Saalian glacial deposits and morphology in The Netherlands

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ABSTRACT: The Saalian glaciation in The Netherlands shows a strong relation between glacial bedforms and the nature of the underlying sequence of unconsolidated sediments. The northern part of The Netherlands is characterized by a fine grained glacier bed. The area has an undulating topography and a continuous till cover. It shows two distinct glacial lineations, an older NE-SW running lineation, which is overprinted by a NNW-SSE lineation in a 15 km wide zone. Small and overridden ice-pushed ridges are found at places where the subsurface favours the buildup of elevated water pressures. Relatively deeply incised fluvioglacial valleys cross the area, but these post-date ice coverage. South of the area the glacier bed changes to coarse sands. That area is characterized by deep glacial basins and high ice-pushed ridges. In this area subglacial scour by basal meltwater increased considerably with respect to the northern Netherlands. It is argued that thickening of the ice cap due to the change in permeability of the glacier bed combined with subglacial piping leads to optimal conditions for glaciotectonic deformation. In the central Netherlands the movement of the glacier is controlled by local glacier bed conditions and is decoupled from the NE-SW directed mass-balance gradient. The interrelation between the forms and deposits of the glacier bed leads us to present a new hypothesis on the sequence of events which explains most of the Saalian glacial features in The Netherlands.

1 INTRODUCTION

At the occasion of the INQUA symposium on "Tills and end moraines in The Netherlands and NW-Germany" held at the University of Amsterdam, September 1986, the Geological Survey of The Netherlands compiled two maps related to the Saalian glaciation of The Netherlands. This paper is an explanation to the map on Saalian glacial deposits and morphology. The map is mainly based on published and unpublished data collected by the Geological Survey. Additional data of the IJsselmeer area were kindly provided by our colleagues of the R.IJ.P. (IJsselmeer Polders Development Authority).

During the Saalian the Scandinavian ice sheet had its most extensive development in the dutch area; its southern boundary comes south of latitude 52°. Earlier glaciations never reached this far, and later glaciations - the Warthe and Weichselian phases - all had their southern boundary north of The Netherlands.

Saalian glaciation in The Netherlands is characterized by the formation of large pushed ridges and deep glacial basins. Although remolded during the Eemian and the Weichselian this landscape can still be recognized in the eastern and central part of the country where the Saalian deposits occur at or near the surface. Due to subsidence, glacial landforms and deposits in the western Netherlands are covered by a succession of younger sediments and can only be reached by mechanical drilling. Consequently, the amount of information on which the map is based differs between the eastern and western Netherlands. For instance, the pattern of Weichselian brooks, eroded into the Saalian till in the northeastern part of The Netherlands (Drente plateau) is also present in the western part but could not be mapped because of a much wider spacing of drill holes. Moreover, the sheets of the 1:50,000 Geological Map of The Netherlands have been surveyed only partly up to now, which also produces some lack of balance. The reader should keep this in mind when using the map.

The interaction between the ice sheet and a subsurface of unconsolidated sediments forms an important item in recent discussions on glacier movement and the resultant bedforms (Boulton & Jones, 1979; Moran et al., 1980; Bluemle & Clayton, 1984; Boulton & Hindmarsh, 1987).

The Saalian glaciation in The Netherlands shows a strong relation between the glacial bedforms and the nature of the underlying sequence of unconsolidated sediments, in particular their hydrologic properties. For that reason this paper will start with a short outline on the composition of the substrate of The Netherlands followed by a more detailed account on the morphology of the area prior to the arrival of the ice sheet.

2 GEOLOGIC OUTLINE OF THE NETHERLANDS PRIOR TO THE SAALIAN GLACIATION

The Netherlands is situated along the southeastern margin of the subsiding North Sea Basin. The boundary between rising uplands in the south and southeast and the subsiding basin is not a simple one; in general terms we can state that the southern Netherlands were more or less stable in the Pleistocene, except for the NW-SE trending Central Graben system. In the east-central Netherlands, Tertiary rocks occur at or near the surface, and the hinge zone in this area roughly runs N-S, to bent to E-W in northern Germany. A simplified version of the hinge zone is given in the inset of Fig. 1. Apart from the Central Graben in the south, the main locus of subsidence is the SE-NW trending Zuiderzee Basin in which more than 300 m of Pleistocene sediments were deposited. Fig. 1, which gives a cross-section of the Pleistocene from the northeastern part of The Netherlands to the southwestern part in the direction of the ice movement (for location of profile sea inset) clearly shows the difference in rate of subsidence between the Zuiderzee Basin and adjacent areas.

The late Tertiary sediments are mainly fine grained sands, silts and clays deposited in a marine environment. Because of their low permeability they form a continuous hydrogeological base in The Netherlands. In the early Pleistocene the sedimentary regime changes and The Netherlands becomes the centre of fluvial sedimentation which, throughout the Pleistocene, keeps pace with subsidence. Two interfingering fluvial systems can be distinguished in the early Pleistocene, one from the south and southeast, including the Rhine and Meuse, and a major

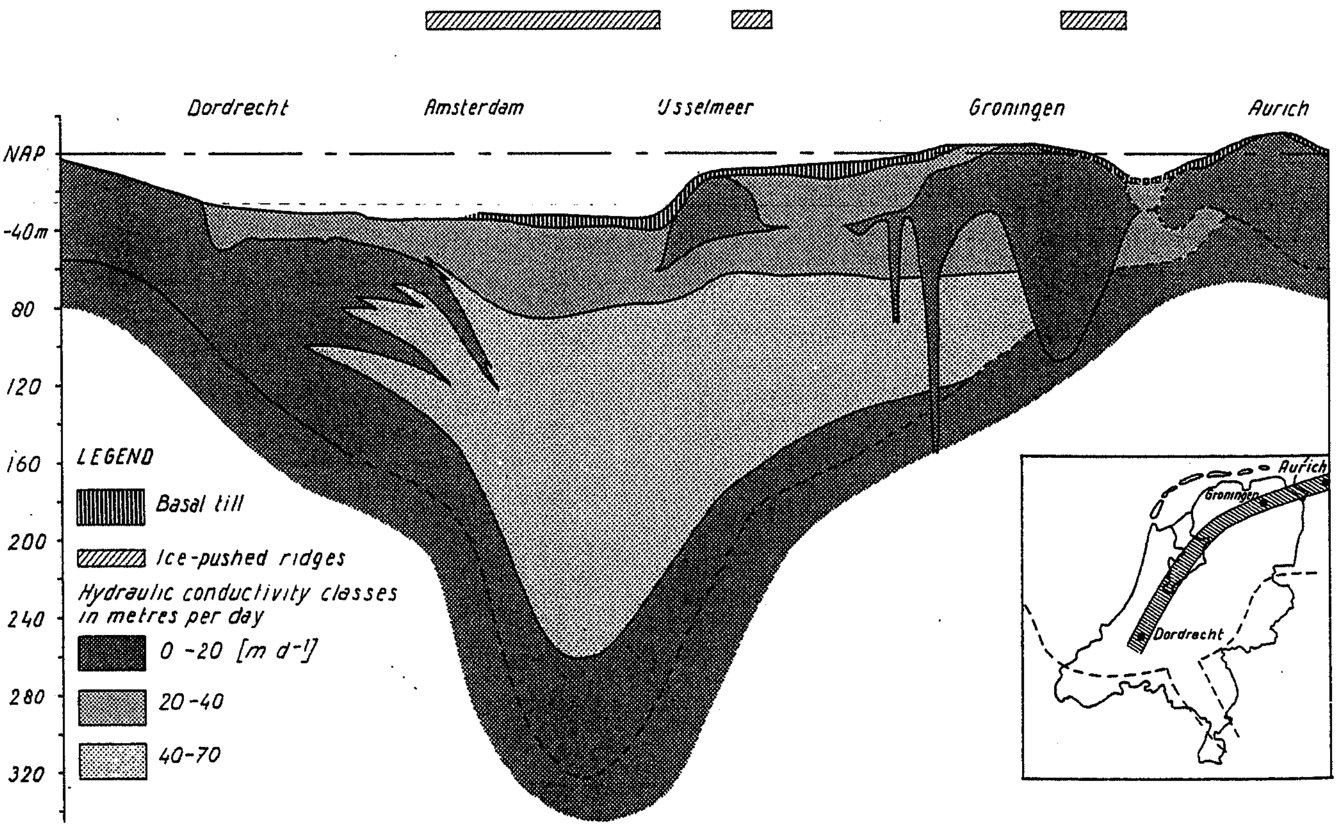

Fig. 1. Simplified hydrogeological transect derived from Fig. 2. The ice flow was from right to left. The bars at the top of the figure indicate the different hydrogeological conditions of the glacier bed under which glacial thrusting occurred.

river system from the east, draining the German Uplands and the Baltic area (Bijlsma, 1981). The latter is the more important of the two and accounts for up to 75 % of the sediment deposited in the Zuiderzee Basin (Fig. 2).

During early Cromerian times, the forerunner of the present drainage system of northern Germany develops and the supply from the east stops. From that time onwards only the Rhine/Meuse system provides sediment to the subsiding northern and western Netherlands.

Because of the dominance of the eastern rivers in the early Pleistocene, deposits of the other river system are restricted to the southern and southwestern part of The Netherlands. They interfinger in the central part of the country in a zone which is roughly parallel to the maximum extent of the Saalian ice sheet.

The Rhine/Meuse deposits are mainly characterized by the alternation of sands, silts and clays, in particular in the centre of The Netherlands, their permeability is highly variable and generally moderate to low. The deposits of the eastern rivers, on the other hand, mainly consist of a thick succession of highly permeable sands and gravelly sands, with clay deposits only in its basal part and, locally, in the top part. From the early Cromerian onwards deposition by Rhine and Meuse dominates. In the northern Netherlands these deposits disconformably overlie sands and gravelly sands of the eastern river system. Deposition is more or less continuous until the invasion of the Elsterian ice sheet in the northern Netherlands. Decay of this ice cap produces a large amount of fine grained glaciolacustrine deposits, both as infilling of deep N-S running depressions and as a continuous sheet of up to 30 m thickness overlying the older deposits. The southern limit of these deposits is a WNW-ESE running line between the towns of Den Helder in the northwest and Almelo in the east.

In the Holsteinian the Rhine/Meuse river system occupies a wide river and delta plain with probably two major branches: a SE-NW and S-N flowing branch separated by an outcrop area of Elsterian glaciolacustrine sediments (Fig. 3). Backswamp clays on top of the river sequence contain pollen assemblages of zone Ho3b (de Jong, 1986; Zagwijn, 1973). For the S-N flowing branch along the eastern boundary of the river plain a gradient can be reconstructed for the Holsteinian Rhine in its lower course which amounts to about 0.15 m/km. This value is similar to that of the present-day lower course of the river Rhine.

The SE-NW flowing branch occurs in the western Netherlands at a much deeper level (Figs. 2 & 3), due to subsequent subsidence of the Zuiderzee Basin. This subsidence may also have initiated the shift of the channels towards the west at the end of the Holsteinian, as in the early Saalian the northward branch of the Rhine has disappeared, and backswamp deposits with a pollen assemblage characteristic

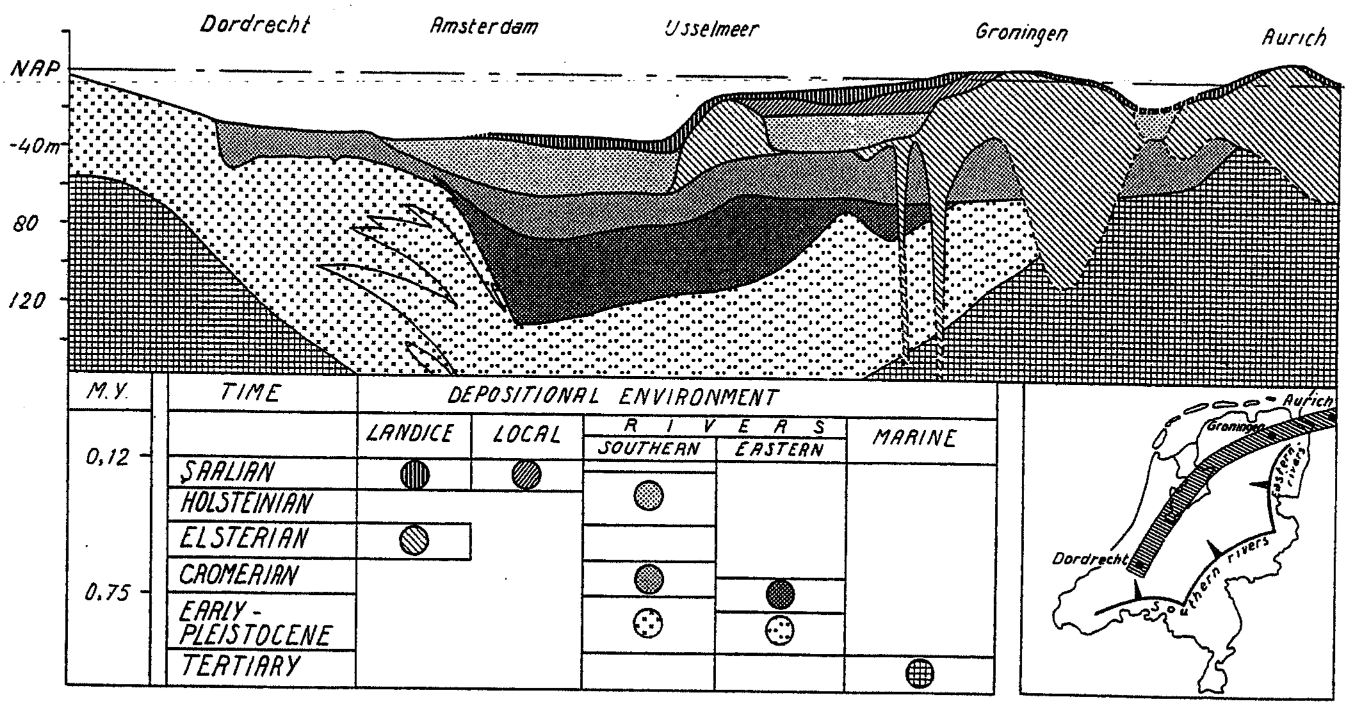

Fig. 2. Simplified cross-section showing the geology of the glacier bed in The Netherlands. The section is drawn parallel to the main direction of ice flow. Post-Saalian deposits not indicated.

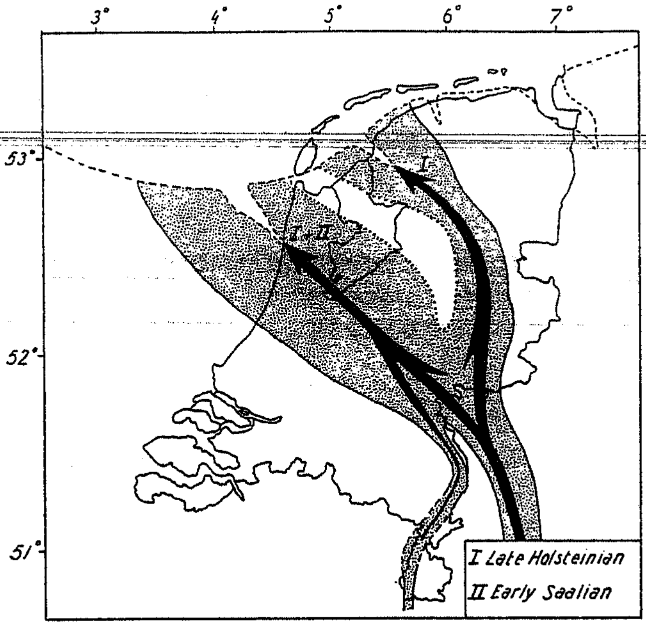

Fig. 3. Paleogeographic reconstruction of the Rhine-Meuse river plain in the late Holsteinian and the early Saalian.

for the Hoogeveen interstadial were found in the northwestern Netherlands (de Jong, loc. cit.).

Periglacial deposits, mainly fine grained eolian sands, with humic intercalations of the Hoogeveen and Bantega interstadials (Zagwijn, 1973) fill up the abandoned river plain in the east (Fig. 2). A low escarpment at the eastern boundary of the river plain is smoothened by the eolian deposits, and no deeply incised valleys occurred when the ice sheet reached the Netherlands.

Concluding we can state that shortly before the arrival of the ice, The Netherlands was a plain with little outspoken topography. The rivers Rhine and Meuse followed a SE-NW course roughly from Nijmegen in the SE to Alkmaar in the West. From the East and NE the plain dipped gently towards this river course. The glacier bed mainly consisted of fine grained deposits in the northern and eastern part of the country. South of the line Almelo-Den Helder the glacier bed changes into a coarser grained sequence in the central and western part.

3 SAALIAN GLACIAL MORPHOLOGY

The Saalian glaciated terrain can be subdivided into three different morphological areas with, in general, gradational boundaries. The "Drente plateau" (Lorié, 1895) in the northern Netherlands with a slightly undulating topography and characterized by a more or less continuous till cover, the central Netherlands with its exposed and buried ice-pushed ridges associated with deep glacial basins, and the eastern Netherlands south of the Drente plateau and east of the large glacial basin of the IJssel valley, which unites features of both the other areas.

3.1 The Drente till plateau

An almost flat, slightly westward-dipping area characterized by a more or less continuous till cover, with scattered small and fluted ice-pushed ridges. The southern boundary of this morphological unit is relatively sharp in the east, but ill-defined in the western part of The Netherlands. The area is crossed by two broad and relatively deeply incised fluvioglacial channels, one running E-W near the southern margin of the Drente plateau, the other running SSE-NNW in the northern part of The Netherlands near to the German border. As will be discussed below, these valleys, named respectively Vecht- and Hunze-valley after present-day brooks, were formed at a late stage of Saalian events in The Netherlands. They contain no till.

In main lines, thickness of the till increases from the northeast towards the southwest (see profile on enclosure). Because of marine erosion in the Eemian and the Holocene, till is absent in large parts of the coastal area in the north and the west. Where the deposits occur at or near the surface two distinct glacial lineations can be distinguished (Fig. 4). An older NE-SW direction expressed by low ridges in the till and the fluted shape of the pushed ridges. Till morphology in NW-Germany shows a similar direction (Ehlers & Stephan, 1983). This direction is overprinted by a NNW-SSE lineation of megaflutes in an up to 15 km wide and 70 km long zone, the Hondsrug complex, which forms the culmination of the Drente plateau and is situated between the towns of Groningen in the north and Schoonebeek in the south. Data on the orientation of clasts in the till confirm the morphological lineation (Rappol, 1983; Rappol & Stoltenberg, 1985). For an extensive review of Saalian till in The Netherlands see Rappol (1987).

Data on the distribution of Fennoscandian crystalline erratics in the till are given by Zandstra (1987). Both Rappol and Zandstra came to the conclusion that almost all till in The Netherlands is subglacial in origin.

Ice-pushed ridges occur in the northeastern part of the area near the village

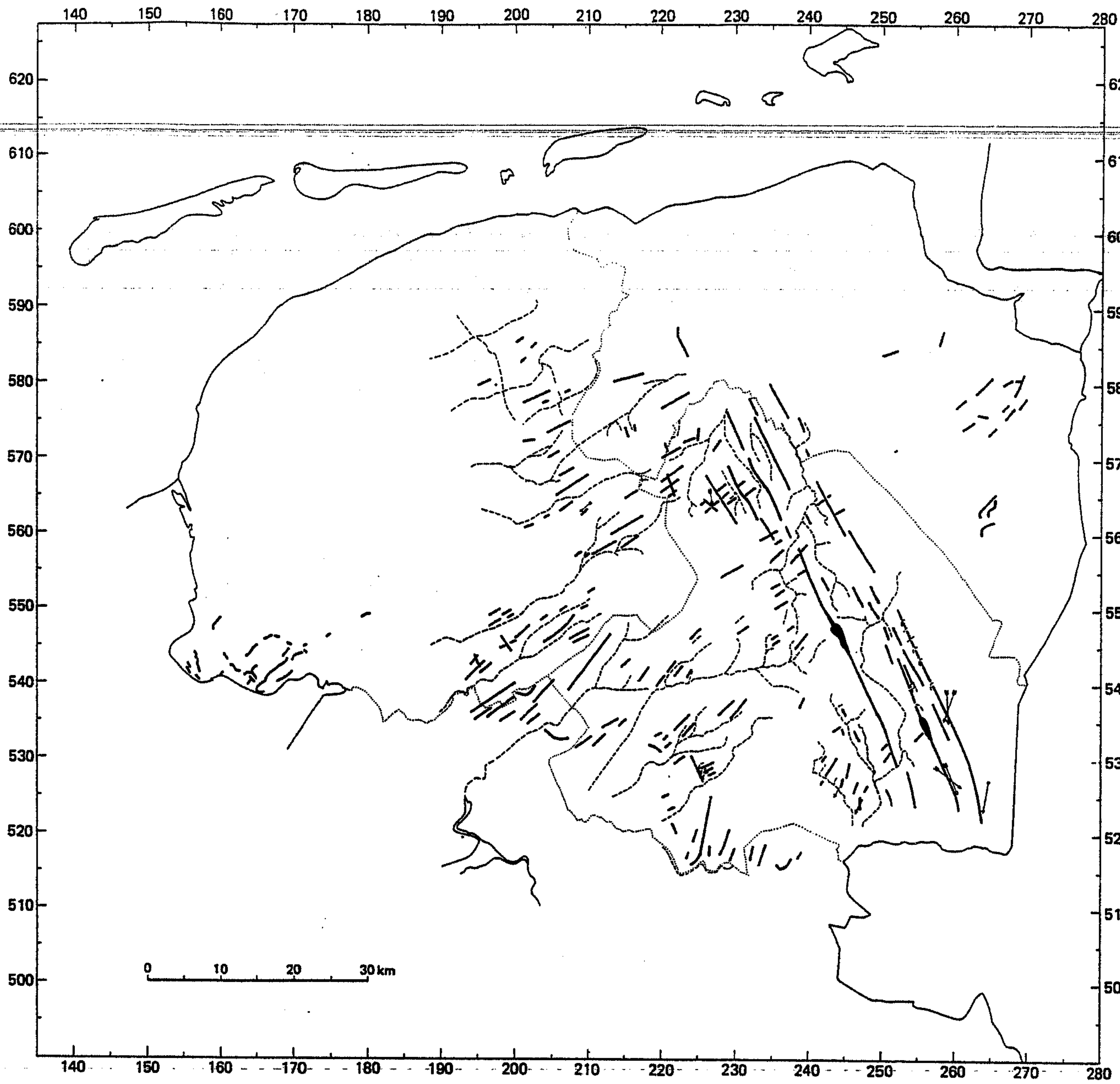

Fig. 4. Low topographic ridges from the basal till plain in the northeastern part of The Netherlands. Two glacial directions can be distinguished: an older NW-SW direction and a younger NNW-SSE direction. The latter forms the megafluted structures of the Hondsrug complex. Arrows indicate the clast fabric of the till (after Rappol, 1984); associated drumlins in black.

of Winschoten, west of the Ems valley; in a zone directly north of the earlier mentioned fluvioglacial Vecht valley between the village of Hoogeveen in the east and the island of Texel in the west, and directly south of this valley. Most of the latter are covered by younger deposits, in particular those in the western part of the country near the towns of Hoorn and Castricum. Their glaciotectonic nature is inferred from the stratigraphic position of the pre-Saalian deposits, which occur slightly higher than in the direct surrounding. These ice-pushed ridges have a number of features in common: a. they are small in comparison to those in the central part of The Netherlands; b. only the uppermost 10 to 20 m of the pre-glacial sequence is involved in tectonic dislocation, and consequently the glacial basins found with the ridges are shallow; c. they are often associated with thick sequences (more than 10 m) of till, which may have been imbricated with the pre-glacial sediment (ter Wee, 1962); d. fluvioglacial sediments such as ice-contact fans or meltwater deposits are not involved in pushing; e. the ridges have been

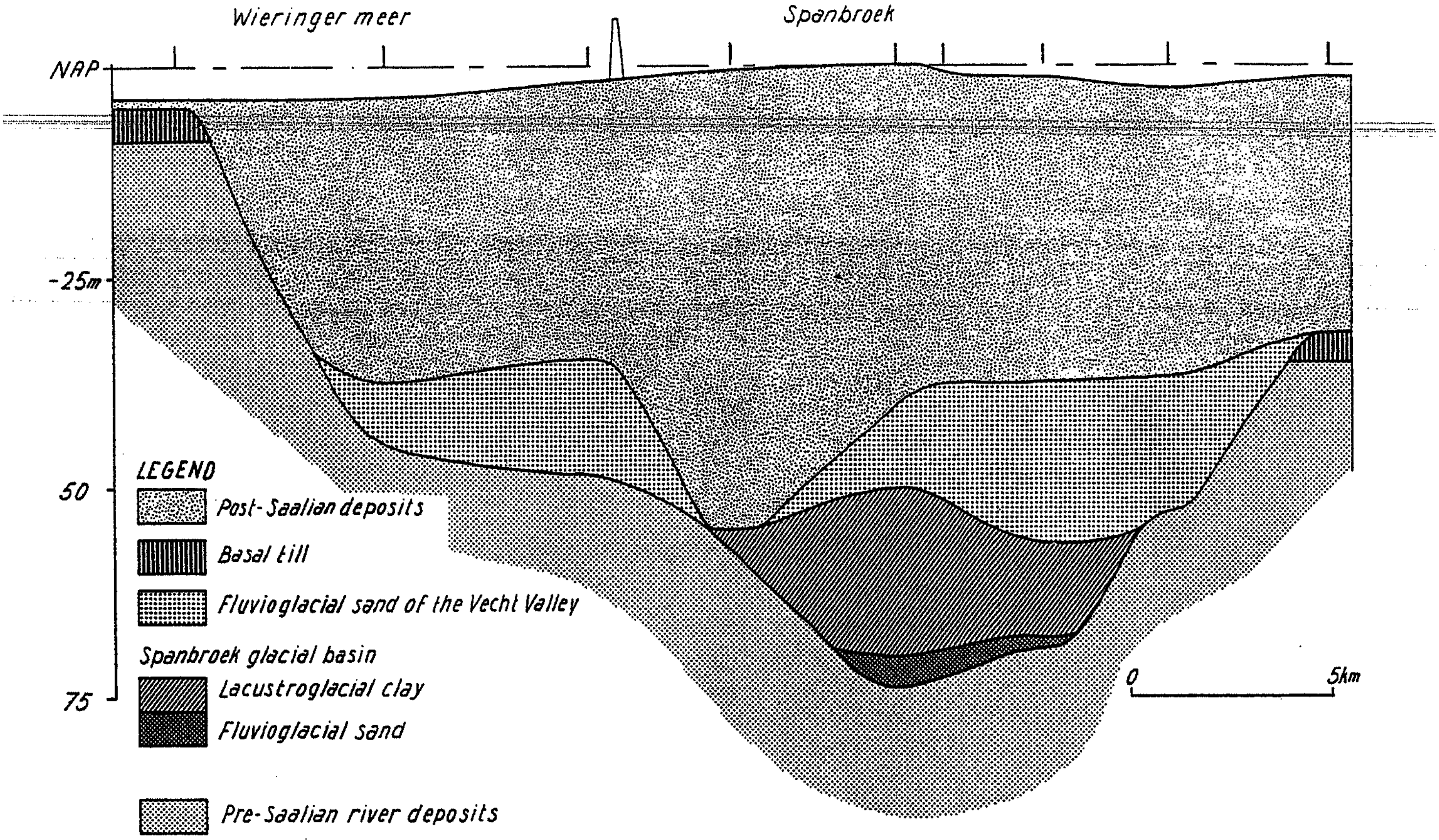

Fig. 5. Cross-section showing the presence of the Spanbroek glacial basin underlying the broad fluvioglacial channel of the Vecht valley. For location see the enclosed map between 5°10', 52°50' and 4°45', 52°37' (resp. left to right in the section).

fluted and drumlinized in a NE-SW direction (Brouwer, 1950; Zonneveld, 1975) and, consequently, have been overrun by the icesheet. As will be discussed in more detail below, the line of ridges between Hoogeveen and Texel are located at the margin of the eastern branch of the Holsteinian Rhine and their position seems to be predestined by the subsurface geology: however, the position of a number of other ridges is less easily explained. Not expressed as a ridge, but definitely of glaciotectonic origin are the stacked nappes exposed in a quarry north of the village of Emmen at the southern extension of the Hondsrug in the northeastern Netherlands (Ruegg & Zandstra, 1977). Nappes or thrust units exposed in the quarry have a thickness of over 40 m and consist of Pliocene and lower and middle Pleistocene deposits. The glacial basin from which the stacked nappes have been removed is probably hidden below the fluvioglacial Hunze valley east of the Hondsrug. The topographic expression of this pushed sequence was destroyed and overprinted by the NNW-SSE running lineation of the Hondsrug.

Below the fluvioglacial and younger infill of the Vecht valley in the western Netherlands s small and shallow glacial basin was found near the village of Spanbroek (Fig. 5). Perhaps the inferred glaciotectonic ridge near the town of Hoorn consists in part of sediments removed from this basin. The presence of a basin with a fill of up to 20 m of glaciolacustrine clays below the fluvioglacial sands of the Vecht valley is one of the arguments in favour of a late origin of this valley.

The southern boundary of the Drente till plateau is relatively sharp in the east, but gradual in the western part of the country. Apart from the more or less continuous cover of till and the smooth topography, one of the main features of the till plateau is the complete absence of ice contact fans, indicating that the ice sheet advanced continuously over the area without a significant standstill. Basal meltwater production was insufficient to produce channels in front of the ice sheet during the advance and subglacial channels during the steady state; meltwater was mainly discharged by groundwater flow. Several of these aspects change southwards. Most important is that the ice field breaks up into separate glacier tongues, which carve the glacial basins by subglacial erosion and pushing aside the pre-glacial sedimentary succession. Note that strikes of glacial basins and pushed ridges differ from the NE-SW lineation of the main ice field, indicating that movement of the glacier tongues is largely defined by local factors and, at least in part, decoupled from the mass-balance gradient of the ice sheet. In addition, meltwater production increases considerably, as appears from deep subglacial channels which have been found both in the western Netherlands near to the town of Alkmaar and in the eastern Netherlands between the towns of Almelo and Aalten (van Rees Vellinga & de Ridder, 1973) and the extensive field of fans fringing the ice-pushed ridges. The rougher topography of the till area south of the Vecht valley and north of the glacial basins of Haarlem and Amsterdam in the western Netherlands is probably also due to subglacial erosion by basal meltwater. Noteworthy is the NE-SW running elongate depression south of the town of Hoorn, which unlike the glacial basins slightly more to the south was not formed by glaciotectonic erosion as it lacks the surrounding pushed ridges.

3.2 The Central Netherlands

Five major glacial basins can be recognized, each rimmed by a belt of deformed sediments. As basins and ridges are deeply buried below younger sediments in the western part of the country, only a few data are available on the two westernmost basins. On the map accompanying this paper the basin of Amsterdam has been roughly drawn as a NE-SW directed ellipse, but newer data, presented by de Gans et al. (1987) shows this basin to have a similar lobed shape as the two major basins more to the east, named respectively Gelderse Vallei and IJssel Basin. Pushed ridges surrounding the basins occur in the subsurface in the western part of the country, but reach heights of over 100 m in the ridge flanking the IJssel Basin.

The glacier bed in which the basins formed, consists of relatively coarse grained and highly permeable fluvial sediments deposited in the actively subsiding Zuiderzee Basin (Figs. 1 & 2) in particular along its southern margin. Hence the pushed ridges consist of sands and gravelly sands both of the eastern fluvial system and the Cromerian and younger Rhine/Meuse system. The SE-NW running southern margin of the pushed ridges from the town of Nijmegen in the east to that of Haarlem in the west, coincides with the lateral transition and interfingering of the coarse grained sediments of the eastern system with the much finer grained Early Pleistocene southern sequence (Figs. 1 & 2). Clays and silts from this latter unit often form the decollement of the thrusts in the pushed ridges along the southern margin.

The Gelderse Vallei Basin has a roughly NW-SE direction, which in main lines follows the fluvial plain of the early Saalian Rhine/Meuse. Sediments of this river occur in the folded and thrusted sequences of the pushed ridges which surround the basin in a more or less symmetric way (Maarleveld, 1953a,b; Ruegg, 1983).It reaches a depth of over 100 m in its proximal part and slopes up very gently to its distal front. The IJssel Basin follows the fluvial plain of the N-S running Holsteinian branch of the Rhine (Fig. 3). The basin is strongly asymmetric with a steeply dipping west flank bordering a broad highly pushed-up ridge, and a gently dipping east flank along which only locally pushed ridges occur. This east flank coincides with the eastern margin of the subsiding Zuiderzee Basin, and is the dipslope of the late Tertiary sediments, which, directly east of the basin, occur at or near the surface. Obviously, the basins form preferentially in coarse grained sequences. Till is only locally found in the glacial basins. In the Gelderse Valley Basin, till is most common along the inner flank of the pushed ridges at the glacier terminus. However, even here it occurs in isolated patches. In the IJssel Basin an over 10 m thick till bed occurs at the proximal end of the basin. Scarce and isolated occurrence of till in the basins suggests considerable subglacial meltwater erosion. This is also suggested by the occurrence of a few metres thick layer of fluvioglacial sands and gravel at the base of the basin deposits, occasionally below the till. Glaciolacustrine deposits, both clays and sands, fill the basins after retreat of the ice lobes (de Gans et al., 1987).

Most of the ice-pushed ridges are slightly asymmetric in shape with the steepest slope towards the glacial basin; the more gentle distal slope grades into the outwash (alluvial) fans of the foreland. Heights of the ridges is variable; those surrounding the Gelderse Vallei Basin reach 60 to 70 m above sea-level; the ridge bordering the IJssel basin on its western side locally attains a height of over 100 m. The ridges are traversed by overflow channels. These occur at various levels and are so common that only a selection is presented on the map. They are often terraced in cross-section. The ridges have plateau-like top levels. Some authors have ascribed this to erosion by ice moving on top of the ridges (Visscher, 1972), but, as shown by van der Wateren (1981), evidence that the ice ever covered the ridges is lacking. Erosion by meltwater (ten Cate & Maarleveld, 1977) seems a better explanation. As the ridges are fringed by alluvial or outwash fans, mainly consisting of sand and gravel reworked from early and middle Pleistocene deposits pushed up in the ridges (Zandstra, 1981, 1983; Ruegg, 1983) it is evident that a considerable amount of the ridges has been washed down by glacial meltwater. Base level of these fans is the late Saalian ice-marginal Rhine/Meuse.

Because of the scarceness of exposures, information on the structure and stratigraphy of the ridges is fragmentary and restricted to a number of isolated quarries and boreholes. Dominant structures are imbricated thrust sheets with thrust planes dipping 30 to 40° towards the glacial basin. As shown by Maarleveld (1953a) bedding planes are generally parallel to the general strike of the ridges. In one of the best studied pits - Kwintelooyen near the village of Rhenen in the southern part of the ridge surrounding the Gelderse Vallei basin - van der Wateren (1981, 1985) describes a 400 m long N-S profile with 8 thrust sheets, imbricately stacked near the ice front and folded into a gentle anticline and syncline with an amplitude of 15 m and a wave-length of about 400 m further from the front. Thrust sheets in pits surrounding the Gelderse Vallei basin vary in thickness from a few metres to about 40 m. As a rule the basal part of the thrust sheets is composed of clay, silt and fine sandy beds, mostly fine grained intercalations in the upper half of the eastern fluviatile sequence (Figs. 2 & 3), but occasionally Holsteinian clays from higher in the section (Fig. 3). The main part of the thrust sheets consists of coarse grained sandy beds: the upper half of the early Pleistocene fluviatile succession of eastern derivation and the Cromerian and younger Rhine/Meuse sediments. The thickness of the thrust sheets of the ice-pushed ridges surrounding the IJssel Basin mostly fall in the same range. However, thrust sheets of up to 90 m in thickness occur in the Hattem pit in the northern part of the ridge near the town of Zwolle. The latter thrust sheets comprise the entire early and middle Pleistocene sandy fluviatile succession (Figs. 2 & 3). The base of these thrusts consists of clays of Tiglian age of the lower part of the eastern fluviatile sequence (Zandstra, 1971.

As mentioned earlier, the ice lobe of the Gelderse Vallei Basin invaded the early Saalian fluvial plain of the Rhine/Meuse. Deposits of this river occur in most thrust sheets in the pits surrounding the Gelderse Vallei.

Although the ice-pushed ridges consist for the greater part of pre-glacial deposits, in particular in the ridges surrounding the Gelderse Valley basin glacigenic sediments, mainly outwash fan deposits often form the top of the stratigraphic succession of the thrust sheets (Ruegg, 1983). These fan sediments vary in thickness from a few to more than 10 metres and consist of parallel bedded, gravelly sands. Similar to the undeformed fans fringing the ice-pushed ridges, these gravelly sands contain only a small amount of Fennoscandian detritus and consist predominantly of reworked sand and gravel of the older Pleistocene deposits. In the undeformed fan, this sand is derived by erosion of the thrusted sequences in the ridges. The composition of the fan deposits in the thrusts indicates that these fans formed by erosion of earlier pushed ridges and that deformation of the subsoil and deposition of the fans is a continuous process as the glacier grows and proceeds. A similar sequence of events is described by Boulton (1986) from Maktak Glacier, Baffin Island, by Boulton & van der Meer (1987) from the pushed ridge of Holmströmbreen in Svalbard and by van der Wateren (1987) from the ice-pushed ridges of the Dammer Berge in the Federal Republic of Germany.

3.3 The eastern Netherlands

In the greater part of this area, situated south of the Drente plateau and east of the IJssel Valley Basin, fine grained Tertiary sediments occur at or near the surface. Only in the north and in the south sands and gravelly sands form the glacier bed. Major glacial basins and pushed ridges occur near the German border in the northern part and are in line with basins and ridges of the Rehburg phase in the Federal Republic of Germany (Meyer, 1980, 1983).

Pushed ridges are formed where the Tertiary basement comes near the surface (Fig. 6). Sediments in thrust sheets consist of late Tertiary and Quaternary deposits; the latter are mostly coarse grained sands.

Similar to the ice-pushed ridges of the Rehburg phase in the Federal Republic of Germany (Meyer, 1983), the ridges are overridden by the ice sheet and, in part, reshaped into crag-and-tail-type drumlins with often thick till deposits (Fig. 7).

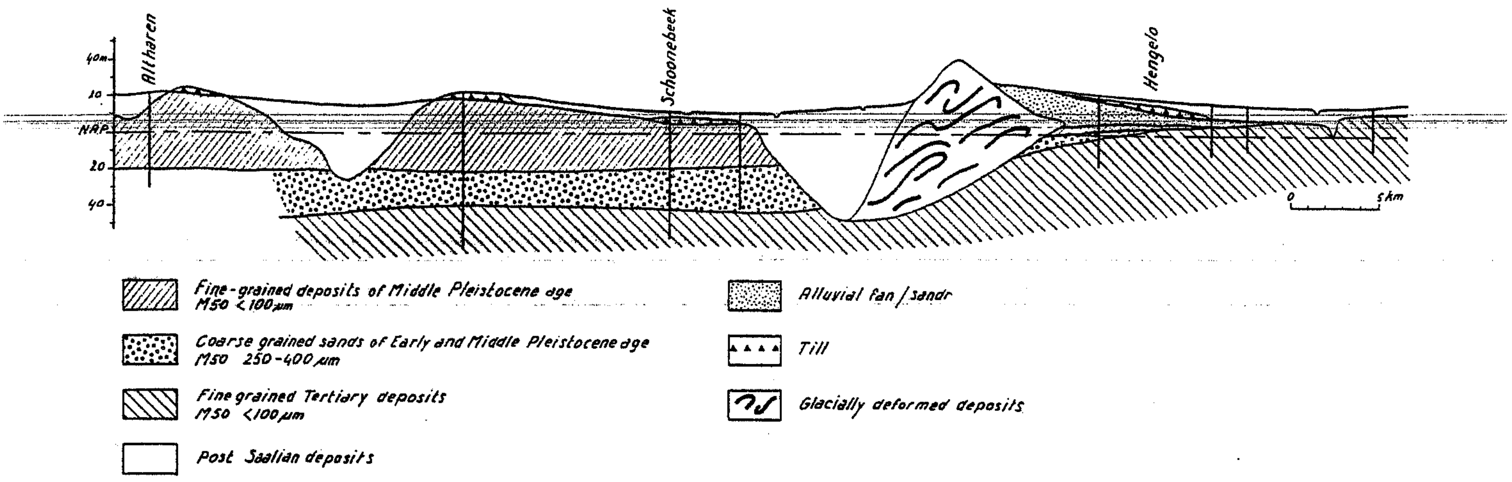

Fig. 6. Cross-section parallel to the ice movement (left to right), showing the position of glacially deformed structures in relation to the rim of the hydrogeological base (i.e. the Tertiary deposits). For location see Schoonebeek and Hengelo on the enclosure; Altharen (FRG) not indicated.

Locally, parts of the ice-pushed ridges have been displaced over a considerable distance (van den Berg, in press) and probably part of the smaller ice-pushed ridges in this area are unrooted, allochthonous blocks.

Till is common in the area but strongly eroded by glacial meltwater streams. As in the Drente till plateau and the central Netherlands one till layer is found, except for the area between Lochem and Neede (see enclosure) where locally two tills occur separated by 10 m of fluvioglacial deposits. It should be stressed that this is the only locality in The Netherlands where two Saalian tills have ever been found.

Outwash fans occur west of the ice-pushed ridge of Ootmarsum and were formed by meltwater eroding the ridge when the ice front stabilized at the Rehburg line and a glacier tongue was situated in the Nordhorn Basin. Unlike those of the central Netherlands, the fans are covered by a basal till formed when the ice sheet overrode the ridges.

Most conspicuous fluvioglacial deposits in this area are a number of subglacial channels which on the map have erroneously been indicated as esker. Only the northern part of the system, north of the town of Almelo stands out as a bead of small hills (Maarleveld, 1956), consisting of gravels and coarse grained sands. They are underlain by till and by coarse grained deposits of the outwash fans and eastern rivers. Towards the south where the fine grained and little permeable Tertiary sediments form the glacier bed, this subglacial meltwater system passes into incised valleys, which, locally, have a depth of up to 70 m below the till surface (van Rees Vellinga & de Ridder, 1973). Little is known of the system in the southern part, but according to the hydrogeological map of Bolsenkötter (1968) the channels seem to shallow between the dutch-german border and the outwash plain south of the town of Rees, where coarse grained sands again form the glacier bed.

The relation between the nature of the glacier bed and the morphology of the sub-

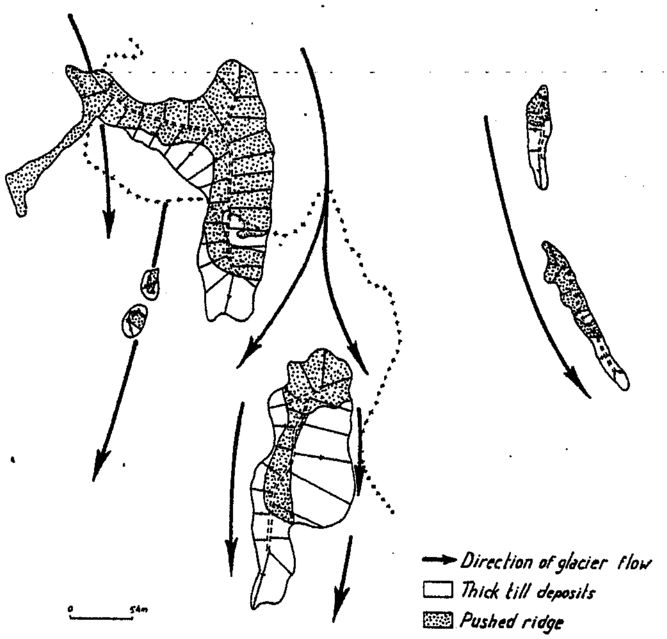

Fig. 7. Crag-and-tail formation by plastering of thick till deposits (over 20 m) against older ice-pushed ridges. The till tails indicate the main direction of glacier flow (see also Fig. 9).

glacial meltwater spillways seems to suggest that where the glacier bed has a high transmissivity an esker or shallow valleys are formed, whereas in impermeable sediment beds the meltwater cuts down deep channels.

Fluvioglacial deposits of undifferentiated origin, consisting of sand and gravelly sand purely derived from the underlying Rhine deposits, admixed with glacially derived sediments occur in a zone 10-20 km wide on the western side of the area. The sequence is up to 10 m thick and is only known from borings. They occur on top of a discontinuous till sheet, which in its turn overlies the Holsteinian Rhine deposits. As mentioned earlier they are overlain by a till which at several localities is fluted in a N-S direction. The nature of these deposits is tentatively related to the subglacial piping process during the initial formation of the glacial basins (see section 5). The presence of two "basal" tills is as yet not understood.

4 AGE AND NATURE OF VECHT- AND HUNZE-VALLEY

As mentioned earlier two major and relatively deeply incised fluvioglacial valleys, the E-W flowing Vecht valley near the southern boundary of the Drente till plateau and the SSE-NNW flowing Hunze valley at the east flank of the Hondsrug in the NE Netherlands, travers the glacial landscape. The fuvioglacial infill consists of 10 to 20 metres of sand, which is mainly derived by erosion of older deposits but which usually contains a small amount of northern crystalline components. The valleys contain no till and must have been formed after disappearance of the ice.

Ter Wee (1962, 1983) and Jelgersma & Breeuwer (1975) suggest these valleys to be ice marginal meltwater streams in front of successive recession stages of the Saalian ice sheet. However, a number of arguments opposes this view. Both valleys are deeply incised into the subsurface, indicating that the valleys were spillways of large amounts of water without much sediment load. Stabilized ice fronts, on the contrary, are the sites of large sediment accumulation (Boulton, 1986) and consequently,little erosion. Neither in the valleys nor in the direct surroundings remains of ice contact fans have ever been found.

As mentioned earlier, in the western part of the country, about 10 km WNW of the town of Hoorn, the sands of the Vecht valley overlie a small glacial basin scoured into gravelly sands to a depth of about 40 m below the till level and filled by a few metres of fluvioglacial sand and up to 20 m of glaciolacustrine clay (Fig.5) If the Vecht Valley really represents an ice-marginal valley, the basin would have been filled by sands at least comparable to those of the overlying Vecht Valley. Its filling with glaciolacustrine clay indicates that the Vecht Valley formed relatively late in the Saalian, probably quite some time after the ice disappeared from The Netherlands. The same conclusion is reached when glaciolacustrine sedimentation in the glacial basin of Amsterdam is considered.

As shown by de Gans et al. (1987) the bulk of the glaciolacustrine clays in this basin forms part of a few delta systems draining the dead ice field and barren till plateau in the north. Absence of dropstones in the glaciolacustrine deposits indicates that the infill is not ice-marginal. The largest delta occurs in the northeastern corner of the glacial basins. If the Vecht Valley existed at the time the glacial basin was filled, the drainage area would have been much too small to account for the delta.

If the Vecht Valley is not an ice-marginal valley, what then is its origin? As mentioned above, we think that downcutting of this valley was only possible if there was a source of water without sediment load. In other words, if it is an overflow channel of a lake which acts as a sediment trap. According to Thomé (1958) and van de Meene & Zagwijn (1978) in the late Saalian after retreat of the ice from The Netherlands the Rhine shifts its course to a more northern direction and debauched in the IJssel Basin, at that time changed into a huge and deep lake. A sandy delta is built between Montferland and the village of Lochem (see Fig. 7 in de Gans et al., 1987). An overflow of the IJssel Basin lies at about 25 m below present sea level at its northern margin.

The 25 m depth contours can be followed from the IJssel Basin into the Vecht Valley. Considering age and setting of the Vecht Valley, its interpretation as an overflow channel of the late Saalian Rhine best explains the present data.

Little is known of the age of the Hunze Valley, except that it is also formed after disappearance of the ice. However, in analogy to the Vecht Valley, we think that the Hunze Valley formed as an overflow channel of the river Ems which flowed into one of the glacial basins of the Rehburg line.

Glacial thrust terrains or ice-pushed ridges occur along former ice-marginal positions. In view of the low yield stress of glacier ice high pore water pressure to decrease the shear resistance of the sediments along which movement takes place is a prerequisite for glaciotectonic deformation (Mathews & Mackay, 1960; Banham, 1975; Moran et al., 1980; Boulton & Jones, 1979; Bluemle & Clayton, 1984) and conditions which favour the build-up of high pore water pressures promote glaciotectonic deformation. Whether permafrost is one of these, is still open to debate. Many authors (e.g. Berthelsen, 1979; Richter et al., 1950; Schindler et al., 1978) consider permafrost a prerequisite for glacial thrusting. Moran et al. (1980), in a review on the Prairie Region of North America, stress the importance of a marginal frozen bed zone. According to those authors, thrust features were formed by plucking of large blocks of sediment from the beds where the advancing glacier was frozen to the substrate. However, as argued by van der Wateren (1985) there is some reason to believe that glacial thrusting of the dutch ice-pushed ridges took place in material that was not cemented by ice, and he concludes that ice-bound conditions are not a necessity for glacial thrusting.

An ice cap on a flat surface only deforms the substratum by transmitting horizontal shear stress. It has been argued that the Pleistocene ice caps, invading lower latitudes, were sometimes forced to move up-slope or to invade pre-existing valleys with escarpments (Banham, 1975). Under these conditions, the effect of the horizontal normal stress becomes more prominent compared to the shear stress parallel to the glacier bed. Recently, Boulton (1986) pointed out that many major Pleistocene ice-pushed ridges are intimately associated with ice marginal fluvioglacial accumulations representing ice contact fans formed during a stabilized glacier front. He argues that a glacier that pushes against a sediment scarp, such as an ice contact face, can more effectively transfer glacier stresses deep into the subsurface to produce major push masses. Van der Wateren (1985) in a paper on the ice-pushed ridge surrounding the Gelderse Vallei, proposes a model in which, in addition to high pore water pressures and basal shear stress, gravitational forces play a major role. Van der Wateren states that basal shear stresses are too low to lift a toe of the size found in most ice-pushed ridges in the central Netherlands. Because ice thickness decreases towards the margin, the substratum is subjected to a decreasing load in the same direction. If the increments of stress difference under a slab of ice in the marginal zone of a glacier tongue are summed, a gradient stress is obtained directed towards the ice-pushed ridge and sufficient to move the toe upwards.

Basically, two types of ice-pushed ridges can be distinguished in The Netherlands:

1) small, horseshoe-shaped ice-pushed ridges as found in the northern part of the country, in which only the uppermost 10 to 20 m of the substrate has been deformed and displaced; and

2) the much larger often tongue-shaped glacial basins surrounded by ice-pushed ridges of the central and eastern Netherlands. Examples of the former are the ridges of Hoogeveen, Steenwijk, Vollenhove, Oudemirdum and Texel-Wieringen.

These ridges all occur near the western boundary of the eastern branch of the Holsteinian Rhine Valley (Figs. 1, 2 & 3) where the sandy deposits of the Rhine pinch out against a valley side of fine grained glaciolacustrine sediments of Elsterian age. This setting is very well suited to build up high pore water pressures in the backswamp clays overlying the river sands, and those clays and the overlying periglacial deposits of early Saalian age are the main components of the pushed ridges. As mentioned earlier, the Elsterian glaciolacustrine sediments are occasionally also involved in deformation. Considering the drumlinized and fluted shapes of the ridges, deformation at this buried valley side occurred in front of an advancing and overriding ice-sheet. Origin and shape of the ridges seems to be similar to the "hill-depression forms" of Bluemle & Clayton (1984) in North Dakota. Probably, the ice-pushed ridge of Winschoten in the northeastern Netherlands falls in the same category, but our data on this area are still scanty.

The ice-pushed ridges of the central Netherlands not only differ in size from the ridges in the north, but also in geologic and glaciologic setting. In the first place, the nature of the glacier bed changes from the fine grained sands and clays of the Drente till plateau to coarser grained fluvial sands in the south. Although this difference is not so evident from Fig. 1, the local, periglacial deposits of early Saalian age of the Drente plateau are much finer grained than the fluvial Rhine sands which form the glacier bed in the central Netherlands. Main effect of this change on the ice sheet will be that the basal friction increases and the ice, consequently, will thicken (Boulton & Jones, 1979). In the second place, basal meltwater production increases south of the Drente till plateau, as discussed above. Meltwater production must be so large that subglacial erosion takes place despite the high permeability of the subsoil, as appears from the NE-SW directed depression south of the town of Hoorn in the western part of the country and a subglacial valley system west of Alkmaar in the same area (Westerhoff et al., 1987; not on map). In the coarse sediments the flow of subglacial meltwater probably resulted in piping (Boulton & Hindmarsh, 1987) so that the ice entrenched itself into the subsoil.This piping might explain why the ice at the margin of the sheet splits up into separate glacier tongues. That basal meltwater plays an important role is also evident from the strike of the glacial basins, which is the Rhine/Meuse fluvial plain of Saalian age for the Gelderse Vallei Basin and the Holsteinian Rhine/Meuse plain for the IJssel Basin. Groundwater flow will follow the coarsest stretches in the subsurface, and basal meltwater emerging at the snout of the glacier will lead the way for the advancing ice.

Thickening of the ice cap because of a higher basal friction in combination with entrenchment by piping will give optimal conditions for glaciotectonic deformation both by gravitational forces (van der Wateren, 1985) and by pushing against the subglacial valley sides.

Because of the permeable nature of the substrate, the buildup of high water pressures can only occur locally and probably for a short time in the clayey intercalations. Short periods of extension of the glacier tongue by deformation of its subsurface will follow by larger episodes in which the glacier will thicken and entrench itself deeper into the substrate by piping. Provided the presence of a clay bed within the glacial stress field in which elevated pore water pressures can be obtained, the glacier will advance again by pushing the sediments aside.

6 SEQUENCE OF EVENTS

The current hypothesis to explain Saalian glacial features in The Netherlands is the recession model of Maarleveld (1953a, 1981) which was extended to the northern Netherlands by ter Wee (1962, 1983) and modified by Jelgersma & Breeuwer (1975). Based on a detailed study of bedding attitudes of the pushed sequences in the central Netherlands in hand-made pits, Crommelin & Maarleveld (1949) and Maarleveld (1953a) distinguished three push moraine lines, which they interpreted as recession lines of the ice front.

Ter Wee (1962) extended this model to the northern Netherlands with two stabilized glacier fronts within the general retreat: the line of pushed ridges between Hoogeveen in the east and the island of Texel in the west as the older of the two and the pushed ridge of Winschoten in the northeastern Netherlands as the younger. He considered the Hoogeveen-Texel line as the continuation of the german Rehburg line and interpreted the fluvioglacial Vecht valley as the ice marginal meltwater stream. The Hunze valley was considered to be the ice marginal meltwater stream of the northernmost stabilized ice front. As these pushed ridges are associated with thick till deposits, ter Wee (1962) assumed the till to be tectonically imbricated. Although the recession model, from the very start, left a number of features unexplained, in its main lines it was accepted as a working model by the dutch geological community. Morphological problems which were not solved by the model were for instance the fluted and drumlinized shape of the small pushed ridges of the Drente till plateau, indicating that these ridges were overridden by the ice (Brouwer, 1950; Zonneveld, 1975), and the NNW-SSE lineation of the Hondsrug complex, as in the recession model ice movement occurred from the NE towards the SW.

The interpretation of the Hondsrug complex as due to faulting, was not corroborated by the data on fault structures in the subsurface (van Montfrans, 1975).

These points were mentioned by Zonneveld (1975) in a discussion of the Maarleveld/ter Wee model. Zonneveld also wondered whether retreat of the ice cap at the latitude of The Netherlands can be compared to that of alpine glaciers, and suggested that retreat of the Saalian ice cap was less systematic and probably resulted in a large dead ice field. In his view, Vecht and Hunze valley were formed during this dead ice stage. Now it has been shown that the pushed ridges of the Rehburg line of Germany have been overridden by the ice (Meyer, 1980, 1983), and that Vecht valley and probably also Hunze valley were formed after the ice had largely disappeared from The Netherlands, we consider the recession model hardly tenable any more.

The sequence of events given by us below and illustrated by Figs. 8 & 9 has the following premises:

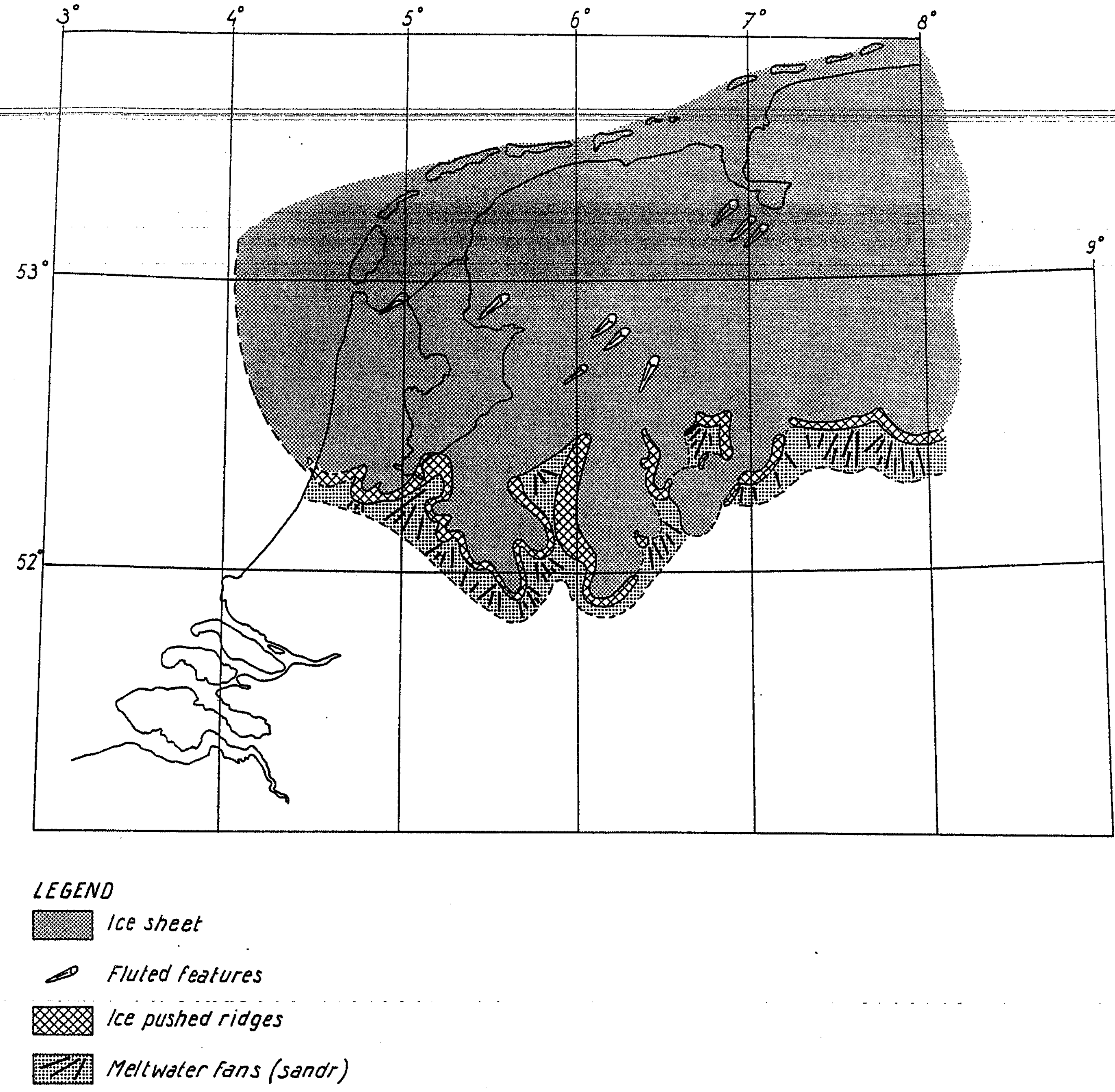

Fig. 8. Extension of the "Rehburg Stage" in The Netherlands. This stage is characterized by a high production of basal meltwater and forms the ultimate stage of the NE-SW directed expanding ice cap. The indicated fluted features are mainly associated with ice-thrust topography.

1. One basal till is found, which implies that the ice sheet in the Saalian only once covered The Netherlands;
2. Both the NE-SW and the NNW-SSE (Hondsrug) lineations of the Drente till plateau are of glacial origin;
3. Pushed ridges in The Netherlands are formed during an advance of the ice sheet;
4. With the exception of the ridges of the central Netherlands all pushed ridges were overridden by the ice.

We propose that in the initial stage the ice sheet advanced from the NE, and, in a relatively short time, covered most of the Drente till plateau. Small pushed ridges formed at the front of the advancing sheet at localities where the subsurface permitted the buildup of high water pressures. Considering the horseshoe shape of these ridges, the snout of the advancing sheet was probably slightly lobed. The advance probably was rapid bacause of the fine

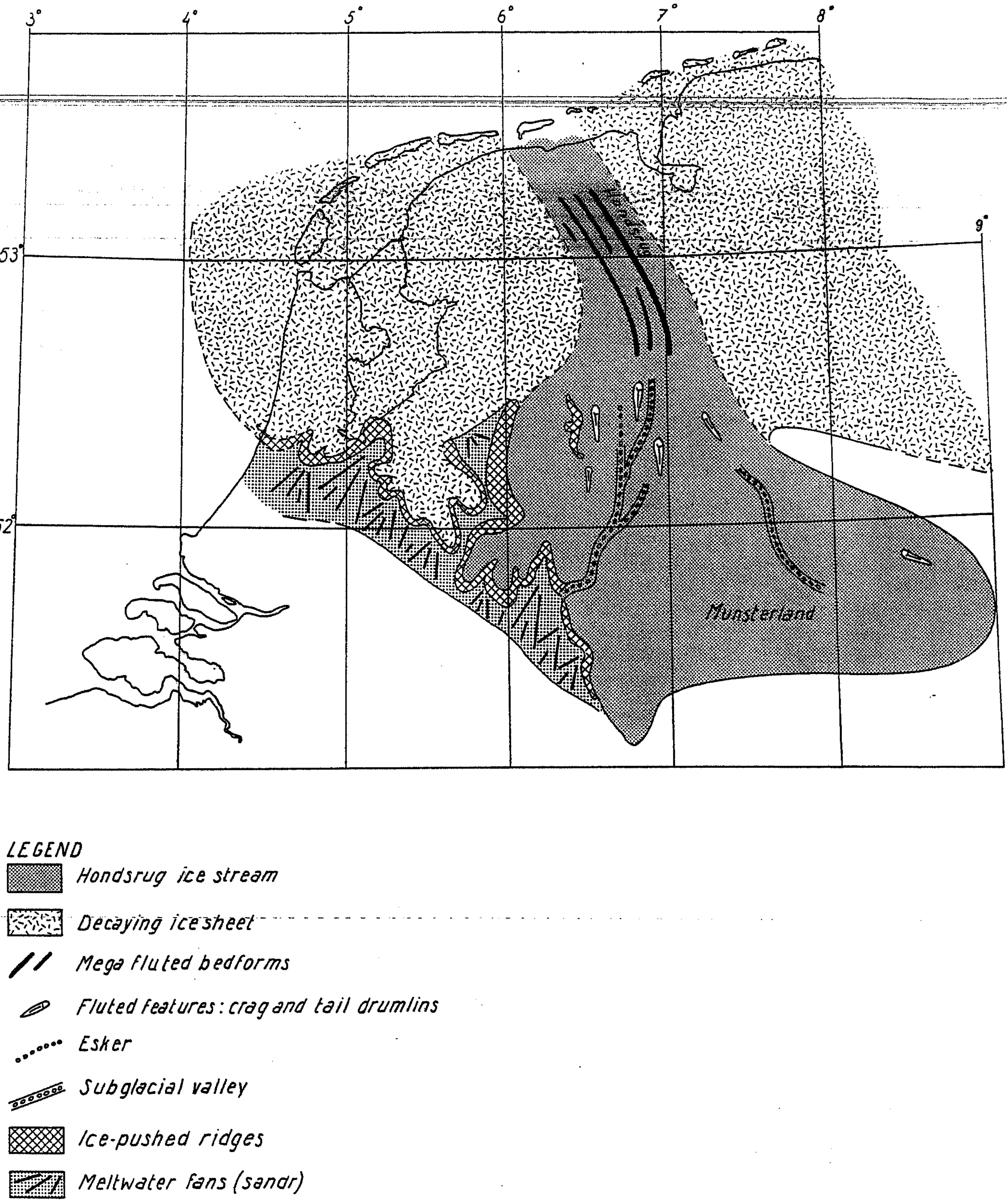

Fig. 9. The Hondsrug ice stream feeding the Münsterlandlobe. This ice stream generated a megafluted bed in the north and reshaped older ice-pushed ridges into crag-and-tail type drumlins.

grained nature of the glacier bed. When the ice sheet reached the southern margin of the Drente till plateau the movement of the sheet was slowed down by the change of the glacier bed to coarser grained sands in the central Netherlands and the northern part of the eastern Netherlands. As described above, the front of the ice sheet was split into separate glacier tongues because of piping and pushing;

in fact, the coarser sediments acted as a kind of ice trap. Perhaps with the exception of the southern extension of the IJssel Basin, we think that the ice tongues of the central Netherlands formed at about the same time as those of the Rehburg line in Germany. This situation is shown in Fig. 8. Ice in the central Netherlands was trapped in the glacial basins. However, the ice tongue in the Nordhorn Basin east of the pushed ridge of Ootmarsum eventually advanced by overriding of its pushed ridge. This difference in behaviour may be due to the difference in the subsoil, which is entirely sandy in the central Netherlands, whereas in the eastern part fine grained Tertiary sediments occur directly south of the sandy strip at the site of the Nordhorn Basin. When the glacier overrode the pushed ridges of Ootmarsum and Oldenzaal-Enschede it could advance southward over the fine grained glacier bed of Tertiary sediments, and we think that this initiated a NNW-SSE to N-S directed ice flow within the existing ice field, draining the ice mass situated towards the north (Fig. 9). This ice flow, which must have been comparable to present-day ice flows in the Antarctic (Hughes et al., 1985), was entirely embedded in the NE-SW directed ice field and only scoured the subsoil at the highest place of the Drente till plateau, the Hondsrug complex. The moment this ice flow started, the ice field west of the Hondsrug was cut off from its source and started to degrade. The Hondsrug flow fed an area reaching from the IJssel Basin in the west to the Weserbergland, Germany, in the east. Its southernmost front eventually reached to the Rheinische Schiefergebirge (Thomé, 1986). This flow probably occurred late in the Saalian glacial history of The Netherlands, and we think that soon thereafter the supply of ice stopped and dead ice conditions set in.

In our view the proposed sequence of events explains most of the Saalian glacial features in The Netherlands. However, to feed the Hondsrug ice flow, we need a considerable ice field in the North Sea, the existence of which is still a matter of debate (Schüttenhelm, pers. comm., 1987). Moreover, this sequence of events only partly explains the distribution of Fennoscandian crystalline erratics as published by Zandstra (1987), except for the association characterized by East-Baltic crystalline rocks, which is clearly related to our NNW-SSE directed ice flow. It is suggested that more to the south this NNW-SSE directed flow deposited a mixture of erratics. An association partly eroded from the till plateau admixed with an East-Baltic association.

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REFERENCES

Banham, P. 1975. Glacitectonic structures: a general discussion with particular reference to the contorted drift of Norfolk. In A.E.Wright & F.Moseley (eds.). Ice ages: ancient and modern. Geol.J. Spec.Issue 6: 69-94.

Berg, M.W. van den (in press). Toelichting bij de geologische kaart van Nederland 1:50,000. Blad Almelo Oost (28 O) en Denekamp West (29 W). Haarlem: Rijks Geologische Dienst.

Berthelsen, A. 1979. Recumbent folds and boudinage structures formed by subglacial shear: an example of gravity tectonics. Geol. & Mijnbouw 58: 253-260.

Bijlsma, S. 1981. Fluvial sedimentation from the Fennoscandian area into the North-West European Basin during the late Cenozoic. Geol. & Mijnbouw 60: 337-345.

Bluemle, J.P. & L.Clayton 1984. Large-scale glacial thrusting and related processes in North Dakota. Boreas 13: 279-299.

Bolsenkötter, H. 1968. Erläuterungen zu der geologischen Karte Nordrhein-Westphalen 1:100,000. Blatt Bocholt, Karte 1, Tafel 5. Krefeld: Geologisches Landesamt Nordrhein-Westphalen.

Boulton, G.S. 1986. Push-moraines and glacier-contact fans in marine and terrestrial environments. Sedimentology 33: 677-698.

Boulton, G.S. & R.C.A.Hindmarsh 1987. A sediment flow law and a theory of subglacial sediment deformation and tunnel

valley formation (in press).
Boulton, G.S. & A.S.Jones 1979. Stability of temperate ice caps and ice sheets resting on beds of deformable sediment. J.Glaciol. 24(90): 29-43.
Boulton, G.S. & J.J.M.van der Meer (eds.) 1987. Preliminary report on the Glacitecs 84 expedition to Spitsbergen. Report Fysisch Geografisch en Bodemkundig Laboratorium, University of Amsterdam. (in press).
Brouwer, A. 1950. De glacigene landschapstypen in Nederland. Tijdschr. KNAG LXVII: 20-32.
Cate, J.A.M.ten & G.C.Maarleveld 1977. Toelichting op de legenda. Geomorfologische kaart van Nederland 1:50,000. Wageningen/Haarlem: Stichting voor Bodemkartering/Rijks Geologische Dienst.
Crommelin, R.D. & G.C.Maarleveld 1949. Een nieuwe geologische kaartering van de zuidelijke Veluwe. Tijdschr. KNAG LXVI: 41-56.
Ehlers, J. & H.J.Stephan 1983. Till fabric and ice movement. In J.Ehlers (ed.). Glacial deposits in North-West Europe, p. 267-274. Rotterdam: Balkema.
Gans, W.de, Th.de Groot & H.Zwaan 1987. The Amsterdam basin, a case study of a glacial basin in The Netherlands (this volume).
Hughes, T.J., G.H.Denton & J.L.Fastook 1985. The Antarctic Ice Sheet: an analogy for Northern Hemisphere paleo-ice sheets? In M.J.Woldenberg (ed.). Models in geomorphology, p. 25-72. London: Allen and Unwin.
Jelgersma, S. & J.B.Breeuwer 1975. Toelichting bij de kaart glaciale verschijnselen gedurende het Saalien, 1:600,000. In W.H.Zagwijn & C.J.van Staalduinen (eds.). Toelichting bij de Geologische Overzichtskaarten van Nederland, p. 93-103. Haarlem: Rijks Geologische Dienst.
Jong, J.de 1986. Pollenanalytisch onderzoek van een aantal boringen ten behoeve van het kaartblad Alkmaar 19 West. Intern Rapport Paleobotanie nr. 1000. Haarlem: Rijks Geologische Dienst.
Lorié, J. 1895. Iets over de hoogvenen in Drenthe. Nieuwe Drentse Volksalmanak: 1-17.
Maarleveld, G.C. 1953a. Standen van het landijs in Nederland. Boor en Spade 6: 95-105.
Maarleveld, G.C. 1953b. De geologische geschiedenis van de zuidelijke Veluwe. Boor en Spade 6: 105-112.
Maarleveld, G.C. 1956. Grindhoudende midden-pleistocene sedimenten. Thesis, Utrecht. Meded. Geol. St. C-€(6;:1-105.
Maarleveld, G.C. 1981. The sequence of ice-pushing in the Central Netherlands. Meded. Rijks Geol. Dienst 34: 2-6.
Matthews, W.H. & J.R.Mackay 1960. Deformation of soils by glacier ice and the influence of pore pressure and permafrost. Trans. R.Soc. Canada 54(IV): 27-36.
Meene, E.A.van de & W.H.Zagwijn 1978. Die Rheinläufe im deutsch-niederländischen Grenzgebiet seit der Saale-Kaltzeit. Überblick neuer geologischer und pollenanalytischer Untersuchungen. Fortschr. Geol. Rheinld.u.Westf. 28: 345-359.
Meyer, K.D. 1980. Zur Geologie der Dammer und Fürstenauer Stauchendmoränen (Rehburger Phase des Drenthe-Stadiums). Festschrift G.Keller, p. 83-104. Osnabrück: Verlag H.Th.Wenner.
Meyer, K.D. 1983. Saalian end moraines in Lower Saxony. In J.Ehlers (ed.). Glacial deposits in North-West Europe, p. 335-342. Rotterdam: Balkema.
Montfrans, H.M.van 1975. Toelichting bij de ondiepe breukenkaart met diepteligging van de Formatie van Maassluis 1:600,000. In W.H.Zagwijn & C.J.van Staalduinen (eds.). Toelichting bij de Geologische Overzichtskaarten van Nederland, p. 103-108. Haarlem: Rijks Geologische Dienst.
Moran, S.R., L.Clayton, R.LeB. Hooke, M.M. Fenton & L.D.Andriashek 1980. Glacier-bed landforms of the prairie region of North America. J.Glaciol. 25(93): 457-476.
Rappol, M. 1983. Glacigenic properties of till. Publ. Fys.Geogr. en Bodemk. Lab., Univ. of Amsterdam 34: 1-225.
Rappol, M. 1984. Till in southeast Drente and the origin of the Hondsrug complex. Eiszeitalter u. Gegenw. 34: 7-27.
Rappol, M. & H.M.P.Stoltenberg 1985. Compositional variability of Saalian till in The Netherlands and its origin. Boreas 14: 33-50.
Rees Vellinga, E.van & N.A.de Ridder 1973. Notes on the Tertiary and Pleistocene geology of east Gelderland, The Netherlands. Eiszeitalter u. Gegenw. 23/24: 26-45.
Richter, W., H.Schneider & R.Wager 1950. Die Saale-eiszeitliche Stauchzone von Itterbeck-Uelsen (Grafschaft Bentheim). Z.d. Dtsch.Geol.Ges. 102(I): 60-75.
Ruegg, G.H.J. 1983. Glaciofluvial and glaciolacustrine deposits in The Netherlands. In J.Ehlers (ed.). Glacial deposits in North-West Europe, p. 379-392. Rotterdam: Balkema.
Ruegg, G.H.J. & J.G.Zandstra 1977. Pliozäne und Pleistozäne gestauchte Ablagerungen bei Emmerschans, Drente, Niederlande. Meded. Rijks Geol. Dienst 28-4: 65-99.
Schindler, C., H.Röthlisberger & M.Gyger 1978. Glaziale Stauchungen in den Niederterrassen-Schottern des Aadorfer

Feldes und ihre Deutung. Ecl. geol. Helv. 71: 159-174.
Thomé, K.N. 1958. Die Begegnung des nördlichen Inlandeises mit dem Rhein. Geol. Jb. 76: 261-308.
Thomé, K.N. 1986. Meltwater drainage pattern of composite glaciers. J.Glaciol. 32(110): 95-100.
Visscher, H.A. 1972. Lexicon voor fysische geografie. Utrecht: Het Spectrum.
Wateren, F.M.van der 1981. Glacial tectonics at the Kwintelooijen sandpit, Rhenen, The Netherlands. Meded. Rijks Geol. Dienst 37-7: 252-268.
Wateren, F.M.van der 1985. A model of glacial tectonics, applied to the ice-pushed ridges in the Central Netherlands. Bull.Geol.Soc.Denmark 34: 55-74.
Wateren, F.M.van der 1987. Structural geology and sedimentology of the Dammer Berge push moraine, FRG. (this volume).
Wee, M.W.ter 1962. The Saalian glaciation in The Netherlands. Meded. Geol.St. 15: 57-76.
Wee, M.W.ter 1983. The Saalian glaciation in the northern Netherlands. In J.Ehlers (ed.). Glacial deposits in North-West Europe, p. 405-413. Rotterdam: Balkema.
Westerhoff, W.F., E.F.J.de Mulder & W.de Gans 1987. Toelichting bij de geologische kaart van Nederland 1:50,000. Blad Alkmaar West (19 W) en Blad Alkmaar Oost (19 O). Haarlem: Rijks Geologische Dienst (in press).
Zagwijn, W.H. 1973. Pollenanalytical studies of Holsteinian and Saalian beds in the northern Netherlands. Meded.Rijks Geol. Dienst, N.S., 24: 139-156.
Zandstra, J.G. 1971. Geologisch onderzoek in de stuwwal van de oostelijke Veluwe bij Hattem en Wapenveld. Meded. Rijks Geol. Dienst, N.S. 22: 215-258.
Zandstra, J.G. 1981. Petrology and lithostratigraphy of ice-pushed lower and middle Pleistocene deposits at Rhenen (Kwintelooijen). Meded. Rijks Geol. Dienst 35: 178-191.
Zandstra, J.G. 1983. Fine gravel, heavy mineral and grain-size analyses of Pleistocene, mainly glacigenic deposits in The Netherlands. In J.Ehlers (ed.). Glacial deposits in North-West Europe, p. 361-377. Rotterdam: Balkema.
Zonneveld, J.I.S. 1975. Zijn de noordnederlandse stuwwallen overreden of niet? Ber. Fys.-Geogr. Afd., Geogr.Inst. Rijks Univ. Utrecht 9: 3-14.