

Late Saalian and Eemian deposits in the Amsterdam glacial basin

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Abstract

During its maximum extension, the Saalian ice cap reached into the central Netherlands, where glacier tongues excavated over 100 m deep basins in the unconsolidated Middle and Early Pleistocene sediments. The basins are filled by relatively thick successions of Late Saalian, Eemian and Weichselian sediments. The fill of the Amsterdam glacial basin is among the best known and studied in the Netherlands. The Late Saalian sediments consist mainly of varves and ill-bedded clays and silts with, along its southern margin, influxes of sands from the surrounding ice-pushed ridges. During deposition of these sediments, the Amsterdam basin formed part of a large lake extending into the present North Sea. Draining of this lake at the end of the Late Saalian left small, shallow pools at the site of the glacial basins.

Late Saalian and Eemian sediments are probably separated by a short break, although sedimentation may have been continuous in the deepest part of the basin. The Eemian deposits consist in main lines of a thin, diatom-rich sapropel at the base, overlain by an up to 30 m thick clay-rich sequence covered by a wedge of sand that measures more than 20 m in the northern part of the basin and that tapers out southwards. As appears from the fauna, most of the clays were deposited in a lagoonal setting shielded behind a threshold and/or barrier. The rate of sediment supply was low so that lagoonal conditions were maintained over a long timespan. Sands derived from the surrounding ice-pushed ridges and transported by longshore drift and tidal currents formed a spit at the northern margin of the basin, which moved southward after eustatic sea-level rise stabilized and the lagoon was filled by clay. Loading of this clay-rich sequence by the spit and its washover fans induced subsidence, however, because of compaction, so that marine conditions were maintained until after the Eemian highstand. Fluvial and eolian sediments of Weichselian age, locally reaching a thickness of almost 10 m, eventually levelled the Amsterdam glacial basin.

Keywords: Amsterdam glacial basin, barrier deposits, compaction, dropstones, Eemian, lake deposits, lake level, Saalian, shallow-marine deposits, varves, washover deposits

Introduction

Increasing interest in late Quaternary climatic conditions, has led to a renewed study of the Eemian type area in the Netherlands. The present contribution reviews the late Saalian and Eemian deposits in the central-western Netherlands, with emphasis on the succession found in the Saalian glacial basin of Amsterdam (Jelgersma & Breeuwer, 1975; Zagwijn, 1983; De Gans et al., 1987). Apart from this large Eemian subcrop occurrence, marine Eemian sediments are also found in the northern and in the southwestern part

of the Netherlands (Fig. 1). In comparison to those in the central-western Netherlands, however, they are far less complete and, in the case of those in the southwestern Netherlands, less well dated and probably partly reworked.

Cores from the type area of the Eemian are situated in deep glacial basins formed by piping and pushing by ice-tongues of glaciers at the Saalian ice sheet margin (Fig. 1). Earlier studies of the late Saalian and Eemian succession in the Amersfoort and Amsterdam basins were carried out by Zagwijn (1961, 1983), Jelgersma & Breeuwer (1975), De Gans et al. (1987)

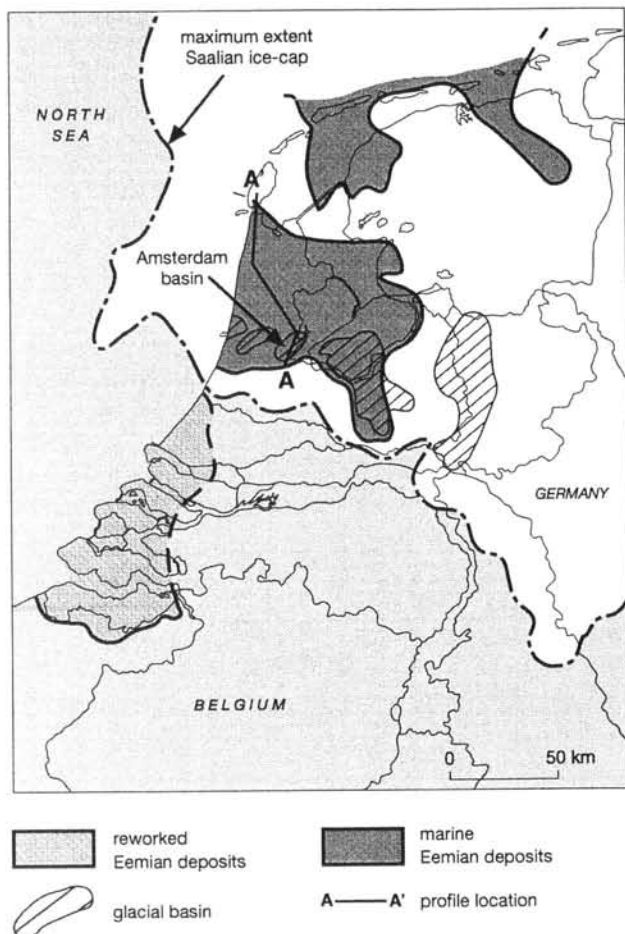


Fig. 1. Marine Eemian deposits and Saalian glacial basins in the Netherlands (after Zagwijn & Van Staaldunin, 1975; Van den Berg & Beets, 1987). AA' is the section presented in Figure 2.

and De Gans (1995). A number of new, continuous cores have been sampled and studied since.

The present contribution focuses on the lithology and sedimentary environment of the succession. Other contributions in this issue provide more detailed information on the fauna, flora, stratigraphy and environmental conditions of the Eemian deposits.

The Eemian of the central-western Netherlands area

The pre-Eemian surface of the central-western Netherlands is characterized by a rough glacial morphology (Figs. 2-3). Most conspicuous are the deep basins flanked by ice-pushed ridges along the southern margin of the sea. The base of these basins reaches over 100 m -NAP (Normaal Amsterdams Peil = Dutch Ordnance Datum = approximately sea level) and, although they were partly filled by lake sediments during the late Saalian, they still formed considerable deeps when they were flooded in the Eemian. In addition, deep basins occurred in the present

coastal zone near IJmuiden and Bergen, and it is inferred that the removed sediment once formed ice-pushed ridges offshore of the present coast (Fig. 3a). The nature of the Bergen basin (Fig. 3a) is still enigmatic; Westerhoff et al. (1987) infer it to be a system of deep subglacial valleys, whereas Van Staaldunin et al. (1979) consider it to be a basin excavated by the glacier. Remnants of the overridden and drumlinised ice-pushed ridge occur in the coastal zone south of the Bergen basin and represent, with its present top at 25-20 m -NAP, a shallow area in the Eemian sea. More ice-pushed sediments occur in the North Sea flanking the Saalian ice margin (Laban, 1995; Joon et al., 1990), but knowledge of the Saalian and Eemian morphology and sediments in the offshore coastal zone is restricted, because of the technical problems of collecting data locally. The formation of basins and push moraines was not restricted to the southern margin of the ice cap, and a number of smaller basins can be recognized in the central-western Netherlands. The sediments removed from these basins were either spread and incorporated in the thick till layer in this area or formed small, ice-pushed ridges (Figs. 2-3).

The Eemian sedimentary succession in the area north of the Haarlem, Amsterdam and Amersfoort basins consists mainly of muds and (shell-rich) sands (Westerhoff et al., 1987). Little is known, however, of the stratigraphy and depositional environment. Most of the deposits are marine, but locally fluvial sands deposited during the Early Weichselian lowstand are incorporated. As these river deposits usually contain reworked marine shells from the surrounding Eemian sediments, they are difficult to distinguish in the yields of bailer cores. It can be said that clay-rich sediments predominate in general in the depressions of the pre-transgressive surface, whereas sand is common on the highs.

The succession differs in a number of important respects from that of the Holocene, although both represent the transgression and highstand of an interglacial. In the first place, peats are absent in the Eemian of the central-western Netherlands except for a few small occurrences in the marginal zones, as, for instance, along the southern margin of the Amersfoort basin (Zagwijn, 1961). In contrast, the occurrence of peat – at the base, intercalated, and at the top – is characteristic of the Holocene succession. In the second place, the area was not filled by sediment during the Eemian highstand: marine sediments deposited during pollen zone E6, when the climate deteriorated and the sea level started to fall, have been found in various cores (Zagwijn, 1983; Cleveringa, pers. comm., 2000). During the Holocene, on the other hand, sedimenta-

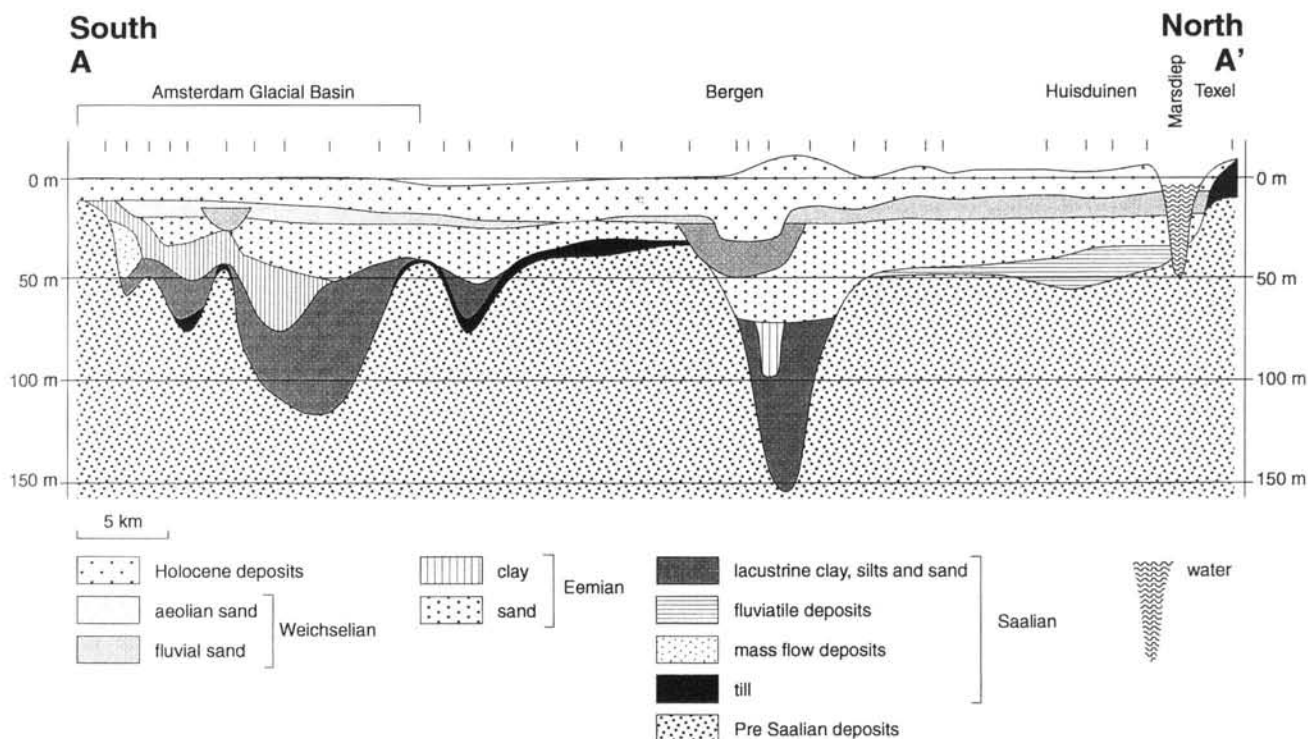


Fig. 2. Cross-section through the central-western Netherlands showing the Amsterdam basin, the sill and the Eemian deposits (see Figure 1 for location).

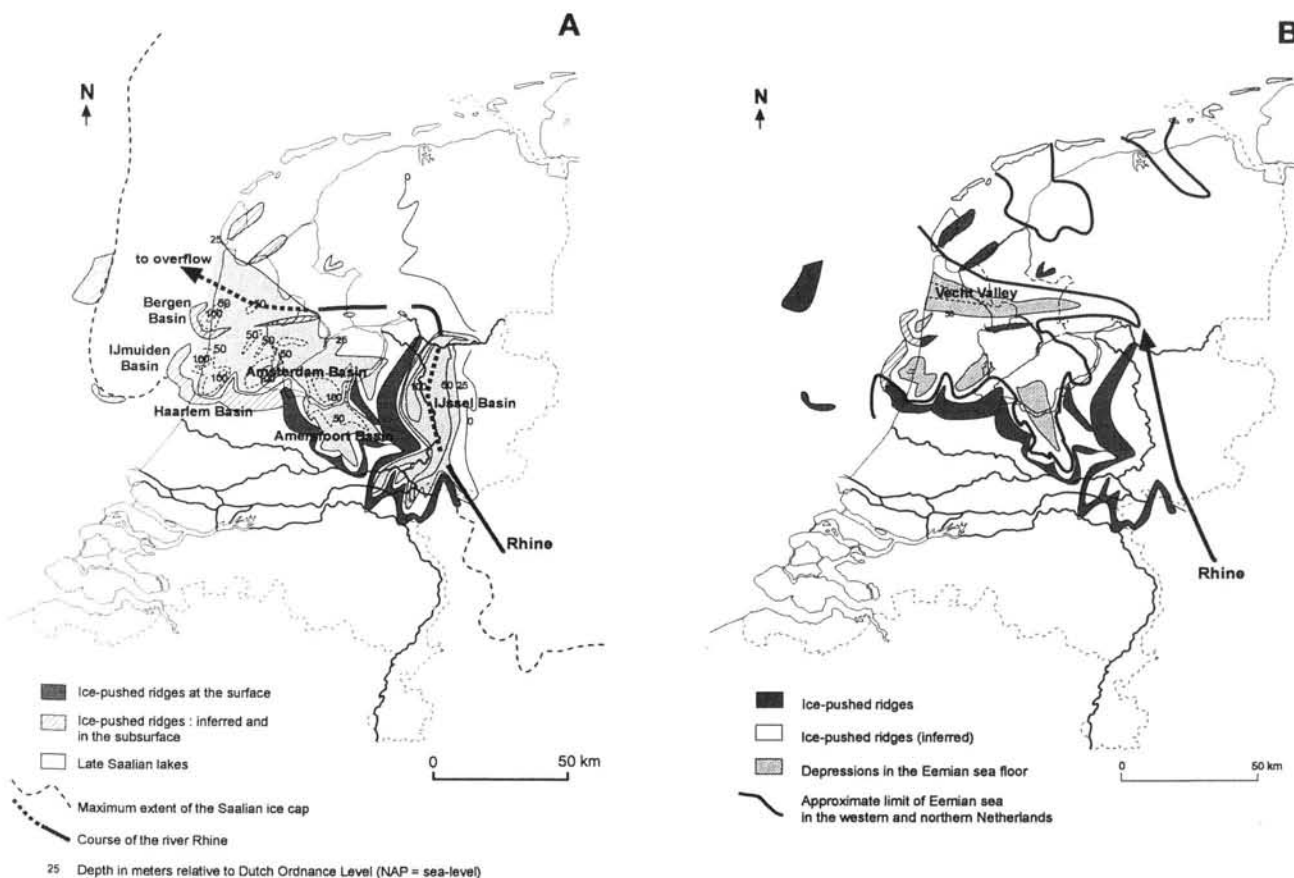


Fig. 3. Morphological elements influencing Eemian sedimentation.

A. Reconstruction of the central-western Netherlands after disappearance of the ice cap in the Late Saalian.

B. Approximate extent of the bays in the western and northern Netherlands during the Eemian sea-level highstand. The Vecht valley was formed in the late Saalian after the lake covering the western Netherlands had been drained.

tion in the Holland tidal basin could keep up with sea-level rise several thousands of years before reaching the highstand (Beets & Van der Spek, 2000).

It is thought that these differences are basically due to the difference in morphology between the pre-Eemian and pre-Holocene basement. The slightly westward dipping Weichselian river plain, smoothed by eolian deposition during the Late Glacial, formed an ideal basement for the development of a barrier/back-barrier system during Holocene sea-level rise. As shown by Beets & Van der Spek (2000), most of the sediment filling the back-barrier basins was derived by the erosion of the basement during recession of the barrier, and brought into the tidal basin by tidal currents. The rate of sediment supply was such that it could easily fill the space created by sea-level rise since 5000 BP. Because of the accidented morphology of the pre-Eemian surface, a similar development was impossible during the Eemian transgression, and the area drowned without strong erosion of the basement. Moreover, as the Eemian sea in the central-western Netherlands formed a bay enclosed between ice-pushed ridges and with an entrance, the Vecht Valley, at its northwestern side (Fig. 3), the influence of the tides was small, because of dissipation of the tidal wave by the scattered shallows and the narrow entrance. The absence of peat below, in and above the Eemian marine sequence is probably also largely due to the rough basement. Basal peat is absent because of a major difference in groundwater flow in front of the transgressing sea; intercalated peat is absent because silting back-barriers were absent, and peat on top could not be formed during the regression.

As mentioned above, the Eemian sea transgressed over the central western Netherlands by way of the incised paleo-valley of the Rhine river formed in the Late Saalian (Van de Meene & Zagwijn, 1978; Westerhoff et al., 1987; Van den Berg & Beets, 1987). This valley is separated from the glacial basins along the southern fringe of the Eemian subcrop area by a broad undulating shoal (Figs. 2-3) at a depth of about 35-40 m -NAP. Due to this threshold and the position of the basins at the fringe of the Eemian sea, deposition in the glacial basins occurred under low-energy conditions in lagoons up to several tenths of meters deep. Currents became important only by the time these basins were largely filled. As the glacial basins were lakes in the late Saalian and early Eemian, they contain almost continuous late Saalian to highstand (late) Eemian (pollen zone E5) successions.

The Amsterdam basin

The Amsterdam glacial basin is situated along the

southern margin of the marine Eemian sediments (Figs. 1-3). It is surrounded at its southern end by ice-pushed sequences the morphological expression of which (i.e., the glacio-tectonic ridges) has disappeared because of subsequent erosion and denudation in the late Saalian, Eemian and Weichselian. The Amsterdam basin is about 25 km long and about 15 km wide. Its maximum depth is 125 m -NAP (De Gans et al., 1987). The basin and its surrounding ice-pushed sequences are buried underneath Holocene deposits. It represents therefore essentially a subsurface structure. The city of Amsterdam is situated on top of the southern part of the basin.

The fill of the Amsterdam basin consists of Saalian, Eemian, Weichselian and Holocene sediments (Figs. 2, 6). The basin deposits are known from hundreds of boreholes, the oldest of which dates from 1605. Apart from the lodgement till, which occurs locally at the base of the sequence, the Saalian and early Eemian (pollen zones E1, E2 and E3) sediments are lake deposits. All the overlying Eemian sediments thus far encountered are of marine origin. They are overlain by fluvial and eolian sediments of Weichselian age. The Holocene cover consists of peat and mud-flat deposits.

The lithostratigraphy of the basin fill was described by Jelgersma & Breeuwer (1975), Zagwijn (1983) and De Gans et al. (1987). To obtain a better insight into the stratigraphy, facies and sedimentology of the basin deposits and in the relation between facies and geotechnical properties, six cored boreholes (Amstelpark, Diemen-Landlust, Willemsluizen, Beursplein, Mirandabad and Terminal) were drilled during the past decade. (Fig. 4a). The lithology – with some interpretations of the depositional environment – is presented in Figure 5. An outline section across the basin, comprising four of these cored borehole data, is given in Figure 6. Maps have been produced of a number of lithological boundaries in the basin on the basis of borehole data available in the NITG-TNO database; about 2280 cores were used to construct the maps, approx. 2000 of which reach a depth of 50 m -NAP, approx. 100 a depth of 100 m -NAP, and approx. 80 deeper levels.

The large volume of data allows a detailed insight into the subsoil morphology of the Amsterdam basin. Figure 4b demonstrates the undulating surface of the basin floor.

Late Saalian deposits

During and after melting of the ice tongue that occupied the basin in the Saalian, the glacial basin was transformed into a lake in which predominantly fine-

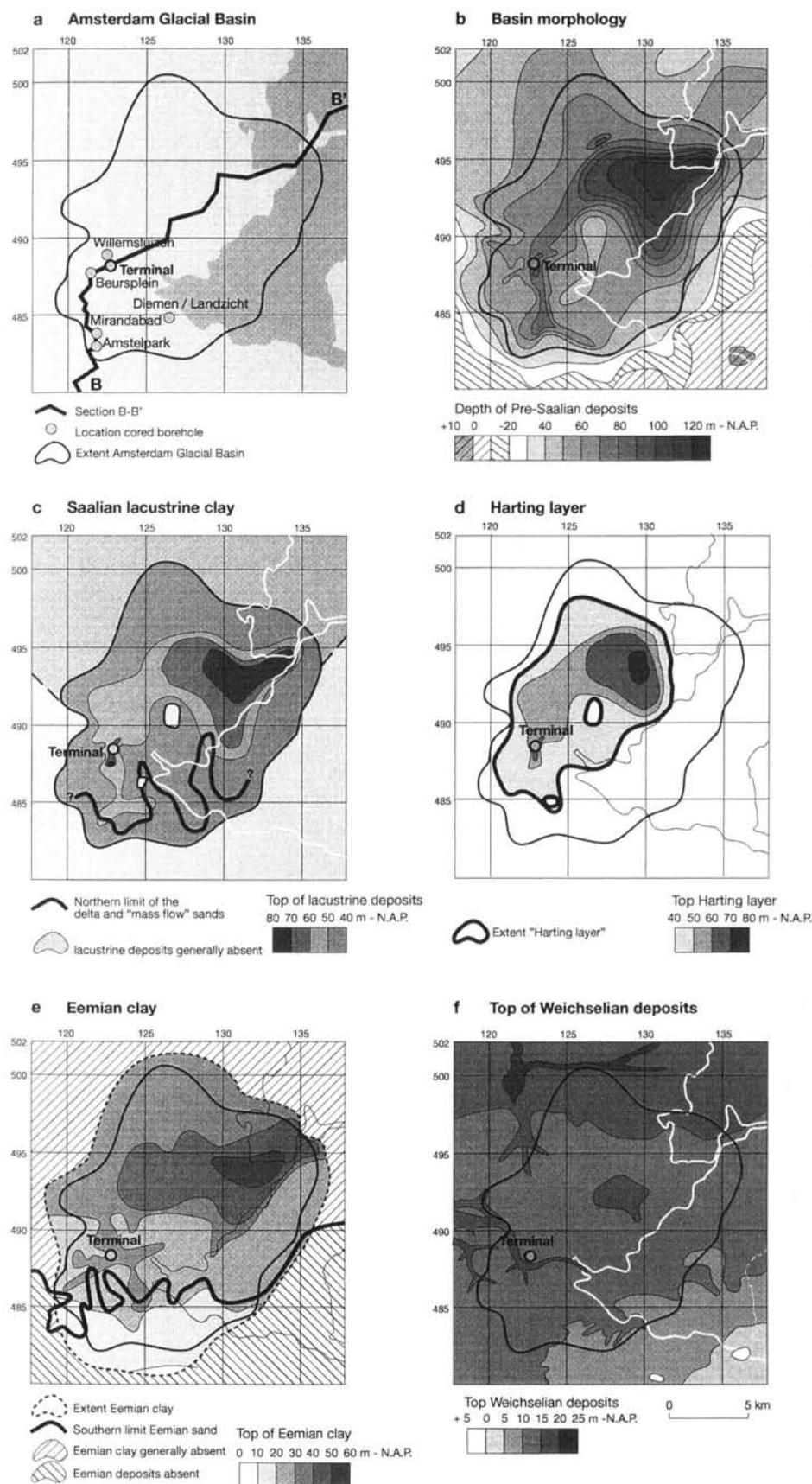


Fig. 4. The Amsterdam basin.

- position of sections and cored boreholes.
- morphology of the basin subcrop.
- top level of the lacustrine clay and silts and extent of the sands derived from the surrounding ice-pushed ridges.
- extent and upper level of the Early Eemian sapropel layer.
- upper level of the Eemian clay and extent of the Eemian sand.
- upper level of the Weichselian deposits.

grained sediments accumulated. Only along the southern margin of the basin, the fine-grained sediments are locally overlain by, or alternate with, medi-

um- to coarse-grained sands derived from the glaci-tectonic ridges (Figs. 3a, 4c, 6). Five main lithofacies are distinguished: (1) till, (2) well-laminated 'varves',

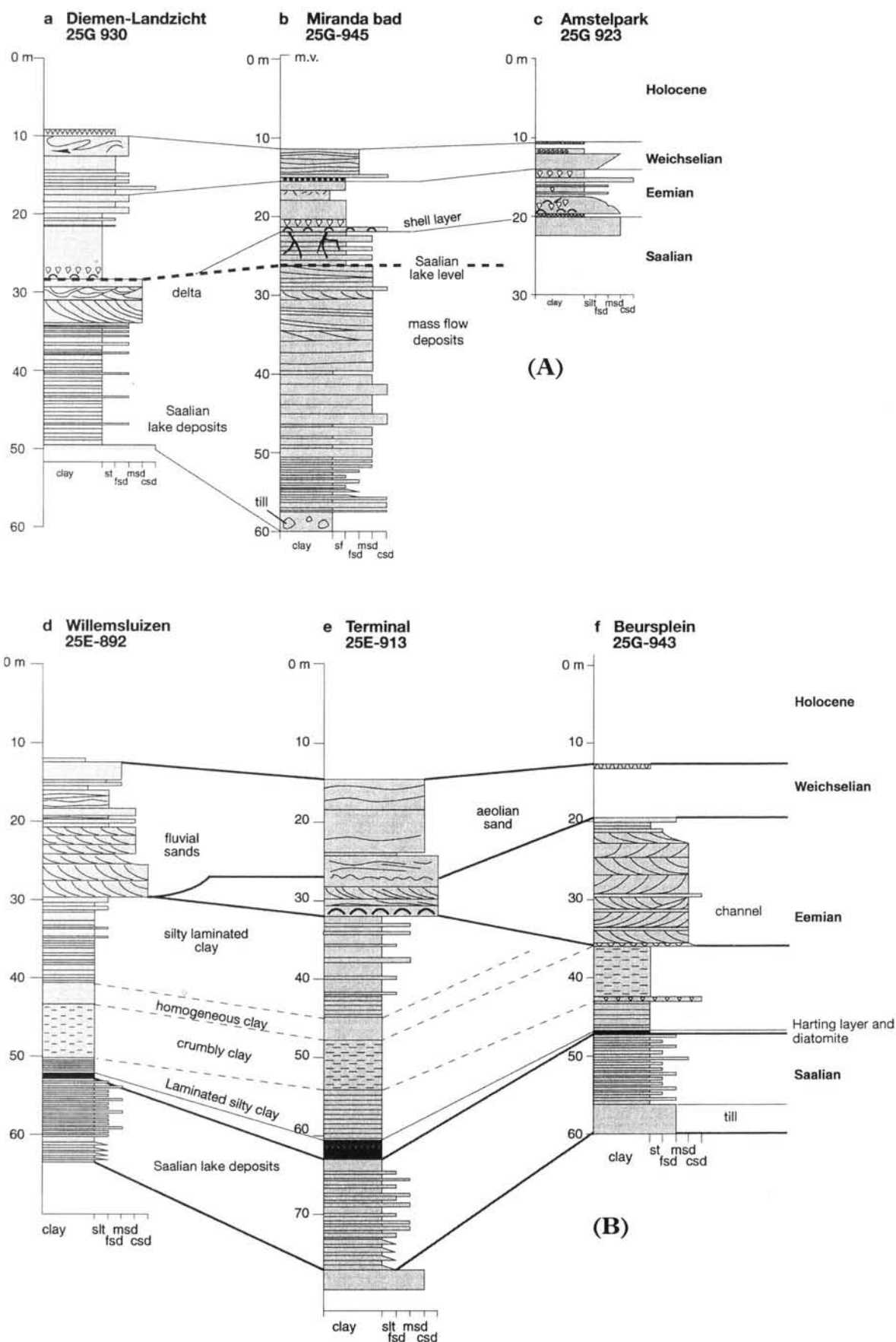


Figure 5. Sedimentary logs of boreholes (positions are given in Figure 4a).

A. Diemen-Landzicht (a), Mirandabad (b) and Amstelpark (c).

B. Willemsluizen (d), Terminal (e) and Beursplein (f).

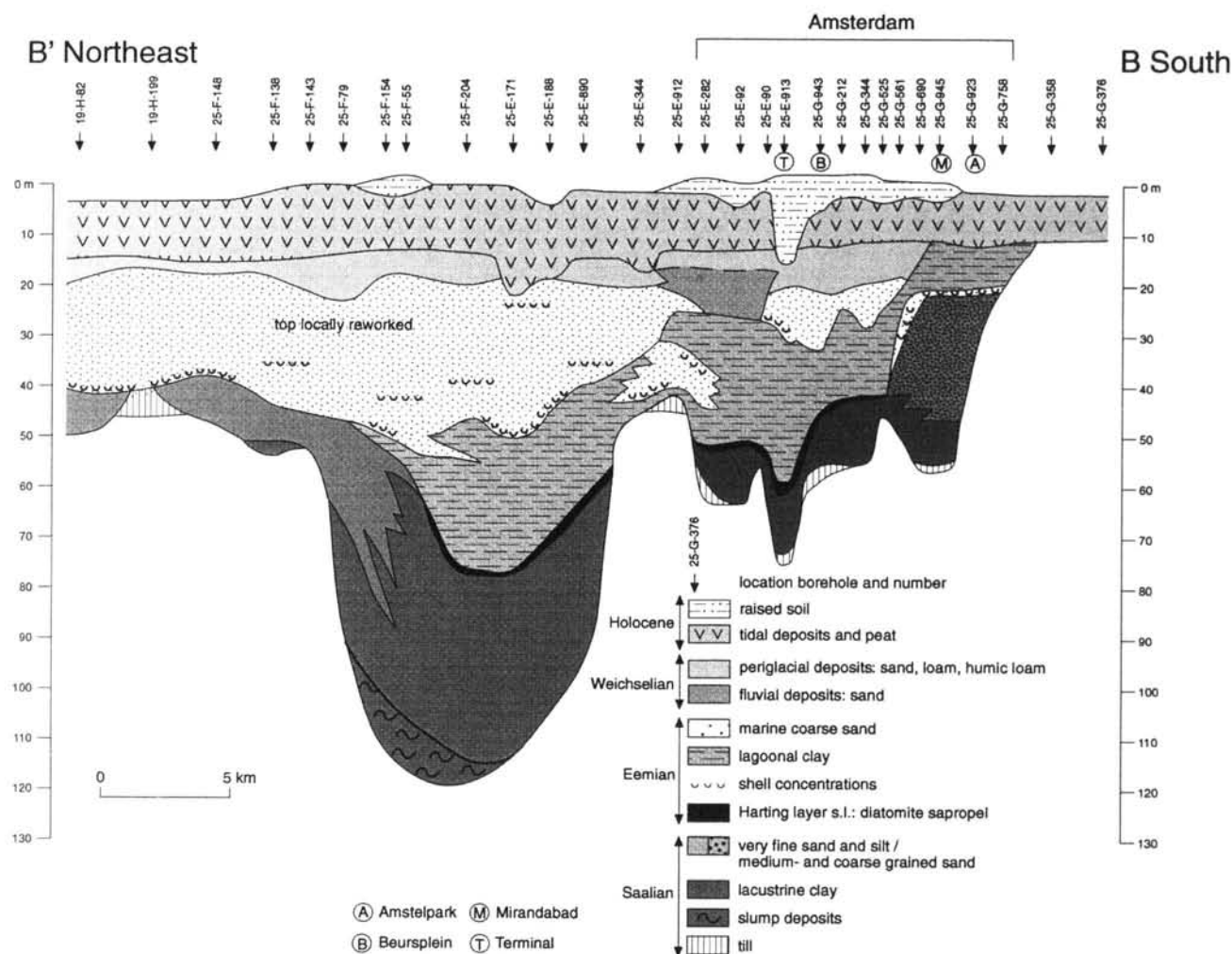


Figure 6. Cross-section of the Amsterdam glacial basin (see Figure 4a for location).

grading into (3) ill-bedded clays with thin intercalations of silt and fine sand, (4) well-bedded medium- to coarse-grained sands along the southern margin of the basin, and (5) fine-grained sands and silts along the northern margin of the basin (Fig. 6).

Till occurs randomly at the base of the succession. Several meters of a well-laminated unit with a 'varve'-type alternation of fine sand and silt with clays overlie the till or the base of the basin in almost all cores. In the upper half of this sequence in the Terminal core (Fig. 5b), the 'varves' consist of dark organic-rich clay alternating with silt. The organic-rich layers indicate anoxic conditions at the base of the water column, and a layered structure of the lake water. This suggests that the lake was not longer in contact with the decaying ice cap at this stage. The laminae are of centimeter scale. In one core on the southern margin of the basin (Mirandabad; 25G945), some thicker 'varves' near the base of the section contain outsized clasts, probably representing dropstones (Fig. 5b).

The 'varves' pass gradually upwards into a thick succession of clays with thin intercalations of silt and

fine sand. The thickness of this succession varies from more than 40 m in the northern part of the basin to less than 10 m in the south. The clays are greenish to brownish grey, have a poorly developed, indistinct bedding except for their basal part, and contain numerous irregular vacuoles and cracks, which increase in number upwards. The clays are overlain by diatomites of early Eemian age. As will be discussed below, most of the fine-grained sediment is thought to be supplied by the Rhine.

Along the southern margin of the basin, the lacustrine clay interfingers with, and is overlain by, sands derived from the fringing ice-pushed ridges (Figs. 4c, 5, 6). The sands are medium- to coarse-grained. The Diemen core (25G-930) shows a thickening and coarsening-upwards sequence starting at 38 m -NAP with up to 5 cm thick sand intercalations in the clay (Fig. 5a). A rapid alternation of thin sand and clay layers characterises the sequence between 38 and 34 m -NAP; it is overlain by 3 m high, Gilbert-type foresets, covered by a few meters of cross-bedded sands. The coarsening-upward character, the upward thick-

ening and the large foresets in this unit show that the sands represent a small delta of a river draining the ice-pushed ridge in the east. The top of this small delta indicates that the lake level was situated at a depth of about 30 m -NAP.

An almost 30 m thick wedge of sand occurs on top of the 'varves' and lacustrine clays along the south-western rim of the basin (Mirandabad core: 25G-945, Figs. 4c, 5b, 6). Clay intercalations are scarce, in particular in the upper 20 m, indicating rapid deposition of the sands. The highest clay intercalation occurs at a depth of 30 m -NAP. Sand beds vary in thickness from 0.1 to over 0.5 m. The beds are massive or show a faint horizontal lamination. Contorted bedding occurs occasionally and points to subaqueous slumping. Some of the coarser-grained beds show a faint normal grading.

Above 35 m -NAP, the horizontal lamination becomes sharper and a few cross-bedded sets occur. Structures and setting of the sand point to transport by sediment gravity-flow or mass-flow processes. At about 26.50 m -NAP, these sands are overlain by 3.5 m of an irregularly bedded succession of sands and silts, which are interpreted as eolian deposits. Irregular light brown and orange colouring in these latter sands are probably due to soil-forming processes. Ghosts of roots occur at the boundary of these sands with the overlying Eemian marine deposits (Fig. 5b). The boundary between the lake and eolian deposits indicates that the lake level during deposition of the mass-flow deposits was situated at about 26-27 m -NAP. It is thought that the difference of 3-4 m with the inferred lake level of the Diemen core (Fig. 5a) is due to a difference in subsidence because of post-depositional compaction.

It is inferred that the gravity-flow sands in the Mirandabad core are derived from collapse of the oversteepened ice-pushed ridge. In view of the abrupt transition from clay to sand deposition, it is not very likely that these gravity-flow sands have been deposited at the front of a fluvial delta. Moreover, the lake was separated by the ice-pushed ridge from a low-lying area towards the south; rivers entering the lake from the south could only be small brooks draining the ice-pushed ridge. Although it is difficult to reconstruct the environment of the Mirandabad sands on the basis of one core, the sequence suggests that the gravity flows were the fronts of fans at the feet of cliffs in sands of the ice-pushed ridges. The gravity-flow deposits overly about 7 m of 'varves' and lacustrine clays at the base of the core (Fig. 5b), indicating that the influx of sand occurred quite some time after the melting of the glacier tongue and the initiation of the lake (about 900 years based on 'varve' counting and extrapolation of the sedimentation rate). This sug-

gests that both oversteepening of the ice-pushed ridge and the delay in its collapse might be due to the presence of permafrost in the deformed sands.

It was assumed up till now that the glacial basins changed into isolated lakes after melting of the ice cap. A lake level at a height of 25-30 m -NAP implies, however, that it surpassed the heights of the sills at the northern margin of the basins, and that all the basins (with the exception of the IJssel basin), formed part of one large lake extending for an unknown distance into the present North Sea. This is supported by the following arguments.

- (1) The patches of lacustrine clays in the subsoil of the area north of the Basin of Amsterdam between the till at the base and Eemian sediments on top (Westerhoff et al., 1987) show that the lake was not restricted to glacially formed basins. In several cores, the clays occur between approximately 45 and 35 m -NAP and overlie till upon an undulating surface (Westerhoff et al., 1987).
- (2) As mentioned above, no ice was present anymore after deposition of the 'varves', so that the threshold could not be composed of glacier ice, as was suggested by Zagwijn (1983).
- (3) The morphology of the area north of the basins differed from that over which the Eemian sea transgressed as the Vecht Valley was not yet in existence when the glacier disappeared (Fig. 3). As shown by Westerhoff et al. (1987), the Vecht valley overlies lacustrine clays that fill the Spanbroek glacial basin, indicating that the valley formed after deposition of the clays in the basin. According to Van den Berg & Beets (1987), the valley formed as an overflow channel of the Rhine, which shifted its course to the IJssel basin lake in the late Saalian (Van de Meene & Zagwijn, 1978). The present late Saalian reconstruction (Fig. 3a) shows an overflow at the northern margin of the IJssel basin lake and a re-entrance along the north-eastern margin of the western lake. The latter had an overflow somewhere in the present North Sea, probably situated near the former margin of the Saalian ice cap. Isostatic rebound of the depressed (glacier-covered) and uplifted (peripheral bulge) crust probably caused the draining of the lake and the formation of the Vecht valley shortly before the Eemian.
- (4) The distribution of the lacustrine clays in the Amsterdam basin and the wedge of silt and fine sand on, and directly south of, the sill (Fig. 6) indicate that the bulk of the fine-grained sediments were derived from the north. For that reason the Amsterdam basin must have had a direct connection with the area towards the north.

- (5) The late Saalian and early Eemian sedimentary sequences in the Amsterdam, Amersfoort, Haarlem and IJmuiden basins are very similar (Zagwijn, 1976, 1983; Westerhoff et al., 1987; Cleveringa et al., 2000 – this issue; Van Leeuwen et al., 2000 – this issue), indicating that they formed part of one system.

As shown in Figure 3, the glacial basins formed, after melting of the ice, part of two large lakes, i.e., a lake in the IJssel basin – which was largely filled before the Eemian by gravel, sand and clay supplied by the Rhine – and a large lake encompassing the other basins. As mentioned, the latter one had an overflow somewhere beyond the present coastline. The Rhine, which lost its bedload in the IJssel basin, brought sufficient suspension load to the western lake to form thick clay sequences. At times, the discharge of the glacial Rhine must have been so large that it produced bottom currents in the lake that could transport very fine sand and silt in addition to the clay. The wedge of very fine sand and silt along the northern margin of the Amsterdam basin (Fig. 6) was formed because of a drop in current velocity going from the relative shallow part of the lake to the deep formed by the Amsterdam basin.

This system ended in the late Saalian when the most western threshold was eroded, the western lake was drained and the Vecht valley was formed. As a consequence of this incision, only small shallow pools remained at the sites of the former glacial basins (Van Leeuwen et al., 2000 – this issue).

The Saalian/Eemian transition

The Eemian deposits present in the Amsterdam basin consist mainly of a sequence of clays of up to 30 m thick, overlain by a wedge-shaped sandy sequence some 30 m in the north but thinning southwards. Beneath about 40 m -NAP, the Eemian clays are separated from the late Saalian deposits by fresh-water diatomites of up to 1.7 m thickness overlain by a 0.1 to 0.5 m thick, dark-coloured layer of a slightly brackish diatomite with a high organic carbon content (sapropel) (Figs. 5d,e,f, 6). The latter is the so-called 'Harting Layer' (Van Leeuwen et al., 2000 – this issue); it passes upwards into a laminated sequence of clays and diatom-rich clays. Above approx. 35 m below NAP, the boundary between the Eemian and Saalian deposits consists of a sandy shell lag of up to 1 m thick, overlain by clays rich in shells in living position (Figs. 5a,b,c, 6). This sequence is only found along the southern margin of the Amsterdam basin.

A 1.70 m thick fresh-water diatomite, ranging in age from pollen zones E1 to E3, forms the base of the

Eemian succession in the Terminal core at a depth of about 62 m -NAP (Fig. 5). Pollen zones E1 to E3 are also found at the base of the Eemian in the Willemssluizen and Beursplein cores (Fig. 5) at a depth of 53 and 47 m -NAP, respectively, but in a condensed level of less than 0.5 m thick. The difference in thickness is probably related to the rising lake level due to Eemian sea-level rise.

When the rising sea level overtopped the shallow between the Vecht valley and the Amsterdam basin (Figs. 3b, 6) at the end of pollen zone E3, the fresh-water conditions gradually changed. Initially the amount of seawater entering the lake in the Amsterdam basin was small because of this broad sill. The denser seawater would flow to the bottom of the lake causing stratification, anoxic conditions at the lake bottom, and deposition of the sapropel. In the Terminal core, a relatively high concentration of organic carbon and sulphur in the laminated clay on top of this sequence (Van Leeuwen et al., 2000 – this issue) suggests that it took quite some time before the mixing of the water column was complete. As will be discussed below, the stratification causing the lamination in the overlying clays might, however, not be due to salinity differences, but to temperature differences, as the laminates are characterized by the regular influxes of an arcto-boreal fauna (Van Leeuwen et al., 2000 – this issue). The black colour of the diatomite, sapropel and overlying clay in fresh cores are probably caused by the high organic content and disseminated pyrite. The black colour changes to greyish within hours after opening of the cores.

The shell lag at the base of the Eemian clay succession above approx. 35 m -NAP in the south of the basin is basically the transgressive shoreline deposit (Fig. 6). Because of the threshold at approx. 35 m -NAP, such a shoreline deposit is absent below this depth. The reworked shell layer grades into clays as the supply of sediment was insufficient to keep pace with the ongoing sea-level rise.

Eemian clay

Throughout the entire Amsterdam basin, the basal Eemian beds described above are overlain by clays and silty clays that vary in thickness from a few to 30 metres (Figs. 4e, 5, 6). As discussed by Van Leeuwen et al. (2000 – this issue), the clays have been deposited in a lagoon with a varying water exchange with the North Sea; for a detailed description and interpretation of the sediment, fauna and flora of the Terminal core, the reader is referred to their paper. In the Beursplein, Terminal and Willemssluizen boreholes (Fig. 5), which are representative for the deeper part

of the basin, the following units are recognized in the clay sequence.

- (1) A laminated (silty) clay sequence, measuring about 6 m in the Terminal core (Fig. 5e). The lamination of this unit is probably due to stratification of the water column; the presence of arcto-boreal diatoms and foraminifers as well as resting spores of oceanic diatoms in this unit (Van Leeuwen et al., 2000 – this issue) suggest that the stratification is due to regular influxes of cold oceanic water. Mixing of the cold influxes with warmer water from the Strait of Dover – Southern Bight area was restricted as the sea level was at 20 m -NAP or lower during deposition of this unit, and as ice-pushed ridges in the present coastal zone of the central-western Netherlands blocked the exchange (Fig. 3b). As discussed by Van Leeuwen et al. (2000 – this issue), foraminifers and molluscs indicate a gradual deepening and increasing salinity of the lagoon. Benthonic diatomites and the presence of the mollusc species *Turboella radiata balkei*, which is assumed to be living on eelgrass (*Zostera*), indicate that the seafloor received sufficient light for plants. In the Terminal core, the laminated (silty) clays occur between about 60 and 54 m -NAP. According to Zagwijn (1983), the Eemian sea level was about 20 m -NAP in pollen subzone E4a during which most of the laminated clay was deposited (Van Leeuwen et al., 2000 – this issue). In view of the vegetation, a depositional depth of 30-35 m seems excessive, even at very low turbidity of the water, and we assume that the present depth is strongly influenced by postdepositional compaction of the clays.
- (2) A sequence of crumbly (silty) clay varying in thickness from a few to almost 10 m, which – according to the data based on foraminifers and pelecypods in the Terminal core – was deposited in a protected, well-mixed lagoon. The unit was deposited during the upper part of pollen subzone E4b and the lower part of E5, when the sea level reached its highstand (Zagwijn, 1983). According to fauna and flora (Van Leeuwen et al., 2000 – this issue), the lagoon reached its maximum depth and the optimal exchange with the open sea during deposition of this unit. Why the clays are crumbled is not understood.
- (3) A homogenous to vaguely laminated clay sequence of about 5 m thick in the Terminal core and almost 10 m in the Willemsluizen core is absent – because of erosion – in the Beursplein core (Fig. 5). The unit dates from pollen zone E5. Remnants of leaves of *Zostera* were found

throughout this sequence, which implies that the depth of deposition was in the depth range of 20 m or less, assuming that the amount of suspension in the water column was low. According to Van Leeuwen et al. (2000 – this issue), the lagoon shallowed and the exchange with the open sea diminished during deposition of this unit. The reduced exchange might be due to the initiation of a barrier on the threshold at the north rim of the basin.

- (4) These homogenous clays grade in the Willemsluizen and Terminal cores into a 5-10 m thick, coarsening-upward alternation of clays with thin beds of silt and fine sand. The sands indicate the presence of currents and suggest a more shallow marine environment. This is consistent with the data supplied by the fauna, which indicate a tidally dominated hyposaline lagoon comparable to the present-day Wadden Sea (Van Leeuwen et al., 2000 – this issue).

The clay sequence dates from pollen subzone E4a and continues into pollen zone E5. In the Terminal core, the top of this sequence – which is composed of clay with sand intercalations – is unconformably overlain by a thick shell lag and cross-bedded sands. The latter were deposited during pollen zone E6, when the sea level was already falling. In the Willemsluizen core, a similar sequence is erosively overlain by a Weichselian river deposit (De Gans & Wassing, in press) and, as mentioned before, brittle clay deposited during the lower part of pollen zone E5 is unconformably overlain in the Beursplein core by channel deposits dating from the upper part of pollen zone E5.

It is obvious that substantial compaction has occurred in both Saalian and Eemian clays of the Amsterdam basin. The top of the clay sequence in the Terminal and Willemsluizen cores at a depth of about 30-40 m -NAP was, on the basis of the faunal data (Van Leeuwen et al., 2000 – this issue), deposited in very shallow water. This level is assigned to the same pollen zone (E5) as the clay sequence in the Mirandabad and Amstelpark cores, where it is situated at 10-20 m -NAP and where the Eemian clay overlies a sand-rich succession that has been compacted only slightly (Fig. 5, 6). In all the Diemen, Mirandabad and Amstelpark cores, the Eemian sequence starts with a sandy shell lag, interpreted as a transgressive shoreline deposit. This deposit is overlain by clays rich in molluscs in living position, among which *Corbula gibba* and oysters (Meijer, pers. comm., 1999), indicating the drowning of the shoreline. Obviously, the sediment supply was insufficient to fill up the space created by the sea-level rise. The presence of *Bittium*

reticulatum, a grazing gastropod, indicates the presence of vegetation on the sea floor and confirms the earlier conclusion that the turbidity of the water column was low. In the Amstelpark core, a few intercalations of shell-rich sands occur, pointing to the occasional presence of currents. The clays gradually pass upwards into barren silts, at their turn overlain by coversands. The silts represent silting up of the margin of the basin; the coversands are thought to be of Weichselian age.

Eemian sand

A southward thinning wedge of predominantly medium- to coarse-grained sands overlies the clay-rich sequence described above. This wedge varies in thickness from almost 40 m in the northern part of the basin to only a few meters in the Terminal core. The sands are absent in the southern part of the basin (Figs. 4e, 6). The shape of the wedge and the absence of sands in the south suggest that sand transport was from the north to the south. The coarseness of the sand indicates, however, that it was provided by a nearby source. It is thought that most of the sand was derived from the ice-pushed ridges and brought into the basin by wave- and tide-induced longshore and cross-shore transport.

The Eemian sands are usually rich in shells and shell fragments. The shells are predominantly reworked molluscs and gastropods characteristic of littoral and other shallow-water environments (Meijer, pers. comm., 1999). Shell lags are common (Fig. 6). The reworked mollusc and gastropod fauna in the shell lag at the base of this sand wedge in the Terminal core (Van Leeuwen et al., 2000 – this issue) contains a relatively large amount of *Spisula truncata*, a mollusc which, at present, lives at the shoreface of the North Sea coast. It also contains gastropods and molluscs that live in a protected shallow-water environment, such as *Peringia* and small *Hydrobia* species. This combination suggests that these shell beds and associated sands are barrier deposits. Intercalated clay laminae and clay layers occur. The boundary between the Eemian clays and sands is usually formed by a shell lag. In the Beursplein and Terminal cores (Fig. 5), the shell-bearing sands show well developed cross-bedding indicating a shallow-water, high-energy environment. Considering the depth of occurrence of the shell lag at the base of the cross-bedded sands in core Beursplein, these sands may have been deposited in a channel. We assume this to be a tidal channel or a washover channel connected to the southward migration of the barrier system. We do not find any morphological expression of large channels at the bound-

ary of the sands and clays in the northern half of the Amsterdam basin, where it forms a relatively smooth surface (Fig. 4e). In the southern half, however, linear depressions in the top of the clay sequence may represent channels. Consequently, we do not think that tidal channels comparable to those in the present and subrecent Wadden Sea with its mesotidal climate (Van der Spek, 1996) are common. The latter channels have depths of 25–30 m at their inlets and erode deeply into the older deposits. As discussed above, the tidal range at the site of the Amsterdam Basin was probably negligible in the early Eemian and still small during the Eemian highstand, in view of the morphology of the sea at the site of the western Netherlands with the Amsterdam basin at its southern margin (Fig. 1). Consequently, we believe that the current velocities due to the tides were low. As might be obvious from the above, this interpretation is corroborated by a low sediment supply, as is evident from the turbidity of the water column during deposition of the clays, and by the presence of marine deposits of pollen zone-E6 age, which in our view have been deposited during falling sea level. The thinning of the wedge towards the south suggest that the base of the sand sequence is diachronous, but our data are as yet insufficient to confirm this. One core in the northern part of the basin, 25 E 890, has this boundary in the second half of pollen zone E5. In the Beursplein core (25 G 943), a similar pollen age is found, and in the Terminal sequence (25 E 913) the base of the sand falls in pollen zone E6. In addition to a lack in age control, little is available concerning the sedimentology of the sands, leaving the interpretation hypothetical and speculative.

The depositional model discussed below should at least explain the shape of the sand wedge, in particular its northward dipping base.

If the tidal range at the site of the Amsterdam basin was small, the sand wedge cannot be seen as the sea-proximal and sea-distal parts of a barrier/back-barrier system with the barrier, ebb and flood tidal deltas in the north of the basin and shallowing channel fills towards the south. Not only does one need tidal currents for this, but also its expression in the grain-size distribution, both vertically and laterally. Medium- to coarse-grained sands occur throughout the sandy succession and their distribution shows a random pattern. The simplest explanation of the southward-rising base of the sand wedge would be that a barrier formed by longshore drift at the northern margin of the Amsterdam basin and shifted southward by washover processes because of the sea-level rise. In this case, the rising base of the sand sheet stands for the curve of the rising sea level. As shown by Zagwijn

(1983), however, the sea level rose from about 24 m -NAP to its highstand at 10 m -NAP during pollen subzones E4a and E4b. Van Leeuwen et al. (2000 – this issue) show that in the Terminal core the exchange between lagoon and open sea was greatest during pollen zone 4b. This suggests that lagoon and open sea were not separated efficiently by a barrier during this interval, probably because the relative sea-level rise outran the sediment supply required to maintain a barrier. Thus it is thought that the spit (barrier) became effective only shortly before the Eemian highstand in pollen zone E5 (Zagwijn, 1983) and that its development was not controlled by the eustatic component of the sea-level rise but rather by subsidence due to compaction of the clays.

It is assumed that the barrier formed initially in the northern part of the Amsterdam basin upon or near the former sill and that it migrated southward by overwash processes. For the barrier to recede, the adjacent clays must, however, have been silted-up almost to sea level. This is confirmed by the fauna in the upper part of the clay sequence in the Terminal core: the coarsening-upward sequence of silty clays between 38 and 32.65 m -NAP (Van Leeuwen et al., 2000 – this issue). Moreover, they indicate that these silty clays currently occur at more than 20 m below the level at which they were once deposited, because of compaction. Southward barrier shifting at a more or less constant eustatic sea level would be feasible only if loading of the clays by the barrier and its washover fans enhanced the compaction of the clays. The sediment supply by longshore drift must have compensated the loss of sand from the wave-affected upper shoreface and foreshore due to this subsidence. The thickness of the barrier sands and the clays are roughly the same, suggesting that – assuming an equal rate of sediment supply – southward barrier shifting slowed as thicker clay sequences were encountered.

This hypothetical yet elegant model cannot explain the entire Eemian sand succession. There must have been some levelling late in the Eemian to explain the more or less horizontal top of the marine sands between about 18 and 22 m -NAP, which not only holds for the top of the sands in the Amsterdam basin, but is found throughout most of the subcrop area of the Eemian in the western Netherlands.

Weichselian deposits

The Eemian deposits are overlain predominantly by Weichselian eolian and fluvial (periglacial) sands (Figs. 5-6). Over large areas, the transition between the Eemian and the Weichselian deposits seems gradual. It is determined on the basis of grain-size differ-

ences and the presence and/or absence of marine shells. Loam, humic loam and thin peat layers are present locally in the Weichselian deposits. These layers have been assigned to the Early and Middle Weichselian by means of radiocarbon data (Van der Hammen et al., 1967) and palynological evidence (Zagwijn, 1983). They do not occur below 20 m -NAP.

In the Willemssluizen core (Fig. 5b), sands with marine shells between 20 and 30 m -NAP are interpreted as a fluvial deposit on the basis of sedimentological data, such as unilateral cross-lamination and the absence of clay drapes (De Gans & Wassing, in press). These fluvial deposits are overlain by Late Weichselian eolian deposits and hence date to the Early-Middle Weichselian. The loam, humic loam and thin peat layers are here interpreted as overbank deposits related to this fluvial (Rhine?) system.

The highstand Eemian clay is capped by a stone line (Mirandabad core, Fig. 5b). The absence of cryoturbation structures in the Eemian clay and the absence of soil indicators suggest erosion of at least two meters of the top of the Eemian highstand clay. The top level of the highstand Eemian clay in the Amsterdam basin was hence of the same order as in the Amersfoort area. The upper level of the Weichselian deposits is presented in Figure 4f, together with the erosion pattern of Holocene tidal channels.

Summary and conclusions

The subglacial and proglacial morphology of the deeply excavated basins flanked by glaciectonic ridges exerted a major control on the sedimentation and erosion during the late Saalian and the Eemian. It defined the location of sediment sinks and sources and, in addition, had a strong impact on the way the Eemian transgression progressed. The major conclusions of the present study relate directly or indirectly to this morphology and are summarised below.

- (1) After melting of the ice, the central-western Netherlands changed into two major lakes: one at the site of the IJssel glacial basin and one in the western Netherlands (including the Amersfoort, Amsterdam, Haarlem, IJmuiden and Bergen glacial basins). The latter lake extended for an unknown distance into the present North Sea.
- (2) The Rhine river, which drained a major part of the meltwater of the Saalian Baltic ice sheet, changed its course after melting of the ice tongues and debouched into the IJssel basin lake (Van de Meene & Zagwijn, 1978). An overflow in the north and a connection to the western lake supplied clay and silt, which settled in the sinks formed by the former glacial basins.

- (3) The lake at the site of the IJssel glacial basin was filled by Rhine sediments before the start of the Eemian. The western lake was drained shortly before the Eemian in the late Saalian, and the Vecht valley was formed as the main channel of the Rhine. This valley would become the main entrance to the central-western Netherlands for the transgressing Eemian sea.
- (4) A threshold separated the Vecht valley from the glacial basins in the south, which – when the sea level was rising – again changed into lakes, probably because of a rising groundwater table. Freshwater diatomites characterize the early Eemian in the Amsterdam basin. Overtopping of the sill by the rising sea initially caused a layered structure in the water mass of the Amsterdam basin, with the deposition of a diatom-rich sapropel, the so-called Harting Layer.
- (5) The Eemian succession in the Amsterdam basin consists of a lower part of predominantly clays. The clays were deposited in a lagoon with a varying exchange with the open North Sea. The turbidity of the water column was low, as appears from the indications for the occurrence of sea grass at the lagoon floor, even at estimated depths of 10 m or more. This also implies low sedimentation rates.
- (6) The clays in the Amsterdam basin are overlain by a wedge of medium- to coarse-grained sands, which are thought to represent barrier and washover deposits. Because of the grain size of the sands, we infer a local provenance from neighbouring ice-pushed ridges. As this wedge has been deposited during the Eemian highstand, it is hypothesized that the barrier recession was mainly due to subsidence because of compaction of the clays.
- (7) Evidence for strong tidal currents during deposition of the Eemian succession are scarce. It is thought that this is mainly due to the bay-like nature of the Eemian sea in the central-western Netherlands and to the dissipation of the tidal wave by the rough morphology of its sea floor.
- (8) The compaction of the Saalian and Eemian clays in the basin is substantial. The concentration of shells on top of the Eemian clay at a depth of 50 m -NAP in the deepest part of the basin (25E171) were deposited in shallow water during pollen zone E5 at the same time as the deposition of the 'highstand clays' at 10 m -NAP. This suggests a compaction in the order of 40 m and of a decrease of 50% of the clay volume. The depression in the upper level of the Weichselian deposits North-East of Amsterdam (Fig. 4f) is the result of

continuous compaction, even after the end of the Weichselian.

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