

Distribution and composition of till on Wieringen and in the northern part of the Wieringermeer, The Netherlands

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Abstract

The former island of Wieringen is part of a series of low ridges along the southern margin of the till plain in the northern Netherlands. Distribution and variations in thickness of Saalian till on Wieringen and in the surrounding area suggest that some of the low hills of Wieringen are ice-pushed ridges and that a major glaciotectonic basin is located to the south of Wieringen, in the northern part of the Wieringermeer.

Compositional characteristics of till indicate the presence of at least two main till types, one in which both flint and smectite are absent and another in which these components are present. An intermediate type contains very little flint but appears to have no smectite in the clay fraction. The flint-poor till is of the Voorst type and belongs to the First Baltic Till as defined for the northern Netherlands.

It is suggested that the present morphology of Wieringen shows features related to two phases of glacial overriding of the previously formed ice-pushed ridges. Firstly, ice moved in a southwestern direction, after formation of the ice-pushed ridges. During a later phase of glaciation, ice moved between Wieringen and Gaasterland in a south-southeastern direction towards the Gelderse Vallei in the central Netherlands. During the latter event, streamlined landforms on eastern Wieringen and western Gaasterland obtained their NNW-SSE orientation. These ice-flow phases can be correlated with ice movements in the northeastern Netherlands, where ice moved first in a southwesterly direction over the till plain and later in a south-southeastern direction in the Hondsrug area.

Introduction

The former island of Wieringen comprises a number of low hills (with a maximum height of 12.8 m above mean sea level near Westerland), consisting of preglacial deposits and Saalian till, often covered by a thin layer of pebbly sand or coversand. These hills are considered part of a series of end-moraines or ice-pushed ridges along the southern margin of the till plain in the northern Netherlands (Brouwer 1950, Ter Wee 1962). This system can be

traced from the island of Texel, through Wieringen, and southwest Friesland (Gaasterland; see Fig. 1), and further eastward along Steenwijk, Hoogeveen, to Coevorden (see Ter Wee 1983). In addition to its topographical expression, the system is characterised by a variable, but locally great thickness of till, and by the presence of large-scale glaciotectonic dislocations of till and/or preglacial deposits (Ter Wee 1962, Zandstra 1971a, Rappol et al. 1989).

Different opinions have been expressed regard-

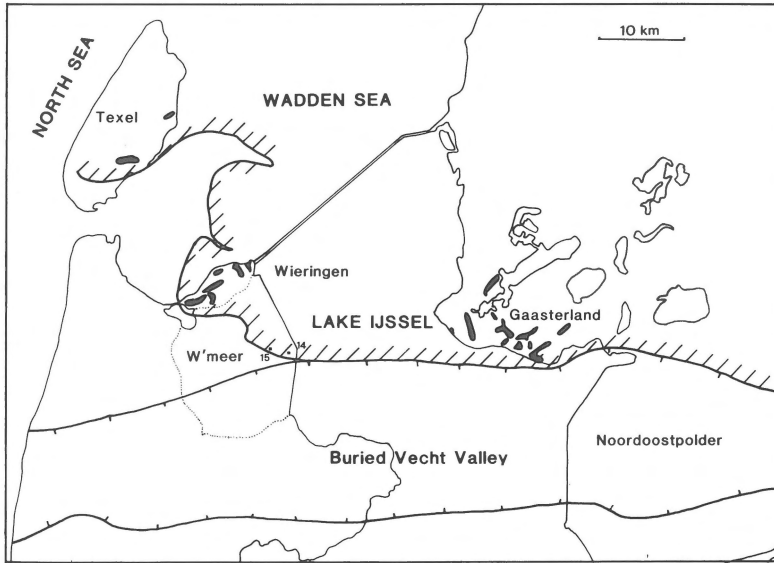


Fig. 1. Location map, showing position of Wieringen within the system of hills (in black) along the southern margin of the till plain of the northwestern Netherlands (line with inclined hatching). Also shown are the locations of sample sites 14 and 15 in the Wieringermeer (W'meer).

ing the question, whether or not the ice-pushed ridges were overridden by the advancing ice sheet after their formation (e.g. Ter Wee 1962, 1983, Zonneveld 1975, Van den Berg & Beets 1987). This is not surprising, since actual observations that could shed any light on this matter are rare and mainly limited to morphological features, such as the recognition of landforms reminiscent of drumlins (e.g. Faber 1926). On the basis of recent observations at an excavation near Steenwijk, where subglacial till was observed to overlie discordantly the ice-pushed strata (Rappol et al. 1989), we assume that ice did advance over the hills after the glaciotectonic event.

The elongated hills of Wieringen exhibit two quite different orientations (Figs 2 and 3). The two easternmost hills of Den Oever and Oosterland have a NNW-SSE elongation, whereas other elongated ridges, more to the west, are oriented ENE-WSW. Similar directions are found for the hills of southwest Friesland, where the most westerly ones, notably those of Warns-Molkwerum, have a NNW-SSE orientation (Fig. 1). Van Cappelle (1895) already was aware of this and considered the NNW-SSE hills to be endmoraines formed transverse to the direction of ice flow, whereas in Ter

Wee's (1962, 1983) model they are interpreted as frontal ice-pushed ridges. However, the same two directions are also found on the till plain in the form of large-scale flutings of the till surface, that can be explained by two successive ice-flow directions (Rappol 1983, 1984, Van den Berg & Beets 1987).

In geological literature reference to the glacial features and history of Wieringen is rare. The most useful sources are reports on the results of drillings in connection with the 'Zuiderzeewerken' (partial reclamation of the former Zuyder Zee, now Lake IJssel) or more recent embankment projects (e.g. Anonymous 1925, 1936, Steenhuis 1936, Krajíček 1980).

Pons (1962) reviewed the geological history of Wieringen, briefly commenting on till occurrences, and suggested that the highest hills of Wieringen have a glaciotectonic origin. It is, however, obvious from his review that very little is known about the glacial history of Wieringen. Since then, as far as we are aware, only Zandstra (1977) presented original material on the area in the form of some gravel and boulder counts.

For the present study, we have processed a large amount of available bore hole data to construct maps and profiles of till occurrences on Wieringen

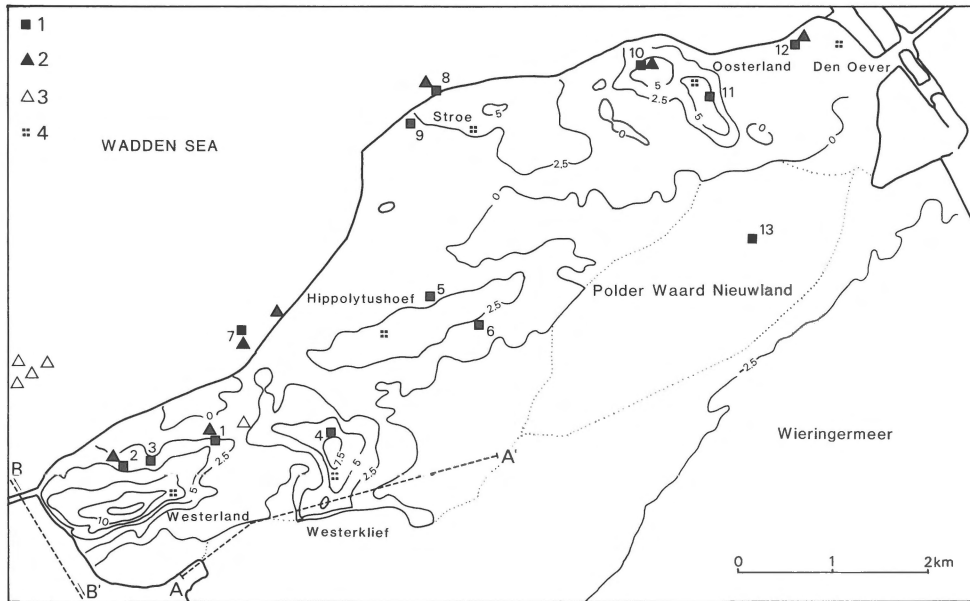


Fig. 2. Contour map of Wieringen with locations of sample sites and geological profiles. Contours at 2.5 m intervals, after topographic map 1 : 25,000, sheet 14 E. 1. sample site; 2, 3. locations where the upper flint-poor unit of the First Baltic Till has been observed or is presumed to occur, respectively; 4. village. Flint-poor till occurrences along the north coast of Wieringen relate to material that was probably brought in during construction of the embankment.

and surrounding areas. We have studied structural characteristics of the few available exposures and determined petrographical characteristics of some 40 till samples. The combined results provide grounds to revise some of the current ideas on the glacial history of Wieringen.

Distribution and thickness of till

Information on till occurrence from over 1100 shallow borings was used to reconstruct the till surface on Wieringen and the northern part of the Wieringermeer (Fig. 3).

The vast majority of the bore hole descriptions were retrieved from the drilling records of the former 'Dienst der Zuiderzeewerken' (government civil engineering service that carried out the large constructions to reclaim the former Zuider Zee). Most of these borings were made in the 1920's. Some drilling data are also reported by Steenhuis (1936), Zuur (1936) and Krajíček (1980), and a few data were retrieved from the boring records of the

Geological Survey of The Netherlands. In addition, we recovered some auger cores ourselves, primarily, however, in order to obtain samples of the till.

Till is found as an almost continuous sheet on Wieringen. In a few small areas, the till is missing. This is the case on the top and southern slope of the Westerland ridge, where coarse-grained sand (Urk Formation?) underlies a thin pebbly sand layer, and at the southern end of the Oosterland ridge, where fine-grained sand of the Eindhoven Formation crops out. However, available data do not allow detailed mapping of these small areas. Also near Wieringerwerf (site 15 in Wieringermeer; see Fig. 1), the till is thin and preglacial deposits of the Eindhoven Formation occur near the surface. In a shallow ditch exposure, these deposits were observed to be strongly deformed and slightly tilted (Fig. 4). The deposits also contained some layers of scattered organic debris.

After deglaciation, the till sheet has been subjected to fluvial as well as marine erosion. In the southern part of the Wieringermeer, till is absent,

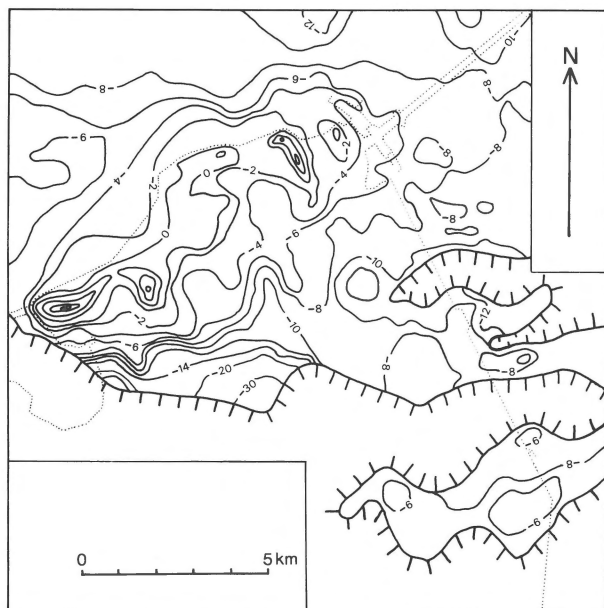


Fig. 3. Top of till, contoured at 2 m intervals, except downward from 14 m below sea level, where only the -20 and -30 m contours are shown. In non-contoured area, the till is absent.

probably as a result of (glacio?) fluvial erosion that cut the Vecht Valley (Fig. 1), and erosion during the Eemian transgression. In the northern part of the Wieringermeer and west of Wieringen, Holocene erosion gullies occur (Pons & Wiggers 1958, Ente 1969), that have eroded part of the till sheet.

On Wieringen, the present topography more or less follows the till surface, the overlying sandy deposits having a thickness of less than 2 m, in general. In the surroundings, the till surface appears to be rather flat, lying between 6 and 10 m below sea level. Very deep occurrences of till are found in the northwestern part of the Wieringermeer (Steenhuis 1936). In one of the borings in this area, two till layers were encountered at depths of about 28–35 and 42–48 m below sea level, separated by fine sand (Anonymous 1936, App. 2). Most likely, this implies a doubling of the till due to glaciotectonic stacking.

Indirect evidence of glaciotectonic disturbance is also found around the hills of Westerland and Westerklijf, where the relief of preglacial deposits is high, and the otherwise rather regular till layer appears to be strongly disturbed (Fig. 5).



Fig. 4. Glacially deformed sediment of the early-Saalian Eindhoven Formation near Wieringerwerf (site 15, Fig. 1). Thrust plane (X) dips 25° to N.

Until now it was generally assumed that the ice lobe responsible for formation of the ice-pushed ridges of Wieringen was located to the north, between Wieringen and the island of Texel (Ter Wee 1962, 1983). However, it now seems more likely that lateral pushing took place by an ice mass located south of Wieringen. Only here very deep till occurrences have been found, suggestive of the presence of a glaciotectonic basin (Fig. 3). Moreover, there are indications for glaciotectonic disturbances in the subsoil of the same area.

Although close to 500 borings reached the base of the till, no reliable map of the depth of the till base or till thickness can be constructed from these data. Firstly, because these data are rather unevenly distributed over the area. Secondly, because the local variability indicated by these data is very large. The latter may be an inherent feature of the area, being a result of glaciotectonic disturbances. It may partly be due, also, to the difficulty of establishing the exact till base in cores, when the lower contact is not sharp, but, instead, shows a more or less gradual change from till to sub-till material.

The greatest thickness is found at Noordburen, north of Hippolytushoef: about 16 m. Thicknesses of about 10 m are common along the north coast of Wieringen between Westerland and Stroe (Krajíček 1980). Also north and east of Den Oever, a thickness of about 10 m has been recorded quite often. Otherwise, till thickness varies mostly be-

tween 3 and 5 m, except in the southeastern part of the area of Fig. 3, where till thickness is generally less than 3 m.

Subglacial till has played an important role in the accomplishment of the 'Zuiderzeewerken'. For construction of the 'Afsluitdijk' (the main enclosing dam) alone, some fifteen million cubic metres of till have been scraped from the sea bottom (Thijssse 1972). Important places for excavating till around Wieringen were located east and north of Den Oever and along the eastern flank of the Amsteldiep, north of the Amsteldiepdijk. On Wieringen, a trench was dug, several metres deep, extending eastward for about 2 km from the Amsteldiepdijk, that was originally planned to route a railway line. At such places, the information given by Fig. 3 cannot apply to the present situation, as most of the processed cores were performed prior to excavation, precisely to locate suitable places for the recovery of till.

Till composition

Methods

In the investigated area only a few small and shallow exposures were available (sites 1, 2, 9, and 15). Most samples obtained are drill cores. Two samples (929, 930) from till balls on the beach may not have been taken from in situ till, but from till that was brought in during embankment construction.

The 3–5 mm gravel fraction was analysed by the standard method (Zandstra 1983). The flint-coefficient value (number of flint particles divided by the number of igneous and metamorphic rock fragments) is used to compare the erratic components of many samples (Rappol 1987).

Clay minerals were determined by X-ray diffraction of the smaller than $2\mu\text{m}$ fraction. X-ray mounts were made on ceramic tiles by filtration of a clay suspension.

Diffraction patterns were obtained from sample splits prepared in the following ways: 1. Mg^{2+} -glycerol saturated, 2. Mg^{2+} saturated at a 55% relative humidity, 3. K^+ saturated at a 55% relative humidity,

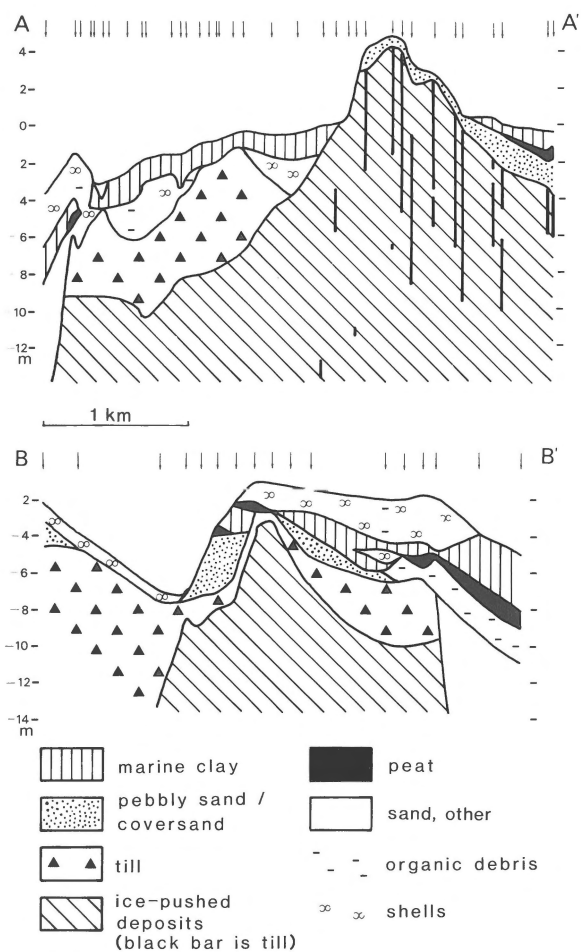


Fig. 5. Geological profiles through the investigated area. For location, see Fig. 2. A-A'. West-east section through Westerkleef ridge, B-B'. North-south section along western tip of Wieringen.

4. K^+ saturated, heated to 300°C for 2 hrs, and 5. K^+ saturated, heated to 550°C for 2 hrs.

Clay mineral abundances were estimated semi-quantitatively (Table 1). The abundances of smectite, vermiculite, illite, and kaolinite/chlorite were calculated by multiplying peak height with width at half height of the d.001 reflections, and multiplying these values by a factor of 1, 2, 4, and 2, respectively. The kaolinite and chlorite content was determined by scanning of the 3.58\AA and 3.54\AA reflections and the 14\AA reflection in the 550°C diffractogram.

Although this method differs slightly from that

used by Haldorsen et al. (1989) and Rappol et al. (1989), the results do not differ significantly. Re-runs of samples analysed by Haldorsen et al. (1989) gave very similar results.

Grain-size composition was determined by dry sieving and pipette method.

At two sites, elongated-clast fabric of till was measured, following earlier described methods (Rappol 1983, 1985). Data were contoured on the lower hemisphere following the method of Kamb (1959), and eigenvectors and λ -values were calculated as described in Mark (1973).

Because only a few calcareous till samples were available, we refrained from an analysis of the content and nature of carbonates in till. Few data are available that determine decalcification depths. On the basis of differences in cone penetration of calcareous and decalcified till along the coast between Westerland and Stroe, Krajíček (1980) found a wavy boundary between the two, lying between 2 and 10 m below the top of the till, usually between 4 and 7 m. According to Pons (1962), calcareous till lies about 5–7 m below surface on the north flank of the Westerland ridge. However, at Den Oever (site

Table 1. Composition of the fine gravel and clay fractions of till on Wieringen and in the Wieringermeer. In the gravel counts C + F + Q + R = 100%, and carbonate rock fragments were counted separately. All samples are from till, with the exception of sample 951, that was taken from a silt layer within flint-poor till, and of sample 956, that was taken from a sandy gravel deposit enclosed in a glaciotectionic mix of till, glaciofluvial, and preglacial deposits. For location of sample sites, see Figs. 1 and 2

location	n	d	C	F	Q	R	F/C	L+D	S	I	K	V	C	
1 Westerland I	918	1.5	61	7	5	27	0.11							
	917	1.5	65	4	3	28	0.06		0	70	15	15		
	916	2.6	not enough gravel in sample							0	74	10	12	4
	911	2.6	65	5	4	26	0.08		0	68	16	16		
	910	2.8	57	13	10	20	0.24		35	42	18	5		
	909	3.5	51	14	17	18	0.27		36	41	17	6		
	908	4.0	52	17	8	23	0.33		33	46	16	5		
2 Westerland II	938	1.5	57	11	10	22	0.20							
	937	2.0	54	10	11	25	0.18		34	39	15	10	2	
	936	2.5	53	13	10	24	0.24							
	935	3.1	not enough gravel in sample							0	64	11	19	6
	934	3.5	58	16	8	18	0.29							
	933	4.5	55	15	14	16	0.28		43	35	13	8	1	
	932	5.5	59	15	9	17	0.24							
3 Westerland III	931	6.0	56	18	6	20	0.33		33	40	15	6	6	
	940	1.0	58	14	7	21	0.24							
4 Westerklief	939	2.5	59	17	6	18	0.28							
	922	1.5	51	9	9	31	0.19							
	921	2.5	52	15	6	27	0.29							
5 Hippolytushoef	920	3.5	52	10	11	27	0.19							
	925	1.6	51	13	10	26	0.26							
6 Elft	770	1.5	51	13	10	26	0.25							
	915	1.3	63	9	10	18	0.15							
	914	3.0	58	11	8	23	0.19							
7 Normerven	930	0.0	53	0	2	45	0.00		0	79	7	3	11	
8 Stroe-beach	929	0.0	52	0	0	48	0.00	53	0	72	4	0	24	
9 Stroe-pit	913	1.0	55	20	9	16	0.37		41	45	13	1		
	912	2.0	63	7	7	23	0.11		39	42	12	7		
10 Vatrop	953	2.5	75	1	3	21	0.02							
11 Oosterland	924	1.2	48	22	8	22	0.48		40	39	15	4	2	
	923	2.2	54	14	13	19	0.27							
12 Den Oever	950	2.3	57	0	3	40	0.00	50	0	64	5	23	8	
	949	3.0	61	0	3	36	0.00	63						
	951	3.7	not present							0	63	5	18	14
	948	4.0	59	0	3	38	0.00	72	0	65	8	17	10	
13 Waard-Nieuwl.	952	2.5	57	12	9	22	0.22							
14 Kreileroord	941	0.8	58	9	11	22	0.15							
	942	1.6	52	9	18	21	0.17							
15 Wieringerwerf	955	0.4	40	13	28	18	0.33							
	956	0.9	38	6	34	22	0.16							
Fine gravel petrography									Clay mineralogy					
n - sample number									S - smectite					
d - depth below surface									I - illite					
in metres									K - kaolinite					
									V - vermiculite					
									C - chlorite					
C - igneous and metamorphic rocks														
F - flint														
Q - quartz														
R - sedimentary rest														
F/C - flint-coefficient														
L+D - limestone and dolostone														

12) we found that very stiff flint-poor till is calcareous virtually to the top of the till (ca. 1.5 m below surface).

Till types and glacial erratics

Originally, only two types of till were distinguished in the Netherlands: a grey, sandy and flint-rich till, containing mostly West-Baltic indicators, and a red, silty and clayey till, virtually containing no flint, but with many East-Baltic indicators and especially also much Paleozoic limestone. Of these two types, the first was considered to be the 'normal' till, whereas the so-called 'red floe-till' was known from only a few places (see e.g. De Waard, 1949).

In a series of publications, Zandstra has increased considerably the number of petrographic till types that can be distinguished (see Zandstra, 1983, for a recent summary). His classification is based on differences in igneous indicator rock assemblages and flint content of the fine gravel fraction. Seven till types are distinguished, divided over four groups, where each till type is still further subdivided in a calcareous and a decalcified type. Amongst other things, two East-Baltic flint-poor till types are distinguished (Emmen and Voorst types), that occur at different levels within the till sheet of the Netherlands.

In view of the available information regarding successive ice movements, petrographic variability and glacial morphology, the till stratigraphy of the Netherlands can be envisaged as shown in Fig. 6. Note, that the superpositions occur within one single till sheet; there are no indications for an important deglaciation phase during the Saalian ice cover of the Netherlands (Rappol 1983, Zandstra 1983).

On Wieringen, as in the surrounding lower areas, till consists mainly of a sandy and flint-rich type. Pons (1962) and also Wiggers (1955), however, reported the local occurrence of red till on Wieringen, meaning the clayey, flint-poor till as known at the time especially from the Noordoostpolder (De Waard 1949). However, without quantitative analyses, colour cannot be used as an unequivocal criterium for till classification. Also dur-

Saalian till subdivision

member	units	till types*	main source of indicators*	ice-flow direction
Second Baltic Till	flint-poor	Rhene Emmen	East-Central Baltic in Guelders Valley and East-Baltic in Hondsrug area	↓
	flint-rich	Amersfoort Assen		
Swedish Till	flint-rich	(Markelo?) Heerenveen	West Baltic (central and southern Sweden)	↙
First Baltic Till	flint-poor	Voorst	East-Baltic	↙
	flint-rich	Heerenveen	mixed assemblages	

* after Zandstra (1983, 1987)

Fig. 6. Proposed stratigraphy of petrographic till types in the Netherlands. For reasons discussed elsewhere (Rappol 1987, Rappol et al. 1989), this scheme differs in several respects from a stratigraphic sequence proposed by Zandstra (1983: Fig. 369).

ing the present investigation, it became again apparent that flint-rich till may be red when in a strongly oxidised state. Moreover, the 'red floe-till' can be grey in some cases (Boekschoten & Veenstra 1967, Rappol et al. 1989).

Therefore, according to Zandstra (1977: p. 52): 'calcareous red floe-till has not been demonstrated but its presence, among other places in the subsoil of Texel and Wieringen is regarded likely'. Zandstra's assumption can now be corroborated (see below). Locations where the flint-poor unit of the First Baltic Till (Voorst type) is found are indicated on Fig. 2.

This figure shows also locations where the presence of this till type is suspected on the basis of the descriptions found in the records of the 'Dienst der Zuiderzeewerken'. In general, these descriptions speak of a grey, sandy to very sandy till, but at locations indicated in Fig. 2, 'a stiff, clayey, brown till with many stones' was named. Local fishermen described the occurrence along the eastern flank of the Amsteldiep as a 'miraculously hard clay' (Thijsse 1972). In the descriptions, the stiff till occurs on top of as well as below the sandy till, with their relative positions changing quickly over short distances. This may suggest that the tills were deformed as a result of ice-pushing and/or by subglacial shearing during overriding, similar to what

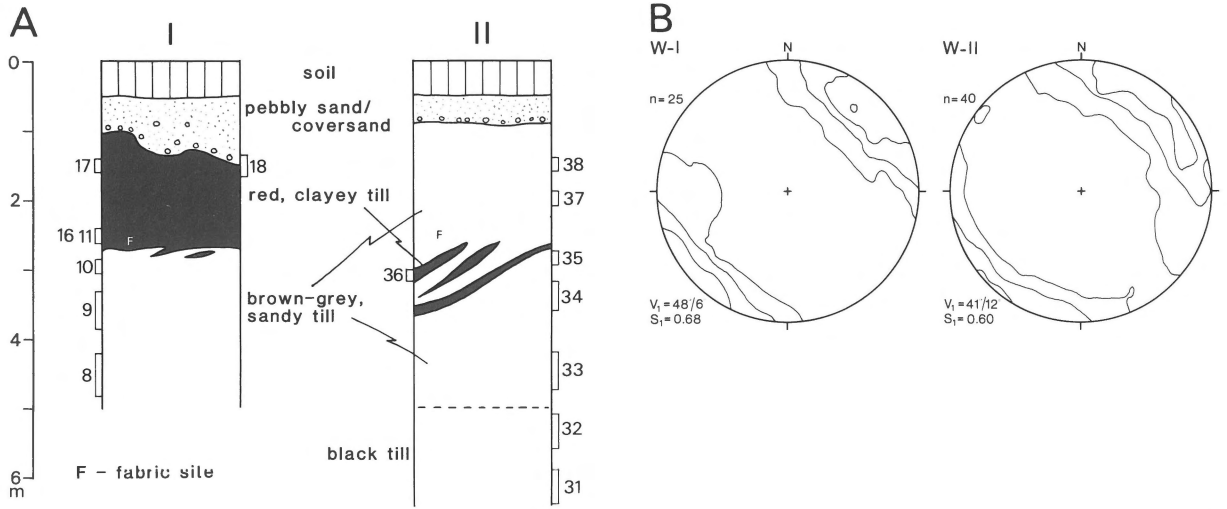


Fig. 7. A. Till sections at sites Westerland I and II, with sample levels. In this figure, sample 18 refers to sample 918 in Table 1. B. elongated clast fabric diagrams at sites indicated in A. V_1 is principal eigenvector, S_1 principal eigenvalue (a measure of fabric strength), n is number of clasts measured.

has been observed at Steenwijk (Rappol et al. 1989).

The stratigraphical relationships between the flint-poor and flint-rich till could also be studied in two small exposures north of Westerland (Fig. 7A). The flint-poor till, although containing no smectite, does not occur here in its purest form, however (see below, and Table 1).

In the first profile (Westerland I), a clayey red till overlies a grey-brown sandy till. The contact between the two dips about 20° northward. Lenses and small wedges of the upper till penetrate the lower till and conversely. In the Westerland II section, a number of stacked shear lenses of red till occur in sandy grey-brown till. Below the grey-brown till, a dark-grey to black till is present, containing some wood fragments. Till with these characteristics is also known from Steenwijk (Ter Wee 1966, Rappol et al. 1989).

In both sections, the orientation and dip of elongated clasts was measured (Fig. 7B). The first series of measurements at the base of the red till in section I shows a rather strong fabric with a preferred NE-SW orientation. The same mean direction is found in the other profile in the sandy till overlying the red-till lenses, but the fabric has rather low strength. A more complex deformation his-

tory is possibly the reason for low fabric strength in this sample.

A number of indicator counts have been reported from Wieringen and surroundings in De Waard (1945) and Zandstra (1971a, 1977, 1987). Most of these counts indicate a mixed assemblage. Similar results have been obtained in SW Friesland and at Steenwijk (see Zandstra 1987). Only from the bottom of Lake IJssel, off the Wieringermeer coast, a West-Baltic as well as an East-Baltic assemblage is known (Zandstra 1987), and recent counts around Kreileroord in the Wieringermeer indicate a strongly West-Baltic provenance of the indicators in this area (Zandstra, in press). Remarkable furthermore is an East-Central Baltic (Uppsala-Stockholm area) component in some of the counts from Wieringen and Texel, which is not found anywhere else in the northern Netherlands. East-Central Baltic components are abundant, however, in the Gelderse Vallei of the central Netherlands, where, in fact, these dominate the indicator assemblages (Zandstra 1987).

Fine gravel composition

As is the case in areas with a similar till petro-

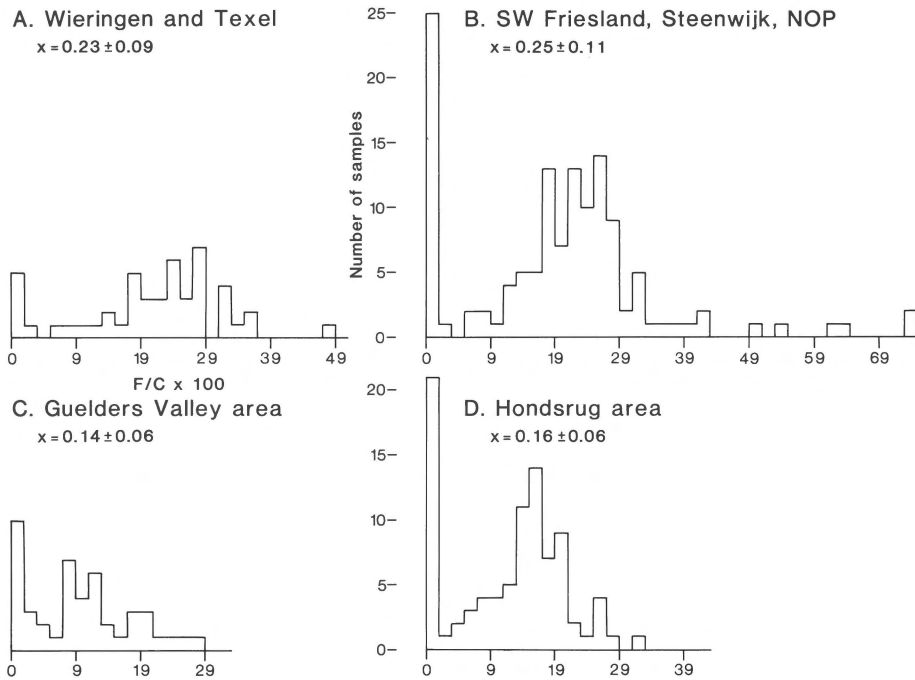


Fig. 8. Frequency distribution of flint-coefficient values in till for different parts of the Netherlands. The mean values (\bar{x}) are calculated comprising flint-rich till ($F/C > 0.03$), only. Frequency bars are erected at 0.02 intervals, starting with 0.00–0.01, 0.02–0.03, etc.

raphy, i.e. southwest Friesland (Zandstra 1971b) the Steenwijk area (Ter Wee 1966, Rappol et al. 1989), and parts of the Noordoostpolder (De Waard 1949, Veenstra 1963), two till types can be distinguished on the basis of gravel petrography (Table 1): a flint-poor type ($F/C \leq 0.03$), which in its calcareous manifestation contains also much limestone ($> 50\%$), and a flint-rich till ($F/C > 0.03$, and usually > 0.10), that was only found in a decalcified state during the present survey.

However, characteristics of the red clayey till in section I of Fig. 7A are partly of an intermediate nature. An apparent mixing of the two main till types has also been observed elsewhere (Zandstra 1971b, Rappol et al. 1989). The composition of this till will be discussed in the section on clay mineralogy.

In a small exposure near Wieringerwerf, till (sample 955) and glaciofluvial gravelly sand (sample 956) contain an anomalous amount of quartz. These materials occur in a strongly deformed complex with preglacial deposits of the Eindhoven For-

mation (Fig. 4). The latter contain sparse well-rounded gravel-sized quartz, deposited in an eolian environment (Zandstra 1977). Massive reworking by glacial processes of these deposits explains the high quartz content of glacial deposits at this site.

The frequency distribution of flint-coefficient values in the investigated area is shown in Fig. 8, in which it is compared with data from other glaciated areas in the Netherlands. The mean value and standard deviation of these values for flint-rich tills in the study area (Fig. 8A) is very similar to those of the related areas of low ice-pushed ridges and thick tills in the northern Netherlands (Fig. 8B). Tills in these areas belong either to the First-Baltic Till or to the Swedish Till (see Fig. 7). However, in areas where the Second Baltic till is found at the surface, i.e. in the Hondsrug area and the Gelderse Vallei, the mean flint-coefficient value is lower and the variation smaller (Figs 8C and 8D).

This lends further support for the subdivision of separate events within the ice cover of the Netherlands, that also follows from morphological, clast-

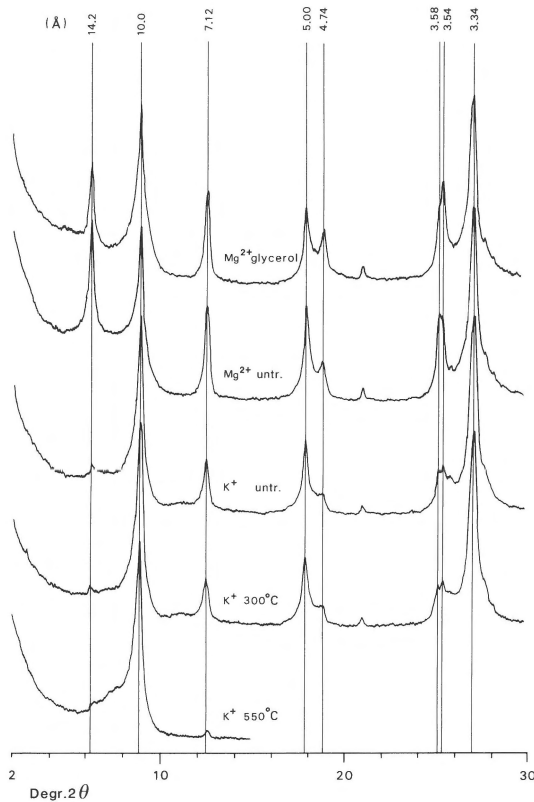


Fig. 9. X-ray diffractograms of flint-poor till from Den Oever (sample 950). See text.

fabric and indicator evidence: an early ice movement in a southwesterly direction, and a second phase with ice flowing south-southeastward (Rappol 1984, 1987).

Clay mineralogy

The clay-mineralogical composition of till can provide important additional information regarding the provenance of till in the Netherlands (Haldorsen et al. 1989, Rappol et al. 1989). In general, it appears that flint-poor till does not contain smectite, whereas flint-rich till types contain 20–50% smectite in the clay fraction. The absence of smectite is due to the scarcity of this mineral in the source area underlain by Precambrian and Paleozoic bedrock, from which flint-poor tills are almost exclusively derived.

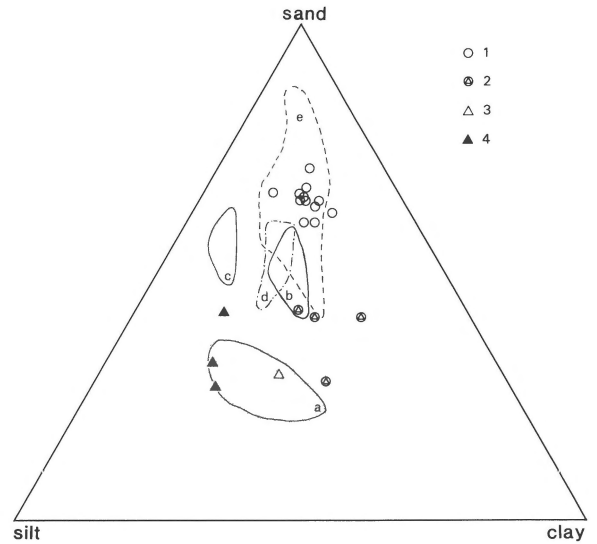


Fig. 10. Sand-silt-clay ratios for till of Wieringen compared with envelopes of such data for till types from other parts of the Netherlands. a. envelope for flint-poor unit of First Baltic Till, b. flint-poor unit of Second Baltic Till, Hondsrug area, c. idem, Gelderse Vallei area, d. till of Markelo type, e. flint-rich till types. Wieringen samples: 1. flint-rich till, 2. red till with very little flint, 3. flint-poor till, decalcified, 4. flint-poor till, calcareous.

Illite, smectite, kaolinite, vermiculite, and chlorite are the main clay minerals that are present in the clay fraction. Although present in some samples, transitional minerals, such as vermiculite-chlorite interstratifications and hydroxy-A1 inter-layered minerals, play only a minor role.

The estimated quantities of clay mineral species in a number of till samples from Wieringen is shown in Table 1, demonstrating that also on Wieringen flint-poor till does not contain smectite in measurable amounts. Moreover, flint-poor till contains less kaolinite and more vermiculite plus chlorite than flint-rich till. Several other points can be noted.

Firstly, the amounts of vermiculite and chlorite show erratic variations, that do not appear to relate to any other variable connected with source materials. The same was noted in Rappol et al. (1989). Comparison in Fig. 9 of the Mg^{2+} and K^+ untreated subsamples reveals a collapse of the 14Å reflection to 10Å and a decrease of the 7.12, 4.74, and 3.54Å reflections (the d.002, d.003, and d.004 reflection

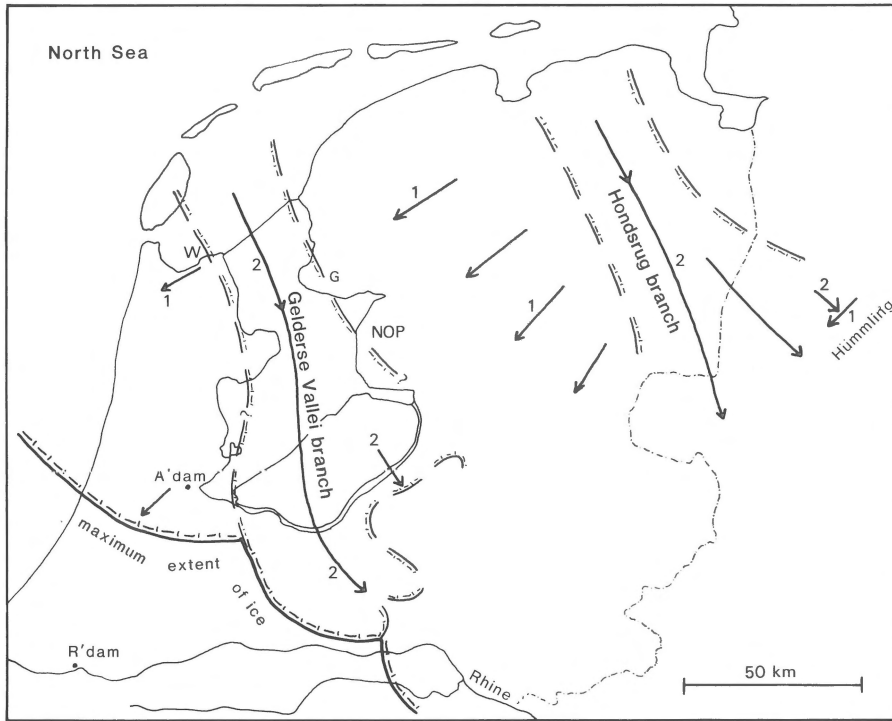


Fig. 11. Two successive ice movements (1. older, 2. younger) in the northern and western Netherlands, as indicated by morphological phenomena and directional features of till. Information on Hümmling area, from Schröder (1978). W – Wieringen, G – Gaasterland (southwest Friesland), NOP – Noordoostpolder.

of chlorite, respectively). In the 550°C diffractogram, a $11\text{--}12\text{\AA}$ reflection remains, which is probably due to a random interstratification of 2:2 mineral (chlorite) and a 2:1 mineral (vermiculite contracted to 10\AA).

These features suggest that most of the original chlorite has weathered to vermiculite by removal of the OH-interlayer sheet, and perhaps in part even to smectite through a mixed layer state. Indeed, it has been found that a few samples of flint-poor till, that showed field evidence of severe weathering, do contain a small amount of smectite (e.g. samples 016 and 601 in Haldorsen et al. 1989). The weathering solution is not clear cut, however, as sample 930, from decalcified flint-poor till, still has a high chlorite content.

On the other hand, it seems clear from the good correlation with gravel petrography, that the estimated quantities of kaolinite and smectite are hardly influenced by weathering, and represent variability due to differences in source materials.

It appears from Table 1 that till with an intermediate composition with respect to gravel petrography from Westerland has a clay mineralogy similar to the flint-poor till. The same applied to a similar sample from Steenwijk (sample 731 in Rappol et al., 1989). This may suggest that this so-called intermediate till type does not represent a simple local mixing of the two main till types, but should be classified as a separate till type. On the other hand, it may well be that smectite content is too low to be detectable by the method used.

Grain-size distribution

Sand-silt-clay frequencies in till from Wieringen are shown in Fig. 10, and are compared with till types in other parts of the Netherlands. The grain size distribution of flint-rich till on Wieringen is similar to such till in other parts of the country. Fine-grained varieties within this group have been

sampled from a pit near Lunteren, central Netherlands, where a thin clay layer was reworked and partly assimilated in the till (Rappol 1983), and from Eastern Overijssel, where fine-grained Tertiary deposits have been incorporated (see also De Ridder & Wiggers, 1956). However, in general, flint-rich tills are very sandy (50–75%), which is primarily due to the large amount of reworked sandy Quaternary deposits in these till types.

Flint-poor till of Wieringen compares well with such till from Steenwijk and the Noordoostpolder. The decalcified samples are generally more clayey, because with dissolution of limestone fragments always some very fine-grained insoluble residue remains in the till.

Till samples with an intermediate gravel petrography, also tend to occupy an intermediate position in the grain-size diagram. Because all these samples were decalcified, they are more clayey than most of the more pure flint-poor till.

In a few closely spaced hand-borings near Den Oever, a calcareous fine silt layer (thickness 10 cm) was found at a depth of about 1.5 m below the top of flint-poor till. The grain-size distribution of this layer is very similar to that of silt layers found in flint-poor till near Steenwijk, containing a modal fraction of 6–7 ϕ (see in Fig. 13 Rappol et al., 1989). Also the clay mineralogy is identical; no smectite is present.

Discussion and conclusions

Compositional aspects of till on Wieringen support the geological relationship of the glacial formations of Wieringen with those of southwest Friesland and Steenwijk. The low hills of these areas consist of till as well as ice-pushed preglacial deposits. Glaciotectonic dislocations on Wieringen, involving preglacial deposits as well as till, are evident from bore-hole records. A glaciotectonic origin seems most likely for the hills of Westerland and Westerkrief. The principal glaciotectonic basin associated with the ice-pushed ridges of Wieringen appears to lie south of Wieringen, in the reclamation area of the Wieringermeer.

Most till sampled on Wieringen during this sur-

vey belongs to the First Baltic Till (see Fig. 6), and was formed during an early phase of glaciation, when the ice margin was lying along the southern margin of the till plain in the northern Netherlands (Brouwer's, 1950, Drentean stage). Some of the flint-rich surface till may have formed in a later phase, during which the ice had advanced further south, but this is very difficult to assess when structural relationships cannot be studied in exposed sections.

No direct and conclusive evidence was found whether these ice-pushed ridges were overridden after their formation, but such an event is assumed on the basis of findings at Steenwijk (Rappol et al. 1989). Morphological arguments that have been used to infer overriding in a southwestern direction (Zonneveld 1975, Van den Berg & Beets 1987: Fig. 8) do not apply to Wieringen, as the hills have variable morphology and very different orientations. The same is actually true for the hills in southwest Friesland (see also Faber, 1942: 210).

West of the Hondsrug system, the glacial morphology on the till plain of the northern Netherlands trends generally NE-SW. It is commonly accepted that this trend reflects the direction of ice movement. However, the hills of eastern Wieringen and of the southwestern tip of Friesland are oriented NNW-SSE. This is the same direction as that of the Hondsrug system, for which a relationship with a SSE flow of ice has been established (Rappol 1983, 1984). The Gelderse Vallei in the central Netherlands represents another area where a southeasterly flow of ice is apparent, both on the basis of the morphology and of the structure of the surrounding ice-pushed ridges (see e.g. Maarleveld, 1981) and on the basis of available, yet scarce, till fabric evidence (Rappol 1983, 1987). Moreover, the Gelderse Vallei area, like the Hondsrug area, is characterised by an indicator assemblage that is totally different from that of the main till plain of the northern Netherlands (see Zandstra, 1987).

We suggest that the ice mass responsible for the East-Central Baltic assemblage of erratics in the Gelderse Vallei area moved between Wieringen and southwest Friesland in a south-southeastern direction, i.e. parallel to and coeval with the shaping of the Hondsrug ridge system (Fig. 11). It there-

by remodelled the morphology of eastern Wieringen and southwest Friesland and created NNW-SSE trending streamlined landforms in these areas. Additional support for this view may be found in the East-Central Baltic component in at least three indicator counts from Wieringen and Texel (Zandstra 1987).

This model is incompatible with the maximum extent of Saalian ice as proposed by Long et al. (1988: see also Joon et al., 1990) for the North Sea Basin area. These authors suggested that the margin of the ice sheet that covered the Netherlands more or less followed the configuration of the present Dutch coast, some 50–100 km offshore. However, in our opinion, it is absolutely necessary that an important part of the central North Sea Basin was ice covered, if only to account for the undisputed ice movement from the north-northwest, irrespective whether this event took place during an early or a late phase of the ice cover (cf. Ter Wee 1962, Rappol 1984, 1987, Van den Berg & Beets 1987, Zandstra 1987, Ehlers 1990). Moreover, this viewpoint is supported by results of petrographic analyses of surface sediments in the North Sea Basin by Baak (1936) and Veenstra (1969). From these studies it appears that the composition of surficial sediments changes between Dogger Bank and Cleaver Bank, reflecting the different source materials of a Devensian British till and a Saalian Fennoscandian till.

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