Saalian offers some clues about the course of the old riverbeds and can be used as a starting point for a palaeoreconstruction. Onshore-offshore correlations in the Late Quaternary are made as well, and important geological events in the area will be indicated and, if possible, dated.

Basic data and methods

For the palaeoreconstruction all cores and borehole samples (about 550, excluding the grabsamples), taken over the years were used. Several samples had already been analysed by various methods (for pollen, molluscs, ostracods, and diatoms) and additional cores from crucial locations were sampled for analyzing. No absolute dates were available. The distribution of all dated cores is shown in Figure 1. Besides the cores, 3.5 kHz seismic lines (about 385 km) were used to draw a contour map of the pre-Eemian in the area (Figure 4). The seismic system used to obtain these lines is composed of eight 3.5 kHz ORE transducers built in a PVC fish, with heave compensation. This system provided very good seismostratigraphic information of the first 10 m below the seabed.

Detailed geological information concerning the land area was obtained from the existing 1:50,000 geological maps of Walcheren and Zeeuwsch-Vlaanderen (Van Rummelen, 1972, 1965) and concerning the offshore area from the 1:100,000 map of the Rabsbank sheet (Ebbing et al., 1993). Also useful archeological data were included in this study, e.g. findings of remains of the Roman occupation in some areas (Ovaa, 1971).

2 Short description of the lithostratigraphic units

The abbreviations used in the descriptions correspond to those concerning the lithological columns of Figure 2. The stratigraphic position of the various formations is given in Figure 3.

* *Eem Formation (EE): Eemian.* Fine to medium-grained, locally gravelly and shelly (especially at the base) sand, with some clay layers or clay laminae. A major component of the gravel is chert. The sand contains a Eemian mollusc association and *Corbicula fluminalis*, as a fresh to brackish estuarine water indicator, as well as a derived weathered mollusc fauna including Early Pleistocene marine species. The coarse lag deposits found in the area of the Vlakte-van-de-Raan (Figure 1) probably represent mainly channel lag deposits (RS, in part FS) and, further offshore to the northwest, a barrier like beach (RS), which becomes finer towards the top (MS). On top of the channel lag deposits intertidal deposits (ES) could develop, in accordance with the findings of De Moor & Mostaert (1988).
* *Twente Formation (TW): mainly Middle- to Late Weichselian.* Well-sorted, fine-grained, predominantly wind-blown sands with some silt intercalations; evidentially deposited in a periglacial environment.
* *Buitenbanken Formation (BTK): Middle- to Late Atlantic.* Yellowish-brown fine- to medium-grained sands sometimes gravelly and/or shelly, and composed typically of reworked Late Pleistocene deposits (RS); locally clay layers are present as well. The sand contains, besides a Holocene mollusc fauna, a reworked mollusc fauna with Late Pleistocene marine and fresh-water species and Early Pleistocene marine species. The deposits can be characterized as nearshore (high energy) (RS) or as channel infills belonging to an outer delta (RS: partly derived from ELW). The nearshore deposits are the result of a reworking of the Eemian barrier beach and the channel infills partially represent a reworking of Eemian channel infills.
* *Elbow Formation (ELW): Middle Atlantic to Late Subboreal.* Clay laminated with fine sand (locally muddy), or fine- to medium-grained sand (locally muddy) with clay layers and clay laminae. The sediment indicates a tidal

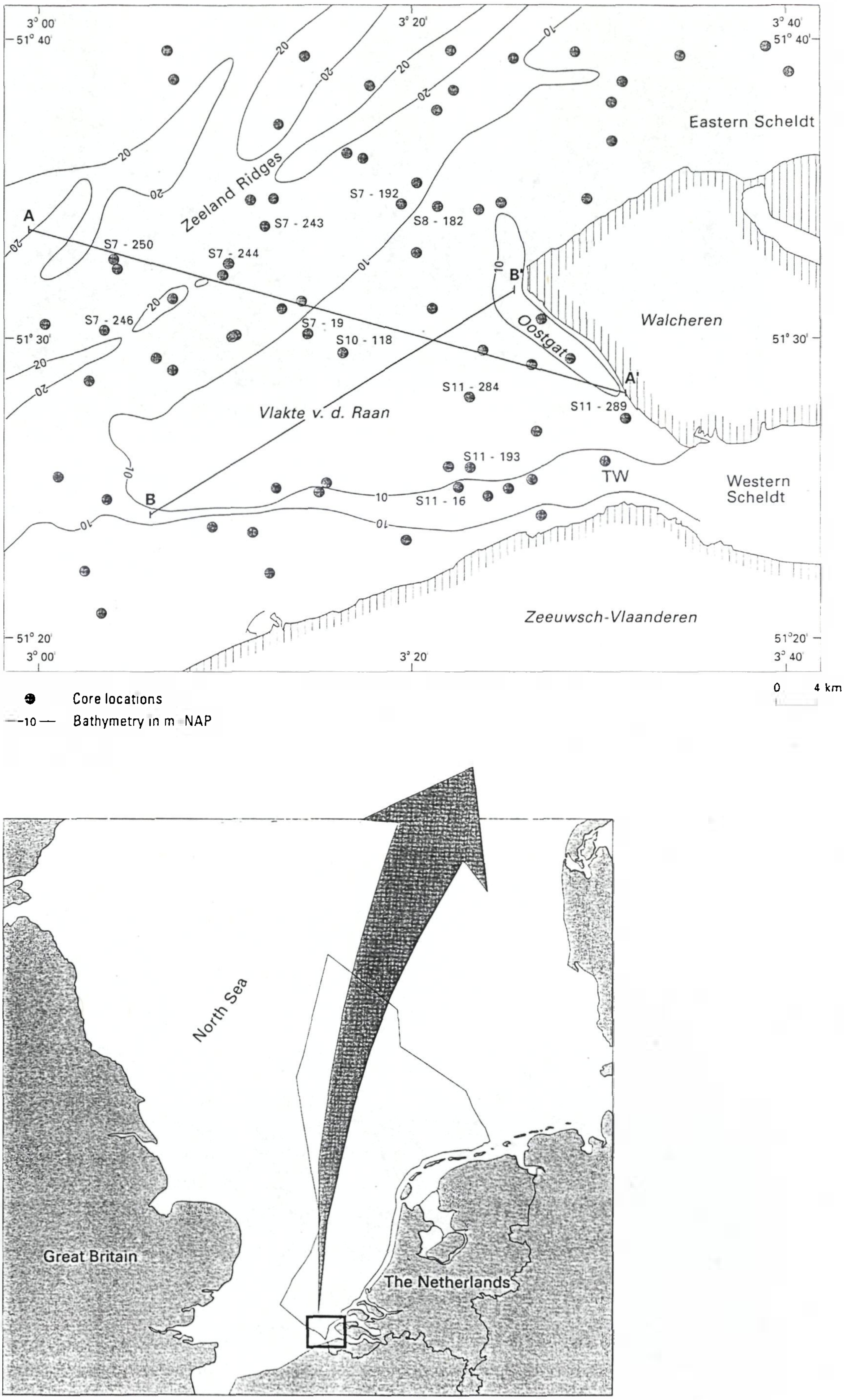
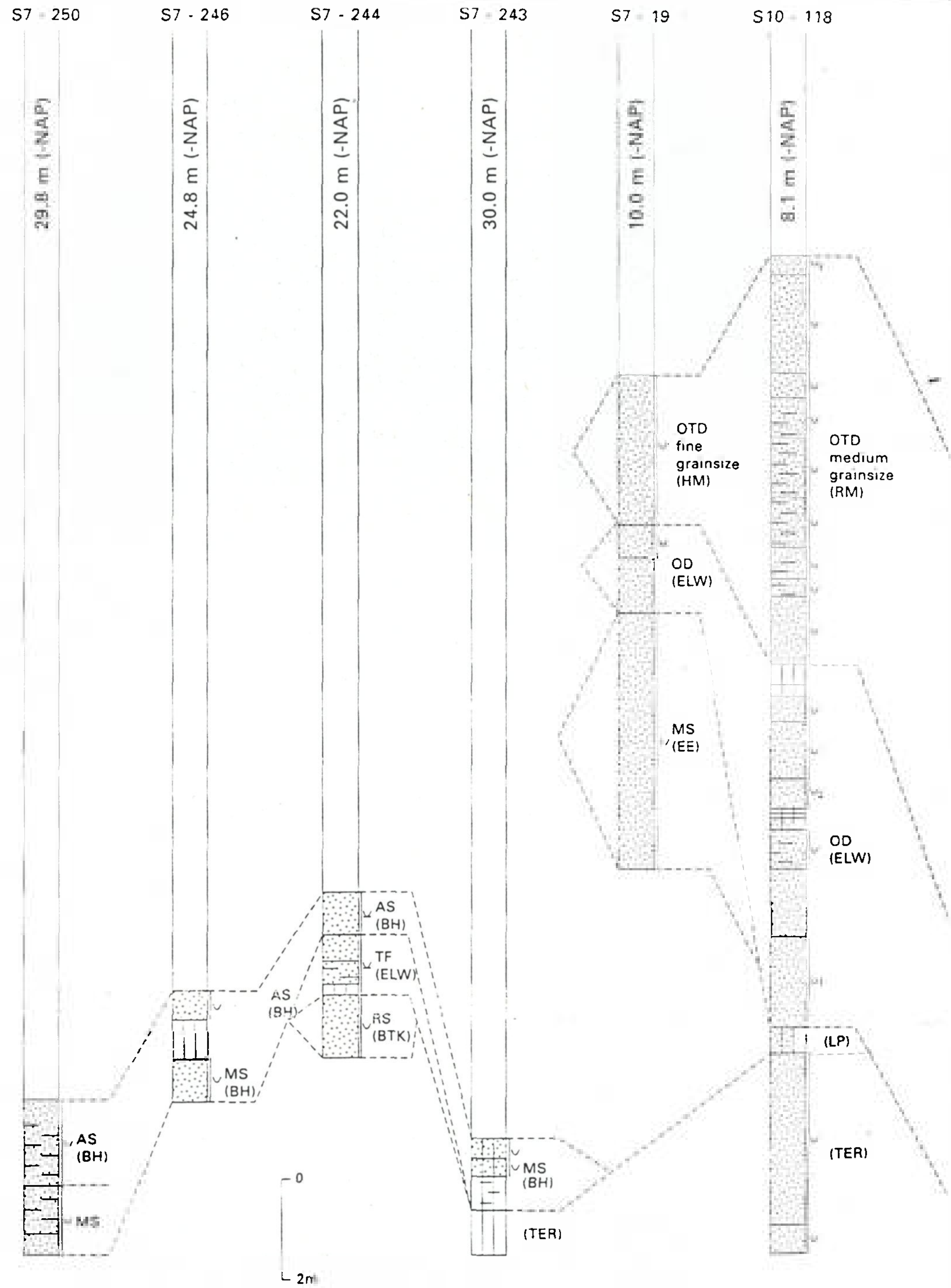


Figure 1
Location map of the study area westerly of Zeeuwsch-Vlaanderen, Walcheren and the mouth of the Western Scheldt. Indicated are the position of two profiles (AA' and BB', see the Figures 6 and 9), and the location of all dated cores. The cores carrying a number are mentioned in the text. 'TW' stands for the position of two adjacent cores in which the Twente Formations has been detected.



Lithology	
Sand	
Sand with clay layers or laminae	
Clay	
Sandy clay	
Laminated clay	
∨	Shell(fragments)
ʼ	Organic detritus

Sedimentology	
OTD	Outer ebb Tidal Delta deposits
OD	Outer Delta deposits
MS	Marine Sand deposits
TF	Tidal Flat deposits
AS	Active Sand deposits
RS	Reworked Sand deposits
FS	Fluviatile Sand/clay deposits
ES	Estuarine Sand/clay deposits

Stratigraphy		
(BH)	Bligh Bank Fm	
(HM)	Hompels Member	Banjaard Fm
(RM)	Raan Member	Banjaard Fm
(ELW)	Elbow Fm	
(BTK)	Buitenbanken Fm	
(EE)	Eem Fm	
(LP)	Lower Pleistocene deposits	
(TER)	Tertiary deposits	

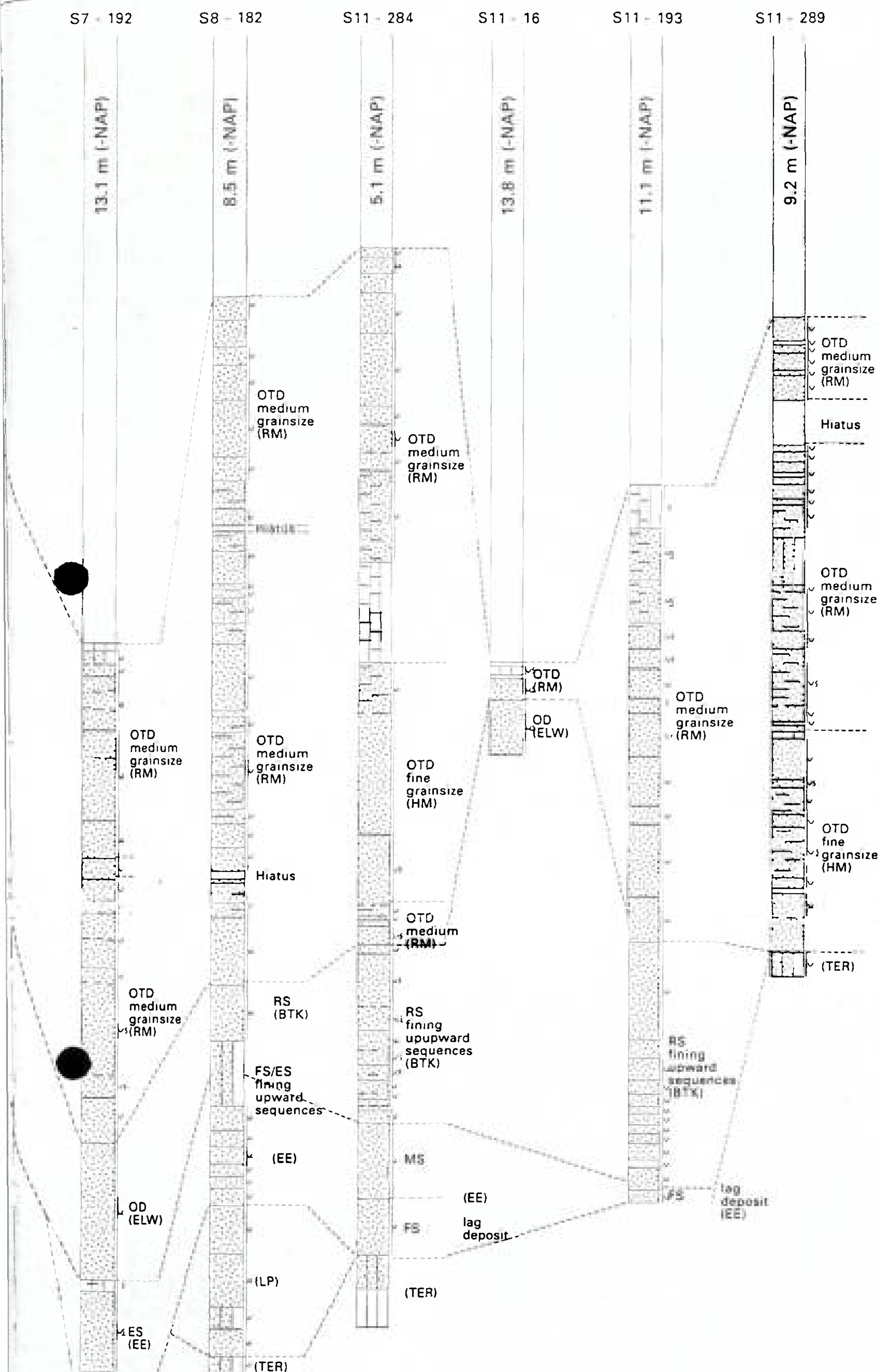


Figure 2

Lithological columns of the cores mentioned in the text, with a sedimentological/ stratigraphical interpretation and correlation lines These lines are not based on seismic evidence and must be treated as indicative Horizontally this figure is not to scale flat (TF) or outer delta (OD) depositional environment. Especially seaward off the Vlakte-van-de-Raan (Figure 1) the Elbow Formation is developed as a tidal flat deposit as a product of the steady Holocene transgression. In the flooded Vlakte-van-de-Raan area the Elbow Formation is developed as an outer delta deposit below the strong wave action. This is reflected by a generally coarser grainsize than that in the area off the Vlakte-van-de-Raan.

* *Banjaard Formation: Early Subatlantic to recent.* This formation is subdivided into two members which pass laterally into one another. The members differ as to the grainsize of the sand fraction, they consist of sandy and silty outer ebb tidal delta deposits (OTD) derived from the coastal area. The sedimentation area is more or less restricted to the Vlakte-van-de-Raan (Figure 1). The longshore current ran and still runs off the Vlakte-van-de-Raan, making it possible for this sedimentation area to be developed as an outer ebb tidal delta with strong wave action.

- *Raan Member (RM).* Grey to light grey, fine to medium-grained sands with clay layers and laminae. The mollusc fauna is marine and includes the *Angulus pygmaeus* fauna (Spaink, 1973).
- *Hompels Member (HM).* Grey, very fine- to fine-grained muddy sands with clay layers and laminae containing the same fauna as the Raan Member.

* *Bligh Bank Formation (BH): Late Atlantic to recent.* Mainly yellowish-brown, fine to medium-grained sands with some gravel and clay laminae. The mollusc fauna is characterised by the presence of the mollusc association of *Angulus pygmaeus* (Spaink, 1973). The sediments are *deposited in an open marine environment* (AS+MS) and consist in the first place of reworked Middle- and Late Pleistocene fluvial deposits. In the study area they can be mainly found on top of all other deposits off the Vlakte-van-de-Raan. In earlier publications these sediments are named Young Sea-sand.

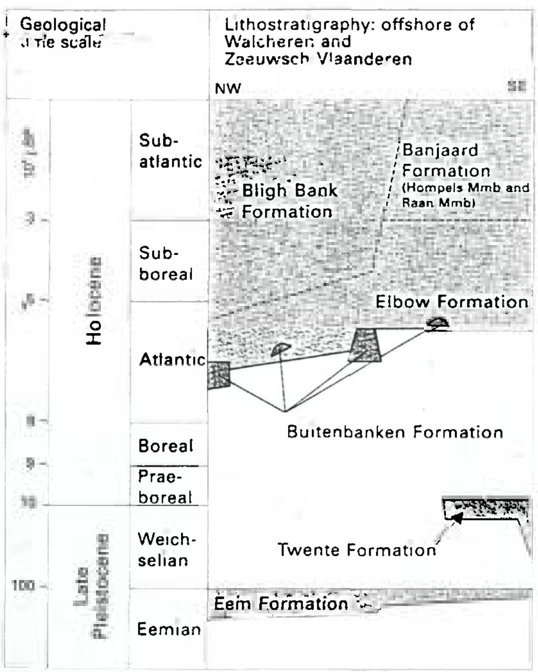


Figure 3
Stratigraphic table with the position of the mapped Late Pleistocene and Holocene formations

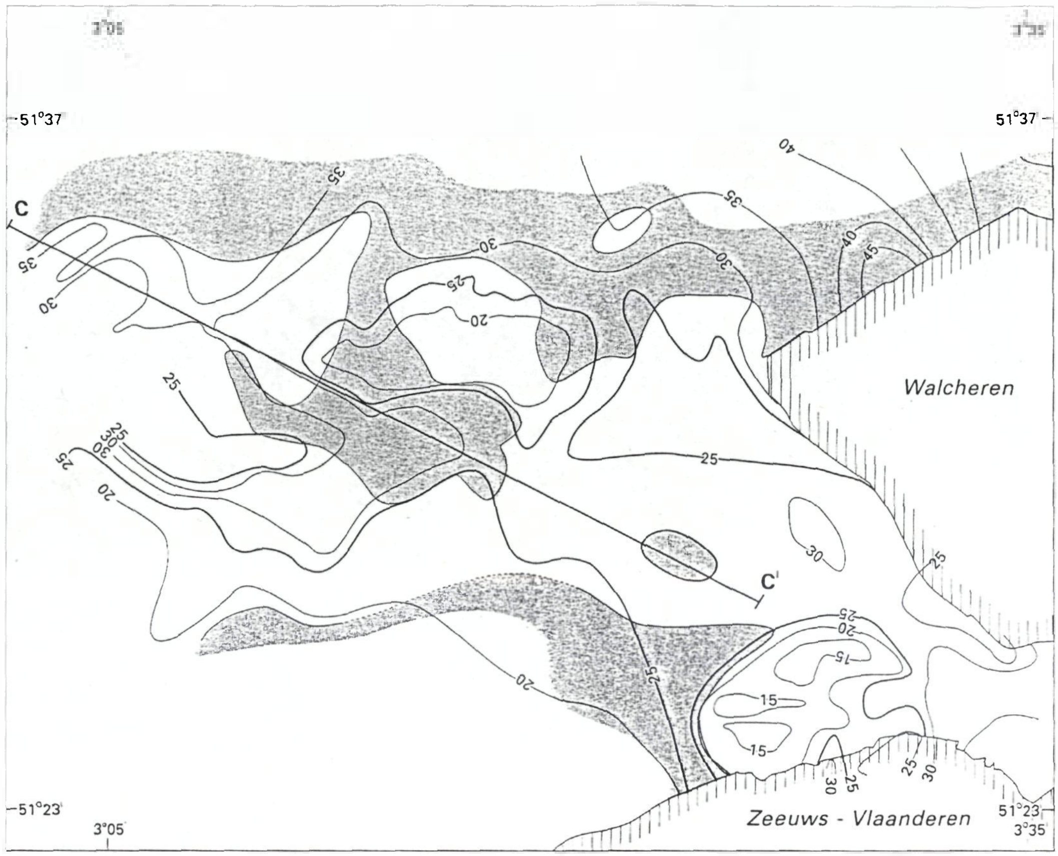
3 Eemian depositional history

The Eem Formation comprises the relative 'warm' post-Saalian / pre-Weichselian interglacial deposits; it is preserved in about half of the study area (Figure 4) with a thickness between less than 1 and 10 meters.

The Eemian deposits in the Dutch sector of the southern North Sea, occur as a more or less continuous layer in the south and also as an infill of glacial depressions of Saalian age in the north (Oele & Schüttenhelm, 1979), see the Indefatigable sheet of the 1:250,000 series (Cameron et al., 1986). The former authors were, however, not certain if Eemian deposits were present in the southernmost part of the North Sea. Between the Western Scheldt and the Sandettie Bank they found only Holocene sediments overlying Tertiary strata. In the present study we found evidence pointing to extensive Eemian deposits off Walcheren and Zeeuwsch-Vlaanderen. This evidence originated from cores S11-284, S8-182, and S7-192 (see Figures 1 and 2) and is supported by pollen-analytical data (De Jong, 1988 & Cleveringa, 1990). In core S7-192, diatoms led to the same conclusion (De Wolf;1990), with the additional remark that is dealt with marine Eemian. The analysis of core S8-182 yielded samples for clay mineral content. The clay mineral distribution is very similar to that found in Eemian sediments from Ostfriesland (Germany) (Zöllmer, pers.comm.). All of the above mentioned information on the age of parts of the cores made it possible to link certain sedimentological features to a time-frame. For the open marine and estuarine sands (MS, ES) in core S7-192 and S11-284, and the fluviatile/estuarine sands in core S8-182 is concluded that the age of those deposits is Eemian (see Figure 2). Several other cores from the study area (e.g. core S11-284, see Figure 2) show lag and/or coarse fluviatile deposits on the Tertiary, containing a partly reworked Early Pleistocene (West Kapelle Ground Formation ≈ Maassluis Fm?) mollusc association with species indicating an Eemian age (Sliggers, 1979; Spaink, 1986; Meijer and Sliggers, pers.comm.).

Figure 4 gives the contour map of the supposed Late Saalian (pre-Emian) morphology, which is almost identical to that of the top of the Tertiary in this area, as Middle- and Early Pleistocene sediments are scarce (Ebbing et al., 1993). Superimposed are the subcrops of the Eemian. A striking feature of the map is that relicts of the Late Saalian morphology show some elongated depressions (riverbeds?). This becomes even more striking if this map is seen in combination with that of Tavernier and De Moor

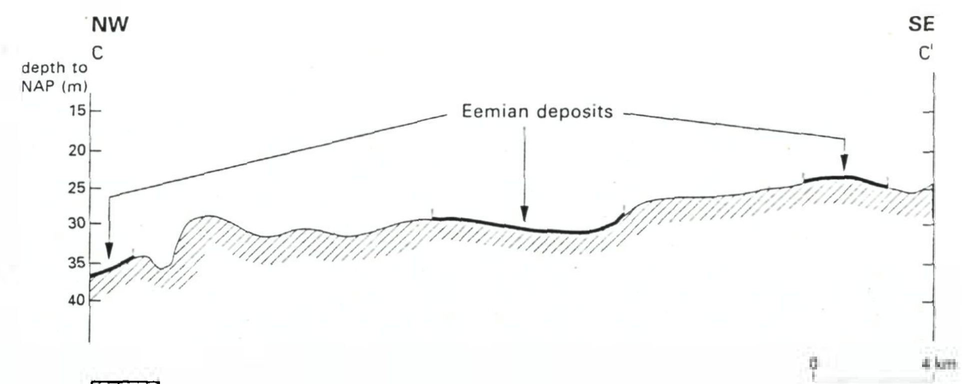
Figure 4
Contour map of the morphology of the pre Eemian, which is almost identical to the top of the Tertiary in this area. The distribution of the Eemian deposits is also indicated. Cross section C-C' shows the escarpments in the Tertiary basement and the distribution of the covering Eemian sediments.



—25— Top of the pre Eemian (generally Tertiary) deposits m NAP

0 4 km

Eemian deposits Eemian Formation



Tertiary deposits

(1974) (Figure 5). While to the north of the southern North Sea, basins or valleys were eroded by the Saalian ice sheet (Oele & Schüttenhelm, 1979; Laban et al., 1984; Joon et al., 1990); to the south, the depressions were probably incised by Saalian (and older) rivers in the Flemish Valley (Tavenier & De Moor,1974). From the composite map the principle discharge directions of Late Saalian to Eemian rivers can be deduced (Figure 5). The discharge direction of the "Leie" and/or "Waardamme" in the offshore part is less certain, but the lag deposit in cores S11-193, S11-284 and the fining upward sequences in core S8-182 (Figure 2) of Eemian age point to a major fluvial system in the offshore area. Probably, cores S8-182 and S11-284 can be linked to the Leie (with a SSE-NNW discharge direction) and core S11-193 to the Waardamme. The Leie possibly had a branch flowing into the Waardamme as indicated in Figure 4. The discharge direction of the Waardamme was also initially SSE-NNW but changed north of core S11-193 to SEE-NWW, evidence for this development will be given below.

The Eemian deposits in the Belgian area start with the reworking of a basal conglomerate on the Tertiary erosional surface, a typical example can be found at Meetkerke (De Moor & Mostaert, 1988) and in the valley of the river Leie (De Moor & Lootens, 1975). The lag deposits found in the offshore area (e.g. cores S11-284 and S11-193, Figure 2) probably correspond with the reworked basal conglomerate mentioned by these authors. According to De Moor and Mostaert (1988), open marine conditions prevailed in the major part of the coastal plain, where as the northern part of the Flemish Valley was a large intertidal estuary. At various places in onshore Belgium they found tidal flat deposits overlying the basal conglomerate. For the present offshore part they postulate an intertidal depositional environment. In core S7-192 an example of this (see Figure 2) is probably found. The estuarine sand (ES) containing many plant remains overlain by the organic rich laminated clay of Late Eemian age (Cleveringa, 1990) possibly represents an intertidal gully. The presence of *Corbicula fluminalis* points to a brackish environment during sedimentation in Late Eemian times. In all probability intertidal sediments were deposited in the offshore area, which were extensively eroded during the Weichselian.

Another interesting feature mentioned by De Moor and Mostaert (1988) are the terrace levels with Eemian deposits, they recognized in the Flemish Valley. In Figure 4 it

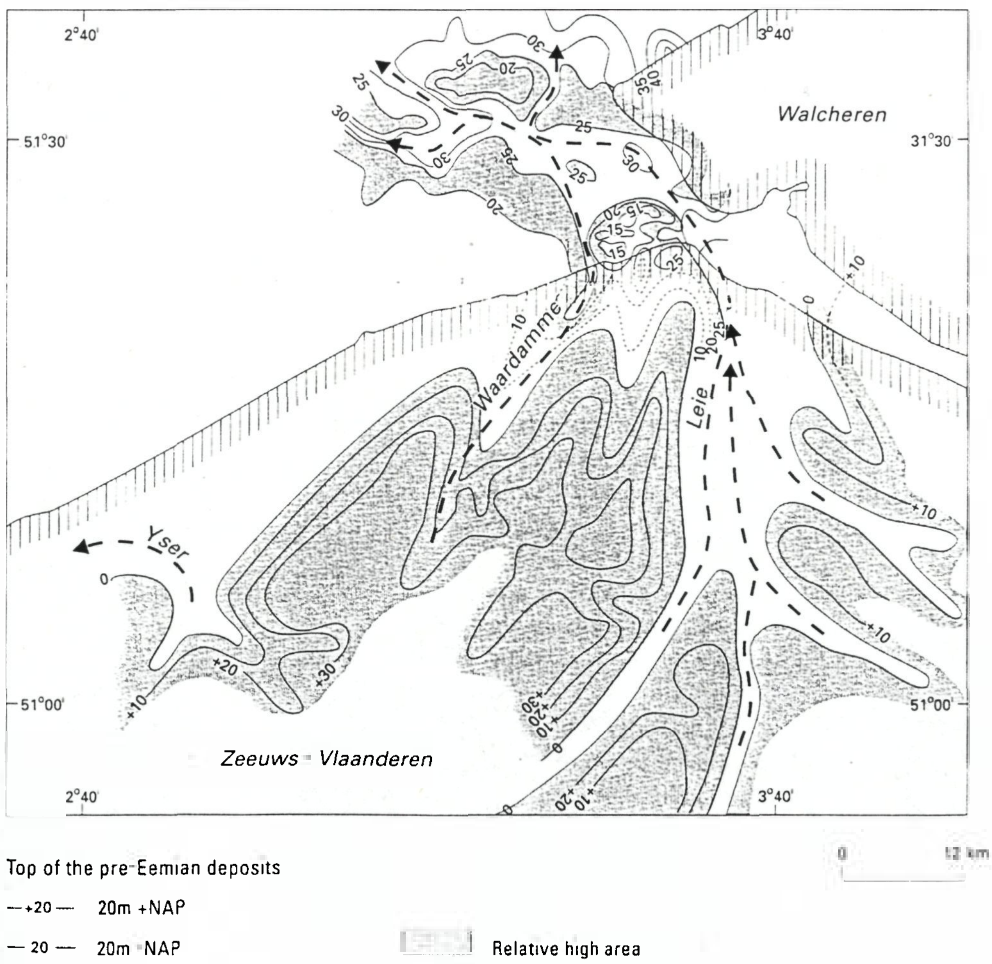


Figure 5
Composite contour map of the supposed Late Saalian morphology of the pre-Eemian, with the principle discharge directions of the Belgian rivers.
After Ebbing et al. (1993) and Tavenier & De Moor (1974).

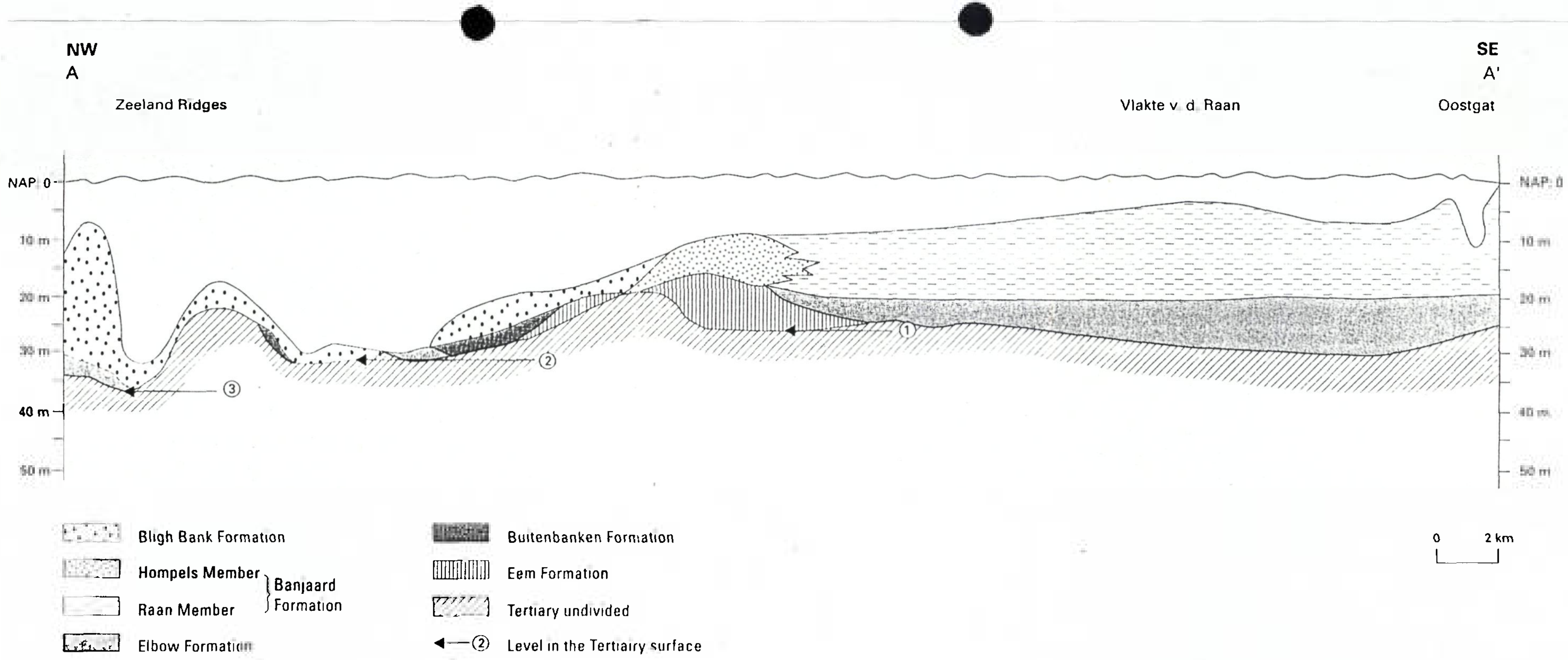


Figure 6
Geological profile A-A' running NE from the mouth of the Western Scheldt (SE). For location see Figure 1.

can be seen that the Eemian deposits are lying on at least two, but probably three, different levels, with differences in elevation of around 5 m due to escarpments in the Tertiary deposits. These escarpments are also visible in Figure 6, where also about three different levels in the Tertiary surface can also be distinguished. These terrace levels bear remnants of Eemian deposits (Figures 4 and 6). The escarpments may have induced a stepwise landward migration of the Eemian coastal barriers or shoreface during the Eemian transgression, behind which intertidal deposits could develop at the landward side. This migration was thus related to the stability of the Tertiary. This could yield information on the Eemian sea-level curve if an accurate dating tool for those deposits were available. Two pollen datings in the area under study (core S7-192 at -26 NAP and core S8-182 at -25.5 m NAP) both belong to the pollen zone E6 (Cleveringa, 1990 and De Jong, 1988) and fit fairly well in the high-tide level curve constructed by Zagwijn (1983), keeping in mind that peat datings are compared with clay datings obtained from inter-tidal deposits. Unfortunately, sufficient new data to improve the curve for this area are lacking.

4 Weichselian depositional history

In the study area the Twente Formation comprises, as stated, Weichselian periglacial deposits; offshore only a very small part of the supposed original formation is preserved (Figure 7); onshore the unit is extensively preserved, often with a thickness of more than ten or even twenty meters.

The Weichselian in the southern North Sea started with considerable erosion (Oele & Schüttenhelm, 1979), which explains the absence of a large part of the Eemian deposits (De Moor & Mostaert, 1988). Particularly the sandy intertidal deposits were relatively susceptible to erosion, preferentially leaving behind the gravelly and coarse-grained lag deposits of the Eem Formation. These remnants and the again re-exposed Tertiary erosional surface became covered by Weichselian sediments in some places. Aeolian and fluvio(peri)glacial sands, gravelly sands and lacustrine clays were reported from the southern North Sea area (Long et al, 1988). In the land area of Walcheren and Zeeuwsch-Vlaanderen predominantly periglacial aeolian sands, loam, and gyttja's were deposited (Van Rummelen,1965 & 1972), thus forming the Twente Formation. Evidence for these continental deposits in the offshore area is very scarce (Figure 7); only two of the cores studied - almost at the same position, taken near the mouth of the Western Scheldt (Figure 1) - contained the typical aeolian sands. It is difficult to prove whether sedimentation during the Weichselian extensively took place in the present offshore part of the study area.

During the Weichselian, aeolian sand was deposited on Zeeuwsch-Vlaanderen and Walcheren in SW-NE running ridges (Van Rummelen, 1965 & 1972). These ridges probably continued in the present offshore area, which implies that sedimentation of aeolian sands also took place in the triangle between Walcheren and Zeeuwsch-Vlaanderen (-Vlakte-van-de-Raan, see Figure 1). If aeolian sands, comparable to the deposits on land, were deposited in that triangle the erosion of them in that area must be explained. Certainly since, the absence of the Twente Formation in the offshore part is clearly shown on the composite map of the base of the Holocene (Figure 7). Almost only within the area where a -10 m (NAP) contour line is drawn, the Twente Formation was found in the subsurface. The postulated deposits of the Twente Formation in the above mentioned triangle (Vlakte-van-de-Raan) must have been eroded; probably the erosion took place during the first half of the Holocene transgression, since Subboreal deposits are found at a depth of at least 20 m (-NAP). This will be elucidated below. A sediment transport direction for the transgression to enter this area (Vlakte-van-de-Raan) has to be determined.

The deposits of the Twente Formation, especially the aeolian sands, form SW-NE running ridges on land as mentioned above. This direction is more or less the same as the direction of most river beds in the Flemish valley at the start of the Eemian (see Tavenier & De Moor, 1974). It is credible that, initially, those ridges had a rather strong influence on the drainage system of the area at the end of the Weichselian and during the Holocene, as shown by the course of the river Scheldt up to 800 BP (Zagwijn, 1986). The Waardamme and the Leie, however, possibly have flowed through the ridges near the mouth of the Western Scheldt during Late Weichselian or Early Holocene times, following the old Late Saalian to Eemian river bed system (Figure 5). This river system can be held partly responsible for the erosion of the aeolian sands and some of the remnants of the Eemian intertidal deposits. More important, however, it created a pathway for the Holocene transgression to enter this area preferentially. Evidence for such a scenario will be given below.

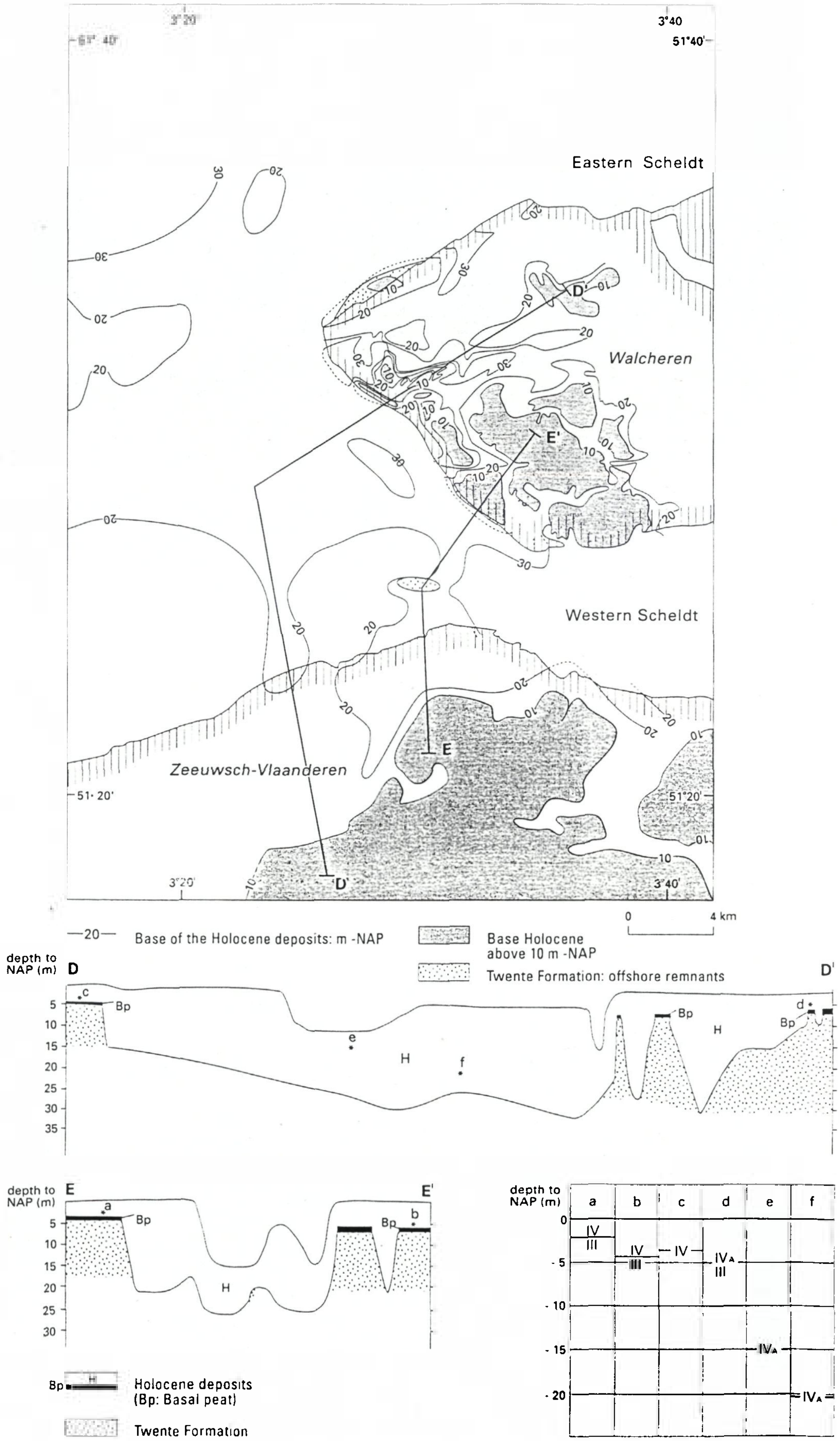
5 Holocene depositional history

Various formations together compose the Holocene deposits (Figure 2 and 3); nearly everywhere in the offshore area a cover of these young sediments is present, locally with a thickness up to 30 meters.

The Vlakte-van-de-Raan (Figures 1 and 6) is traditionally dealt with as a more or less uniform sedimentation basin behind coastal dunes, at least until 1900 BP, according to Zagwijn (1986), with salt marshes in which peat developed at the margin. Or rather as a lagoon behind a barrier during the Atlantic (De Jong et al.,1960). The mapping of the offshore part of the study area yielded new data, which prove that marine conditions had been present in that area at an earlier stage.

Several long cores (S10-118, S7-92, S8-182, S11-284: Figures 1 and 2) have been dated by pollen for this study

Figure 7
Composite map of the base of the Holocene, after Ebbing et al. (1993) and Van Rummelen (1965, 1972), with the offshore subcrops of the Twente Formation. Two profiles (D-D' and E-E') running through the area are displayed as well. The by lettering indicated positions in the profiles (e.g. a, b and c) show the relative depth of deposition of the Subboreal (pollen zone IV) sediments. A compilation of this data is given in the accompanying diagram: note the large discrepancy between the offshore and onshore sites. Cores e and f correspond to cores S11-193 and S11-284 in Figure 2.



(De Jong, 1988 , Cleveringa, 1990), older cores were dated before (De Jong, 1970). The results show in general a post-Roman age of the top part of the cores, with a maximum depth of ca. -20 m (NAP). The sediments of that age all were deposited in a wave-dominated outer ebb tidal delta environment (OTD, see Figure 2). Below that depth, or shallower (e.g.: in core S11-16 at -15 m NAP), marine sediments are present. It seems that the latter were deposited below the strong wave action in an outer delta environment (OD) with a Subboreal age (pollen zones IVa and IVb). On a profile running from NW to SE, into the mouth of the Western Scheldt, the Quaternary sediments on the Vlakte-van-de-Raan have been interpreted as belonging to the Banjaard Formation on top and below that to the Elbow Formation (Figure 6) (Ebbing et al, 1993). Offshore of the Vlakte-van-de-Raan studies have shown tidal-flat deposits (TF) (core S7-244: Figure 2) with an Atlantic age, and marine sand/clay deposits (MS) (cores S7-250, S7-246, S7-243: Figure 2) with a Subatlantic age (Cleveringa , 1990). The tidal flat deposits belong to the lower part of the Elbow Formation. The other cores contain sediments that can be characterized as recent marine sand or clay deposits, which are considered to be long to the Bligh Bank Formation.

The age of the outer delta deposits of the Elbow Formation in this area has been established as Subboreal (5000-3000 BP, see above), which fits well in the model of Eisma et al. (1981). These authors estimated that the southern area of the Dutch part of the North Sea was occupied by the sea only after 5500-5300 BP. Since the offshore sediments were deposited during the Subboreal, this could lead to the assumption that they correspond to the Calais Deposits on land. The Calais Deposits which were deposited in a tidal-flat environment contain peat and lagoonal sediments (Zagwijn, 1986). They are invariably shallow water deposits. In a tidal-flat setting only in the channels or tidal inlets deeper water deposits can be found. Although many of the Calais Deposits found on Walcheren are channel deposits (Van Rummelen, 1972). It seems unlikely that all dated cores in the offshore part were taken in old channel infills. In core S11-284 and in a part of core S8-182 there is sedimentological evidence pointing to a channel deposit during the Subboreal. This evidence is based on some distinct fining-upward sequences situated on top of each other (Figure 2). Core S11-193 also shows fining-upward sequences (Figure 2), belonging to a channel infill of Subboreal times. This core also contains an Eemian lag deposit, in this area often related to an old riverbed. The channel deposits represent outer delta channel infills, since the sea level at the start of the Subboreal was -5 m NAP and thus the channel infills are found well below the Subboreal sea level (see Figure 2). In all probability, the outer delta channels of Subboreal times used old riverbeds as "starting point" (core S11-193). In the case of core S11-193 (Figure 1), the location of the core points to the Waardamme (Figure 5) as being the river creating the bed. During the Subboreal the Scheldt was following a course flowing into the Eastern Scheldt (for location, see Figure 1). Steur and Ovaa (1960), who reported a reconstruction of the course of the Scheldt during pre-Roman and Roman times, concluded that during the pre-Roman transgression the coast remained closed between Zeeuwsch-Vlaanderen and Walcheren. Zagwijn (1986) concluded that that course persisted until after 800 BP. Vos (in prep.) has offered some evidence that a branch of the river Scheldt was already partially dewatering in a NE-SW direction through Walcheren during the Subboreal. Nevertheless, this would imply that it would work as a tributary of the above mentioned Waardamme. The other cores reaching into Subboreal deposits do not contain sedimentological evidence for a channel infill. A good example is core S10-118 (Figure 2), which contains in the Elbow Formation gray sands (d50: 125-260) with clay laminae and layers of Subboreal age. If during the Subboreal the offshore part (Vlakte-van-de-Raan) had been a tidal-flat environment the sediments in this core are deposited on a tidal-flat and not in a channel, they are, however, fairly coarse for such an environment.

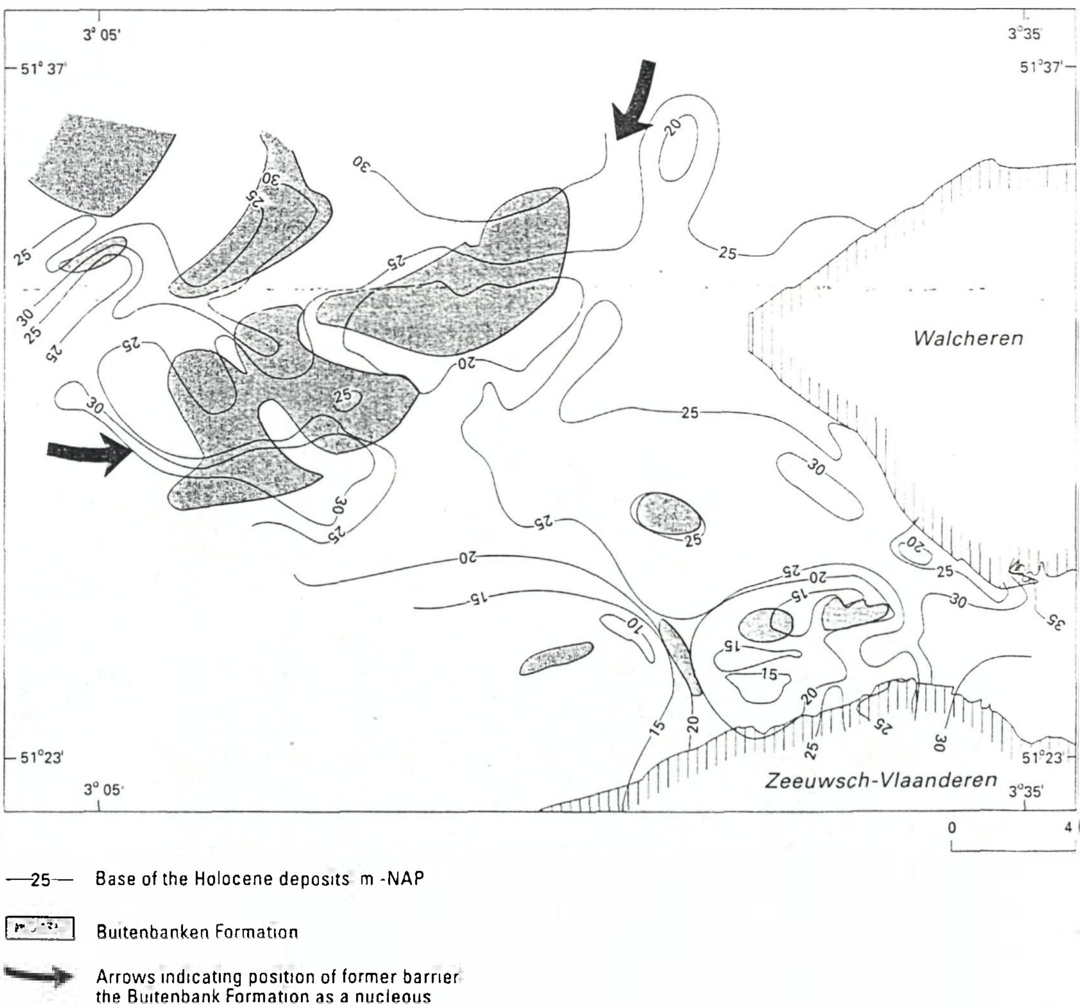
Now there is a discrepancy, as illustrated in Figure 7. Onshore Subboreal (pollen zone IV) peat deposits are found at 2-4 m (-NAP), formed at the Subboreal mean sea-level stand (locations a, b, c and d in Figure 7). In some cases (locations a, b and d) below this Subboreal peat, there are peat deposits with an Atlantic age (pollen zone III). In contrast, offshore "tidal-flat" deposits of Subboreal age at -20 m or -15 m (NAP) would be found at locations e and f in Figure 7 and in the cores S11-16 and S10-118 of Figure 1. Typically, tidal flats develop at shallow waterdepths and subaerially, and not in a waterdepth of 15 m. Furthermore, they usually show strong bioturbation.

It is now acceptable that deposits such as the gray sands in core S10-118 (Figure 2) belonged to an outer-delta setting during the Subboreal. This is supported by finding no evidence for strong bioturbation in the Subboreal deposits. This implies that at the moment of entering of the sea, about 5000 BP, an old riverbed system was drowned, where peat and/or tidal flats could not or could only marginally develop and erosion could start. The transgression must have eroded the remaining Late Pleistocene sediments substantially, thus creating an outer-delta setting. Peat could only develop further land inwards, where the Twente Formation maintained a topographic high (Figure 7). On land at location c (Figure 7) no peat layers of pollen zone III (Atlantic age) were found, but at the other land locations they occur. This would point to an ingression of the Late Atlantic sea from the north, as suggested by Zagwijn (1986), who stated that coastal dunes existed in front of the Vlakte-van-de-Raan (Figure 1). In conflict with his view, however, tidal flats or peat could only develop at a small scale behind a barrier. Since, the flooding of the sea during the Late Atlantic to Early Subboreal created an outer-delta environment, as postulated above. Pointing to an ingression of the sea coming from the northwest or west. Perhaps can this event also be linked to the breakthrough of the NE-SW running branch of the Scheldt, mentioned Vos (in prep.).

Additional evidence for deeper water deposits (5-15 m) in the offshore part of the study area can be found in the work of Eisma et al. (1981). These authors determined the chlorinity distribution for the Southern Bight during the Early and Middle Holocene based on ribbon countings of *Cerastoderma edule*. An interesting feature of their findings is the relatively high value (17 promil) found offshore of Schouwen and Walcheren (Vlakte-van-de-Raan, Figure 1) compared to that for the remaining southern part of the Dutch sector of the North Sea. Lower chlorinity values (10-16 promil) correspond to the intertidal zone and the higher values (16-18 promil) to zones lying below the strong wave action (water depth 5-15 m). This means that the Middle Holocene deposits in front of Walcheren must have been deposited in deeper water (5-15 m), which fits with an outer-delta environment.

The river system in front of Walcheren and Zeeuwsch-Vlaanderen, which was used as a starting point for erosion to create an outer-delta environment during Early Subboreal and perhaps also Late Atlantic times, was created at the end of the Weichselian or at the beginning of the Holocene by Belgian rivers, as already stated. The relicts of Eemian barriers as highs might have served as a nucleus for newly formed barriers, or even coastal dunes, during the Early Holocene. Analysis of the subcrops of the Buitenbanken Formation (Figure 8), an Early- to Middle Holocene deposit, shows that they overly the Eemian sediments. The composition of the former sediments suggests a reworking of the Eemian deposits. Thus, the same sediments served again as barriers and further land inwards as channel fills. These barriers and/or coastal dunes moved landward (possibly stepwise) during the Holocene transgression. The relicts of those barriers coincide with the edges of the already mentioned escarpments of the Tertiary (Figure 6). The last barrier system (indicated by an arrow in Figure 8) probably persisted until 5000 BP. After which the old river bed system behind it was invaded by the sea and reshaped into an outer delta. The date 5500-5300 BP is mentioned in the literature as the moment of flooding of the Vlakte-van-de-Raan by Eisma (1981), and Zagwijn (1986). This agrees quit well with the datings already mentioned in this study. Perhaps parts of those barriers are now incorporated into the Zee-

Figure 8
Map of the base of the Holocene, with superimposed the subcrops of the Buitenbanken Formation. The arrows indicate the last recognized barrier, which probably resisted the Holocene transgression until 5000 BP.



land Ridges (see Figure 1). Laban and Schuttenhelm (1981) found evidence for an "initial ridge" in the Schouwen Bank (20-30 m -NAP), overlying the Eem Formation, with an Early Atlantic to Atlantic age. That initial ridge could very well represent one of the escarpments that created a moment of standstill for the Holocene transgression. An other escarpment or standstill could be represented by the initial ridge of the Buitenbanken, found at 30-40 m below NAP, although at present no proof of this is available.

Offshore on the Vlakte-van-de-Raan (Figure 1) there is evidence obtained by pollen analysis in combination with shallow seismics, indicating an important post-Medieval transgression phase. This transgressional phase can be linked to the final breakthrough of the river Scheldt allowing it to reach its present position as the Western Scheldt. Various pollen analyses (Cleveringa, 1990; De Jong, 1988) have shown that at least the top few meters of the sediments (e.g.: core S10-118, S8-182, S11-284, see Figure 1) on the landward side of the Zeeland ridges are of Late Medieval age. On a seismic line (Figure 1, B-B'), which runs over the Vlakte-van-de-Raan, there is an erosional surface visible below which an infilled gully system occurs (Figure 9). This system probably belongs to an environment of salt marshes with gullies, which existed there for several centuries as postulated by Ovaa (1971). With the help of cores (S11-284 and S10-118) this erosional surface could be approximately dated. It is probably of Medieval age (1300 BP), see the pollen diagram of core S11-284 (47F23-1) in Figure 10, and can be reconstructed at several places in the nearshore area (Ebbing et al, 1993).

Another interesting feature of the seismic line in Figure 9 is the evidence of the landward migration of the Oostgat, a depression (old tidal channel?) present off the southwest coast of Walcheren, since Medieval times. This fits with the observation of Trimpe Burger (1960), who found evidence for the disappearance of a settlement on Walcheren under the landward moving dunes at 1000 BP (thus probably accompanied by a landward movement of the shoreface). On the seismic line the major channel infill below the erosional surface (Figure 9) might be linked to the course of a major tidal channel during Roman times and earlier, which coincides with the position of the former riverbed of the Waardamme (see Figure 5).

Proof for a breakthrough of the Scheldt during Medieval times can be found in the increased fresh-water influence indicated by Ostracod assemblages in the top of the Banjaard Formation (Verbeek, 1977a-c). This agrees with Zagwijn (1986) who concluded that the Scheldt followed it's old course until after 800 BP.

6 Conclusions

The Eemian terraces known from the Flemish Valley can also be recognized in the part off Walcheren and Zeeuwsch-Vlaanderen. There, three of them are linked to the old Tertiary morphology with escarpments of around 5 m each and these probably had a barrier function. More landward, the Eemian deposits are fluviatile infills of pre-existing riverbeds. Former Pleistocene rivers created the river system belonging to the so called Flemish Valley. The Eemian ended with intertidal deposits.

Especially these intertidal deposits were eroded during the Early Weichselian. Then the deposition of predominantly aeolian sands took place. The aeolian sequence was partially eroded again during the Late Weichselian and at the onset of the Holocene by rivers (Waardamme and Leie) using the old riverbed system.

When the Holocene transgression flooded the Vlakte van de Raan, around 5000 BP, it eroded and reworked remaining parts of the Late Pleistocene deposits and deposited outer delta sediments during the Subboreal. For its in-

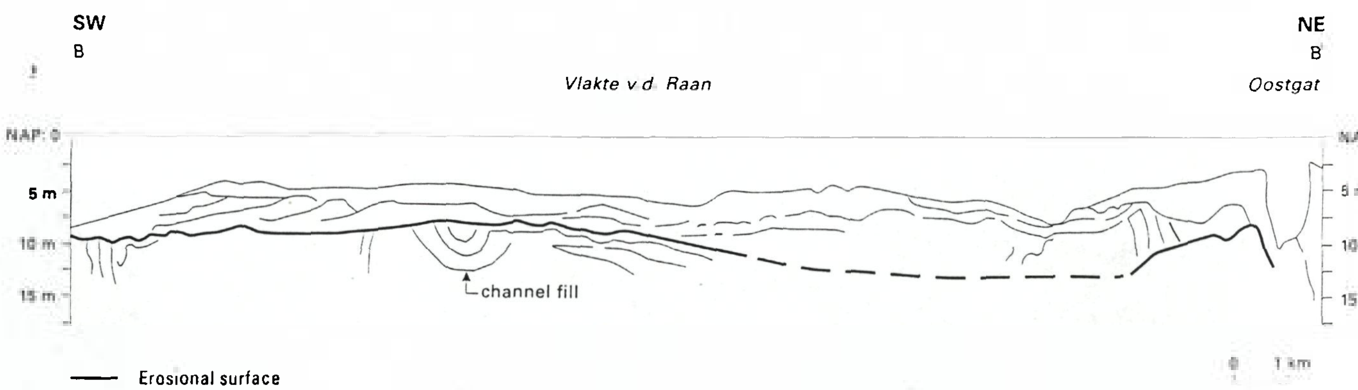


Figure 9

Seismic cross-section B-B'. Displayed is an erosional surface of Medieval times and below that surface a channel infill belonging to a former creek in an environment of salt marshes. To the northeast, above the Medieval surface, seismic features are representing a landward movement of the Oostgat.

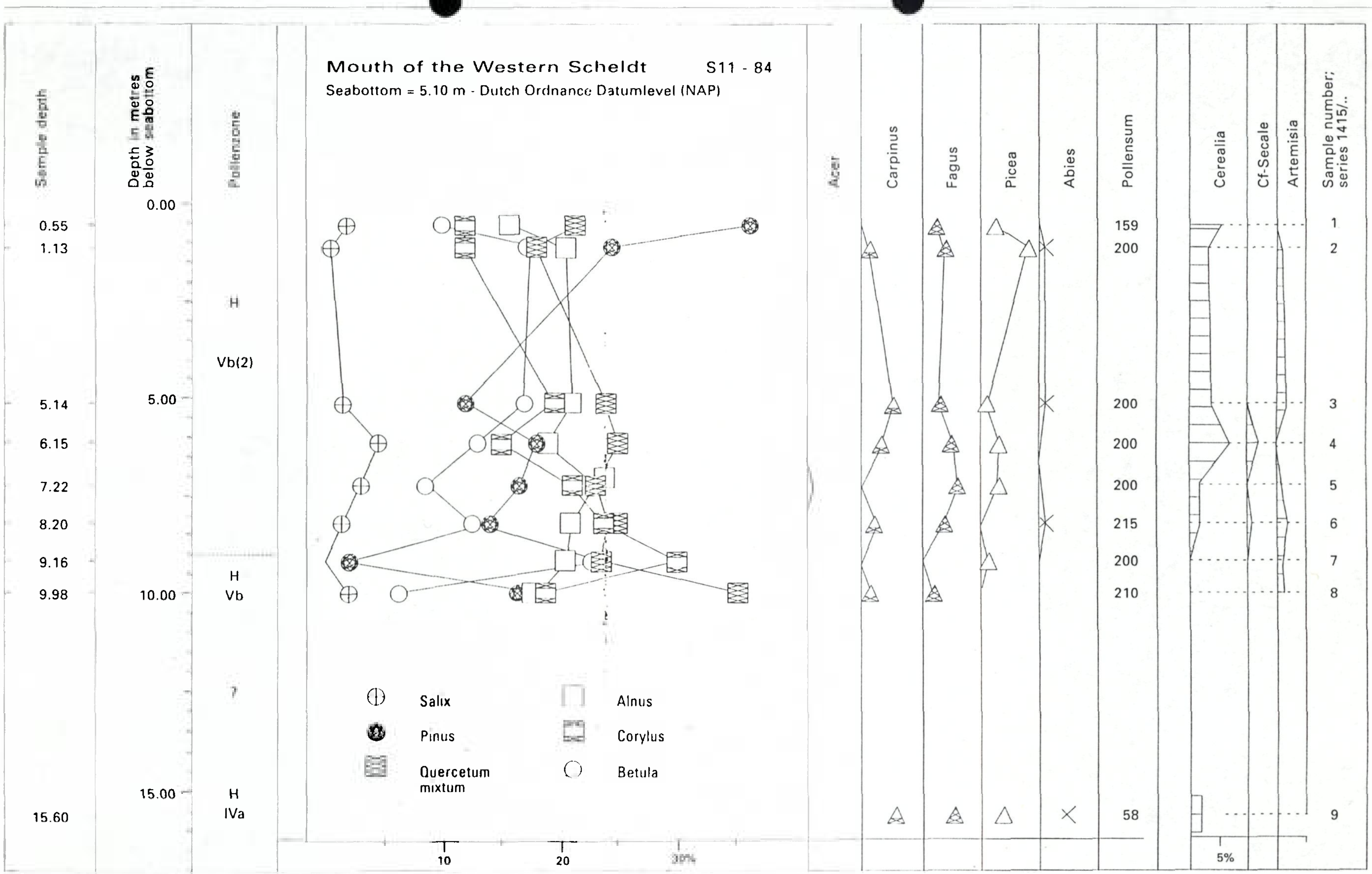


Figure 10

Pollen diagram of core S11-284 (for location, see Figure 1). The presence of Abies, Carpinus, Fagus, Picea and Cereals (e.g. Cerealia and cf-Secale) in the spectra of the upper part of the diagram (0.00-8.20 m) contrast with the lower spectra. On the basis of these pollen data the erosional surface in Figure 9 can be dated.

gression, the old riverbed system was used once again. Linked to this transgression a landward movement of barriers can be postulated, which was perhaps related to the Tertiary escarpments already mentioned. As soon as the outer delta was filled, an outer ebb tidal delta could develop after the onset of the Subatlantic. In these deposits an erosional surface of Medieval times was discovered, which can be linked to the final breakthrough of the river Scheldt into this area.

An additional result of this study is that a correlation diagram, mainly based on pollen analysis, can be drawn concerning the stratigraphy of the studied offshore and adjacent onshore areas: Figure 11.

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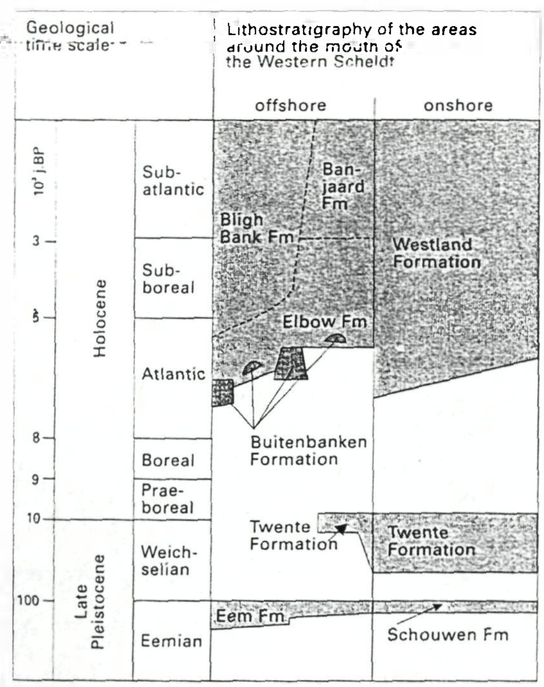

Figure 11

Correlation diagram of the lithostratigraphic systems used in the described offshore and adjacent onshore areas.

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