Contr. Tert. Quatern. Geol. 36(1-4) 59-72 15 figs, 1 tab Leiden, December 1999

THE CAMPINE CLAYS AND SANDS IN NORTHERN BELGIUM: A DEPOSITIONAL MODEL RELATED TO SEA LEVEL FLUCTUATIONS

FRIEDA BOGEMANS
Vrije Universiteit
Brussels, Belgium

Bogemans, Frieda. The Campine Clays and Sands in northern Belgium: a depositional model related to sea level fluctuations. — Contr. Tert. Quatern. Geol., 36(1-4): 59-72, 15 figs, 1 tab. Leiden, December 1999.

The first in a series of contributions on Quaternary deposits in the northern Campine area (Belgium), the present paper discusses the conditions of deposition and processes involved, as well as a reconstruction of sedimentary palaeoenvironments and the stratigraphic position of these strata within the Quaternary sequence. Only the sedimentary characteristics of the lowermost portion of these deposits are outlined; these consist of sandy-clayey sediments, reaching a thickness of more than 40 metres. Five sedimentological units are recognised; each unit accumulated either in an estuarine or in a fluvial-aeolian environment. The succession of palaeoenvironments occurs in an alternating pattern, with fluvial-aeolian deposits following upon estuarine strata. The transitions between these are primarily the result of sea level fluctuations within that particular stratigraphic interval. In contrast, the continuous evolution within estuarine deposits is tectonically induced.

Key words — Lower quaternary, estuarine environment, fluvial and aeolian deposits, sea level fluctuations.

Dr F. Bogemans, Vrije Universiteit Brussel, Department of Geography, Pleinlaan 2, B-1050 Brussels, Belgium.

CONTENTS

INTRODUCTION

The lowermost portion of the Quaternary sequence in the northern Campine area, known as the Campine Clays and Sands (Tavernier, 1942, 1954; Paepe & Vanhoorne, 1970, 1976), has been a matter of dispute for over a century. These strata consist of sandy and clayey sediments, and reach a thickness of more than 40 metres in most areas (Bogemans, 1994, 1997, 1998). The controversy concerns both the genesis and stratigraphic position of these deposits. In the present paper, an attempt is made to reconstruct their origin and the evolution of the sedimentary environment within the interval represented. The stratigraphic position of these strata within the Quaternary sequence will discussed in full in a forthcoming paper.

Delvaux (1891) was one of the first to present an interpretation of these deposits; he first of all pointed out that they displayed a complex composition. In addition to clay also sand, gravel and an alternation of sandy and clayey sediments were observed. Delvaux interpreted these as part of a vast delta, in which constant physical changes occurred; either marine or fluvial conditions predominated.

Rutot (1897) elaborated on Delvaux's data, and assigned these deposits to a fluvio-lagoonal environment, formed in the Meuse delta.

Lorié's (1907) work is a milestone in geological studies of the Campine area. On the basis of field work data collected in 46 clay pits, he introduced four lithological units, discussed their mutual relationship and reconstructed the palaeosedimentary setting. With the exception of the uppermost unit, which was considered to be marine in origin, Lorié favoured an estuarine depositional environment.

A change in the interpretation of the Campine area deposits came with Tavernier's (1942, 1954) papers: no longer were these considered to be estuarine or marine, but fluvial. How he arrived at this conclusion is not explained in the cited papers.

Dricot (1961) rejected this interpretation. The large concentration of Chenopodiaceae, in combination with phanerogamic halophytes, that occur in the clay facies suggests the vicinity of a coast, more precisely of a salt marsh. Besides, granulometric characteristics and bioturbation traces in the underlying micaceous stratified fine sand pointed to a tidal flat depositional environment.

Paepe & Vanhoorne (1970) bundled a series of observations made in several clay pits, down to depths of 10 metres. Two clay units were introduced, separated by a sand unit. In the uppermost clay unit at least three phases of deposition were found to be distinguishable. These are separated by phases of gully incisions, infill and peat formation. The whole series is situated in a tidal flat environment. The underlying sand unit is of fluvial and aeolian origin and is typified by peat horizons and periglacial phenomena. The lowermost clay unit has sedimentary features identical to those of the uppermost unit; here only two clay members were observed.

Geys (1975, 1978) again introduced the fluvial origin interpretation, on the basis of granulometric analyses together with microscopy of quartz grain morphology. His conclusions, however, lack accuracy.

The most recent work is that of Kasse (1988, 1990), who followed the tripartite subdivision introduced by Paepe & Vanhoorne (1970, 1976), as well as their genetic interpretation, although he went into more detail here. On the basis of a study of heavy minerals, Kasse concluded that both the upper and lower 'clay' units had an unstable heavy mineral association, supplied by the River Rhine. A stable heavy mineral association, derived from central Belgium by rivers such as the Scheldt typifies the intercalated unit. His observations involved a section to depths of more or less 30 metres, so that still portions of the Campine Clays and Sands were not reached and remained uninterpreted.

STUDY AREA

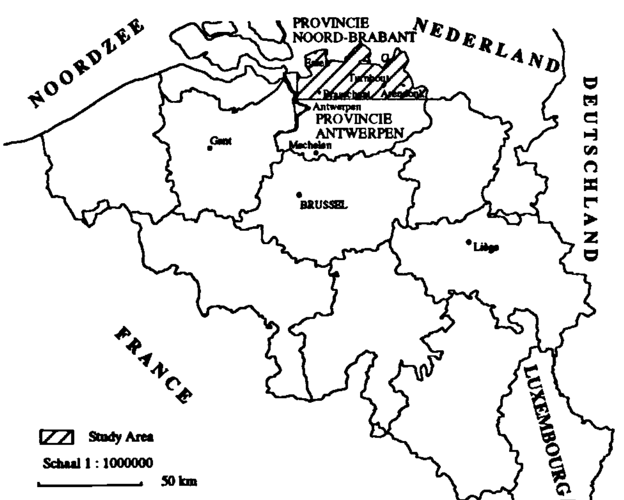


Fig. 1. Location of the study area.

The study area is situated in northern Belgium, in the province of Antwerp (Fig. 1), being known as the northern Campine area, with the Netherlands (province of Noord-Brabant) bordering in the north. In the southern Netherlands and northern Belgium the Campine Clays and Sands predominate in the Quaternary sequence.

With the exception of the most southeasterly part of the study area, the Cenozoic substratum is the Lillo Formation (de Meuter & Laga, 1976), which consists of grey and greyish brown shelly sands. The lower part is clayey and contains several shell layers. In the upper part, clay content gradually decreases as does the shell content. In the southeasterly part of the area either the Poederlee or Mol formations form the upper part of the Cenozoic sequence. The Poederlee Formation is a fine, slightly glauconitic sand with small lenses of clay in the lower part, and a base of gravel of rounded quartz, flint and silicified carbonates. The upper part is occasionally strongly oxidised and contains limonitic sandstones with shell moulds. The Mol Formation contains pure white medium-fine to coarse sands, with lignitic horizons and lenses of micaceous clay; these are the famous quartz sands used in the glass industry.

In between the above-mentioned Cenozoic substratum and the Campine Clays and Sands is the Merksplas Formation (de Meuter & Laga, 1976; Bogemans, 1994, 1997, 1998), consisting of grey, medium- to coarse sands, sporadically medium fine (180-250 μm), occasionally containing gravel, shells and shell fragments. Silty to clayey lenses or layers, whether or not organic, as well as wood fragments are scattered all over facies (Bogemans, 1994).

The most easterly part of the study area is situated in the border region of the Roer Valley Graben, which started to develop during the Cenozoic in response to the Alpine stress regime (Ziegler, 1978). Tectonic units which have a direct impact on the geological history of the area are the Eastern and Western Campine Blocks, which are regions of intermediate subsidence to the west and southwest of the graben (Geluk *et al.*, 1994). As a consequence, sedimentary thickness in the study area remained rather limited in comparison to the active graben itself.

DESCRIPTION SEDIMENTOLOGICAL UNITS

Unit A - a sandy complex

Unit A is the lowermost member of the Campine Clays and Sands, and is present all over the study area, reaching a thickness of 30 metres. This sandy complex has a grain size distribution ranging from very fine to medium fine sand, medium sand being less common. In some restricted places, mud deposits dominate. Besides typical minerals such as micas and glauconite, also vegetation remains, peaty dots, peat lumps and wood fragments are part of the general composition of Unit A. Within this unit two distinct facies are recognised:

— *Facies I*: consists of very fine to medium fine sand, in which particles less than 63 μm are distinct. These are deposited as layers or are part of a stratum, the latter forming wavy bedding or flasers (Fig. 2).

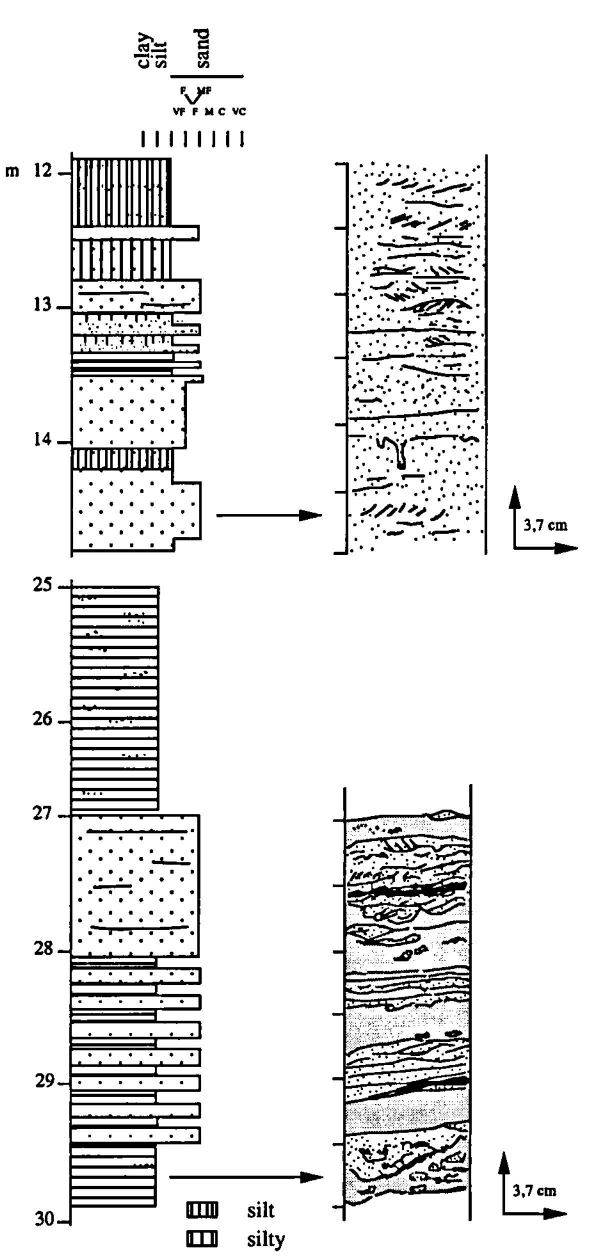


Fig. 2. Sedimentological description of Facies I of Unit A; for legend see appendix.

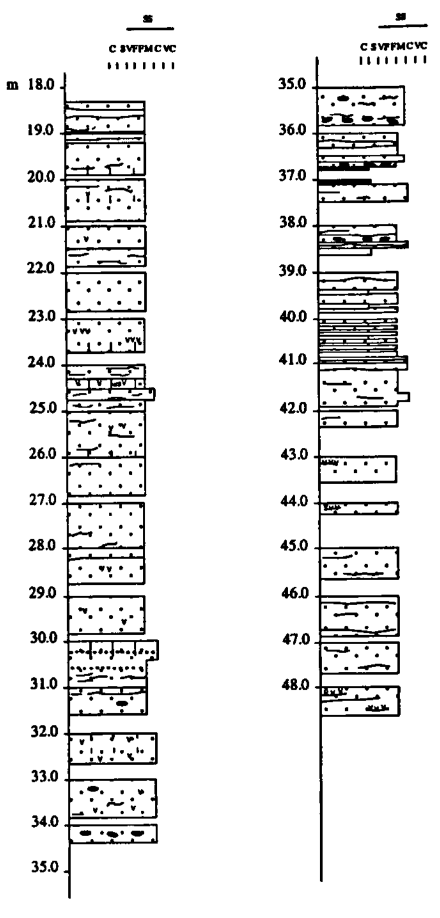


Fig. 3. Sedimentological description of Facies II of Unit A; for legend see appendix.

Other typical structures are horizontal stratification, massive bedding, and low-angle and planar cross stratification. The orientation of planar cross stratification changes over limited depths. Scour structures, microfaults and deformation structures also are very common. Less frequent are bioturbation traces, small-scale ripple bedding and organic horizons. As noted above, in some restricted places of the study area this facies is predominantly a clay facies, massive or with lenticular or wavy bedding. In the wavy-bedded parts load casts may occur. Bioturbation traces are rather uncommon.

— *Facies II*: may be very thick (Fig. 3), with sand generally fine to medium fine. Medium sand, if present, is in a basal position, occasionally resulting in fining-up sequences. The wavy bedding as well as flasers are strongly reduced. The horizontal stratification and planar cross bedding are occasionally vague and contain water escape structures. Very typical in this facies is the presence of several reactivation surfaces. Where this facies is found at the top of Unit A, a soil horizon is sometimes developed.

Unit B - a complex of fining-up successions

Resting on top of Unit A, this unit is restricted to the southerly portion of the study area and may reach a thickness of 9 metres there. It consists of fining-up successions the number of which ranges from 2 to more than 7, with the mean vertical extension of a succession being 1 metre. Apart from the topmost part the greatest portion of the succession is composed of fine to medium-fine sand, with homogeneous sand being rather exceptional. There is a continuous transition from one sand fraction to another. A poor degree of sorting is further induced by large amount of silt and clay particles. Glauconite is very common, although the concentration limited; in contrast, micas are virtually absent. Different types of cross bedding together with convolutions are the typical sedimentary structures (Fig. 4).

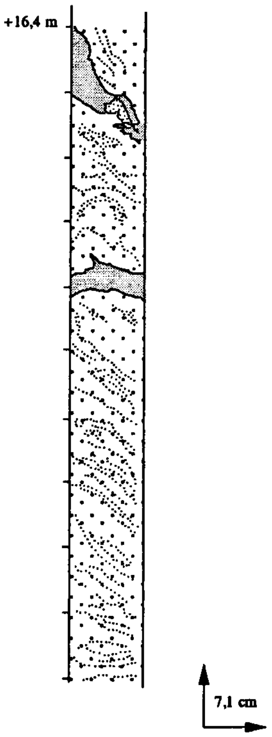


Fig. 4. Typical sedimentation pattern of deposits of Unit B.

The convoluted bedding is frequently related to loamy layers. In the basal portion bioturbation traces occasionally occur. The uppermost layer of a succession consists of fine clastic material, ranging from very fine sand to clay. In both clayey and sandy top layers, peat, vegetation remains and relicts of pedogenic processes may occur (Fig. 4). A sandy top is either homogeneous or contains finer-grained clastic layers. In the contact zone between the uppermost layer and the underlying sediments deformation structures may occur.

Unit C - a clayey/sandy complex

If Unit B is present, Unit C lies directly on top of that, otherwise it rests on Unit A. Although in a restricted region of the study area, a funnel-shaped depression in the vicinity of Ballematen, the thickness of Unit C attains 20 metres, the commoner thickness ranging from 5 to 10 metres. In general, two sedimentation cycles are observed in this unit, except for the funnel-shaped depression, where three cycles succeed each other. Apart from the northerly, the most southerly and easterly portions of the area, the fraction smaller than 63μm is distinct in this unit. Sediments are micaceous, glauconite being less common.

— *Facies I*: is restricted to the funnel-shaped depression; the infilling material is predominantly silty and, contrary to expectation, calcareous. Within the depression both grain size distribution and sedimentary structures change depending on location. In the southerly part, massive and lenticularly stratified mud deposits are observed, together with some obliquely to subhorizontally laminated, wavy mud layers with clear lower bounding surfaces. At some levels, heterogeneous sand deposits intercalate. The typical sedimentary structures in these sands are horizontal stratification, massive bedding and planar cross stratification.

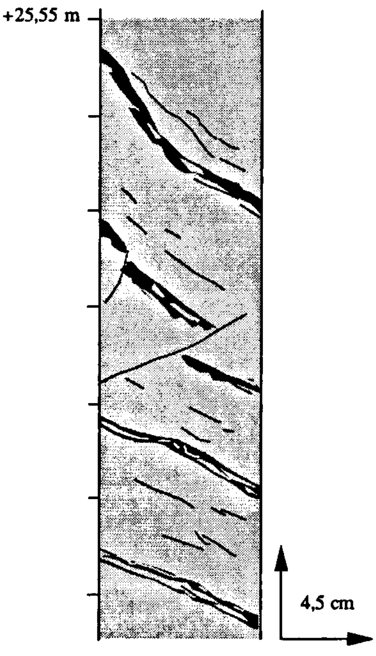


Fig. 5. Paler and darker zones in the mud deposits of Facies I of Unit C, with microfaults.

Very typical for the southerly and central portions of the depression are paler and darker zones (Fig. 5) within the mud deposits, just as the alternating complexes of greyish brown, medium-fine sand layers and grey, stratified clayey silt layers in which vertically oriented vegetation remains and dessication cracks occur (Fig. 6). In the mud deposits, microfaults are quite common (Fig. 5). As in the northerly part of the depression, sand input increases in the mud deposits, wavy and lenticular bedding becoming the dominant stratification. Within the ripples foresets are preserved, and show bidirectional orientations. The sand layers present in this part of the depression show identical sedimentary structures. Locally, large concentrations of loadcast structures exist. Less frequent, but more vertically extended, are chaotic deformations composed of sand and mud. Bioturbation traces are not common at all.

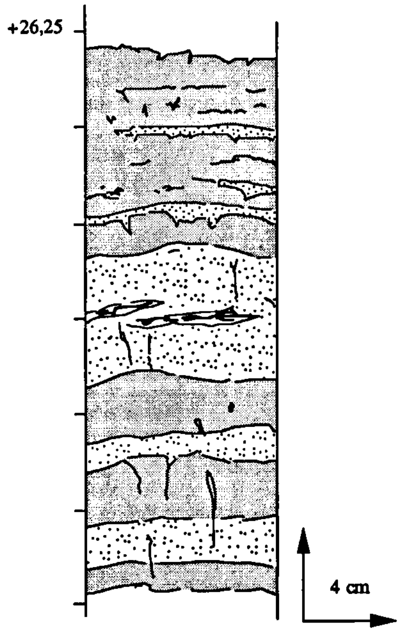


Fig. 6. Vertically oriented vegetation remains and dessication cracks within Facies I of Unit C.

— *Facies II*: is generally distributed in the area, and is composed of a clayey-sandy, non-calcareous micaceous complex. Vegetation remains and wood fragments are quite common, but occur in rather small amounts. Localisation within the study area determines the sandy or clayey nature of the complex. In the central part, clayey sediments prevail (Fig. 7), while in other areas sandy sediment predominate. In a clayey complex, deposits consist of mainly grey to bluish grey clay, silty or not. The prevailing structures are massive bedding, lenticular and wavy bedding with some deformation structures (Fig. 8). Small sets of alternating clay and sand layers, with a dominance of sand layers, also are common. In a predominantly sandy complex the texture of the sand ranges between very fine and medium fine. In restricted places, however, a coarser sand fraction is observed, mostly in the basal position of the facies. The stratification is massive, subhorizontal to planar, the latter with changing orientations, either curved or not.

Unit D - a sand complex with several soil horizons

This unit has a very restricted distribution, being limited to the vicinity of Merksplas, Rijkevorsel, Malle, Beerse and Oud-Turnhout (Fig. 9). Although the thickness is between 1.5 and 3 m., the depositional sequence is rather intricate. Two lithofacies are distinguished, always in the same order. One of the two, however, may be absent:

— *Facies I (lowermost facies)*: consists of fining-up successions, with the formation of a succession invariably preceded by an erosional phase.

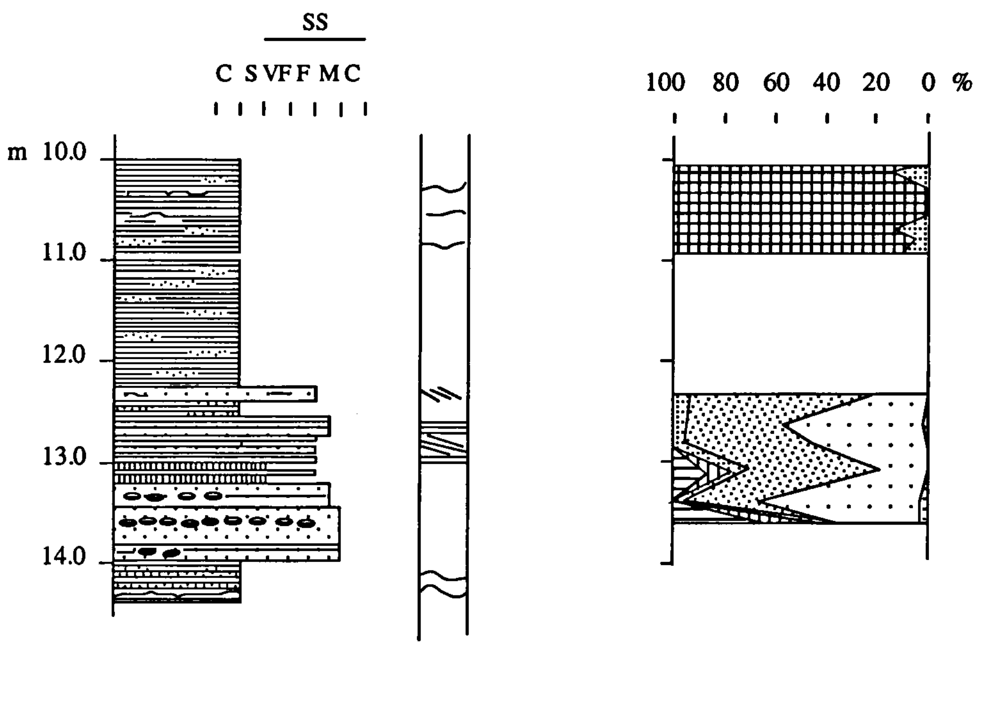


Fig. 7. Sedimentological description of a predominantly clayey complex of Unit C; for legend see appendix.

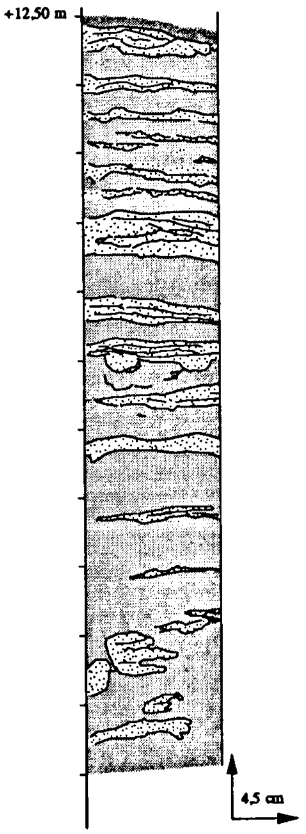


Fig. 8. A detail of the prevailing structures within a clayey complex of Unit C.

The coarsest fraction consists of medium-fine sand and constitutes with fine sand the greatest part of a succession. The stratification varies from continuous, even horizontal to continous and discontinuous slightly oblique to wavy bedded. A lot of deformation structures, such as dewatering structures, slumping and convolutions, appear. Also typical are vegetation remains, which may either have accumulated simultaneously with the deposition of clastic sediments or be preserved in growing position. The top facies of a succession comprises clayey silt, silt or black sand, the last-named compacted. Peaty material, either deformed or not, is quite common (Fig. 10). Ripple bedding and convolutions are the dominant sedimentary structures; highly interesting also is the presence of frost cracks and wedges.

— *Facies II* (*uppermost facies*): is preceded by a limited erosional phase; the lowermost bed is made up of sand, slightly silty at the base with diffuse horizontal to massive bedding (C) (Fig. 11). On top of this follows a podsol, which is also cryoturbated (D). In these deposits frost cracks which are formed in the superimposed layers are present. On top of the podsol is a unit composed of loam at the base followed by an alternating complex of sand and loam layers (E). The whole unit is wavy stratified. These sediments were post-depositionally modified by secondary displacements and deformations. Large epigenetic frost cracks are observed in these deposits.

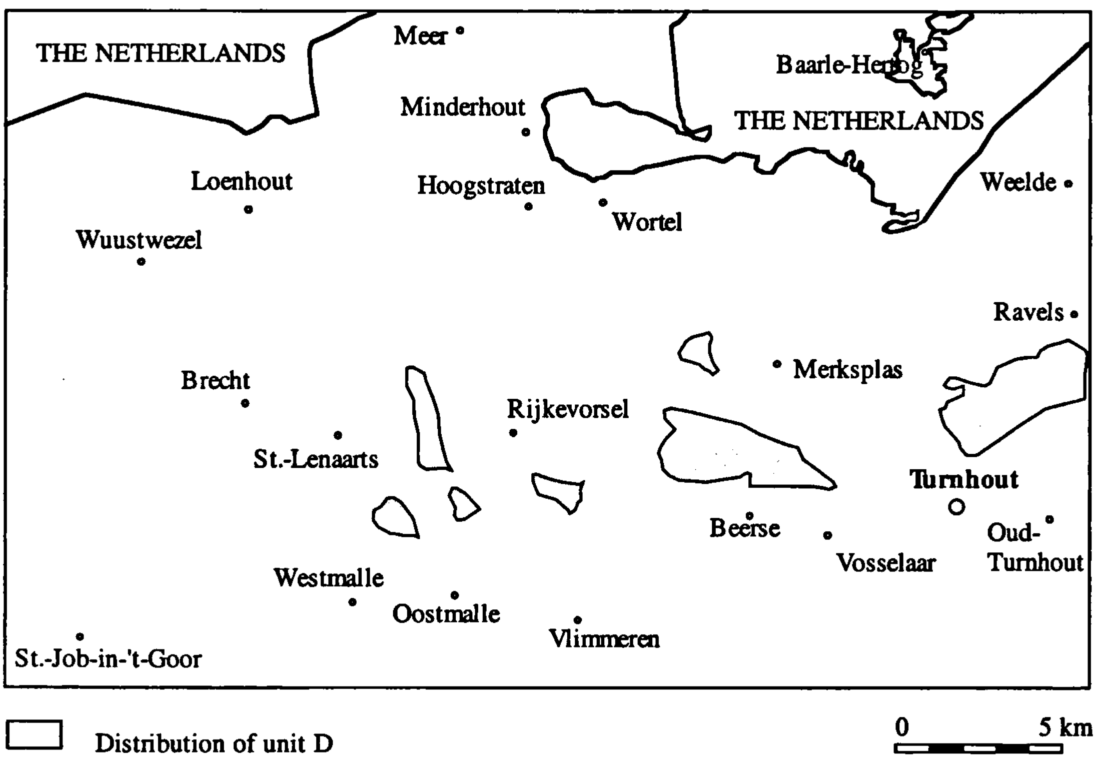


Fig. 9. Illustration of the limited distribution of Unit D (topographic map Turnhout no. 8, scale 1:50 000).

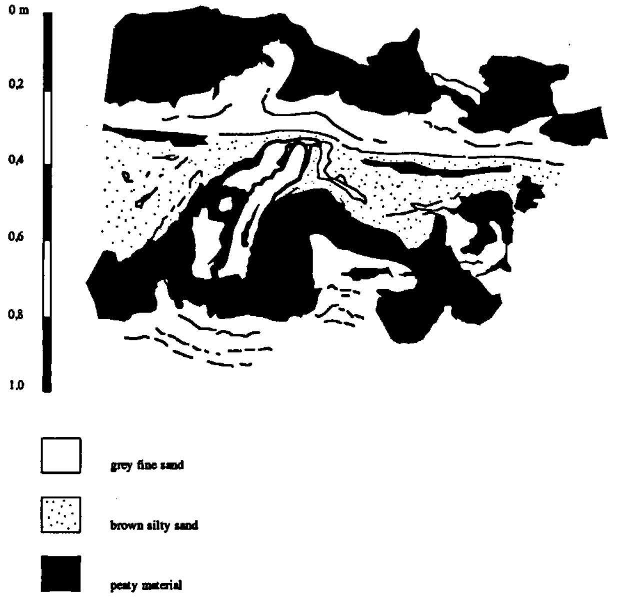
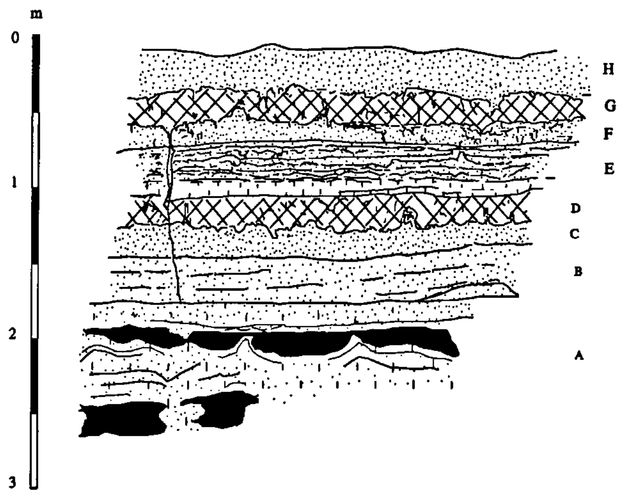


Fig. 10. Close-up of deformation structures within the peaty material of Unit D.



The following unit (F) is composed of a subhorizontally stratified grey, fine sand layer at the base, followed by brown compacted slighty silty sand which corresponds with the B horizon of a podsol. Within this unit, pale sand intercalations both horizontal and vertically oriented, occur of which a decrease in concentration towards the base is recorded. The frost cracks, which are formed superimposed on the older ones, are confined to the sediments below the B horizon.

Unit E - a clayey/sandy complex

Unit E is the uppermost unit of the Campine Clays and Sands. If Unit D is present, Unit E lies directly on this, or, rests on Unit C. Its distribution area is more limited to the south in comparison to that of Unit C. Generally, the thickness of these deposits increases in a northerly direction. Four to five metres in the south, to 10 metres and more, as in the central part of its distribution area. Unit E is predominantly a fine-grained, micaceous non-calcareous complex in which the silt fraction is strongly limited. The clay deposits are massive, subhorizontal and lenticularly stratified, more limited is wavy bedding. The lenticular and wavy bedding are composed of clay, fine sand and/or coarse silt. In the clay deposits appear also continuous and discontinuous sand layers, with internal stratification in the thicker layers (Fig. 12). Typical within the clay deposits are one or several organic horizons or soil horizons. Moreover, small vegetation remains are scattered all over the clay facies. Bioturbation traces are quite common, but with varying density (Fig. 13).

Deformation structures with a predominance of load casts in the wavy-bedded deposits and intricate deformation structures in the massive and lenticular-bedded facies are also noted. The sandy deposits, if present, have a grain size distribution ranging from very fine to medium fine. The massive, horizontal even and oblique, slightly wavy stratification prevail, whereas foresets and ripple laminations are much less common. The clayey intercalations in these sandy deposits are present either as discontinuous and continuous oblique to subhorizontal layers or as pebbles and lenses. Deformation structures through water expulsion, just as bioturbation traces, microfaults and organic horizons are observed in the sand deposits.

RECONSTRUCTION OF DEPOSITIONAL ENVIRONMENTS

Sedimentological characteristics of Unit A suggest a tidally dominated estuarine environment. The first depositional facies (facies I) is composed of strata formed on sand flats, mudflats (higher and lower mudflats, see Evans, 1965), or in gullies, the latter with or without bar deposits and, to a lesser degree, consists of salt marsh deposits. However, one of the tidal subenvironments may dominate the sequence. Facies II is composed mainly of sediments which accumulated as intertidal sand bodies and sand flats. Within Unit A, two types of sequences are observed: one composed mainly of fining-up cycles, and another dominated by a coarsening-up cycle. In the latter case, a fining-up succession may be present in a basal position. The coarsening-up cycle is restricted to an easterly depression (located on sheet Turnhout, map scale 1:50000) and is composed of mudflat deposits and occasionally salt marsh deposits at the base, followed by channel deposits and sand bar deposits at the top.

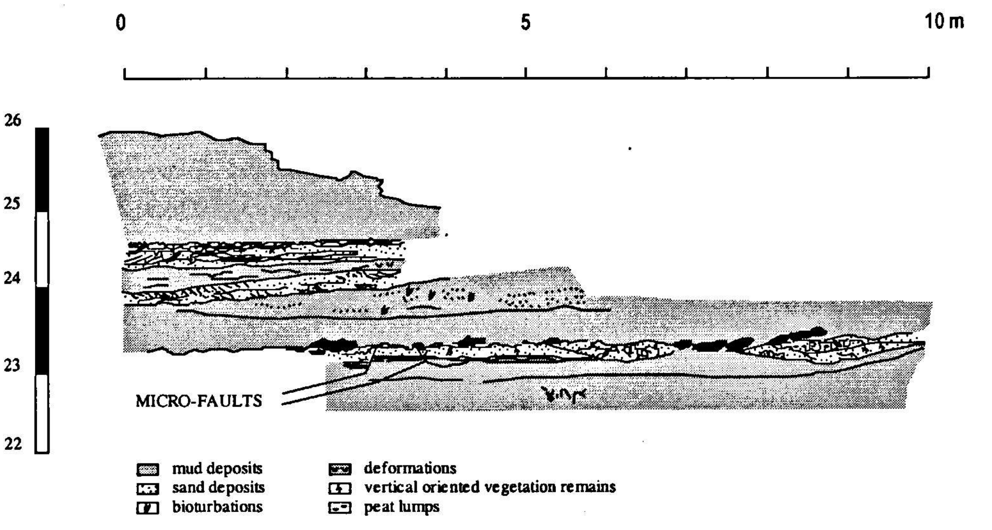


Fig. 12. A cross-section through a clayey complex of Unit E.

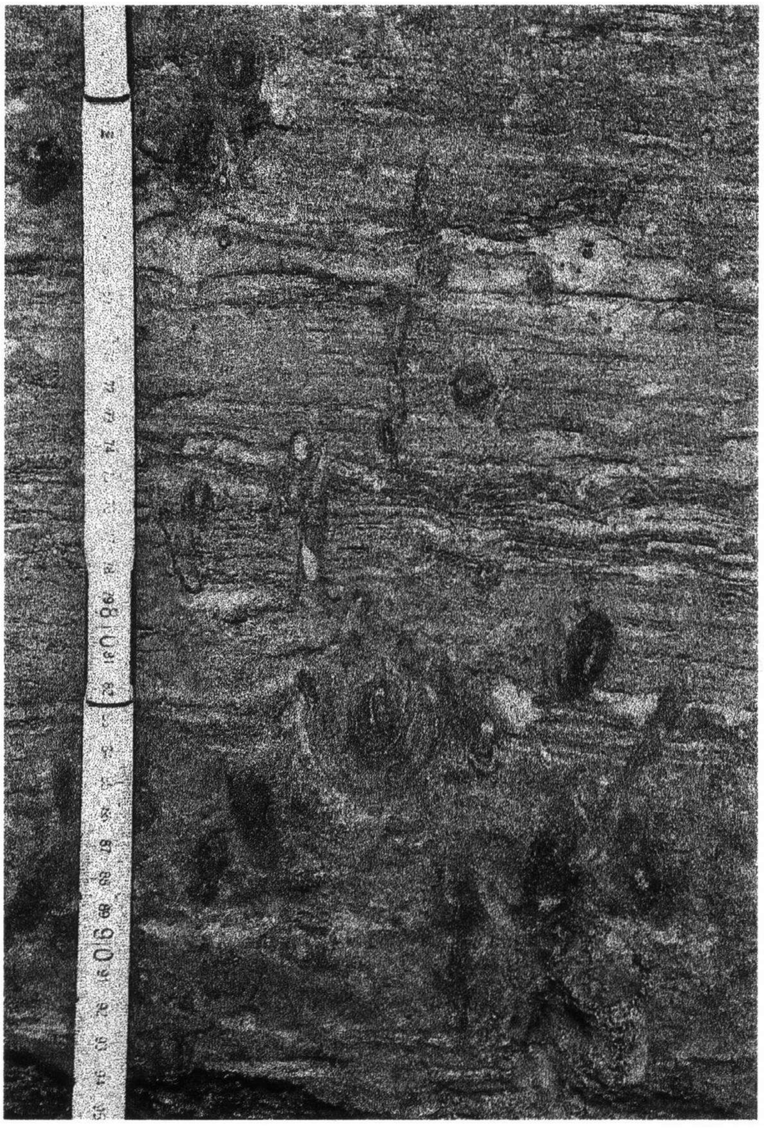


Fig. 13. Typical bioturbation found in Unit E.

The fining-up cycles consist mainly of sand flat and intertidal sand body deposits in a basal position and superimposed by finer-grained deposits in a progradational order. Salt marsh deposits are rather exceptional.

The sedimentary structures described for Unit B are typical of a fluvial environment in which downstream accretion elements (Miall, 1996) prevail. Since this depositional unit consists of a succession of bars, the lateral migration of the fluvial system in question was probably limited whereas downstream migration of the bars predominated. The convolutions present in the sand deposits most probably formed due to partial liquefaction of water-saturated sediments as the result of migration of large bedforms over unconsolidated sandy sediments during high-flow stages (Plint, 1983), rather than represent the result of a combination of disintegration of organic matter and presence of loamy material (Barwis, 1978). The deformation structures observed at the contact zone between the uppermost bed and the underlying sediments are ascribed to fast uprising bars, with water expulsion taking place (Singh, 1977); dewatering pipes may form. These data together with the limited extension of the successions point to a braided character of the fluvial system, to a perennial sandy braided river system. Because most top facies are preserved, accumulation most probably was the dominant process in this environment.

On the basis of sedimentary structures the two facies of Unit C are interpreted as having been deposited in a tidally dominated estuary. The spatial variation of facies I of this unit is the result of the transition of depositional subenvironments within the estuary. In the southerly part of the funnel-shaped depression floodplains, channels and natural levees dominate the environment. These features belong to a tidally influenced channel (sensu Dalrymple *et al.*, 1990) or to the upstream part of an estuary according to Woodroff *et al.* (1989). Going northwards, the depositional features evolve from point bars and floodplains into tidal flats. The latter are typical of the upper flow regime sand flats (Dalrymple *et al.*, 1990). As a consequence of low sand input, mudflats replace the sand flats. The high percentage of silt in the south points to a river supply (Wartel, pers. comm.), which is indeed confirmed by the reconstructed palaeoenvironment.

In the clay-dominated facies II of this unit, sediments are deposited on a mudflat and/or floodplain, sometimes adjoined by sand flats. The depositional areas may be dissected by gullies. In the sand-dominated facies, sand flat deposits are the most important.

The sedimentary characteristics of Unit D point to a terrestrial origin of this facies. The lowermost facies is fluvial, consisting of bar, bench and floodplain deposits. Very typical are the peaty floodplain deposits together with crevasse splay deposits, flashflood or sheetflood deposits. The sedimentary characteristics of the uppermost facies are related to an aeolian environment in which several subenvironments are recognised. Units C and D in Fig. 11 are typical of deposition under dry conditions. Unit E, the alternating complex, accumulated in a rather wet environment where adhesion structures formed (Glennie, 1970; Hunter, 1973, 1980; Kocurek & Fielder, 1982). Periglacial phenomena are present in both the fluvial and aeolian deposits. Besides the typical cryoturbations (Fig. 10) and frost cracks also imprints of segregation ice (van Vliet-Lanoë, 1985) occur in the aeolian sediments (Unit F, in Fig. 11). All palaeosols, organic horizons and podsols are soils with a short duration of formation (Meyer, 1987; Retallack, 1990), during periods of stagnation in between depositional phases.

Unit E has the sedimentary features of a tidally dominated estuary. In the greatest part of the distribution area the sedimentation cycles are dominated by mudflat, salt marsh and floodplain deposits. Sand flat deposits are less important. In the northerly part, however, a fining-up sequence of sand flat, mudflat and salt marsh and/or floodplain deposits occurs. All these deposits are situated in the intermediate zone between the purely estuarine and the tidally-influenced fluvial zones. Pollen analyses (Alam, 1989) and clay fabric studies (Sethi, 1989; Wartel *et al.*, 1997) confirm that within the depositional environment alternating freshwater and brackish water conditions prevailed.

DISCUSSION AND CONCLUSIONS

The above description of the Campine Clays and Sands shows the constant repetition of the sedimentation pattern, 'estuarine-fluvial and/or aeolian'. This repetition is the consequence of sea level fluctuations, which will be explained below (Fig. 14). In addition, within the depositional model a constant evolution to a final phase of a purely terrestrial environment may be noted.

The components of Unit A, the fining-up as well as the coarsening-up cycles (the latter observed in a single depression) accumulated during one oscillatory motion of sea level. Indeed, the fining-up cycles most probably formed when the sea level rise was already diminished and sediment input became the modifying factor in the formation of the depositional sequence. This phenomenon has already been observed in many estuaries and been modelled by Knight & Dalrymple (1975), Woodroffe *et al.* (1989), Dalrymple *et al.* (1992), Allen (1990), Nicols *et al.* (1991) and Woodroffe *et al.* (1993). When an estuary has reached its inland position, the final infilling starts and results in the sequence described above (Nicols & Biggs, 1985; Dalrymple, 1992). The presence of several fining-up cycles within Unit A is attributed to the lateral migration of the system and not to variations in sea level or sediment input. In between the cycles no deposits are found that point to a rearrangement of the depositional environments; moreover, no large-scale erosion took place. The coarsening-up cycle formed when sea level dropped again. Consequently, erosion occurred, followed by channel infilling. Similar phenomena were described by Ricketts (1994) from the Late Palaeocene Cape Pillsbury Member of Ellesmere Island (Canada).

The process continued in a later phase outside the depression and resulted in the deposition of purely fluvial sediments of braided origin. This evolution fits in a continuous process through which no large-scale erosion occurred in between the accumulation of units A and B. This hypothesis is corroborated by the presence of important bioturbation traces in the basal strata of Unit B. Unit B dips in a northerly direction just as does Unit A. No similarity exists concerning thickness. Thickness of Unit B decreases to the north whereas that of Unit A increases. Besides, near the northern margin of the distribution area of Unit B the topmost bed of the uppermost succession is missing. Both elements, together with the absence of Unit B in the northern part of the study area, are the result of sideway cutting (Howard *et al.*, 1968) of streams when they reach their base level, in this case sea level. During this particular period, the coastline was nearby (Zagwijn, 1979, 1989).

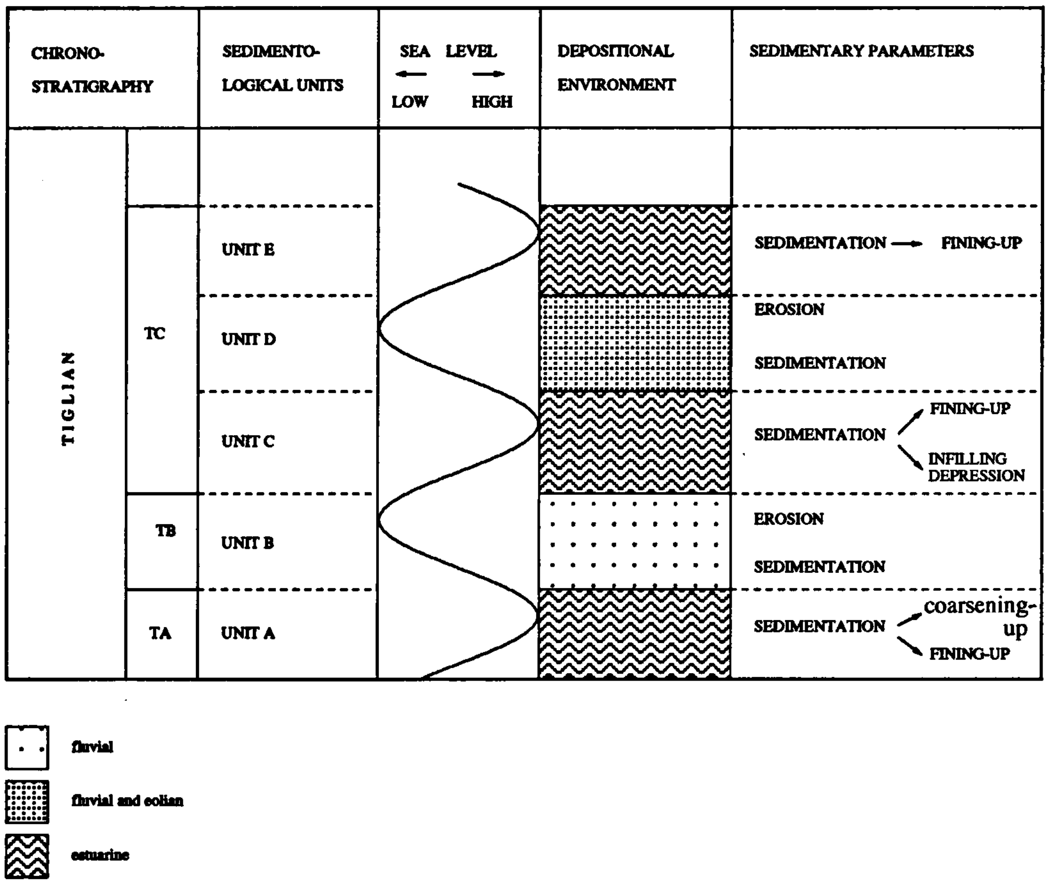


Fig. 14. Illustration of the relationship between sea level fluctuations and patterns of sedimentation.

This erosional process continued in a restricted area near Ballematen and resulted in the formation of the funnel-shaped depression. Unit C is unique in the sense that in the funnel-shaped depression a complete sea level rising stage is preserved. The infilling of this depression took place during rapid sea level rise, forming a succession of mudflat deposits in the north and meandering to estuarine deposits in the central and southern part. In the next stage, when the estuary invaded more inland, the whole area was flooded (Fig. 15) which produced some fining-up cycles predominantly composed of mudflat and sand flat deposits in the north and mud flat and/or floodplain deposits together with channel and point bar deposits in the south. Sand flat deposits are less common.

On the basis of the depositional features of both units A and C it seems that the coastline was situated more north-westerly during the formation of Unit C than during the accumulation of Unit A. This finding corresponds to the palaeogeographic reconstruction of the North Sea basin as presented by Zagwijn (1989).

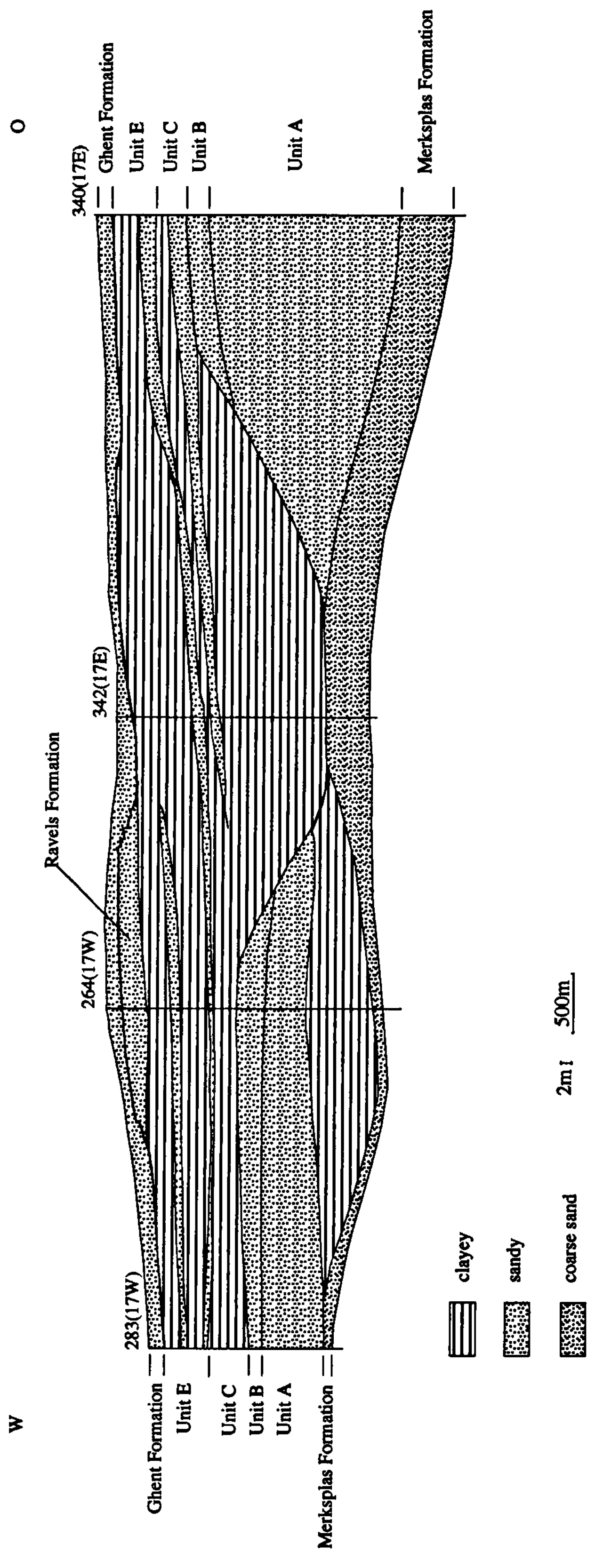


Fig. 15. Geological constitution of the Campine clays and sands in the vicinity of Ballematen.

The succession of units C and D is quite similar to that of units A and B. First of all, erosional activity in between both units was also negligible. The lowering of sea level made it also during that period possible that a purely fluvial depositional environment was established. Different, however, is the presence of aeolian deposits. The evolution of sedimentary characteristics within the aeolian deposits points to an evolution into drier circumstances. Very striking is the limited and moreover fragmentary preservation of unit D. This situation is most probably the result of combined action of downcutting and sideway cutting of active streams (Howard *et al.*, 1968). The southern part, where Unit D is preserved, was located above base level and was consequently incised whereas the northern part, situated around base level, was subject to sideway cutting, resulting in the total disappearance of the unit.

The depositional features of Unit E are typical of the final phase of a transgression when the estuary reaches its furthest position inland. In the first phase, those areas were invaded where Unit D was eroded and sand flat deposits accumulated. In the final stage, the entire area was covered by the estuary and mud flat, floodplain and/or salt marsh deposits formed in the southern part, while in the north also sand flats were deposited.

The presence of the above-mentioned depositional features indicate that during the deposition of Unit E the coastline was at a larger distance from the study area than during accumulation of units A and C. This finding is in agreement with Zagwijn's (1974, 1979, 1989) hypothesis concerning the continuous migration of the coastline in a northwesterly direction during the Late Tiglian.

The formation of the Campine Clays and Sands as a succession of estuarine and purely terrestrial deposits is primarily the result of sea level fluctuations induced by climatic oscillations. However, the evolution within the estuarine deposits is tectonically determined. Tectonic activity is indeed the reason why no more estuarine deposits accumulated during the remainder of the Quaternary in this particular area. Mainly in the southern part of the North Sea there was a gradual narrowing since Late Miocene until the sea completely retreated in the early Middle Pleistocene. According to Zagwijn & Doppert (1978) this situation is the result of epeirogenic uplift or tilting of the central European hinterland and the changing pattern of subsiding areas in the basin.

ACKNOWLEDGEMENTS

I am greatly indebted to Professor R. Paepe (Vrije Universiteit Brussel), who made this work possible, to the Belgian Geological Survey (Brussels) for putting geological data at my disposal, and to Professor P. de Boer (Universiteit Utrecht) for comments on an earlier typescript. During the start, the present study was supported by a grant from the National Science Foundation, which is gratefully acknowledged.

REFERENCES

Alam, S.H., 1989. Palynological studies of the Lower Pleistocene deposits in the Campine area, northern Belgium. Brussels (final report – Vrije Universiteit Brussel), 66 pp.

Allen, J.R.L., 1990. The Severn Estuary in southwest Britain: its retreat under marine transgression, and fine-sediment regime. — Sedim. Geol., 66: 13-28.

Barwis, J.H., 1978. Sedimentology of some South Carolina tidal-creek point bars, and a comparison with their fluvial counterparts. *In*: A.D. Miall (ed.). Fluvial sedimentology. Calgary (Canad. Soc. Petrol. Geol.): 129-160.

Bogemans, F., 1994. Toelichting bij de Quartairgeologische kaarten van Vlaanderen: Turnhout-Meerle. Brussels (Min. Vlaamse Gemeensch.), 102 pp.

Bogemans, F., 1997. Toelichting bij de Quartairgeologische kaarten van Vlaanderen: Essen-Kapellen. Brussels (Min. Vlaamse Gemeensch.), 65 pp.

Bogemans, F., 1998. Toelichting bij de Quartairgeologische kaarten van Vlaanderen: Maarle-Arendonk. Brussels (Min. Vlaamse Gemeensch.), 77 pp.

Dalrymple, R.W., 1992. Tidal depositional systems. *In*: R.G. Walker & N.P. James (eds). Facies models, response to sea level change. Ontario (Geol. Assoc. Canada): 195-218.

Dalrymple, R.W., R.J. Knight, B.A. Zaitlin & G.V. Middleton, 1990. Dynamics and facies model of a macrotidal sand-bar complex, Cobequid Bay - Salmon River Estuary (Bay of Fundy). — Sedimentology, 37(4): 577-612.

Dalrymple, R.W., B.A. Zaitlin & R. Boyd, 1992. Estuarine facies models: conceptual basis and stratigraphic implications. — J. sedim. Petrol., 62(6): 1130-1146.

Delvaux, E., 1891. Étude stratigraphique et paléontologique du sous-sol de la Campine, d'après des documents nouveaux provenant d'une forage exécuté par M. le baron O. van Ertborn, dans l'établissement colonial de Merxplas, situé sur l'arête de partage des bassins de la Meuse et de l'Escaut. — Ann. Soc. géol. Belg., 18: 107-156.

Dricot, E.M., 1961. Microstratigraphie des argiles de Campine. — Bull. Soc. belge Géol., 70(2): 113-141.

Evans, G., 1965. Intertidal flat sediments and their environments of deposition in the Wash. — Q. Jl geol. Soc. Lond., 121: 209-245.

Geluk, M., E.J.T. Duin, M. Dusar, R.H.B. Rijkers, M.W. van den Berg & P. van Rooijen, 1994. Stratigraphy and tectonics of the Roer Valley Graben. — Geol. Mijnbouw, 73: 129-141.

Geys, J.F., 1975. De sedimentologie en de morfogenetische betekenis van de Oudpleistocene afzettingen in de Antwerpse Noorderkempen. Gent (Universiteit Gent), 230 pp. (unpubl. PhD thesis).

Geys, J.F., 1978. The palaeoenvironment of the Kempenland clay deposits (Lower Quaternary, N. Belgium). — Geol. Mijnbouw, 57(1): 33-43.

Glennie, K.W., 1970. Desert sedimentary environments. Amsterdam (Elsevier), 222 pp.

Howard, A.D., R.W. Fairbridge & J.H. Quinn, 1968. Terraces, fluvial - introduction. *In*: R.W. Fairbridge (ed.). The encyclopedia of geomorphology. Stroudsburg (Dowden, Hutchinson & Ross): 1117-1124.

Hunter, R.E., 1973. Pseudo-crosslamination formed by climbing adhesion ripples. — J. sedim. Petrol., 43: 1125-1127.

Hunter, R.E., 1980. Quasi-planar adhesion stratification. An eolian structure formed in wet sands. — J. sedim. Petrol., 50: 263-266.

Kasse, K., 1988. Early-Pleistocene tidal and fluviatile environments in the southern Netherlands and northern Belgium. Amsterdam (Vrije Universiteit Amsterdam), 190 pp. (unpubl. PhD thesis).

Kasse, K., 1990. Lithostratigraphy and provenance of the Early-Pleistocene deposits in the southern Netherlands and northern Belgium. — Geol. Mijnbouw, 69: 327-340.

Knight, R.J. & R.W. Dalrymple, 1975. Intertidal sediments from the south shore of Cobequid Bay, Bay of Fundy, Nova Scotia, Canada. *In*: R.N. Ginsburg (ed.). Tidal deposits. New York (Springer): 47-55.

Kocurek, G. & G. Fielder, 1982. Adhesion structures. — J. sedim. Petrol., 52: 1229-1241.

Lorié, J., 1907. La stratigraphie des argiles de la Campine belge et du Limbourg néerlandais. — Bull. Soc. belge Géol., Paléont., Hydrol., 21: 531-576.

Meuter, F.J. de & P.G. Laga, 1976. Lithostratigraphy and biostratigraphy based on benthonic foraminifera of the Neogene deposits in northern Belgium. — Bull. belg. Ver. Geol., 85(4): 133-152.

Meyer, R., 1987. Paléoaltérites et paléosols. Orleans (BRGM), 13: 164 pp.

Miall, A.D., 1996. The geology of fluvial deposits. Berlin (Springer), 582 pp.

Nicols, M.M. & R.B. Biggs, 1985. Estuaries. In: R.A. Davis (ed.). Coastal sedimentary environments. New York (Springer): 77-186.

Nicols, M.M., G.H. Johnson & P.C. Peebles, 1991. Modern sediments and facies model for a microtidal coastal plain estuary, the James Estuary, Virginia. — J. sedim. Petrol., 61: 883-899.

Paepe, R. & R. Vanhoorne, 1970. Stratigraphical position of periglacial phenomena in the Campine clay of Belgium, based on palaeobotanical analysis and palaeomagnetic dating. — Bull. belg. Ver. Geol., 79: 201-211.

Paepe, R. & R. Vanhoorne, 1976. The Quaternary of Belgium in its relationship to the stratigraphic legend of the geological map. — Toel. Verh. geol. Krt Mijnkrt Belg., 18: 1-38.

Plint, A.G., 1983. Sandy fluvial point-bar sediments from the Middle Eocene of Dorset, England. *In*: J.D. Collinson & J. Lewin (eds). Modern and ancient fluvial systems. Oxford (Blackwell Scient. Publ.), Spec. Publ., 6: 355-368.

Retallack, G.J., 1990. Soils of the past. Boston (Unwin Hyman), 519 pp.

Ricketts, B.D., 1994. Mud-flat cycles, incised channels and relative sea-level changes on a Paleocene mud-dominated coast, Ellesmere Island, Arctic Canada. — J. sedim. Res., B64: 211-218.

Rutot, A., 1897. Les origines du Quaternaire de la Belgique. — Bull. Soc. belge Géol., Paléont., Hydrol., 11: 1-40.

Sethi, P.S., 1989. A comparative study of limnic, estuarine and marine sediments, on the basis of micro-structures and on the use of clay-fabric as a tool for Quaternary lithofacies interpretation. Brussels (final report – Vrije Universiteit Brussel, 1), 63 pp.

Singh, I.B., 1977. Bedding structures in a channel bar of the Ganga River near Allahabad, Uttar Pradesh, India. — J. sedim. Petrol., 47: 747-752.

Tavernier, R., 1942. L'âge des argiles de la Campine. — Bull. Soc. belge Géol., LI: 193-209.

Tavernier, R., 1954. Le Quaternaire. *In*: P. Fourmarier (ed.). Prodrome d'une description géologique de la Belgique. Brussels (Soc. géol. Belg.): 555-590.

Vliet-Lanoë, B. van, 1985. Frost effects in soils. *In*: J. Boardman. Soils and Quaternary landscape evolution reconstruction. — J. Quat. Sci., 3(1): 85-96.

Woodroffe, C.D., J. Chappell, B.G. Thom & E. Wallensky, 1989. Depositional model of a macrotidal estuary and floodplain, South Alligator River, northern Australia. — Sedimentology, 36(5): 737-756.

Woodroffe, C.D., M.E. Mulrennan & J. Chappell, 1993. Estuarine infill and coastal progradation, southern van Diemen Gulf, northern Australia. — Sedim. Geol., 83: 257-275.

Wartel, S., P.S. Sethi & F. Bogemans, 1996. Clay fabric as an indicator of cyclic changes in an estuarine palaeoenvironment - Lower Pleistocene, northern Campine area, Belgium. — Bull. Inst. r. Sci. nat. Belg., Sci. Terre, 66: 193-202.

Zagwijn, W.H., 1974. The palaeogeographic evolution of the Netherlands during the Quaternary. — Geol. Mijnbouw, 53: 369-385.

Zagwijn, W.H., 1979. Early and Middle Pleistocene coastlines in the southern North Sea basin. *In*: E. Oele, R.T.E. Schüttenhelm & A.J. Wiggers (eds). The Quaternary history of the North Sea. — Acta Univ. ups. Symp. Univ. Annum Quingent. celebr., 2: 31-42.

Zagwijn, W.H., 1989. The Netherlands during the Tertiary and Quaternary: a case history of coastal lowland evolution. — Geol. Mijnbouw, 68: 107-120.

Zagwijn, W.H. & J.W. Doppert, 1978. Upper Cenozoic of the southern North Sea basin: palaeoclimatic and palaeogeographic evolution. — Geol. Mijnbouw, 57: 577-588.

Ziegler, P.A., 1978. Northwestern Europe: tectonics and basin development. — Geol. Mijnbouw, 57: 589-626.

Manuscript received 8 October 1997, revised version accepted 27 March 1999.

LEGEND

Lithology

- clay
- silt
- sand
- silty
- clayey
- soil horizon
- clay lenses
- peat dots
- peat lumps
- peat or peaty material

Sedimentary Structures

- ripple lamination
- trough cross-bedding
- planar cross-bedding
- massive bedding
- wavy bedding

Texture

C : clay
S : silt
SS : sand

- clay
- silt
- fraction 0-62μm
- very fine sand
- fine sand
- medium sand
- coarse sand
- very coarse sand

Table 1. Legend to logs.