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COMPOSITION AND ORIGIN OF PETROGRAPHICALLY-STRATIFIED THICK TILL IN THE NORTHERN NETHERLANDS AND A SAALIAN GLACIATION MODEL FOR THE NORTH SEA BASIN

by

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The southern marginal zone of the Saalian till plain in the northern Netherlands is marked by a series of low glaciotectonic hills that are characterised by exceptionally thick till occurrences and a high degree of compositional variability within this till. Structural and compositional analyses of a construction site near Steenwijk and of some related shallow exposures lead to the following reconstruction for the sequence of glacial events in the region.

A temporary halt and wastage of the advancing Fennoscandian ice sheet caused excessive till accumulation. Compositional variations in this till reflect an englacial debris stratification in the form of a flint-poor unit on top of flint-rich till.

Deposition of till is followed by glaciotectonic disturbance, affecting till as well as preglacial sediments. The configuration of ice-pushed ridges suggests an ice lobe moving towards the southwest after reactivation of the ice sheet.

Subsequently, the ice-pushed ridges were overridden by ice moving towards the southwest, forming a discontinuous veneer of predominantly flint-rich till over the deformed sediments.

Petrographic parameters of the ice-pushed till suggest it was deposited during an ice-flow configuration of the Fennoscandinavian ice sheet featuring a "Baltic Ice Stream", resulting in the large amount of Precambrian and Palaeozoic components in this till. The upper flint-poor unit appears to be composed exclusively of such components and to have been transported englacially over a distance of 1000 km or more. During overriding of the ice-pushed ridges, the ice is assumed to have followed a course over Sweden and Denmark.

A second phase with ice movement following the Baltic depression is represented by till of the Hondsrug and Gelderse Vallei areas, deposited by a younger ice movement towards the southeast. It is suggested that this second Baltic ice-flow configuration was generated by the development of a marine ice stream and calving bay in the Norwegian Channel-Skagerrak trough.

The Saalian glaciation model here proposed is speculative on several points due to the paucity of available and reliable data on the Saalian Glaciation of the North Sea Basin, but also on much of the land area surrounding the North Sea extent and flow directions of the Saalian ice cover are uncertain.

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CONTENTS —

SAMENVATTING

Samenstelling en herkomst van petrografisch-gelaagde keileem van grote dikte in Noord-Nederland en een model voor de Saalian glaciatie van het Noordzeebekken.

De zuidelijke begrenzing van het noordnederlandse keileemplateau wordt gemarkeerd door een aantal lage stuwwallen, waarvan ook dikke keileemvoorkomens bekend zijn. Deze keileempakketten bestaan gedeeltelijk uit zeer verschillende keileemtypen.

Keileem en glaciotectonische verschijnselen konden worden bestudeerd in een grote ontsluiting bij Steenwijk en in enkele ondiepe afgravingen op andere plaatsen in het gebied. Uitkomsten van het onderzoek naar de samenstelling van de keileemtypen en structurele gegevens leiden tot de volgende reconstructie van de glaciale geschiedenis voor Noord-Nederland.

Een tijdelijke stilstandsfase van het oprukkende Fennoscandinavische landijs ging gepaard met afzetting van een dik keileempakket. Verschillen in de samenstelling in een verticaal profiel van de keileem weerspiegelen een stratificatie van erratisch materiaal, welke aanwezig was binnen het ijs vóór afzetting. We vinden een vuursteen- en smectiet-arme keileem bovenop een keileem die rijk is aan deze componenten.

Vervolgens werd keileem en materiaal van de ondergrond gestuwd. De oriëntatie van stuwwallen en glaciaal bekken duidt op een zuidwestelijke bewegingsrichting van het ijs.

De stuwwallen werden naderhand overreden door een ijsbeweging in zuidwestelijke richting, waarbij een onderbroken dek van niet-gestuwde vuursteen-rijke keileem werd afgezet.

De samenstelling van het gestuwde keileempakket duidt er op dat het werd afgezet tijdens een stromingsbeeld van het landijs waarin een zogenaamde Baltische IJsstroom figureerde. Dit verklaart het grote aandeel van Palaeozoïsche bestanddelen in deze keileem. De bovenste vuursteen-arme eenheid blijkt in alle fracties uitsluitend uit Precambrische en Palaeozoïsche componenten te bestaan en moet op enige hoogte boven de basis van het ijs over een afstand van 1000 km of meer zijn getransporteerd, zonder vermengd te worden met materiaal van meer lokale herkomst.

Tijdens de overrijdingsfase volgde het ijs waarschijnlijk een traject over Zweden en Denemarken, aangezien de keileem aan het oppervlak van het keileemplateau (met uitzondering van het Hondsruggebied) vooral zweedse gidsgesteenten bevat.

Een tweede fase waarin het ijs de baltische depressie volgde wordt vertegenwoordigd door keileem afgezet in het Hondsruggebied en in de Gelderse Vallei en omgeving. In Nederland stroomde het ijs toen in zuidoostelijke richting. Dit jongere baltische stromingsbeeld werd waarschijnlijk veroorzaakt door de ontwikkeling van een mariene ijsstroom en kalvende baai in het Skagerrak.

Het model voor de Saalien vergletsjering zoals hier voorgesteld is speculatief op enige punten vanwege het geringe aantal beschikbare en betrouwbare gegevens over deze vergletsjering in het Noordzeebekken, maar ook voor een groot deel van het de Noordzee omgevende land zijn de uitbreiding en bewegingsrichting van de Saalien ijsbedekking onzeker.

INTRODUCTION

A fairly continuous till sheet in the northern Netherlands (Fig. 1) preserves evidence of a major glacial cover during the Older Saalian Glaciation of the Fennoscandian Ice Sheet (Ehlers *et al.*, 1984). Two successive directions of ice movement have been recognised through morphological, petrographical, and clast-fabric analyses of the till-sheet: an older movement towards the southwest and a younger movement towards the southeast or south-southeast (Rappol, 1984, 1987; van den Berg & Beets, 1987).

The younger ice flow event is petrographically distinguished by the prevalence of East-Baltic (mainly Finnish) crystalline indicator boulders in till of the Hondsrug ridge-complex and East-Central Baltic indicators in till of the Gelderse Vallei area in the central Netherlands (see Zandstra, 1987 and Fig. 2 for provenance areas). These tills represent deposition during a Baltic ice-flow configuration ("Baltic Ice Stream") in a late phase of the Older Saalian ice cover (Rappol, 1985, 1987; see also Ehlers, 1983; Ehlers *et al.*, 1984) and consist of an upper flint-poor and a lower flint-rich unit

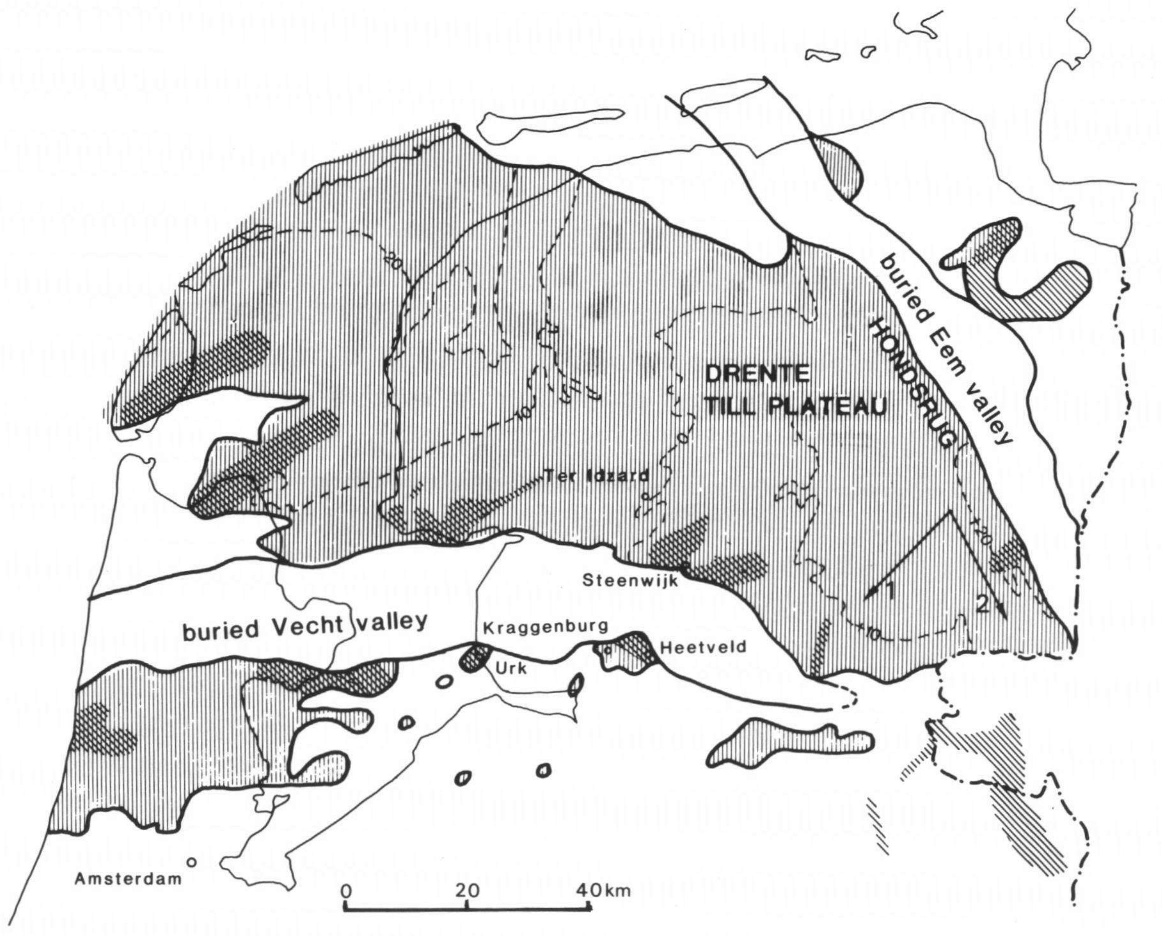


Fig. 1. Distribution of ice-pushed ridges (inclined hatching) and till plain (fine vertical hatching) in the northern Netherlands. Dashed lines give altitude of top of till with respect to sea level (after van den Berg *et al.*, 1986). Arrows indicate two successive ice movements recorded on the till plain: 1. older, 2. younger.

(*e.g.* Zandstra 1983; Rappol, 1987). In Zandstra's (1983) petrographic till classification, tills of this event belong to the Assen and Rhenen Groups.

Till associated with the older ice movement towards the southwest is generally characterised by a predominance of West- and South-Baltic (Swedish) indicators and a high flint content (Heerenveen Group).

However, indications of an earlier Baltic transport route, *i.e.* following the Baltic depression, are presented by occurrences of another till rich in East-Baltic, notably Palaeozoic, indicators and in which flint is virtually absent. This till is known especially, but not exclusively, from the area of low ice-pushed ridges and thick till along the southern margin of the till plain (see Fig. 1). This flint-poor "First Baltic Till" is also known as the Voorst Till Group (Zandstra, 1983).

Position and structural characteristics of the "Second Baltic Till" of the Hondsrug area have been studied in considerable detail. The "First Baltic Till", however, was previously known only from shallow and poor exposures or from drill-hole extracted cores. In 1987, cuttings for road construction near Steenwijk (Fig. 3) offered good opportunities to study the "First Baltic Till". In the

Fig. 2. Geological sketchmap showing distribution of pre-Quaternary bedrocks divisions. Roman numerals indicate Hesemann division of source areas for crystalline indicators: I. East-Baltic (mainly southwest Finland and Åland Islands), IIa. East-Central Baltic, IIb. West-Central Baltic, III. South Baltic, IV. Oslo area. A Hesemann Formula (H.F.) of 6310 indicates 60% indicators from area I, 30% from area II, 10% from area III and 0% from area IV.

present paper, we discuss results of structural and compositional analyses of this exposure and of nearby exposures showing related features. These results necessitate a revision of current views on the course of glaciation in The Netherlands. A newly revised model for glaciation during the Older Saalian ice cover of the northern Netherlands and adjacent areas will be presented at the end of this paper.

SETTING AND PREVIOUS WORK

Three low hills surround the basin of the Steenwijker Aa Valley near Steenwijk (Fig. 3). The ice-pushed nature of these hills was already recognised by van Cappelle (1892), and is demonstrated clearly by the irregular surface topography of the sub-till Eindhoven Formation (early-Saale periglacial deposits) and by the locally great, but highly variable thickness of till (ter Wee, 1966, 1983). Relief created by the glaciotectonic action is estimated from ter Wee's (1983: fig. 402B) cross-section of the Steenwijker Aa Valley to be at least 40 m. Whereas van Cappelle (1892) and ter Wee (1983) assume ice retreat after formation of the ice-pushed ridges, Brouwer (1950) and Zonneveld (1975) infer subsequent overriding. Among other things, the streamlined morphology parallel to the supposed direction of ice movement (Fig. 3) suggests remodelling of the hills by an active ice cover (Zonneveld, 1975).

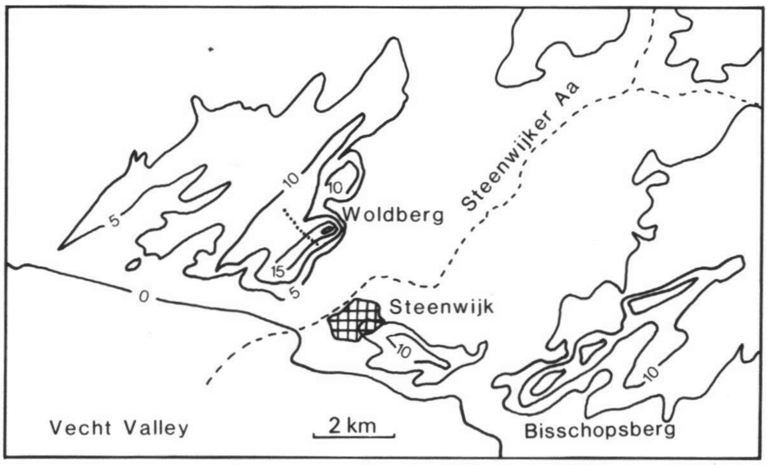


Fig. 3. Topography of the Steenwijk ice-pushed ridges, with location of the road section (stippled).

Compositional data of till from the study area are given by de Waard (1949), Veenstra (1963), Zandstra (1971), among others. Results of these studies indicate the presence of a clayey-silty, flint-poor and highly calcareous till, rich in East-Baltic indicator boulders, on top of or as lenses in the upper part of a sandy, flint-rich till with a mixed indicator assemblage.

De Waard (1949) reported on counts of crystalline indicator rocks (> 2 cm Ø) at Urk and near Kraggenburg. The mean Hesemann Formula (see caption of Fig. 2 for explanation of its determination) for four samples from flint-poor till is 6220, indicating a predominantly East-Baltic provenance (mainly Åland Islands, between southwest Finland and Sweden). The mean value of eight samples from flint-rich till is 4330.

From counts of sedimentary indicator rocks, de Waard (1949) obtained similar results.

A recent summary by Zandstra (1987) shows that most crystalline indicator counts along the southern margin of the till plain indicate highly mixed indicator assemblages with representatives from all main provenance areas, with the exception of the Oslo region. Few counts indicate a predominance of either East- or South-Baltic indicators.

However, the significance of these data is difficult to assess, especially within the present study area. Invariably, they concern material sampled at or near the land surface, which may have been reworked and mixed by postglacial processes. This presents a problem in the study area because different till types crop out repeatedly over very short distances as a result of glaciotectonic (frontal as well as subglacial) deformation.

Recently, Schuddebeurs determined indicator assemblages at Ter Idzard and Steenwijk at the same exposures as discussed in this paper. In the flint-rich surface till of both locations, a Hesemann Formula of 2260 was determined. A mixed sample from flint-rich and flint-poor till at Steenwijk gave H.F. 4240 (Schuddebeurs, unpubl.; pers. comm.).

In the Steenwijk area, ter Wee (1966) distinguished three till types as exemplified in Fig. 4. Two different flint-rich tills are recognised: a grey surface till and a dark-grey to black subsurface till, separated by a flint-poor till. Similar stratigraphies have been described by Zandstra (1971) from southwest Friesland, west of the Steenwijk sections.

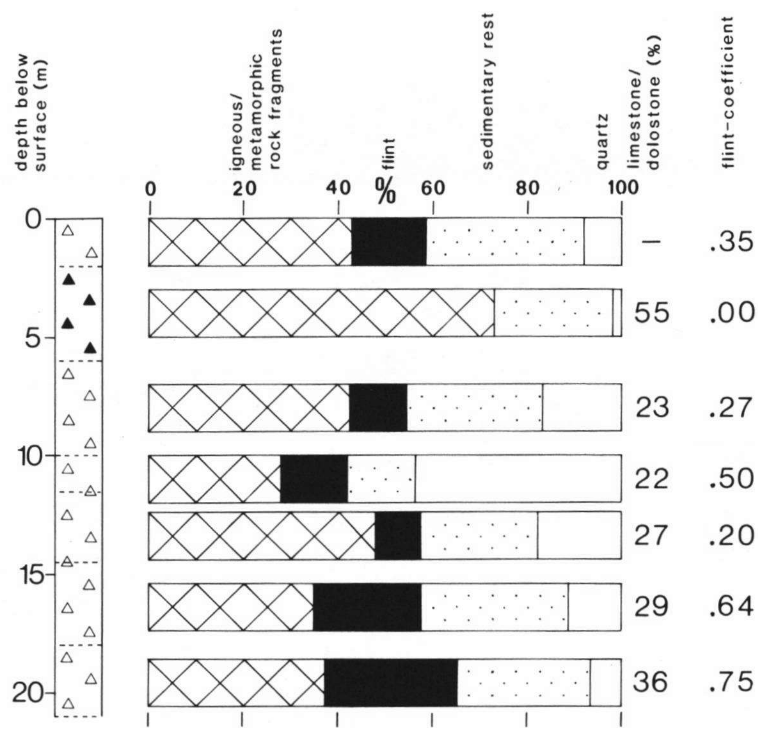


Fig. 4. Fine gravel composition of till in a borehole core from the Bisschopsberg, east of Steenwijk (after data given by ter Wee 1966, fig. 10). From top to bottom, the section consists of grey, largely orange-oxidised, flint-rich till (0-2 m), red and flint-poor till (2-6 m) and dark-grey, flint-rich till (6-21 m).

OUTCROP DESCRIPTION

The exposure at Steenwijk consists of a 4-5 m deep trench, over 1 km long, and approximately transverse to the elongation of the Woldberg ridge (Fig. 3). Most of this trench exposes apparently flat-lying, grey and flint-rich till. However, in sections proximal to the Steenwijker Aa Basin, structural features are complicated and flint-poor till constitutes most of the outcrop (Fig. 5). In what follows, the petrographic till types and units are labelled flint-poor and flint-rich till in reference to the gravel composition, but there are large differences for other compositional parameters as well (see below).

Field evidence suggests the presence of three till units: a lower flint-rich till, a flint-poor till, and an upper flint-rich till. Lower flint-rich till and overlying flint-poor till have been deformed and thrusted by glaciotectonic action. These are overlain discordantly by the upper flint-rich till. The upper flint-rich till thus represents deposition during overriding of the ice-pushed ridges. It is missing in the eastern part of the sections, but here drag structures in the upper part of the profile (Fig. 5: north face, 65 m from flyover) are indicative of overriding after thrusting. Note that the borehole section from the Bisschopsberg, on the eastern side of the Steenwijker Aa Valley, shows the same till stratigraphy (Fig. 4).

The flint-poor till is usually red, but grey or purple where least weathered. Diagenetic alteration of the red coloured part is indicated by numerous secondary carbonate concretions that are not present in the grey and purple varieties. These concretions consist of calcite-cemented fine-grained

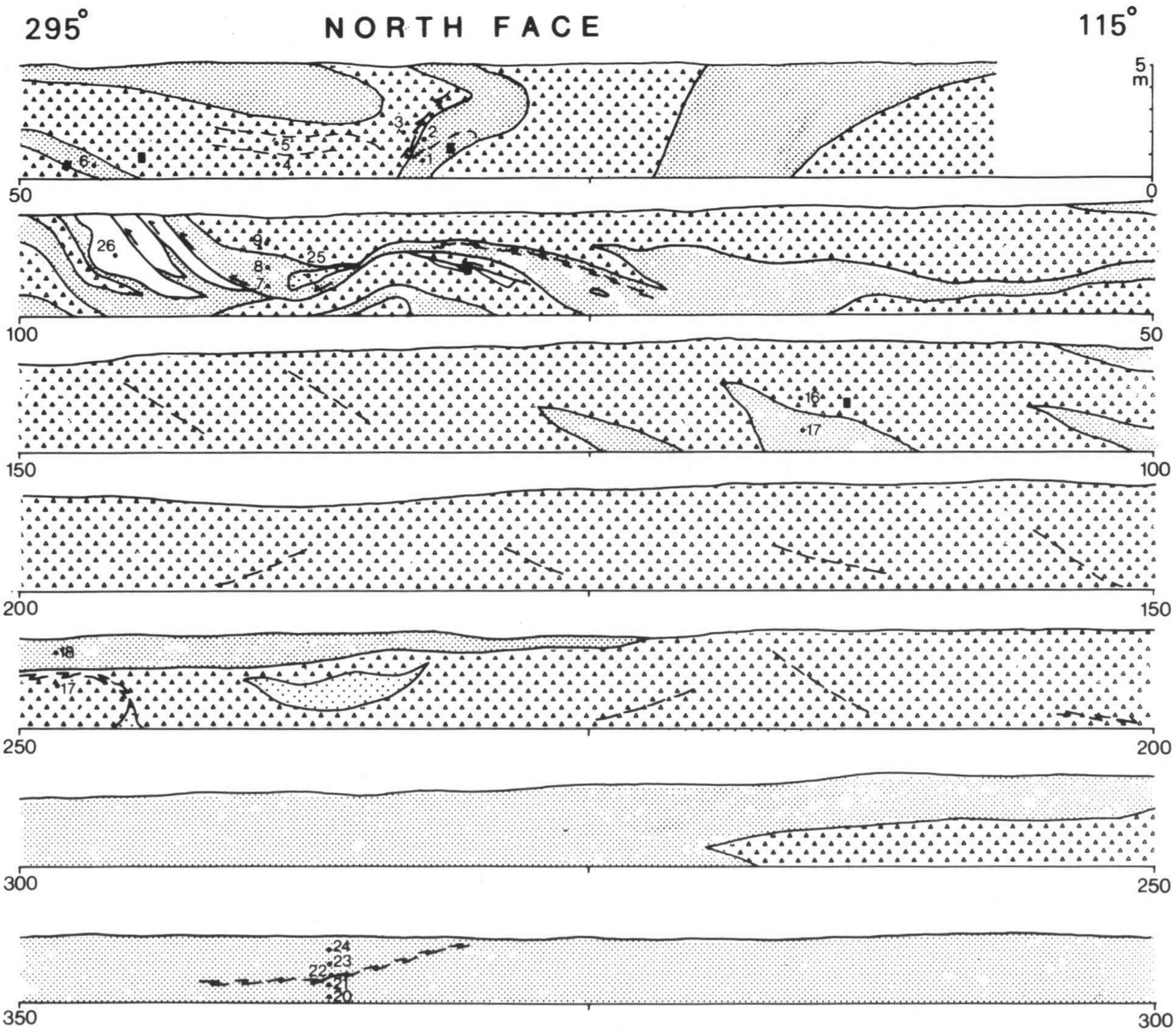
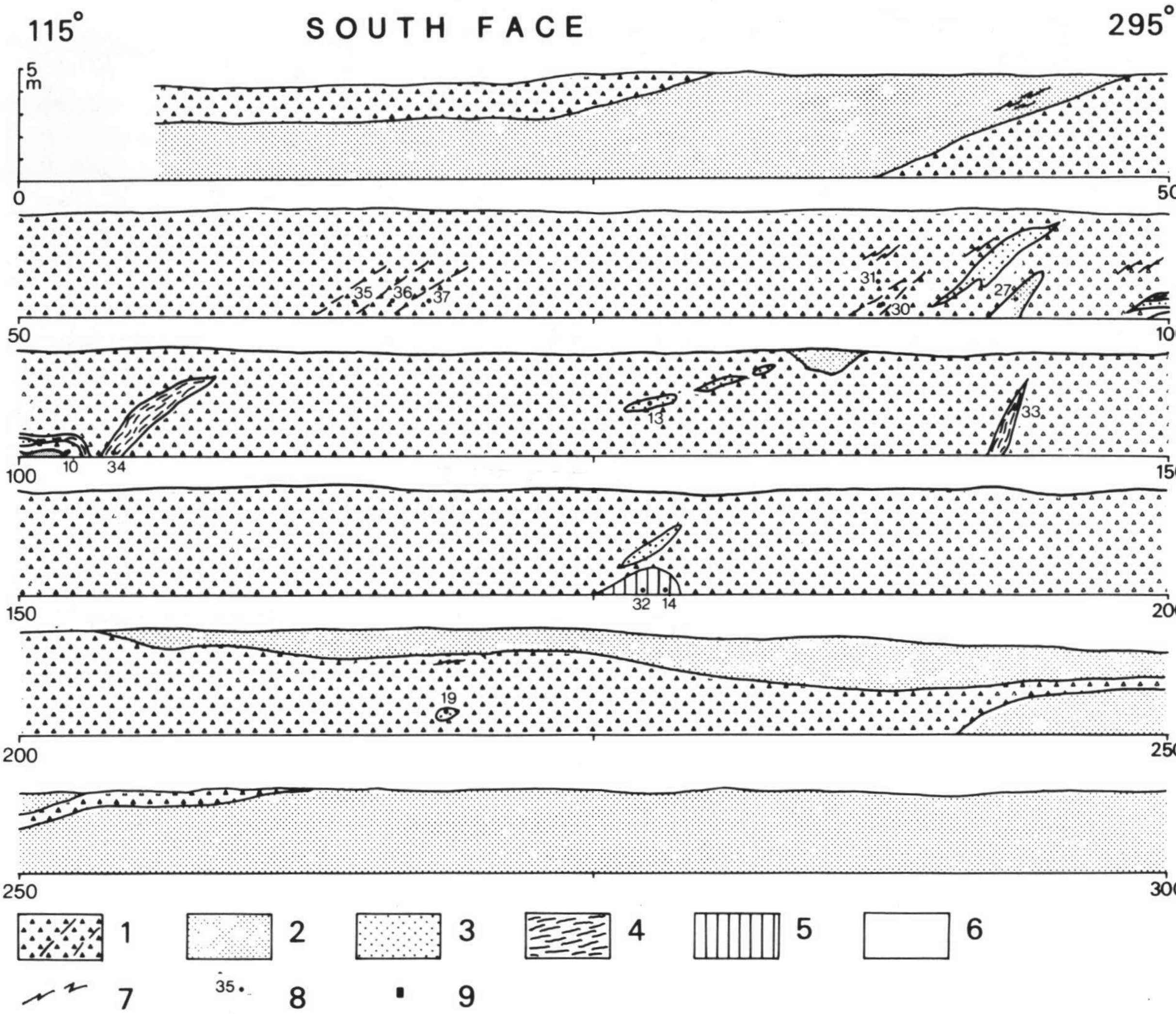


Fig. 5. Basin-proximal part of sections exposed in north and south face of roadcut near Steenwijk (for location see Fig.2). Distance in m from first flyover at Steenwijk (topogr. map-sheet 16E: 52°48'25"N / 6°05'40"E). 1. flint-poor till, 2. flint-rich till, 3. gravel and coarse sand lenses, 4. buff silt lenses, 5. black clay, 6. fine-grained, preglacial sand, 7. sheared sand or silt partings and lenses, 8. sample location, sample no. 735, 9. thin section sample site.

till and are of very irregular shape (see de Waard, 1949: fig. 118). Flint-rich till is black to dark-grey when calcareous, and light greenish grey when decalcified. The dark colour may be due to a high content of organic material probably derived from Tertiary lignitic deposits.

Aspects of faults and deformed beds in the ice-pushed till are quite variable, but appear to suggest a main direction of tectonic transport towards the west-northwest (Fig. 6A). This is almost transverse to the orientation of the ice-pushed ridge, which was probably formed in a lateral position to the ice-tongue occupying the Steenwijker Aa Basin (see Fig. 3).

Two fabrics measured in flat-lying flint-rich surface till show preferred northeast-southwest clast orientations (Fig. 6B and 6C). This is the same direction as measured in surface till of the central



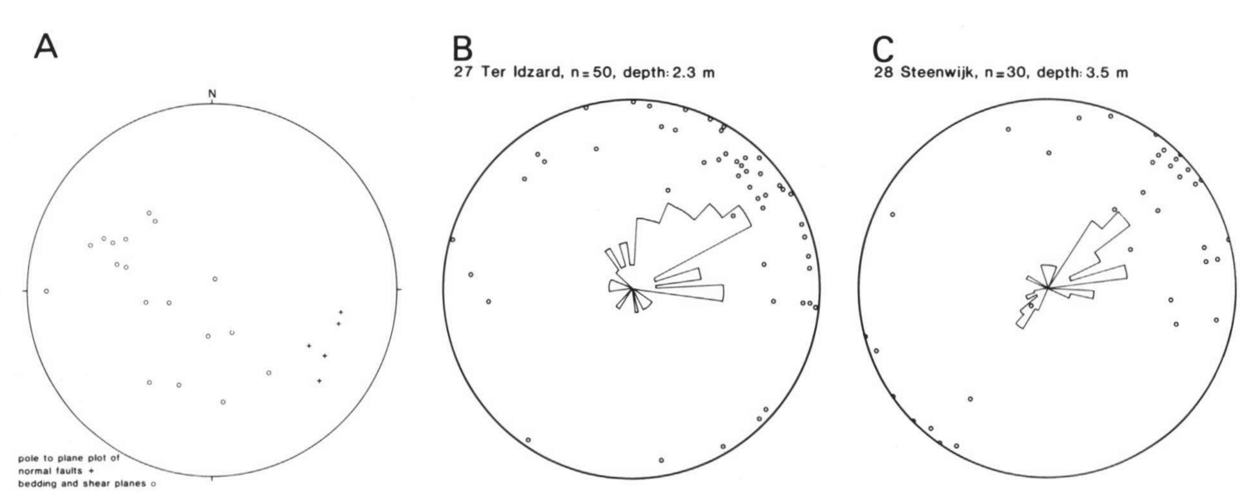


Fig. 6. A. Orientation of tectonic structures in the ice-pushed tills
B. Clast fabric at Ter Idzard
C. Clast fabric at Steenwijk in flat-lying flint-rich till, 800 m west of flyover.

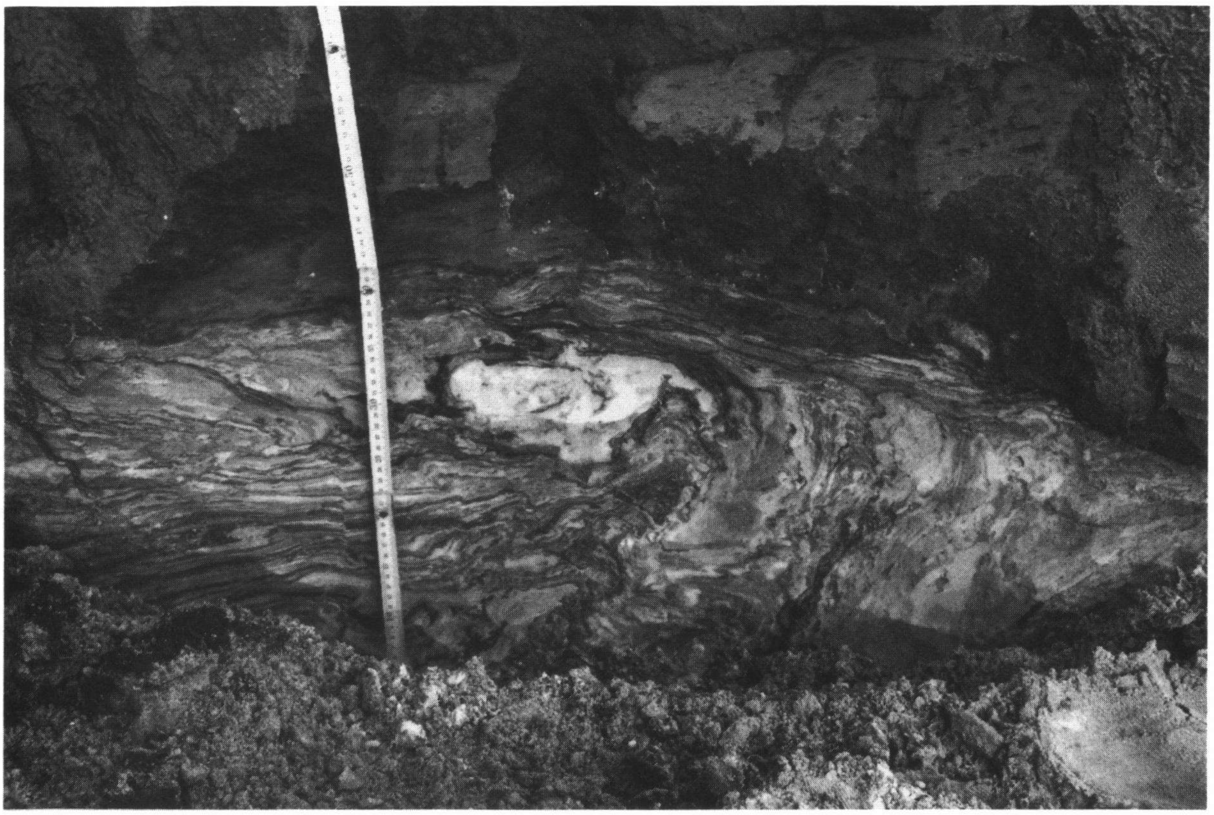


Fig. 7. Strongly deformed preglacial sand in contact with flint-rich till, 500 m west of flyover.

part of the Drente till plain (Rappol, 1987) and reflects ice movement towards the southwest. These fabrics probably originated during the overriding phase. However, it should be noted that, in the case of flat-lying, uninterrupted flint-rich till sections, we cannot really distinguish between upper and lower flint-rich till on the basis of petrographic parameters used in this study.

Floes of preglacial, early Saale sediments of the Eindhoven Formation have been sheared high up in the section along a major thrust plane, about 90 m from the flyover (Fig. 5: north face). Large lenses of preglacial sediments were also found embedded in flat-lying flint-rich till, west of sections shown in Fig. 5. Invariably, these glacial rafts are strongly sheared (Fig. 7).

Sandy partings and thin attenuated sand lenses are found to be fairly continuous in places where the upper flint-rich till overlies the flint-poor till (between about 225-275 m in Fig. 5) and within the

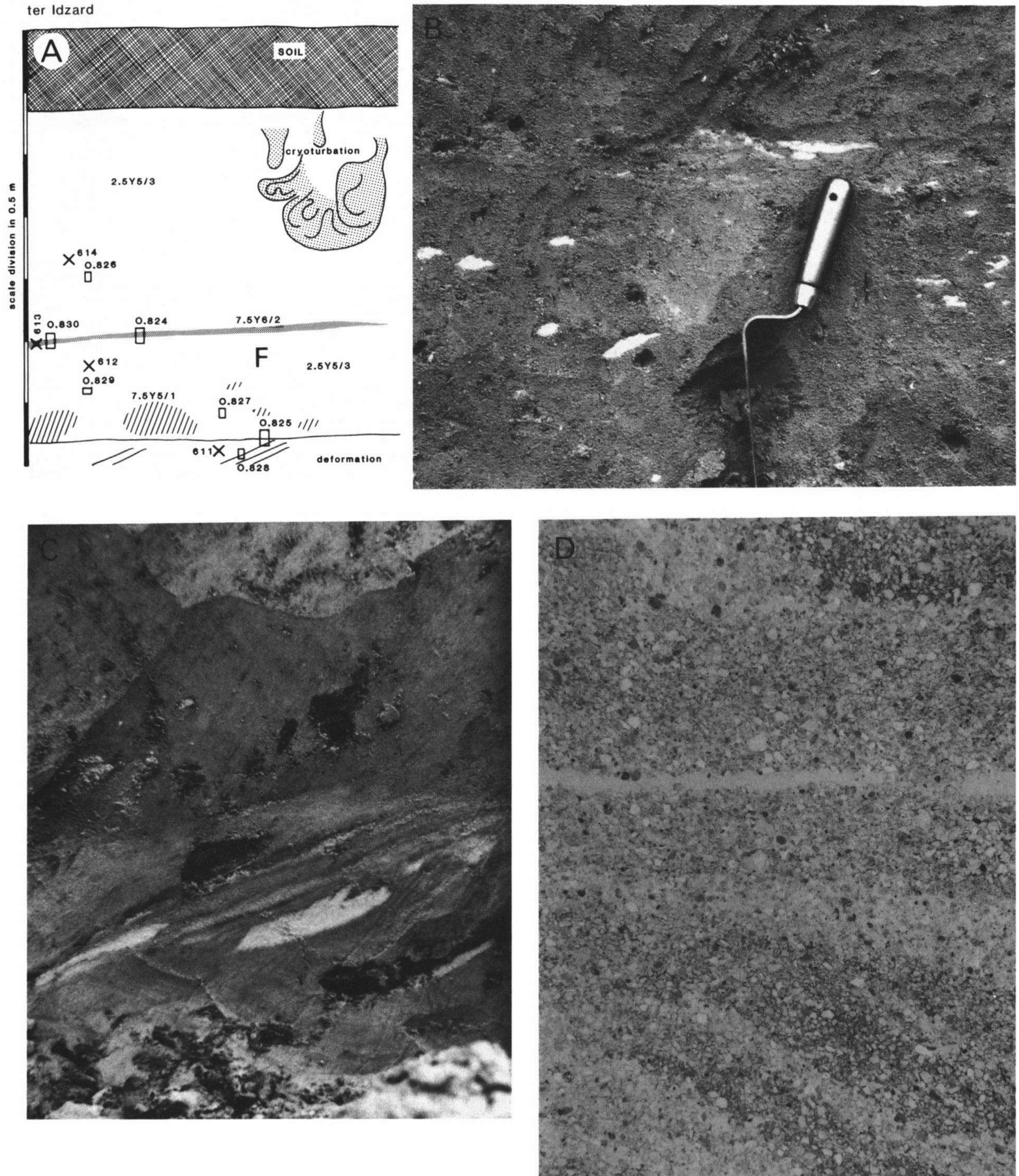
Fig. 8. Characteristics of the section at Ter Idzard.

A. Sketch of part of the till section with sample locations (X = bulk samples, rectangles = thin section samples) and fabric site (F). The upper part of the till is cryoturbated and mixed with coversand to a depth of 1.5 m. At about 80 cm from its base, the till contains a darker, slightly more clayey band (shaded) and near its base some irregular darker zones (inclined hatching). Ice movement from left to right.

B. Unconsolidated clasts of preglacial sand at F in Fig. 8A.

C. Basal part of till with clasts of unconsolidated sand.

D. Photomicrograph of thin section 0.825 at till base, showing deformed sub-till sediments. Ice movement from right to left (approx. 7×).



ter Idzard
A
SOIL
cryoturbation
2.5Y5/3
scale division in 0.5 m
614
0.826
613
0.830
0.824
7.5Y6/2
F
612
2.5Y5/3
0.829
7.5Y5/1
0.827
0.825
611
0.828
deformation
B
C
D

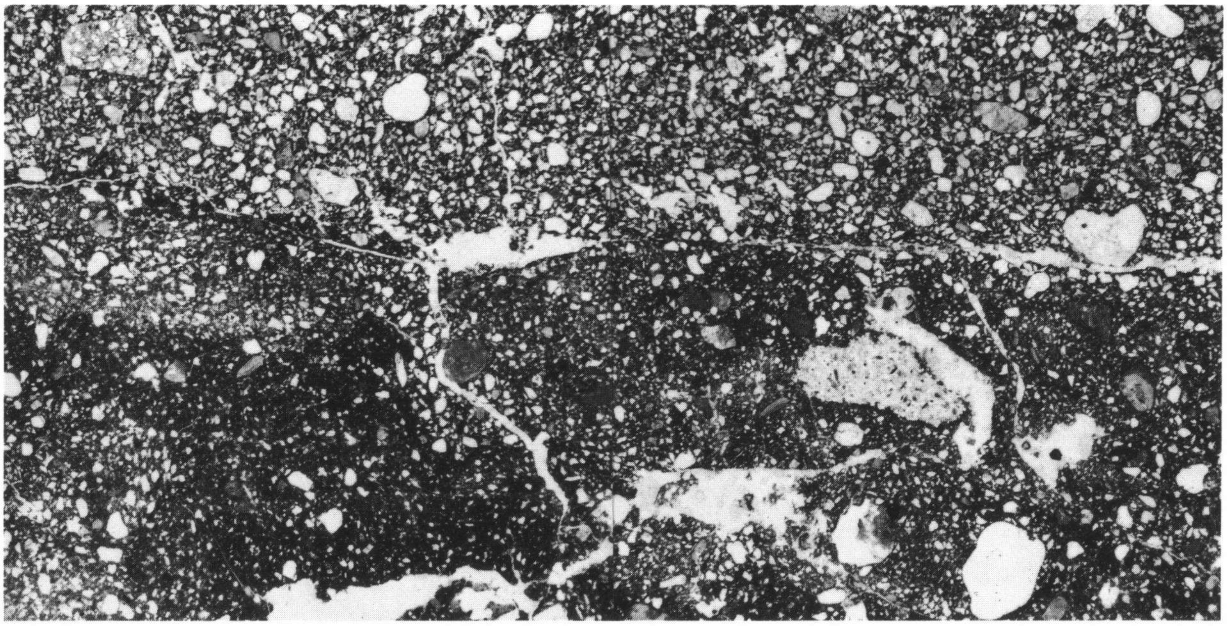


Fig. 9. Sharp contact between flint-rich and flint-poor till at Steenwijk. Upper third of photomicrograph is sand-supported flint-rich till and lower part matrix-supported, clast-rich flint-poor till (approx. 7×). Thin section from north face of exposure, 48 m west of flyover.

flint-rich till beyond 275 m, generally about 2-3 m below surface (*e.g.* at 335 m in north face of Fig. 5). In the latter case, sometimes thin streaks of flint-poor till are found associated with these sand lenses, that therefore probably represent the contact between upper and lower flint-rich till.

The basal contact of till and sub-till sediment was only observed at one site near Ter Idzard, about 15 km north-northwest of Steenwijk (Fig. 8). The lower part of the till at this site is very sandy, containing numerous clasts of unconsolidated preglacial sand (Fig. 8B), illustrating the reworking of subglacial materials by subglacial shear. Incorporation of local sediments by subglacial deformation is a common feature of flint-rich till in The Netherlands (Rappol, 1987) and explains many of its typical compositional characteristics.

Also the contact of flint-poor and flint-rich till is sometimes sheared, showing a zone of mixed composition (Table 1) or banded alternation of till types. More commonly, however, this contact is remarkably sharp (Fig. 9).

In the sections of Fig. 5, it is especially the flint-poor till that is rich in sorted inclusions. In coarse-grained lenses, the gravel fraction has the same composition as that of the till, and in fine-grained lenses, the clay mineralogy is similar to the till: no flint and no smectite (see below). At one site, east of the flyover, a unique boulder layer was observed (Fig. 10).

Of special interest in this context are abundant, strongly sheared, silty sediment lenses, the occurrence of which is only schematically indicated in Fig. 5. These occur only in the flint-poor till.

One occurrence of a laminated, but strongly sheared body of black and extremely clayey material is found in the lowermost part of the section (Fig. 5: south face, 175 m from flyover). From the exposed part of the sediments, it is not clear whether this lense occurs within the flint-poor till or at the contact of flint-poor and flint-rich till.

A

sample no.	number of particles	crystalline	flint	quartz	rest	flint-coeff.	limestone/ dolostone	till colour
	n	C	F	Q	R	F/C	L	
701	196	52	14	13	21	0.27	38	black
702	210	55	16	12	17	0.29	29	grey
704	273	15	0	1	84	0.00	52	red
705	300	63	0	6	31	0.00	72	grey
706	206	58	13	11	19	0.22	28	black
707*	300	62	7	8	24	0.11	54	black
708*	330	56	4	3	37	0.08	50	grey
710	300	60	0	2	38	0.00	69	purple
713	300	72	0	1	27	0.00	66	
715	349	56	11	7	26	0.19	45	black
716	303	70	1	3	25	0.00	68	red
717	302	75	0	4	21	0.00	63	red
718	213	53	13	7	26	0.25	--	grey
720	166	57	9	9	25	0.16	--	grey
721	192	58	10	7	25	0.17	--	grey
723	179	54	14	7	25	0.26	--	grey
724	198	63	11	7	20	0.18	--	grey
727	195	54	12	9	25	0.23	37	black
730	300	62	0	3	34	0.00	71	grey
731*	238	55	4	2	37	0.07	63	red
735	300	65	0	1	34	0.00	67	grey
736	331	49	0	2	49	0.00	72	red
737	349	50	0	2	48	0.00	66	purple

*sheared mixture of flint-poor and flint-rich till

B

sample no.	depth (m)	n	C	F	Q	R	F/C	L
Steenwijk-Zuidveen								
371	1	180	49	16	21	15	0.33	--
374	2	146	53	17	11	19	0.32	--
378	3	159	48	11	12	29	0.23	--
380	4	191	45	17	14	24	0.37	--
Steenwijkerwold								
210	1.5	166	48	13	18	21	0.26	--
212	1.5	174	54	9	16	21	0.16	--
Ter Idzard								
612	2.5	104	45	14	21	19	0.32	--
613	2	153	58	12	9	22	0.20	--
614	1.5	115	64	14	12	10	0.22	--
Urk								
602	2	118	61	12	13	14	0.19	32
603	1.5	170	56	15	9	21	0.26	40
604	1	127	64	11	9	16	0.27	29
605	1	221	76	0	3	22	0.00	48
606	1.5	306	78	0	1	21	0.00	66
607	1	274	70	0	6	24	0.00	69
608	0.5	264	77	0	2	21	0.00	69
Kraggenburg								
381	1.2	239	55	0	2	43	0.00	61
382	1.6	260	60	0	1	39	0.00	63
386	2.4	68	59	11	10	20	0.18	--
387	2.0	114	52	12	14	22	0.22	26
Heetveld								
160	1	98	55	14	10	21	0.26	--
163	1	148	57	16	11	16	0.29	--
164	1.5	100	55	12	22	21	0.22	--

Table 1. Fine gravel (3-5 mm) composition of till samples from A: exposure at Steenwijk (for sample locations, see Fig. 4), and B: other exposures (for locations, see Fig. 1). The limestone/dolostone group is counted separately.

Flint-poor and flint-rich till were also sampled at sites near Urk and Kraggenburg. At these sites, the flint-poor till occurs as irregular patches on top of flint-rich till. A considerable part of these sections must have been eroded by marine abrasion (de Waard, 1949; van der Meer & Lagerlund, in press). For more details on these sites, the reader is referred to de Waard (1949) and Veenstra (1963).

At other sites, only flat-lying flint-rich till was observed. This includes a 4 m thick till section, penetrated by auger, in the frontal ice-pushed ridge of the Steenwijker Aa Basin at Zuidveen, just south of Steenwijk. The section at Heetveld is briefly described in Rappol (1983).

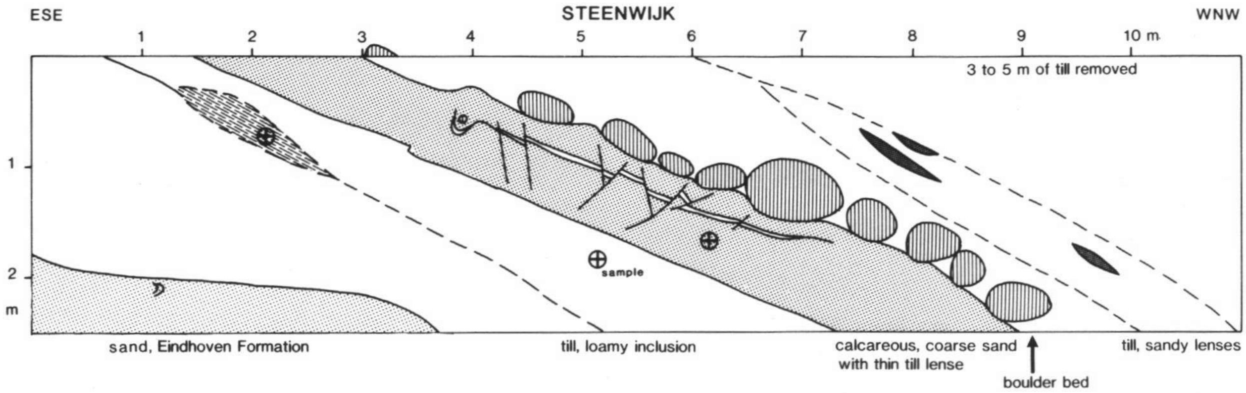


Fig. 10. Boulder bed and intra-till sand lenses in part of the section east of the flyover, south face of roadcut. Till at sample site is flint-poor as is probably the till associated with the boulder bed. In this part of the section flint-poor till was observed to directly overlie ice-pushed beds of the Eindhoven Formation.

MICROSCOPIC OBSERVATIONS

A total of 17 thin section samples were collected at the sites of Steenwijk (see Fig. 5 for sample locations) and Urk, from both flint-poor and flint-rich till, and from Ter Idzard, where only decalcified flint-rich till was exposed. Observations concerning texture, plasmic fabric and diagenetic changes were made in the thin sections. For information on method, terminology and additional references, the reader is referred to van der Meer (1987).

The flint-poor till contains less skeleton (sand) and coarse silt grains than flint-rich tills. In most samples of both till types, the distribution of skeleton grains is not even and zones with almost no skeleton grains are not exceptional. However, no clear pattern in the distribution of these zones was observed.

Clasts of unconsolidated material are common in a number of samples. Till pebbles are common in penetratively sheared intra-till lenses of sand or silt. At Ter Idzard, numerous silt and clay pebbles, up to 1 cm in diameter (Fig. 8D) are produced by subglacial shearing of fine-grained preglacial sediments. Part of the flint-poor till at Urk appears to be composed almost entirely of rounded till pebbles.

Several types of plasmic fabric (*i.e.* the distribution and patterns of oriented domains of fines and their relationship to larger particles) were observed (see van der Meer, 1987, for illustration). The observed strength of these fabrics is variable and depends partly on the abundance of clay minerals in the matrix, partly also on the presence of fine-grained carbonates that tend to obscure plasmic fabric patterns.

A skelsepic fabric, *i.e.* concentric orientation of fines around skeleton grains, is observed in almost all samples, in both flint-poor and flint-rich till. Many samples also show a tendency towards a lattisepic fabric, in which two sets of short linear-oriented domains occur at more or less right angles to each other. Both these fabrics have been observed repeatedly in till by different authors, and are commonly ascribed to shearing. Similar structures may form as a result of swelling of expandable clay minerals, but as such minerals are virtually absent in the flint-poor till (see section on clay mineralogy), this process is not applicable here.

Strong unistrial fabrics (masepic fabric) are observed in flint-poor till only. It is common also in fine-grained and deformed sorted sediments at the base of till or occurring as lenses within till. Such fabrics are typical of zones of concentrated shear.

As far as the genesis of the tills is concerned, especially the observations on plasmic fabric are relevant. The occurrence of fine-grained zones with an absence of skeleton grains, together with small soft-sediment clasts and the characteristics of the plasmic fabrics, points to deformation as a major process in the formation of these tills.

Features due to diagenetic changes are present in most samples, and include precipitations of iron-manganese compounds, clay translocation, silt droplets, and secondary carbonate concretions (see van der Meer, 1987; van der Meer *et al.*, 1985).

RESULTS OF COMPOSITIONAL ANALYSES

Fine gravel petrography

Gravel composition was determined for the 3-5 mm fraction. Distinguished rock types and results are shown in Table 1. The geological sketch map (Fig. 2) indicates the source areas for some of the rock types: igneous and metamorphic rock fragments are derived from the Precambrian Shield, limestone and dolostone from Palaeozoic rocks, and flint mainly from Mesozoic (Cretaceous) outcrops.

The results show a strongly bimodal distribution for flint content, a fact that has been repeatedly demonstrated for till in different parts of The Netherlands (*e.g.* Zandstra, 1971, 1983: Rappol, 1984, 1987; van der Meer *et al.*, 1985).

The absence of flint is always accompanied by low quartz and very high limestone/dolostone contents. The Palaeozoic components (limestone and dolostone) are in fact the most important constituent of the flint-poor till, in general comprising more than 60 % of all rock fragments in the gravel fraction.

The lower flint-rich till contains between 25 and 40 % Palaeozoic components and, in addition, it contains much Cretaceous chalk. This latter constituent is however sparse in the counted material since the majority of these soft fragments were decomposed and lost during sample preparation.

Samples from the upper flint-rich till are decalcified, but otherwise do not appear to be much different from the lower flint-rich till.

Gravel counts from other exposures in the study area show basically the same results (Table 1B).

At about 800 m west of the flyover, a section of flint-rich till in the north face of the Steenwijk exposure was sampled in more detail (Fig. 11). Two distinctive features are apparent: 1. the highest flint contents (F/C-values) are found at the base of the section, and 2. the limestone/dolostone content of the calcareous samples is low compared to other calcareous samples of flint-rich till at Steenwijk.

An increase of flint content towards the base of till sections is frequently observed in till of south-east Drente (Rappol, 1984) and also shown in Fig. 3. The low percentages of Palaeozoic carbonate rocks may be a result of incomplete decalcification, although it is normally observed that the contact between calcareous and decalcified till is fairly sharp. Perhaps it reflects rather a change in the relative contribution of different source areas, where higher flint content indicates more Mesozoic and less

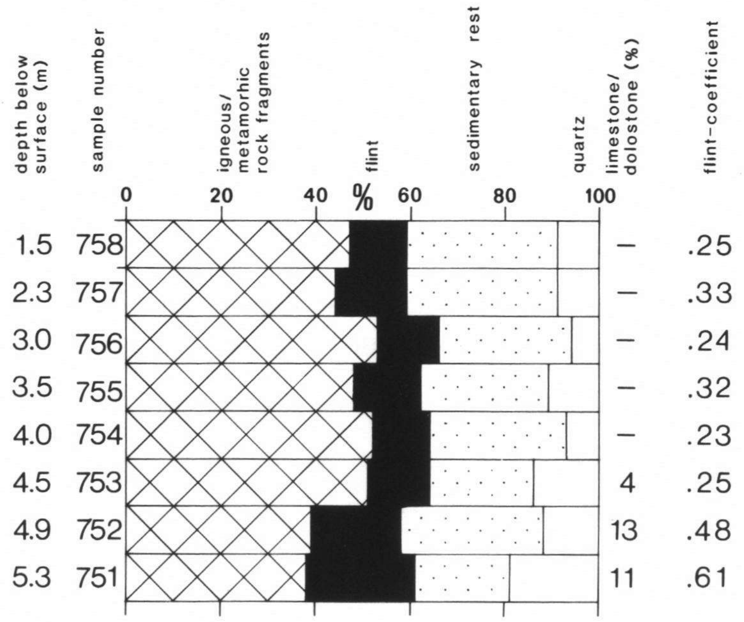


Fig. 11. Gravel composition (3-5 mm) of flint-rich till section in north face of Steenwijk exposure at 800 m west of flyover.

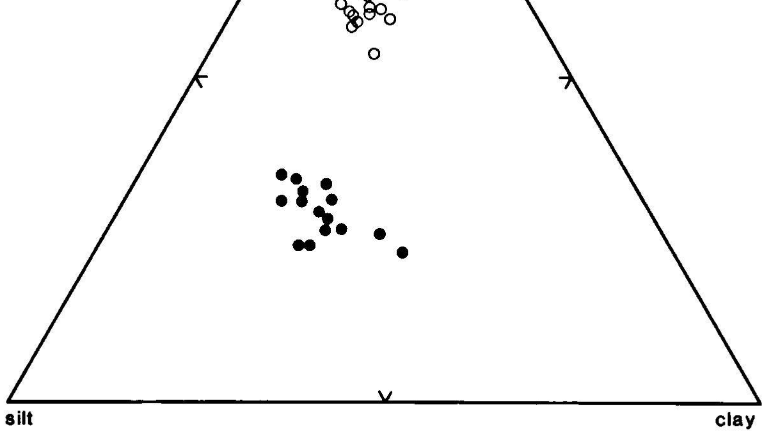


Fig. 12. Sand-silt-clay ternary diagram for flint-poor and flint-rich till of study area.

Palaeozoic source material. It is commonly observed that more distantly derived material is less abundant in the lower part of till (Rappol & Stoltenberg, 1985). Note, however, that this relationship is not present in the borehole section described in Fig. 4.

Grain size distribution

Grain size distribution was determined by dry sieving at 1 φ intervals for gravel and sand fractions (> 0.063 mm or 4 φ) and by pipette method for clay and silt fractions.

Grain size composition of the till matrix is given in Fig. 12, showing a distinct difference between flint-poor and flint-rich tills. Flint-rich tills contain more than 50% sand and about equal amounts of silt and clay (15-20%). Decalcified samples are not significantly different from calcareous ones, perhaps showing a faint tendency to contain slightly more clay.

The flint-poor till is a very dense, clayey-silty till, with only 25-40% sand.

Fig. 13A shows that the sand fraction in flint-rich tills is concentrated in the 1-4 φ range, with a modal fraction of 2-3 φ. Flint-poor till shows more evenly distributed frequencies, with minor modes in the 3-4 and 6-7 φ fractions. In this, it also differs from the flint-poor unit of the ,,Second Baltic Till'' of the Hondsrug area, which has a distinct mode in the 2-3 φ fraction (Fig. 12A).

Silty lenses in the flint-poor till have a major mode in the 6-7 φ fraction, whereas the black clay is extremely clayey: about 70% clay (Fig. 13B).

Carbonate content

A Chittick apparatus (Dreimanis, 1962) was used to determine total carbonate content and calcite-dolomite ratio for the < 2 mm fraction of till samples from exposures at Steenwijk, Urk, and Kraggenburg. For a number of samples, the results were checked by X-ray analysis. This gave similar results, although dolomite content tends to be slightly lower according to X-ray analysis.

Total carbonate content of flint-poor till varies between 17.8 and 27.4% (14 samples). For flint-rich till, values between 3.8 and 10% (10 samples) were measured. With the exception of sample 751 (see Fig. 11), all the flint-rich samples are from flint-rich till overlain by flint-poor till.

The large difference in carbonate content of flint-poor and flint-rich till may partly be texture-related. It has been demonstrated that the carbonate content of the matrix fractions has its lowest value in fine sand (Lüttig, 1958; Rappol, 1983), which is also the fraction in which the flint-rich till has its major textural mode (Fig. 13A). However, results of the gravel counts indicate that there is definitely a difference in the contribution of Palaeozoic material to the two till types.

Whereas total carbonate content thus clearly distinguishes between flint-poor and flint-rich tills the calcite-dolomite ratio does not (Fig. 14). On average, dolomite constitutes about 30% of the carbonate fraction in flint-poor till and 23% in flint-rich till samples. However, flint-poor till samples with a comparatively low dolomite content (or high calcite-dolomite ratio) are those samples that also show clearest evidence of post-depositional diagenetic alteration (red till with secondary carbonate concretions). Samples from grey or purple flint-poor till contain consistently more dolomite than flint-rich till samples, and plot in the upper left-hand corner in Fig. 14.

Higher calcite content of flint-rich till is likely to be caused by the admixture of Cretaceous chalk (calcite only) with the Palaeozoic carbonate rocks: in flint-poor till, Palaeozoic rocks are the only source of carbonates.

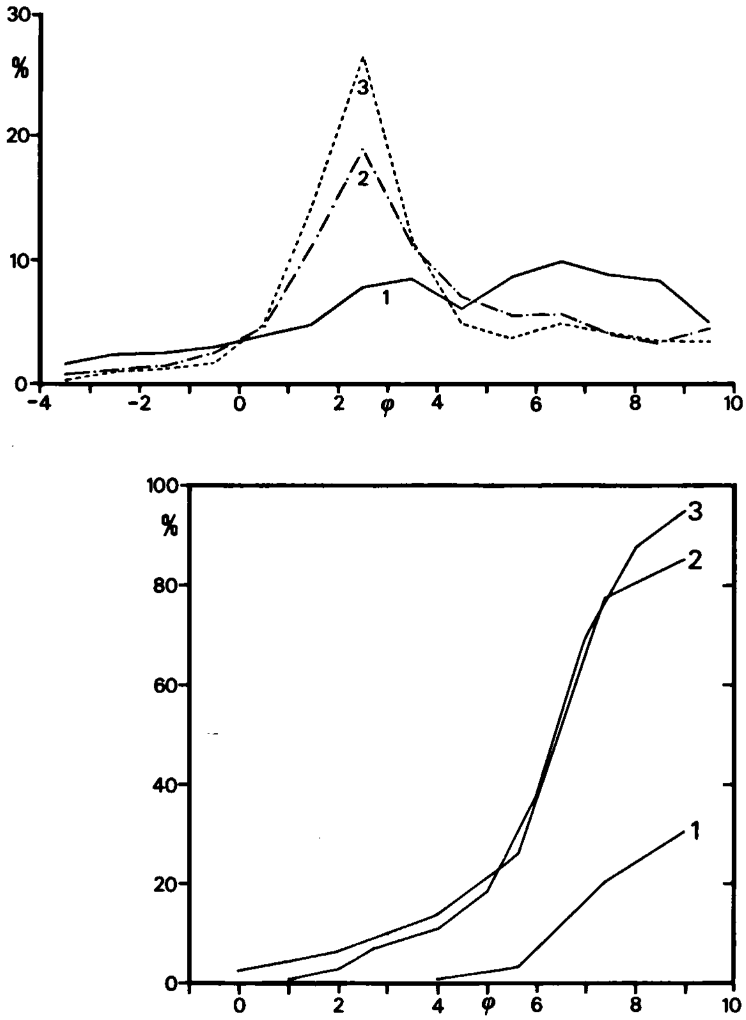


Fig. 13. A. Mean frequency size distribution of 1. flint-poor till at Urk and Kraggenburg (mean of 5 samples), 2. flint-poor till in southeast Drente (Second Baltic Till, mean of 11 samples), 3. flint-rich till of present study area (mean of 14 samples).
B. Cumulative frequency curves for black clay (1) and buff silt lenses (2,3) in flint-poor till at Steenwijk.

It should be noted here, that according to Valeton & Khoo (1981) all carbonate in till of the Hamburg area is calcite. If this signifies a genuine geological difference between till of the Hamburg area and that analysed here, this would suggest that all till analysed by Valeton & Khoo did not contain any East-Baltic dolostone. Possibly, all their samples are from till that was deposited by ice flowing from the western Baltic (Sweden). However, Ehlers (1978) shows that Palaeozoic components including dolostone are common in some tills around Hamburg.

Clay minerals

The method involves the replacement of exchangeable ions by Mg^{2+} and the preparation of X-ray mounts by filtering a film of material > 2 μm onto a porous ceramic disk. X-ray diffractograms were obtained after the following treatments of each sample: 1. stored overnight at room humidity,

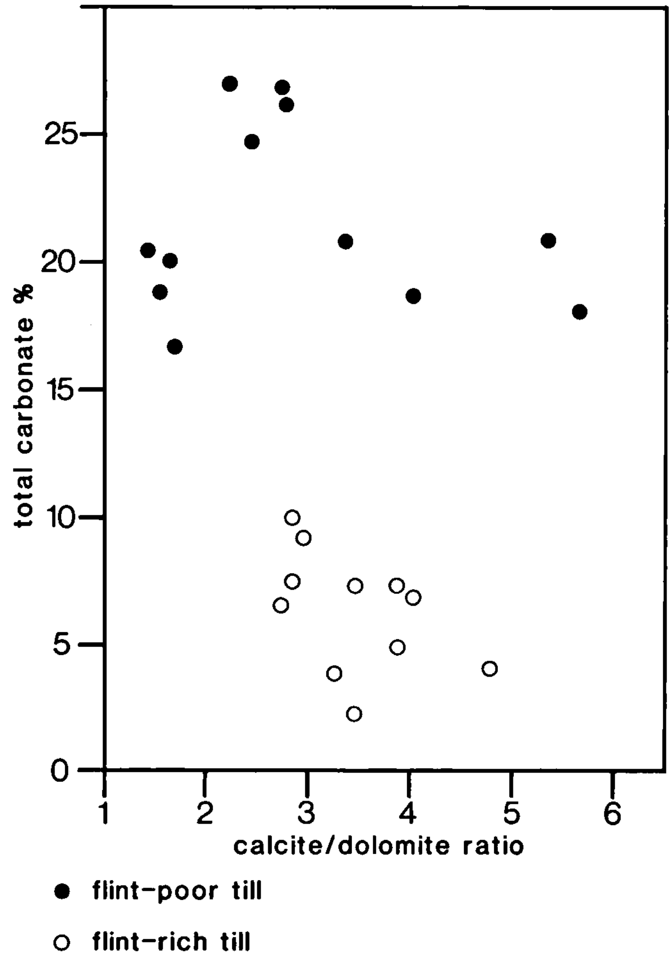


Fig. 14. Total carbonate content plotted against calcite-dolomite ratio for flint-poor and flint-rich till samples from exposures at Steenwijk, Urk and Kraggenburg.

2. stored overnight at 80°C in ethylene glycol vapour, 3. heated one night at 300°C, and 4. heated one night at 550°C. In addition, all samples were treated with hot (80°C) 1N HCl for 8 hours, after which changes in the $I_{7Å}/I_{10Å}$-ratio illustrate the destruction of chlorite. Quantification of the results was achieved by using the same intensities for pure minerals as in Haldorsen *et al.* (in press).

On the basis of clay mineralogy, the samples can be sub-divided into two groups: samples without smectite and samples containing 15-40% smectite (Table 2). These groups match perfectly with the till types distinguished on the basis of gravel petrography, *i.e.* flint-poor and flint-rich till, respectively. Note also, that the sample with the highest flint-coefficient value and lowest content of Palaeozoic limestone contains the highest percentage of smectite as well (sample 751).

Two samples are discussed here in more detail, in order to illustrate the composition of both till types.

In sample 710 (Fig. 15A), the strong 10 Å peak and higher order basal-peaks are due to illite. Heating the sample to 550° results in a strong reflection at 13.6 Å, since chlorite is a major consti-

	sample no.	quartz	albite	k-feldspar	calcite	illite	chlorite	smectite	kaolinite	vermiculite
smectite-free till samples	704	4	0	1	8	58	23	0	5	0
	705	5	5	4	14	44	24	0	6	0
	710	5	3	2	14	47	23	0	6	0
	716	5	2	3	15	43	5	0	7	21
	730	5	3	4	17	42	24	0	6	0
	731	5	5	3	14	43	6	0	9	16
	735	5	5	4	10	45	26	0	6	0
	736	4	1	1	4	58	13	0	5	14
	737	4	0	1	8	59	24	0	5	0
samples with smectite	701	5	5	5	7	35	13	16	16	0
	702	5	2	3	8	38	3	24	17	0
	706	5	5	6	5	33	15	16	15	0
	715	5	5	6	12	36	8	17	12	0
	718	5	1	4	0	47	1	24	18	0
	720	5	0	2	0	56	1	19	16	0
	727	5	5	5	11	34	12	15	14	0
	751	5	2	1	0	31	3	40	19	0
clay	732	6	6	6	2	43	18	4	15	0
silt	734	5	5	4	19	40	8	0	5	16

Table 2. Quantitative estimates of mineralogical composition of the clay fraction (weight %) of till at Steenwijk. For additional data, see Haldorsen *et al.* (in press).

tuent of the clay fraction. Treatment with hot HCl results in a strong reduction of the 7 Å peak-intensity as well as the $I_{7Å}/I_{10Å}$-ratio. This illustrates that the 7 Å peak observed before heating is mainly due to chlorite and that the sample contains only a small amount of kaolinite. Some samples in the smectite-free group have a 14 Å peak which was not influenced by the E.glyc.-treatment, but it disappeared after heating to 300°. These samples contain vermiculite.

In sample 702 (Fig. 15B), the strong 14 Å peak that shifts to 17 Å after E.glyc.-treatment is due to smectite. The sample contains a considerable amount of illite (10 Å). Only a small peak at 13.6 Å is found after heating to 550°. It follows that the sample contains only a small amount of chlorite. The strong 7 Å peak observed before heat treatment must be due to kaolinite. A strong 7 Å peak that is present after HCl-treatment as well as a small reduction in the $I_{7Å}/I_{10Å}$-ratio verifies these conclusions.

Only three flint-poor till samples were found to contain vermiculite (Table 2), for which there is no obvious explanation. These samples do not show any relationship in other petrographic parameters, except that their chlorite content is lower than in other samples. In fact, the sum of chlorite and vermiculite is remarkably constant.

Apart from phyllosilicates, most samples contain some quartz, feldspar, and calcite.

Fig. 16 shows that samples containing smectite also contain more kaolinite than the smectite-free samples. It further shows that decalcification is accompanied by destruction of chlorite and vermiculite.

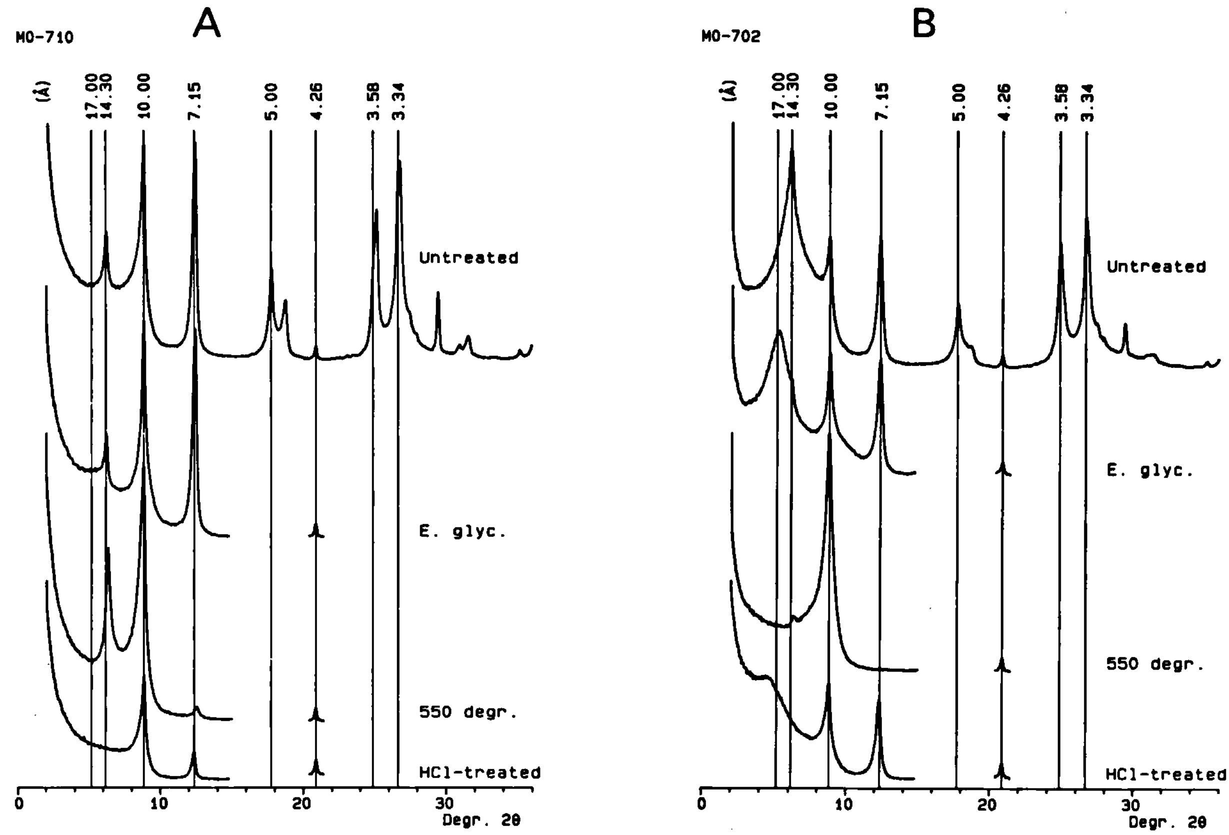


Fig. 15. X-ray diffractograms of: A. clay of flint-poor till, sample 710, and B. clay of flint-rich till, sample 702.

Haldorsen *et al.* (in press) show that a very low smectite content is characteristic of flint-poor till types throughout The Netherlands. This clearly indicates that also the clay fraction of flint-poor till is entirely of East-Baltic origin. Smectite-rich clay is mainly derived from Tertiary deposits and deposits containing a large amount of reworked Tertiary material (*e.g.* the pottery clay or Lauenburger Ton of the Elsterian glacial period). For further discussion on this subject, see Haldorsen *et al.* (in press).

Table 2 also gives the composition of the < 2 μm fraction separated from a silt and clay sample from the Steenwijk exposure. The sample from a sheared silt lense embedded in the flint-poor till (734) is compositionally identical with the flint-poor till. Composition of the black clay found at the bottom of the exposed section (see Fig. 5), is different in that it contains a few percent of smectite and more kaolinite than flint-poor till samples. However, the clay is extremely fine-grained (Fig. 13B). The difference between silt and clay samples may therefore be related to texture, rather than to different source areas. In any case, smectite content of the clay is much lower than of the flint-rich till samples and is also different from equally fine-grained but very smectite-rich Elsterian glaciolacustrine deposits present in The Netherlands (see Haldorsen *et al.*, in press).

According to Emelyanov & Kharin (1988), glacial deposits and modern sediments of the present eastern Baltic may sometimes contain a few percent of smectite.

The absence or very low content of smectite in the intra-till sediment lenses suggests an East-Baltic origin of these materials and demonstrates their close relationship to the flint-poor till.

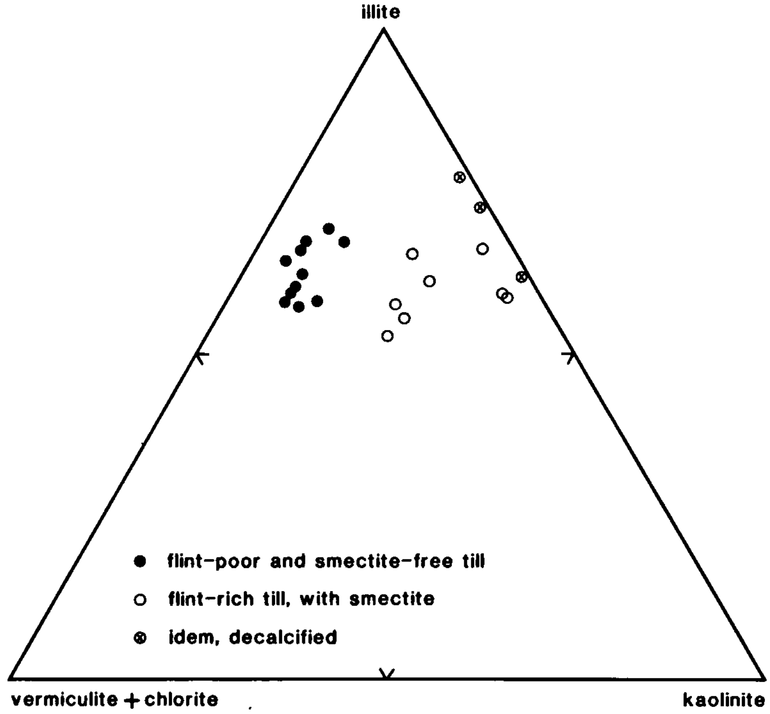


Fig. 16. Clay mineralogy of till samples from Steenwijk, Urk and Kraggenburg. This diagram shows the positive correlation between smectite and kaolinite abundances and the destruction of vermiculite and chlorite with weathering.

Heavy minerals

Heavy mineral weight percentages and composition was determined for the 0.25-0.125 mm (2-3 φ) fraction, unless stated otherwise. Heavy minerals were separated by use of bromophorm (s.g. = 2.9) and transparent heavy mineral species were determined after mounting on slides with Canada balsem. Samples from the Steenwijk exposure were not analysed for heavy minerals, but data are available from the till sections at Urk, Kraggenburg, Heetveld, Steenwijk-Zuidveen and Ter Idzard. De Waard (1949) and Zandstra (1971) gave additional heavy mineral data for the area.

De Waard (1949), using the 0.04-0.5 mm fraction, observed heavy mineral weight percentages in the flint-poor till to be twice as high as in flint-rich till: about 1.0 and 0.5%, respectively. Similar values were found during the present study in the 0.125-0.25 mm fraction.

Fig. 17 compares the size distribution of light and heavy minerals for two samples from Urk. Whereas in flint-poor till these distributions are more or less the same, flint-rich till shows a clear shift of the modal fraction towards a finer size fraction. The same is found for tills formed during the second Baltic ice-flow configuration (Fig. 17).

This difference results from the fact that most heavy minerals in flint-poor till are derived from igneous and metamorphic rock types of the Precambrian Shield, whereas those in flint-rich till are to a large extent derived from Tertiary and Quaternary sedimentary rocks, in which the heavy mineral size distribution is generally skewed towards finer grain sizes (Füchtbauer, 1974).

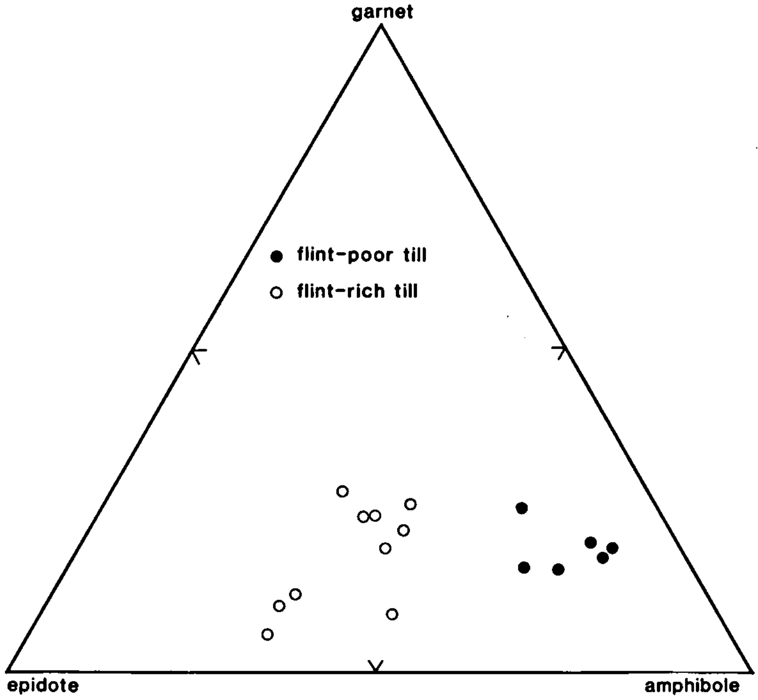


Fig. 17. Comparison of the size distributions of heavy and light fractions for till samples from Urk (605, 603) and Emmerschans, Hondsrug (196, 174), representing First and Second Baltic Till, respectively.

This difference in source material is also indicated by the composition of the transparent heavy minerals (Fig. 18). Flint-poor till is characterised by very high amphibole percentages, whereas flint-rich till contains more epidote. Moreover, flint-rich till contains more opaque, stable and metamorphic minerals than flint-poor till.

For a number of till samples from sites throughout The Netherlands, the size distribution of individual heavy-mineral species was calculated from heavy-mineral analyses of three different size fractions (Fig. 19). In general, all heavy mineral species show a size distribution that is skewed towards the finer sizes compared to that of the light minerals, but, for example, amphibole much less so than the heavier opaques.

Whereas amphiboles derive from the same source (Precambrian Shield) for all till types, epidotes are derived from two different sources. Epidotes in the flint-poor till are shield derived, and show a minor modal fraction of 2-3 φ. In flint-rich till, however, most epidote comes from Cenozoic sedimentary source rocks, showing a modal fraction of 3-4 φ or finer (see also Henningsen, 1978).

Garnet content shows large variations that do not correlate with variations in any of the other heavy minerals (see Table II in Rappol, 1987). Also the size distribution of this mineral shows large variations (Fig. 19). In the present study area, flint-poor till and the underlying flint-rich till always show comparatively high garnet percentages. Large variations in garnet content seem to be connected with the upper flint-rich till.

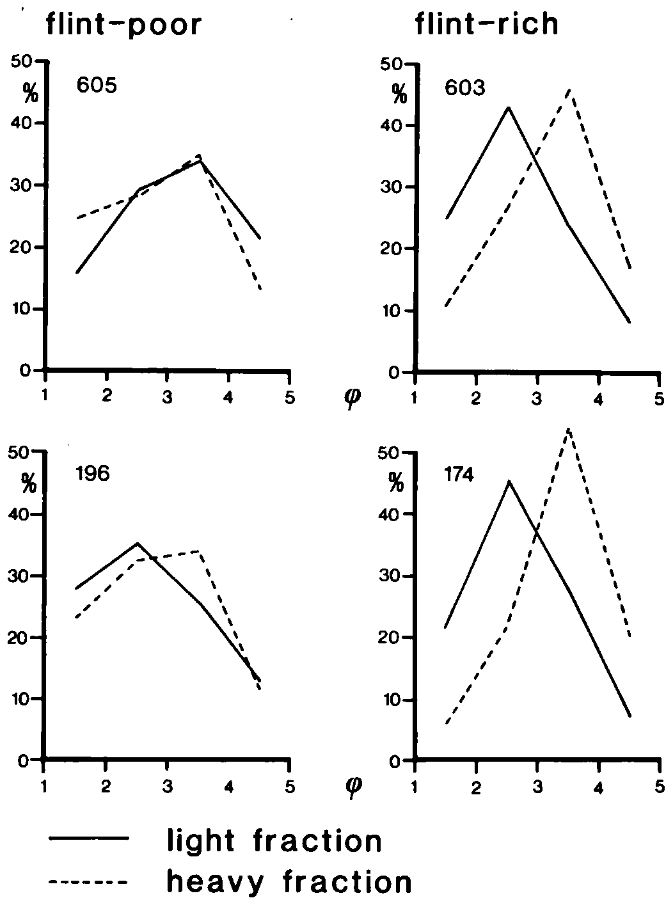


Fig. 18. Heavy-mineral composition of till in the study area, illustrated by a ternary diagram featuring the three main components of the heavy-mineral fraction. Analysed fraction is 2-3 φ (0.25-0.125 mm).

POLLEN ANALYSIS

It has been established that flint-rich till in The Netherlands contains a reworked pollen assemblage of Tertiary (mainly Miocene and Pliocene) and Quaternary pollen (van Gijzel *et al.*, 1959; Zagwijn, 1973). Glacigenic deposits in general (including Saalian and Elsterian glaciolacustrine clays) are characterised by a certain amount of Miocene, and to a lesser extent also Mesozoic palynomorphs, generally with marine indicators (de Jong, 1989). No published information seems available concerning the flint-poor till types. A sample of grey flint-poor till from Steenwijk (sample 705) did not contain any pollen, but this may not be a general characteristic of flint-poor till.

Pollen and other microfossils are present, however, in the black clay lense (sample 714) and in intra-till buff silt lenses (sample 734). Moreover, the black clay contains abundant organic debris, but pollen are comparatively rare, whereas the sample from the silt contains abundant pollen.

The following is entirely based on a palynological analysis and report by de Jong (1989).

The black clay contains Tertiary palynomorphs like *Sequoia*-t., *Taxodium*-t., *Nyssa*, cf. *Pollenites villensis*, *Pollenites pseudocingulum*, *Tricolpites liblarensis*, *Platycarya*, cf. *Lycopodium*, as well as a number

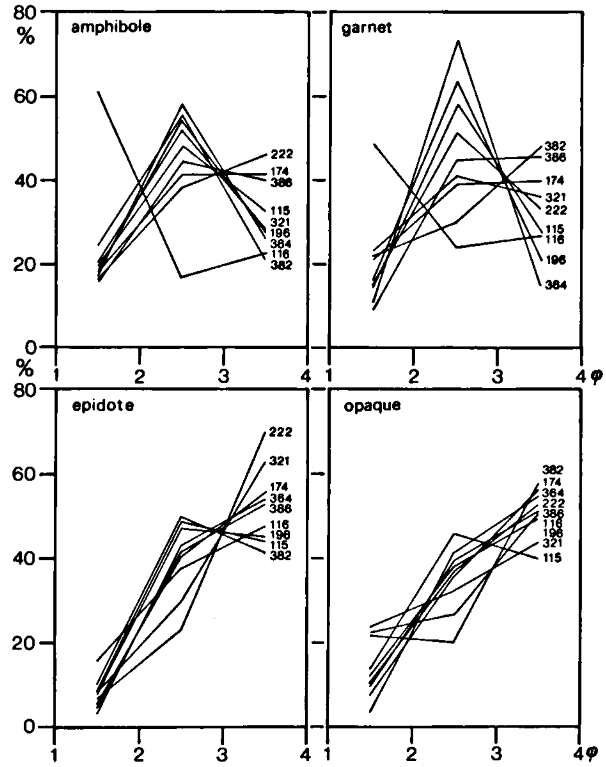


Fig. 19. Size distribution of individual heavy-mineral species or groups for the 1-4 φ size range.

of pollen grains from species still present in the Quaternary: *Alnus*, Gramineae, Ericales, *Dryopteris*-t. Present is also the freshwater alga *Botryococcus*. Marine indicators are absent.

The pollen spectrum of the black clay suggests that it consists of reworked Tertiary deposits, probably mainly of Miocene age. The absence of marine indicators and also the low abundance of bisaccate conifers is different from the composition normally encountered in glacigenic deposits in The Netherlands. Moreover, the presence of Tertiary pollen was not expected on the basis of the results of the clay-mineralogical analysis. For the present, the origin of this deposit is therefore somewhat enigmatic and awaits further research.

Sample 734 from a buff silt lense contains no pollen characteristic of Tertiary or Mesozoic deposits. Besides Quaternary species like *Pinus*, *Alnus*, *Betula* and *Sphagnum*, the spectrum contains a large amount of unknown palynomorphs, as well as many acritarchs, some Hystrichosphaeridae, and *Botryococcus*. Acritarchs appear to be predominantly of Mid-Devonian age (pers. comm. S.E. Hagenfeldt, Univ. Stockholm). Rocks of this age occur only in a small area of the Baltic Sea, off the Latvian coast, and more eastward on the adjacent land area (see Emelyanov & Kharin, 1988, fig. 1). Some of the unknown palynomorphs show a resemblance to those described by Eisenack (1938) from the Baltic Silurian.

It appears that the silt lenses contain a mixture of Quaternary and Palaeozoic spectra, which is in accordance with the position within the flint-poor till. The presence of Quaternary pollen suggests that these lenses represent floes of interstadial or interglacial deposits from the East-Baltic region, presumably of terrestrial origin.

DISCUSSION

The sequence of glacial events in the northern Netherlands.

Results of our study support Zonneveld's (1975) interpretation of the hills at Steenwijk as overridden ice-pushed ridges.

The ice-pushed till units (First Baltic Till) found associated with these ridges must have formed from a thick englacial debris zone. The absence of flint in the gravel and smectite in the clay fraction of the flint-poor unit indicates that it is composed exclusively of far-travelled (1000 km and more) material. Its components were transported above the level of high deformation rates in the base of the ice, preventing it to be mixed with down-ice and local lithologies (Rappol & Stoltenberg, 1985; Haldorsen *et al.*, in press). The great thickness of the till, having been formed prior to glaciotectonic disturbance, suggests a considerable time period with areal stagnation or a stationary frontal position.

The genesis of the flint-poor unit of what we called the "First Baltic Till", also known as "red till floes" or "Voorst Group", has been a widely discussed problem. This problem arose because this till generally does not form a coherent till sheet, but occurs mainly as lenses of limited extent, usually on top of or in the upper part of the flint-rich till. According to de Waard (1949), this till represents floes of reworked Elsterian till. Faber (1950) suggested that it was related to an East-Baltic glacier lobe, riding on top of ice from a West-Baltic source. Veenstra (1963) and Zandstra (1971) assumed that this till represented floes of till originally deposited in the East-Baltic source area, but subsequently eroded, transported, and deposited in The Netherlands and northern Germany. In northern West Germany, Woldstedt & Duphorn (1974) and Ehlers (1981) suggested that the East-Baltic ice overrode a dead-ice zone of the earlier West-Baltic ice flow event.

On the basis of available evidence, we see no reason to consider the flint-poor unit of the First Baltic Till as anything else but a 'normal, subglacially deposited, till', be it that it represents the upper part of the englacial basal debris in the ice sheet. In this respect, it is essentially similar to the flint-poor unit of the Second Baltic Till (Rhenen and Assen Groups), as interpreted by Rappol & Stoltenberg (1985). The present geometry of the First Baltic, flint-poor till bodies is primarily a function of post-depositional deformation during formation and subsequent overriding of the ice-pushed ridges.

The sequence of glacial events at Steenwijk is reconstructed as follows:

1. Initial ice advance, presumably from an east-northeasterly direction, reaching the southern margin of the till plain in the northern Netherlands (Fig. 20A). The exact southern limit of this advance is uncertain.

2. Stagnation phase or stationary ice margin along this line, during which a thick sequence of englacial debris is released, resulting in deposition of a flint-poor till unit overlying a flint-rich till unit. Together these represent the First Baltic Till.

In this context, the available information from indicator counts should be briefly commented on. As mentioned earlier, both flint-poor and flint-rich tills contain mixed indicator assemblages, be it that the flint-poor unit contains more East-Baltic indicators than the flint-rich one. If this highly mixed provenance of the coarse material is not a result of the sampling practice, but a primary characteristic, these results probably reflect reworking of material derived from an earlier radial flow event from the Scandinavian peninsula. As was the case during the Weichselian, it is likely that the

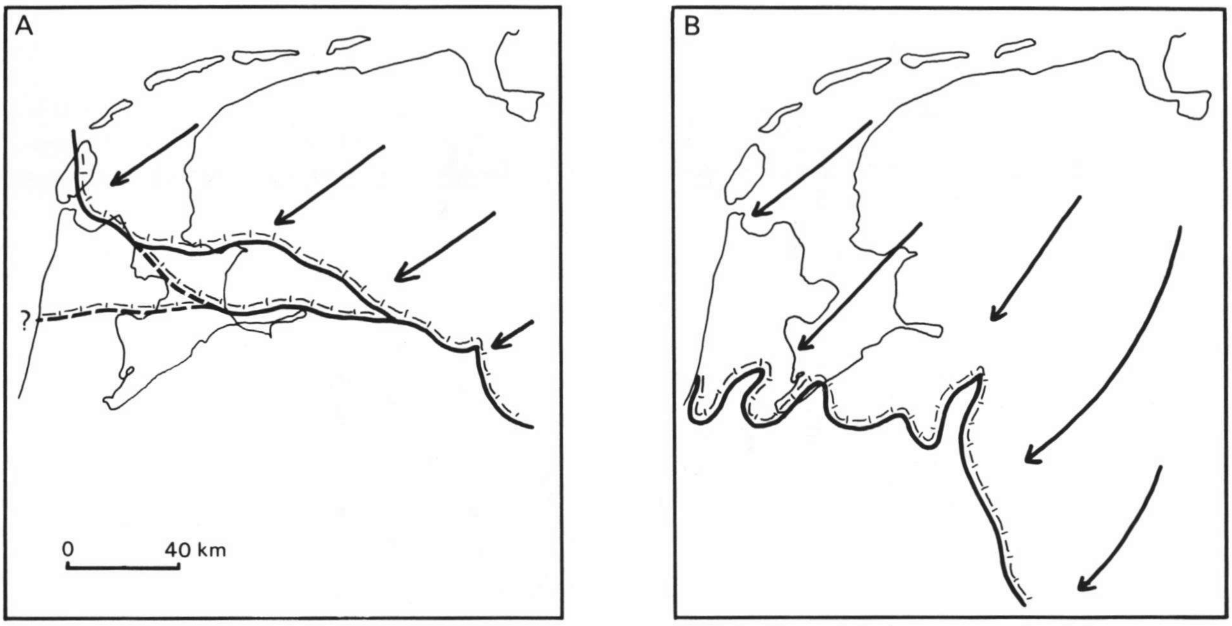


Fig. 20. Two phases in the extent of the ice sheet in The Netherlands during the southwesterly flow event: A. ice margin during deposition of the First Baltic Till and formation of ice-pushed ridges at Steenwijk, B. approximate maximum extent of the ice sheet during the southwesterly flow event, after overriding of the Steenwijk ridges.

First Baltic ice flow configuration was preceded by a radial flow, delivering material from Sweden to the Baltic depression (*e.g.* Lundqvist, 1986; Lagerlund, 1987).

3. Formation of ice-pushed ridges, involving glaciotectonic disturbance of till and sub-till sediments.

4. Overriding of these ridges by ice moving in a southwesterly direction (Fig. 20B). How far this ice movement reached into the central Netherlands remains questionable. The extent as proposed in Fig. 20B is a rough estimate, based on the distribution of till types (Zandstra, 1987) and the sequence of ice-pushed ridges formation as given by Maarleveld (1983), be it partly reinterpreted.

5. Regional stagnation (Fig. 21).

During the last phase of stagnation in the Steenwijk area, the Second Baltic Till was deposited in other parts of The Netherlands. This younger, south-southeasterly ice movement did not affect the larger part of the till plain, and it is therefore assumed that during this phase ice movement was channelled through large bodies of stagnant ice (Rappol, 1984; van den Berg & Beets, 1987), as depicted in Fig. 20. Whereas van den Berg & Beets (1987, fig. 9) depict only one major terrestrial ice stream in the Hondsrug area, Rappol (1984) indicates at least three areas where late southeasterly ice movements are suggested by directional features of glacial landforms or sediments: one following the Gelderse Vallei in the central Netherlands (a former Rhine-Meuse valley), the second along the Hondsrug complex and the former Ems valley, and the third in the Syker Geest area near Bremen, F.R.G., following the Lower Weser valley. It is remarkable that all these ice streams followed major pre-existing depressions; apparently, conditions of the glacier bed materials affected the position of these ice streams.

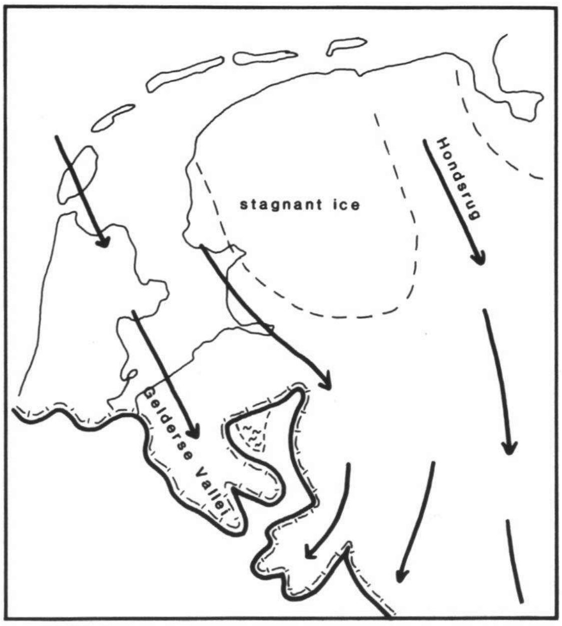


Fig. 21. Reconstruction of ice movement during formation of the Second Baltic Till. Ice movement is partly channelled through large areas of stagnant ice, thereby preserving till and surface morphology of the earlier southwesterly movement in these areas. In the central Netherlands, ice occupied the Gelderse Vallei and was standing at the Stakenberg, while an ice-dammed lake occupied the Leuvenumse Beek valley.

In Fig. 22, the ideal stratigraphic sequence of till units is shown, following the interpretation of the sequence of events, as sketched above. The First Baltic Till is shown at the base of the schematic section. High frequencies of East and East-Central Baltic crystalline indicators in the flint-poor till unit (de Waard, 1949), much dolomite in the matrix and abundant Palaeozoic calcareous rock fragments throughout the till, suggest deposition by ice that followed the Baltic depression (Fig. 23). It can only be assumed that ice movement in The Netherlands during this phase was in a southwesterly direction.

The Swedish Till is probably correlative with the phase during which the ice-pushed ridges at Steenwijk were overridden. The major part of the till plain is formed of till containing predominantly South-Baltic indicators, whereas overlying pebbly sand (reworked till) contains much material from the West-Central Baltic (Dalarne) source area (Zandstra, 1987). No flint-poor facies of this till is known at present.

Finally, a radical change in the ice flow pattern of the ice sheet is necessary in order to account for ice movement in a southeasterly direction in The Netherlands during deposition of the Second Baltic Till. To explain a southeasterly flow in The Netherlands, coalescence of the Fennoscandian and British ice sheets is assumed. Evidence for such conditions during a pre-Weichselian glaciation are also found in northeastern Scotland (see review by Sutherland, 1984: 170-172) and could explain the occurrence of Oslo indicators on the Shetland Islands (Schuddebeurs, 1988). The high frequency of Åland and southwest Finland indicators in till of the Hondsrug area and Stockholm/Uppland indicators in till of the Gelderse Vallei area (Zandstra, 1987), often with extreme values in the upper flint-poor till unit, indicates deposition during a Baltic ice-flow configuration, as depicted in Fig. 24.

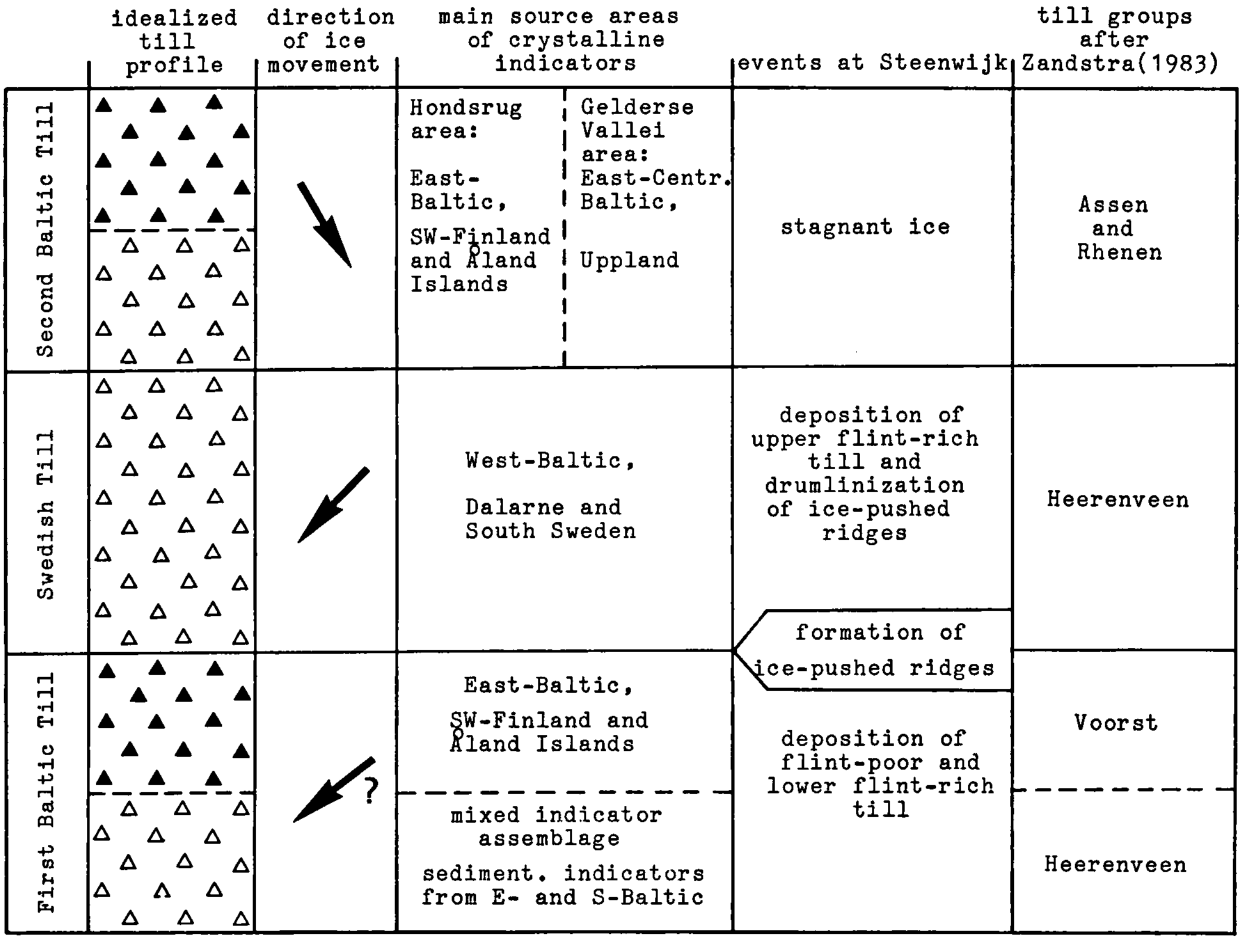


Fig. 22. Schematic stratigraphic sequence of till types in The Netherlands.

Towards a model for the Saalian Glaciation of the North Sea Basin

A number of models have been proposed to account for the development of a "Baltic Ice Stream" during the late phase of Saalian and Weichselian Glaciations. In general, an eastward migration of the main ice divide during the course of a glacial period is assumed, in order to explain deposition of East-Baltic till material at the end of a glaciation (Woldstedt & Duphorn, 1974; Ehlers *et al.*, 1984; Lundqvist, 1986; Houmark-Nielsen, 1987), mainly as a response to climatic factors.

Alternative models include: a westward transport of East-Baltic material by drift ice along the glacier margin (Overweel, 1977), an intermittent transport of East-Baltic material by marginal domes (Lagerlund, 1987), and the development of a "Baltic Ice Stream", generated by a deformable bed in the Baltic depression (Boulton *et al.*, 1985).

With respect to the deformable bed model, it may be argued that it should rather apply to an early phase of glaciation, when much fine-grained interglacial or interstadial sediment is present in the Baltic depression. Indeed, the First Baltic Till is extremely fine-grained and contains lenses of supposedly Baltic (lacustrine or marine) sediment. However, after a prolonged period of ice cover, we expect most unconsolidated material to have been eroded by these earlier ice movements.

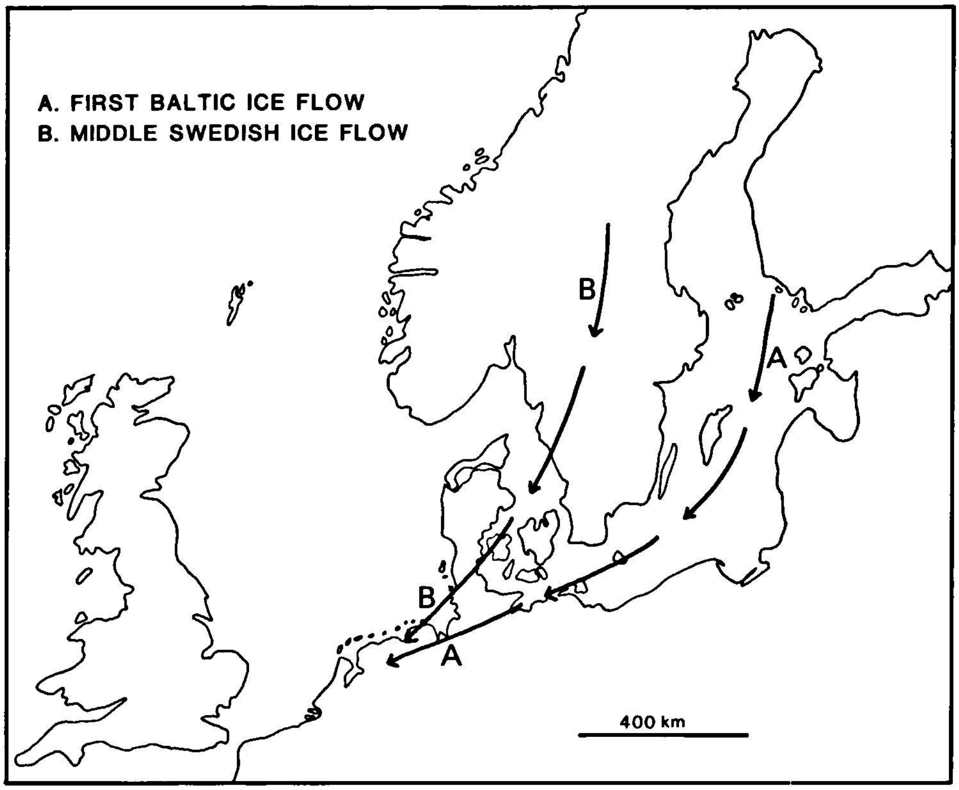


Fig. 23. Schematic representation of flow lines during the early southwesterly flow event of the Older Saalian or Main Drente ice cover.

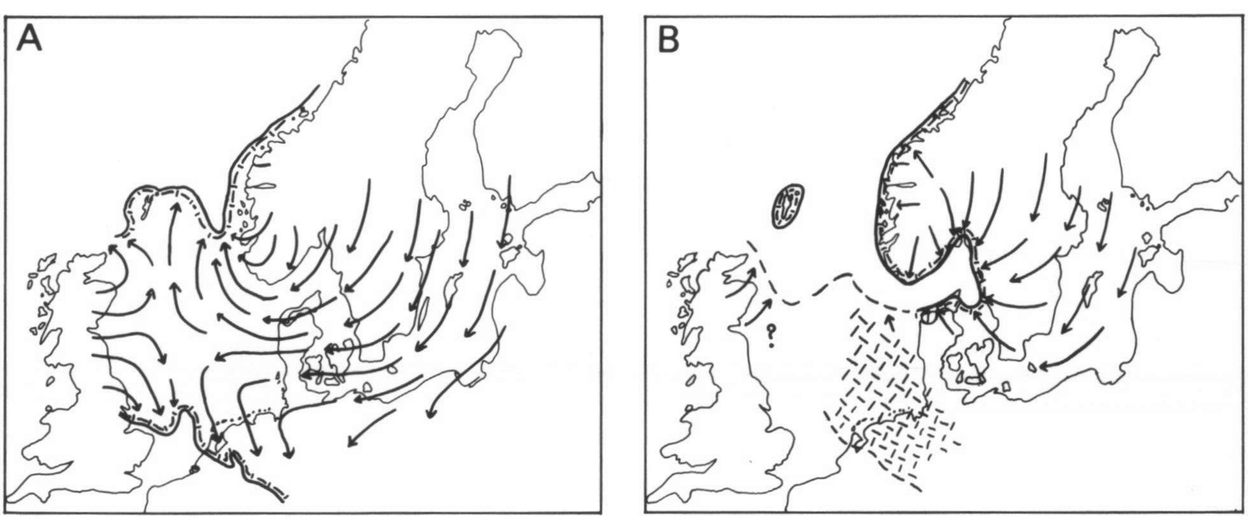


Fig. 24. Ice-flow configuration during formation of the Second Baltic Till.
A. Situation just after a calving bay starts to develop in the Norwegian Channel.
B. After the calving bay reaches the Oslo Fjord, leaving the southwestern part of the ice sheet cut off from its source.

Critical to the model proposed here, is the development of a major marine ice stream in the trough formed by the Norwegian Channel and Skagerrak, that encircles southern Norway. Because of its position, connecting the continental shelf edge with the interior of the ice sheet, and its great depth (down to 700 m below present sea level in the Skagerrak: see bathymetric map in Caston, 1979: figure 7.1), this trough represents an ideal setting for the inception of a marine ice stream, to be followed by the progression of a calving bay up the trough. Such events take place after relative sea level rise due to glacioisostatic depression of the ice covered area, causing drawdown in low areas.

Marine ice streams are capable of discharging very large volumes of ice (Hughes, 1987; Clarke, 1987). Given the size of the trough in question, the development of such an ice stream could greatly alter the ice-flow pattern in a large part of the ice sheet, as envisaged in Fig. 24.

With time, due to lowering of the ice surface, discharge through the ice stream will decrease and a calving bay may start to develop (Fig. 24A). Rapid progression of the calving bay up the Norwegian channel will finally cut off a large portion of the southwestern part of the ice sheet from its source, resulting in stagnation and degradation of the ice cover over the North Sea Basin (Fig. 24B). This explains why we have no record of deglacial retreat phases for the Older Saalian ice cover in the entire southwestern part of the ice sheet.

This model might also explain readvances of the Saalian ice cover, such as those of the Middle Saalian or even Warthe Glaciation (see Ehlers *et al.*, 1984). Once the calving bay reaches the Oslo Fjord area and the ice becomes grounded, the pulling force of the ice stream (Hughes, 1987) ceases to exist. At this point, when the climatic conditions are still favourable, the ice could re-expand.

In essence, this model is similar to the reconstructed deglaciation history of the St. Lawrence Valley in eastern Canada (Thomas, 1977; Chauvin *et al.*, 1985), where such a model explains successfully much of the observed glacial features (*e.g.* Lortie & Martineau, 1987; Rappol & Russell, 1989).

The model is speculative on several points due to the paucity of available and reliable data on the Saalian Glaciation of the North Sea Basin, but also on much of the land area surrounding the North Sea extent and flow directions of the Saalian ice cover are uncertain.

The extent of Saalian ice in England is subject to much debate (see *e.g.* Bowen *et al.*, 1986; Rose, 1987), but appears limited compared to the extent on the nearby continent (Bowen *et al.*, 1986: fig. 5). Moreover, it has been suggested recently, that also the extent of Saalian ice in the southern North Sea is more limited than previously assumed (Cameron *et al.*, 1986; Joon *et al.*, in press). The evidence for coalescent British and Fennoscandian ice sheets (Sutherland, 1984) might represent Saalian as well as Elsterian conditions.

The existence, at one time, of a so-called Skagerrak Glacier that followed the Skagerrak trough in a westerly direction, has been proposed several times in order to account for some, compositionally anomalous, glacial deposits on the Norwegian south coast, but has been rejected an equal number of times (see Haldorsen, 1981: paper 1, for historical review). However, a Skagerrak glacier appears again in very recent publications (*e.g.* Cameron *et al.*, 1987).

Clearly, the model presented here stands or falls with final solutions to these and other problems connected with the extent and flow directions of the Saalian ice cover in the North Sea Basin and surrounding land areas.

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