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ABSTRACT

The morphology of the central Netherlands is dominated by a series of ice-pushed ridges dating from the Saalian. Exposures often show imbricated thrust-sheets, consisting of early to middle Pleistocene fluviatile sediments. Till is never found intercalated in these sediments, strongly suggesting pushing in front of the glacier. Scanty till remnants on the ridges indicate that these were (partly) overrun by the glacier.

In a pit in the ice-pushed ridge near Lunteren, till and fluvioglacial sediments were exposed. This till became known as the 'Lunteren flowtill' among earth scientists in the Netherlands. The reason for calling it a flowtill was most probably the peculiar shape of the till bed and its banded appearance.

By studying the till over a couple of years, we were able to demonstrate that the till is actually a basal till. This is based on the following observations:

- the till bed is of a relatively constant thickness throughout the pit.
- elongated clast fabric in the till is consistently oriented NW-SE
- the presence of a continuous shear zone underneath the till, and associated drag structures, sometimes indicating up-slope movement.
- banding of the till is due to differences in incorporated local material; this banding is not a sedimentary stratification but shear banding.
- the till consists of a flint-poor type on top of a flint-rich type, just like many other tills in the Netherlands.

Interpretation of the till as a basal till leads to a better understanding of glacial events in the Central Netherlands.

INTRODUCTION

The morphology of the Central Netherlands is dominated by a series of ice-pushed ridges that were formed during the penultimate or Saalian glaciation. The ridges are predominantly built of preglacial sediments. On account of structural and morphological data Crommelin & Maarleveld (1949) and Maarleveld (1953) could distinguish several phases in the formation of these ridges. Although occasionally ice-pushed glacial sediments are found, no equivalent phasing of glacial deposition has been established up to now. Neither have any indications been found about the significance of, or the length of the periods between the different phases of glacial pushing (Maarleveld, 1981). Till is scarcely found on the flank and on top of the ridges, but in many places residual boulders and boulder pavements are present. It seems that most till material has been removed by solifluction and erosion (Edelman & Maarleveld, 1958). It has been thought for quite some time that the flat highest parts of the ice-pushed ridges are the result of overriding ice. Consequently, it came as quite a surprise when it was found that part of the top of the Goudsberg, E of Lunteren, consisted of thick fluvioglacial deposits (fig. 1C). The Goudsberg is the culmination of the Oud-Reemst ice-pushed ridge, which meets the Ede ridge, E of Lunteren. According to Maarleveld (1981) the Ede ridge belongs to his phase a, whilst the Oud-Reemst ridge belongs to phase b (fig. 1B). Originally two large sandpits were present in the Goudsberg. The E pit showed ice-pushed, mainly preglacial sediments. The W or 'Vink' pit has attracted more interest, but is finished and levelled by now. Over the years the sediments and/or special features from this pit have been described by several authors. The result of a 'Hesemann count' of fennoscandian indicator boulders and the sedimentary sequence were described by Zandstra (1974). He distinguished four units, i.e. from bottom to top: ice-pushed preglacial deposits, lower fluvioglacial deposits, till (Amersfoort and Lunteren type), and upper fluvioglacial deposits. A more detailed description of the fluvioglacial deposits was given by Ruegg (1977) in a paper on so-called sandur deposits. Van der Meer & Semeijn (1981) also gave a description of the sedimentary sequence, but put the emphasis on synsedimentary frost cracks in the upper fluvioglacial deposits. Zandstra (1983) mentions the occurrence of the flint-poor Rhenen till type on top of the Amersfoort + Lunteren type. They differ in fine gravel petrography and heavy mineral content but possibly not with respect to crystalline indicator boulders. The mineralogical composition of what we tentatively consider the lower till, was studied by Riezebos (1983). He showed that the compositional layering (see below) of the lower till is - at least - partly caused by differences in the amount of incorporated local material. In a preliminary report of this study the present authors reached the same conclusion on similar grounds (Van der Meer et al., 1982), and stressed the difference in this respect with the overlying flint-poor upper till (Rhenen type). Rappol (1983) gave some preliminary results, but focussed on the till. Semeijn (1983) gave a description of the fluvioglacial deposits and their areal distribution.

It must be mentioned here that (by composition) two main till types are known from this part of the Central Netherlands: the Rhenen and the Amersfoort type, respectively a flint-poor and a flint-rich type (Zandstra, 1974, 1983). Both types are decalcified and possess a Central-Baltic indicator boulder assemblage. The calcareous counterpart of the Amersfoort type is called the Lunteren type by Zandstra (1974, 1983). The till types also show differences in grain-size distribution, heavy mineral content, and colour.

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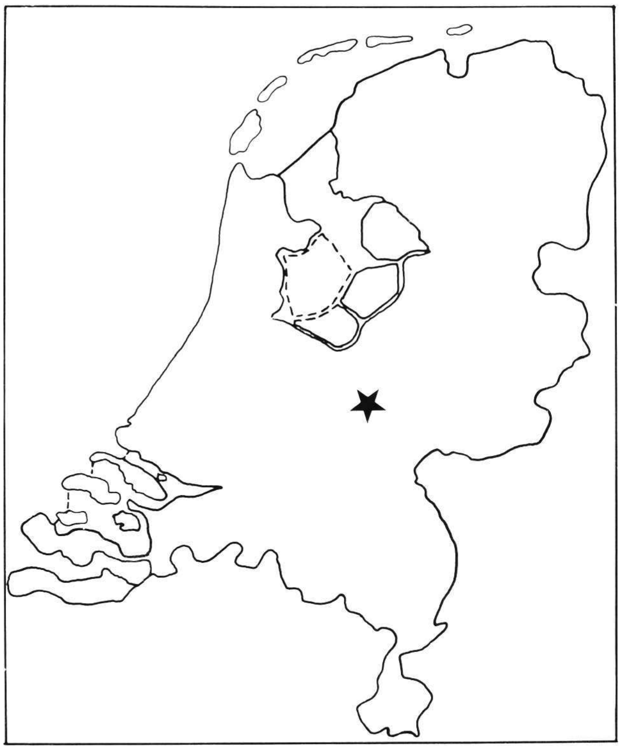

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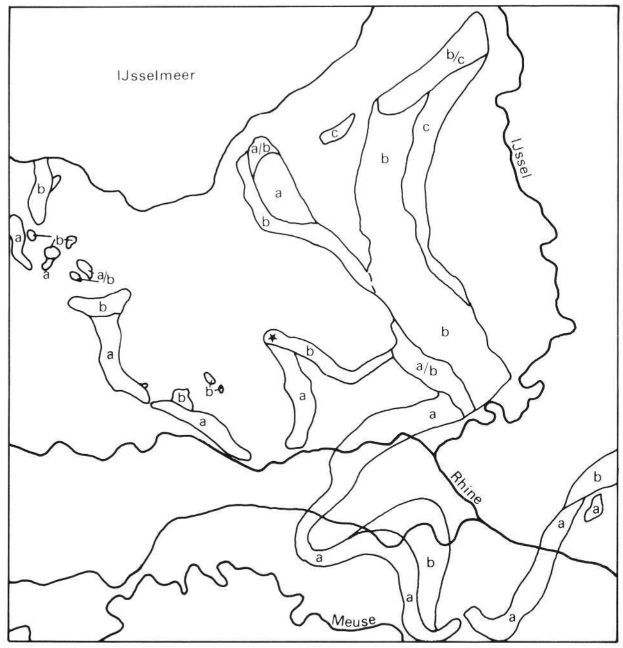

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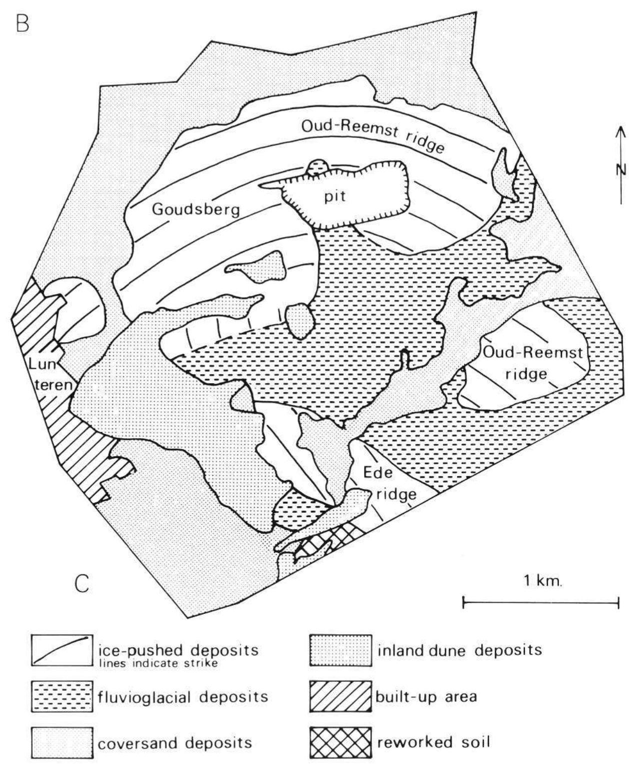


C

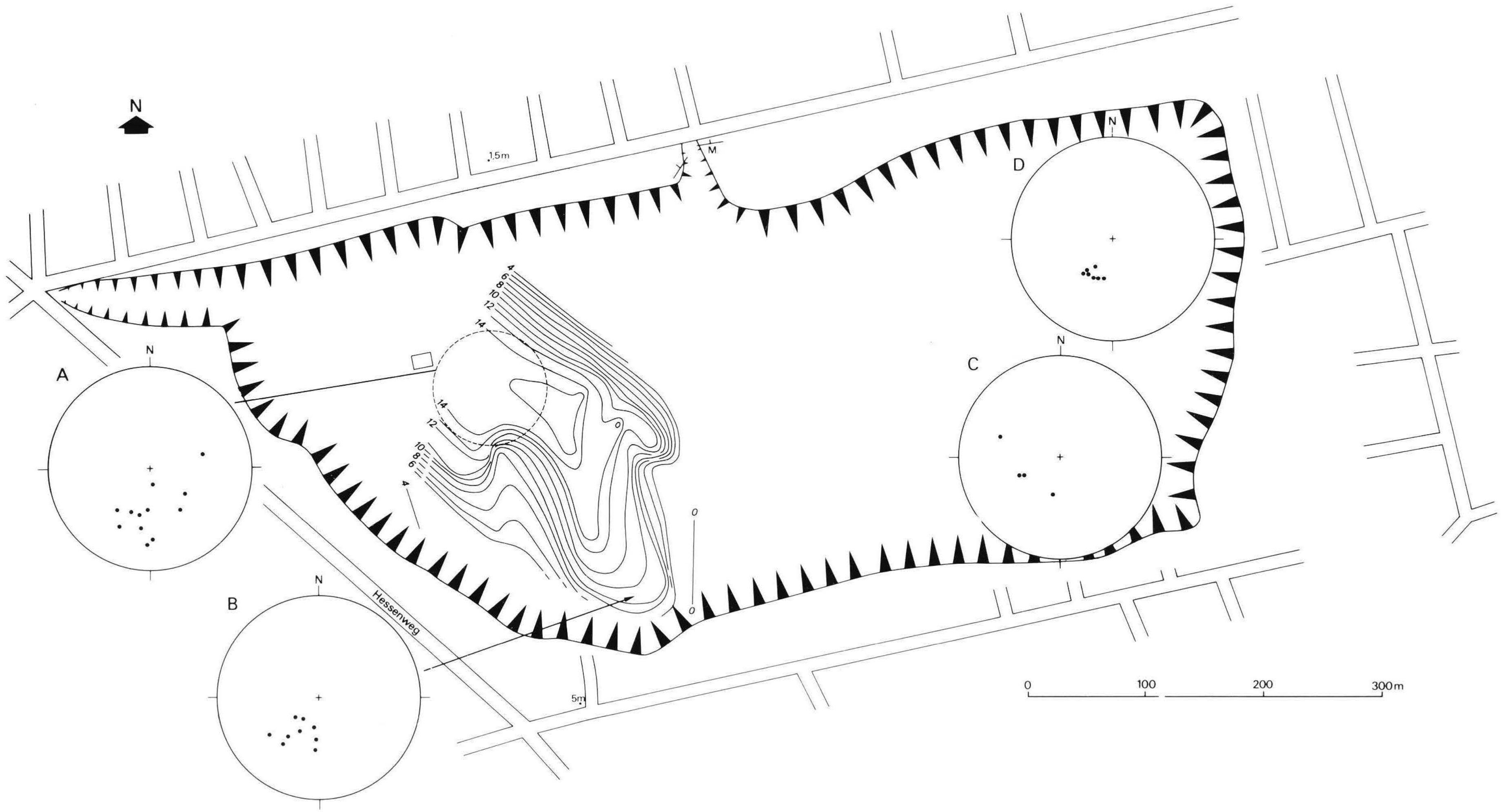
1. A. Location of the Vink pit in The Netherlands
B. Phasing of ice-pushed ridges of the Central Netherlands acc. to Maarleveld (1981). a - oldest, c - youngest phase, asterix indicates Vink pit
C. Simplified map of the surficial geology of the Goudsberg area, acc. to Semeijn (1983).

PURPOSE AND METHODS OF THE INVESTIGATION

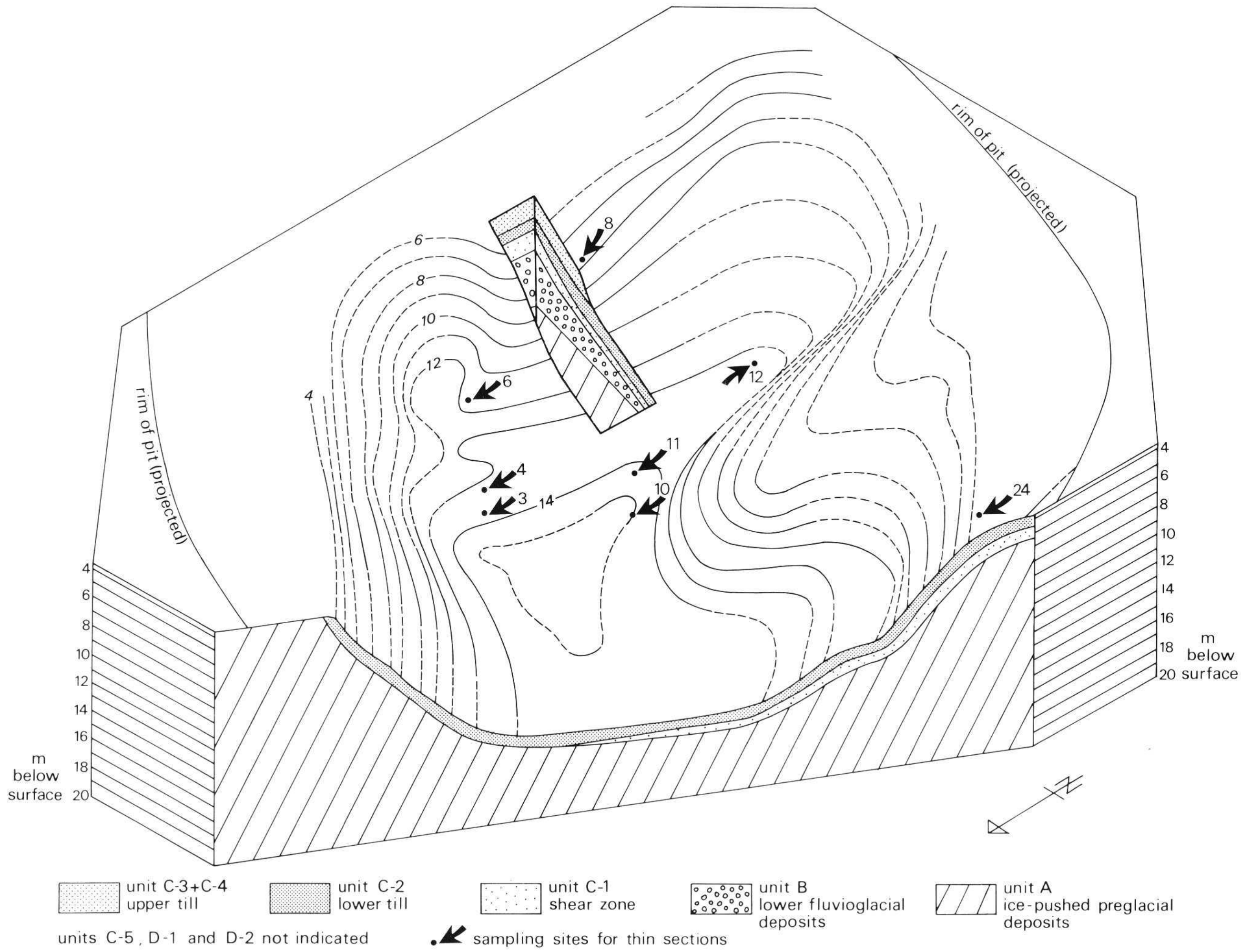
As the genesis of ice-pushed ridges is still one of the main problems in the glacial geology of the Netherlands (Boulton et al, 1984), it is desirable to learn more about the events that shaped them. In order to reconstruct glacial events on the SW Veluwe it was first of all necessary to establish the nature of the Lunteren till. Up to recently this till was known as the 'Lunteren flowtill' among earth scientists in the Netherlands. If it is a flowtill, pushing by ice occurred after its deposition mainly because the till floors a basin with pretty steep slopes and is still almost everywhere of equal thickness. However, if it is a basal till, its deposition occurred subsequent to ice-pushing. Since the layering of the till was one of the main reasons for calling it a flowtill, this layering was studied in detail at a number of sites (see fig. 4).

The till in the pit has been studied by the present authors over a couple of years (1977-1984) as the exploitation of the pit continued.

Twice the exact depth of the upper surface of the till with respect to the rim of the pit was measured by



2. Depth contours of the till bed in the Vink pit (see fig. 3 and 4 for details) and pole to plane plots of: A. C. and D bedding planes in ice-pushed deposits. B - shear planes in presumably fluvioglacial, ice-pushed deposits. Till was also encountered in two auger-holes (1.5 and 5 m) N and S of the pit. Near the entrance of the eastern pit two strike/dip measurements of ice-pushed deposits are indicated (M = acc. to Maarleveld).



3. Block diagram of the till bed in the Vink pit and association with underlying units.

theodolite. Together with further field observations and information provided by the exploiter this gave the possibility to reconstruct the shape of the till body. It forms a basin that has an elongate form with a WNW to ESE long axis which turns to SSE in the E part of the pit. The basin shape is not smooth but shows several indentures, one to the E and one to the S (fig. 2, 3). Directly outside the pit till has been found by augering only twice (fig. 2). To the W of the pit only ice-pushed deposits have been found, indicating that the basin did not extend much further to the W than indicated in fig. 2. This gives a length of at least 300 m for the basin and a width of about 250 m.

To study the deposits the following methods were used:

The surroundings of the pit were mapped in detail with respect to surficial geology and geomorphology (Semeijn, 1983).

In the pit, sedimentary and deformation structures were described in as much detail as possible, and the directional aspects measured. Samples for grain-size and fine-gravel petrographical analyses were collected at a number of sites (fig. 4), while also a number of box samples for mammoth-sized thin sections were taken. At seven localities elongated clast fabric was sampled in the glacigenic units.

Grain-size composition was determined by dry sieving of the sand and gravel fractions at 0.5 and 1 ψ intervals respectively. Clay and silt fractions were determined by pipette method at 1 ψ intervals. Organic material was removed first by a solution of 30 % H_2O_2. Numerical results, together with Folk & Ward (1957) parameters are given in Appendix III.

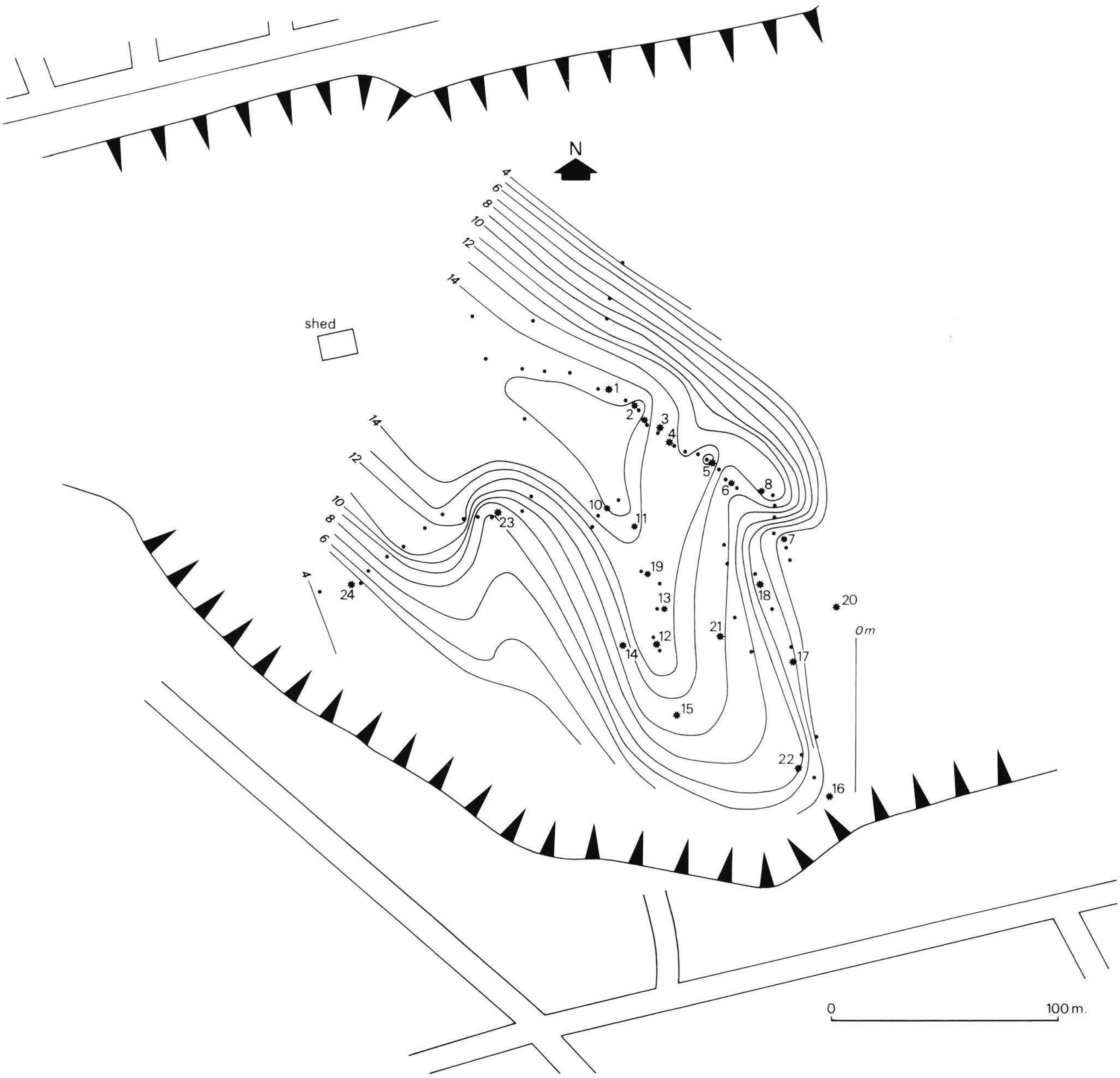
Gravel petrography was studied by methods described by Maarleveld (1956) and Zandstra (1959, 1978).

Elongated clast fabric was sampled by measuring orientation and dip of the long axis of 40 elongated clasts with an a/b axis ratio of at least 1.4.

Heavy minerals have been separated by use of bromophorm (s.g. 2.89) for the fraction 2-3 ψ. Composition was established by the determination of 300 grains in each slide.

SEDIMENTOLOGY OF THE LITHOSTRATIGRAPHIC UNITS

Over the years the ideas on the lithostratigraphy of the pit varied only a little. Zandstra (1974) recognised four different units, the till of which was divided into two types, the flint-rich Amersfoort type and its cal-

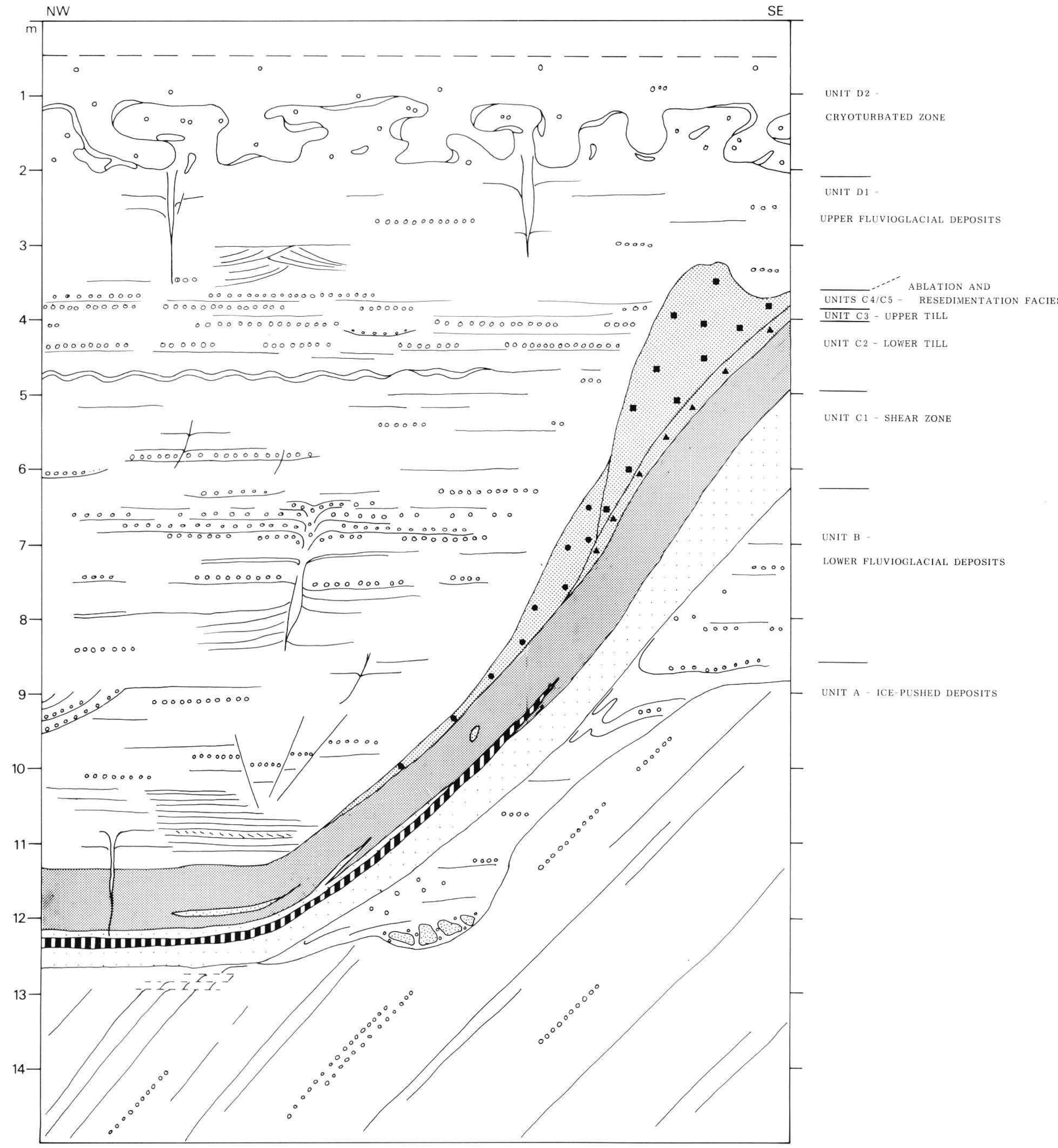


4. Observation sites plotted in the contour map of the till bed. Dots denote theodolite stations on which the contouring is (partly) based.

careous counterpart, the Lunteren type, while later the flint-poor Rhenen type was recognised (Zandstra, 1983). Ruegg (1977) mentions the same four units, and states that the (upper) fluvioglacial unit contains at least three angular unconformities due to syngenetic glacial pushing. Van der Meer & Semeijn (1981) added one more unit overlying the upper fluvioglacial deposits. They also mention two till beds, while in the upper fluvioglacial deposits three subunits were recognised. After further study by Van der Meer et al. (1982) the number of units was reduced again to four, the upper unit only being regarded as a subunit of the upper fluvioglacial deposits. The till unit was further subdivided into five subunits, because different facies of the upper till had been recognised and because underneath the lower till a shear zone had been observed. Here the same subdivision will be maintained (fig. 5). The sedimentary structures, granulometry and sedimentary petrography of the different units and subunits will be described in detail. Only the micromorphological observations will be treated in a separate section.

UNIT A: ICE-PUSHED FLUVIATILE DEPOSITS

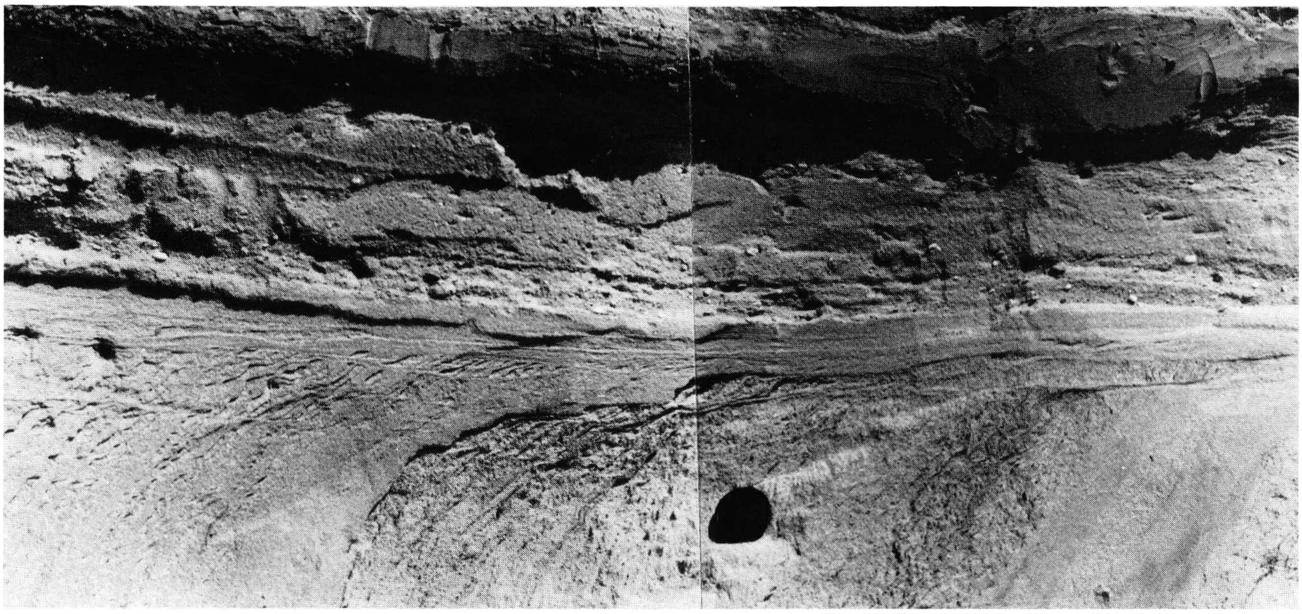
Sediments exposed in the deeper part of the pit consist of fluviatile, mainly sandy, deposits. These are predominantly cross-bedded, and according to Zandstra (1974) it concerns Middle Pleistocene Rhine deposits belonging to the Urk Formation. Due to ice-pushing during the Saalian the beds are found in an inclined position. Some beds have been preserved fairly intact, while others are more or less brecciated.



5. Schematic lithostratigraphy of the Vink pit.

Although no systematic structural study has been made, it is clear from a number of measurements that the direction in which pressure was exerted varied between S and W (fig. 2).

In the SE part of the Vink pit, around site 16, ice-pushed sediments with a sedimentary structure strongly resembling the fluvioglacial deposits, were exposed. In colour they differed from the lower fluvioglacial deposits however (brown and white resp.). It concerned parallel-bedded sands and fine gravel deposits (sheet flood deposits), dissected intensively by NE dipping low-angle thrust faults (fig. 2) and associated high-angle reverse faults. At site 16 these were directly and discordantly overlain by the glacigenic units C1 and C2. According to Ruegg (pers. comm., and mentioned in Ruegg, 1983), fluvioglacial sediments are thrust up together with the preglacial sediments and constitute the uppermost stratigraphic unit of these, in the E pit at Lunteren. In the ice-pushed sediments of the Vink pit no fennoscandian components have been found, but because of the sediment-structural pattern these sediments may be interpreted



6. Low-angle shear planes in ice-pushed preglacial deposits associated with unit C-1. In the upper part of unit C-1 the rhythmites are visible (site 10). Orientation N-S.

as of fluvioglacial origin (Ruegg, 1983).

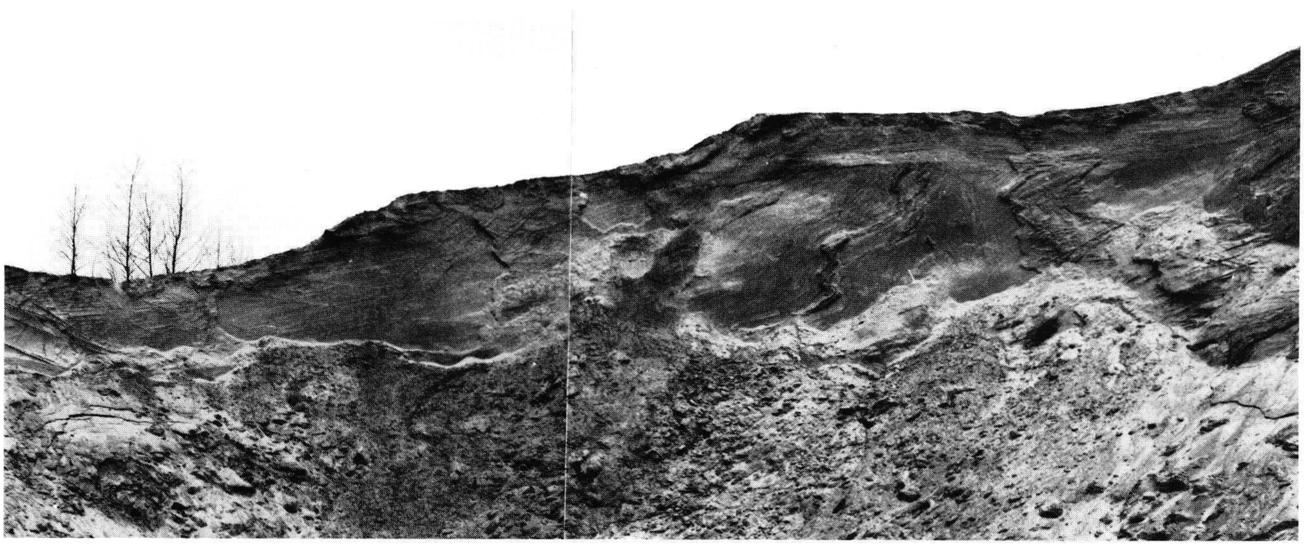
The upper part of unit A sometimes shows deformation structures, like recumbent folds and low-angle shear planes (fig. 6) which are thought to have been caused by sub-glacial shearing.

Petrographically the fine gravel consists predominantly of quartz (around 60 %, see Appendix I) and sedimentary rest (± 40 %). The coarser gravel fractions contain a considerable amount of flint particles (see Appendix I). These flints generally are characterised by well-rounded edges and a brown colour. They are of a southern provenance. Because of the variability in grain-size only some samples for granulometric analysis have been collected (see Appendix IV).

UNIT B: LOWER FLUVIOGLACIAL DEPOSITS

This unit mainly consists of white sandy-gravelly, parallel and thinly bedded deposits, which discordantly overly the ice-pushed sediments (fig. 7). Within the gravel fennoscandian components are occasionally found (see Appendix I) Bedding characteristics are indicative of deposition by sheet flood as described by Augustinus & Riezebos (1971) and Ruegg (1977). Cross-bedded units and gullies have hardly been observed, and no reliable general direction of streamflow could be derived.

Part of this unit (site 23) has been deposited in standing water. The latter consists of an alternation of up to several cms thick sand and clay lenses. The clay



7. Unit B: parallel bedded lower fluvioglacial deposits (for right), discordantly overlying ice-pushed preglacial deposits (near site 7); orientation is NE-SW.

8. Gully-filling consisting of poorly sorted gravelly sand with a high concentration of unconsolidated sand clasts. Base of unit B as exposed between sites 4 and 5.

lenses are thought to have been deposited in shallow pools. Water-escape structures disrupt the original bedding.

Near site 3 a several metres wide and about one metre deep channel with a channel-lag deposit was observed. The lag deposit occasionally contained crystalline blocks of fennoscandian origin (maximum diameter about 15 cm) and a number of large rounded and angular sand blocks (diameter over 50 cm: fig. 8). The latter must have been transported in a frozen state, thus preserving their internal structure. Ice-cemented sand-blocks have been described from a number of localities in the Netherlands (Maarleveld, 1962; Augustinus & Riezebos, 1971; Ruegg, 1977). The poorly sorted sediment around the boulders suggest transport and deposition by sediment flow as described by Postma et al. (1983).

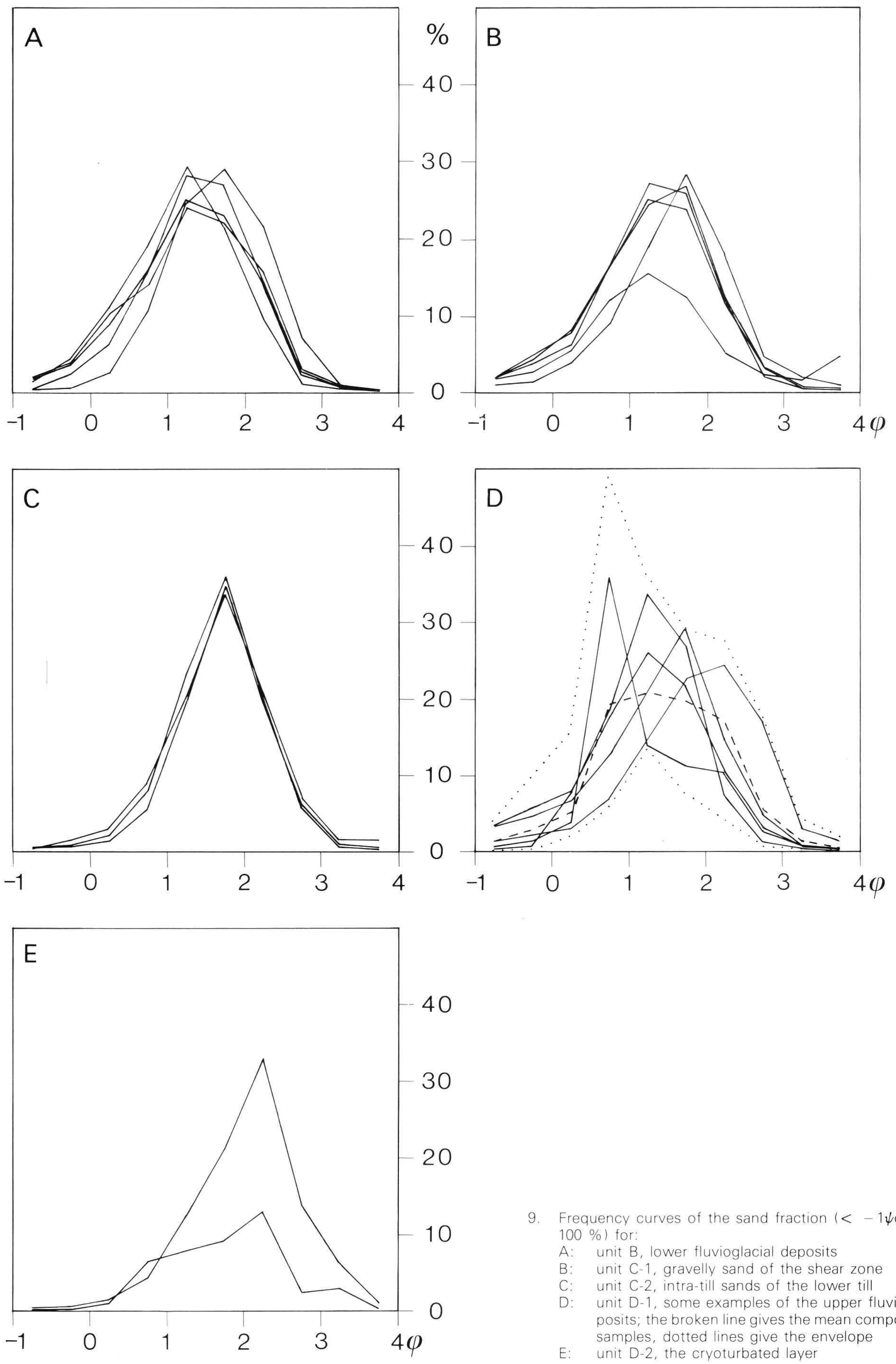
This unit is not present throughout the pit. In the W it was virtually absent while to the E it reached thicknesses of over 5 metres. Everywhere the lower fluvioglacial deposits were uncomformably overlying the ice-pushed deposits. Partly they have been found in an inclined position, which is interpreted as being the result of sub-glacial deformation of Units A and B. Sub-glacial deformation is also indicated by the shear phenomena in the top of the ice-pushed deposits as mentioned above.

The grain-size distribution of a number of samples collected from the parallel-bedded deposits of this unit is presented in fig. 9A. All samples show a distinct mode between 1 and 2 ϕ. Fine gravel petrography is characterised by the same components as the ice-pushed deposits (Appendix I), although occasional fennoscandian components are found, among which the boulders mentioned above.

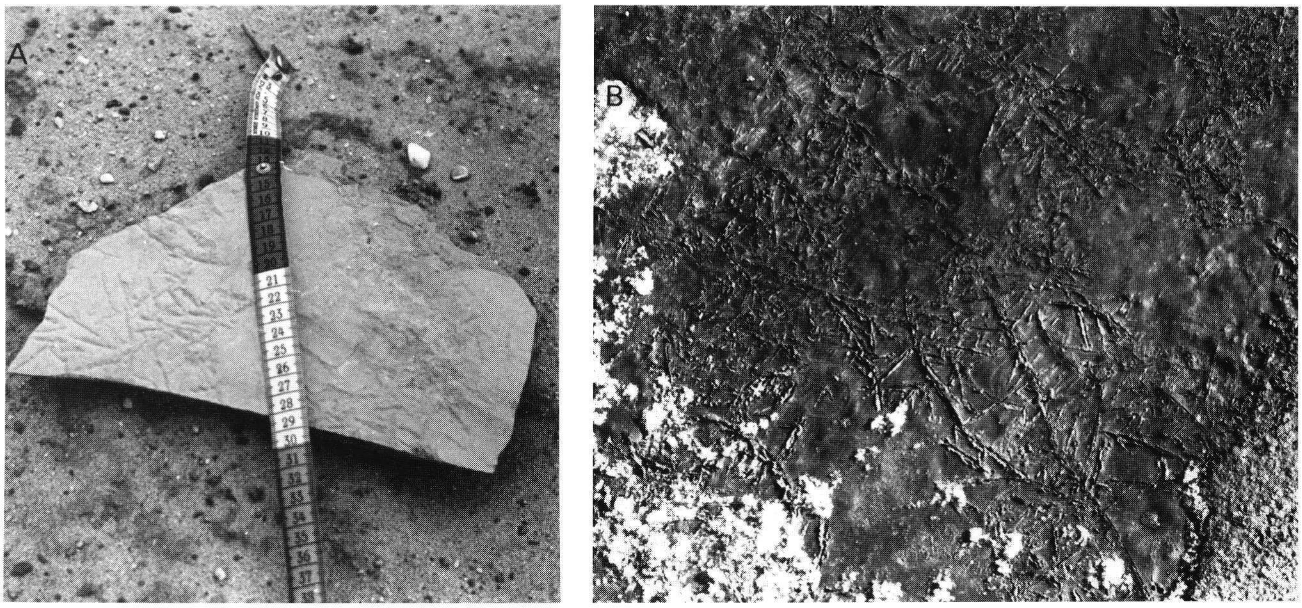
UNIT C-1: SHEAR ZONE BELOW TILL

A massive to faintly banded gravelly sand layer overlies the lower fluvioglacial deposits or, if these are absent, the ice-pushed deposits. It forms a layer, up to 1.5 m thick, parallel to the lower boundary of the till (fig. 5), and is thus related to the formation of the till. At its base, the underlying sediments are commonly deformed. These deformation structures include low-angle shear planes (fig. 6), recumbent folds, and other drag structures, which generally indicate dislocation in a SE direction. This is also roughly the direction indicated by a sample of elongated clast fabric (fig. 18).

This layer is interpreted as the basal shear zone associated with the till. The deformation structures are typically those formed as a result of subglacial shear. Because some of the deformation structures are directed in an up-slope direction, an origin of this layer as a result of sediment gravity flow can be excluded. Almost everywhere the boundary between this zone and the underlying sediment is sharp. The layer represents a zone of penetratively deformed pre-existing sediment, analogous to Banham's (1977) zone C of penetratively sheared sediment. In some classification



9. Frequency curves of the sand fraction (< −1φ or 2 mm = 100 %) for:
A: unit B, lower fluvioglacial deposits
B: unit C-1, gravelly sand of the shear zone
C: unit C-2, intra-till sands of the lower till
D: unit D-1, some examples of the upper fluvioglacial deposits; the broken line gives the mean composition of 18 samples, dotted lines give the envelope
E: unit D-2, the cryoturbated layer

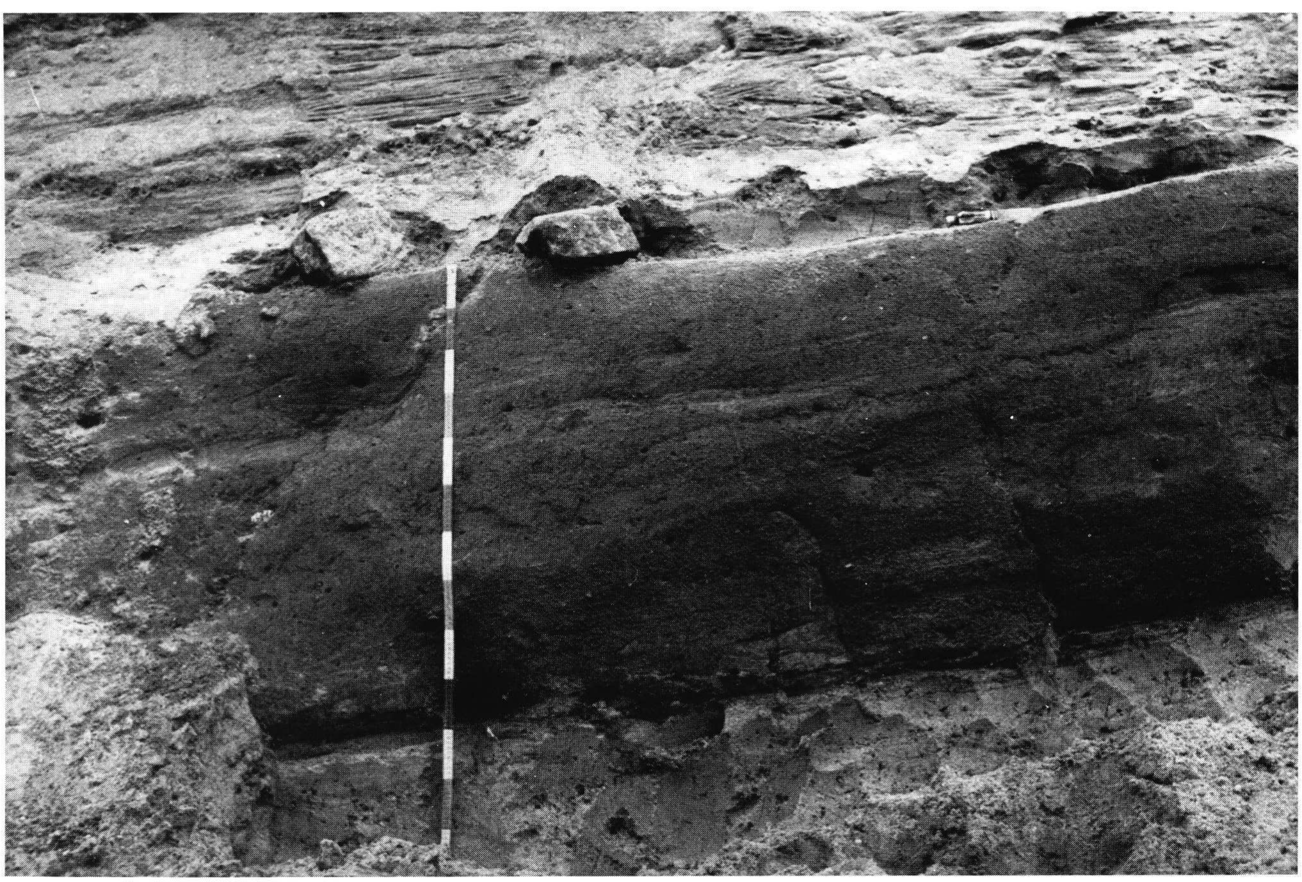


10 A. Fossil ice-needle casts in rhythmites of unit C-1 (near site 10)

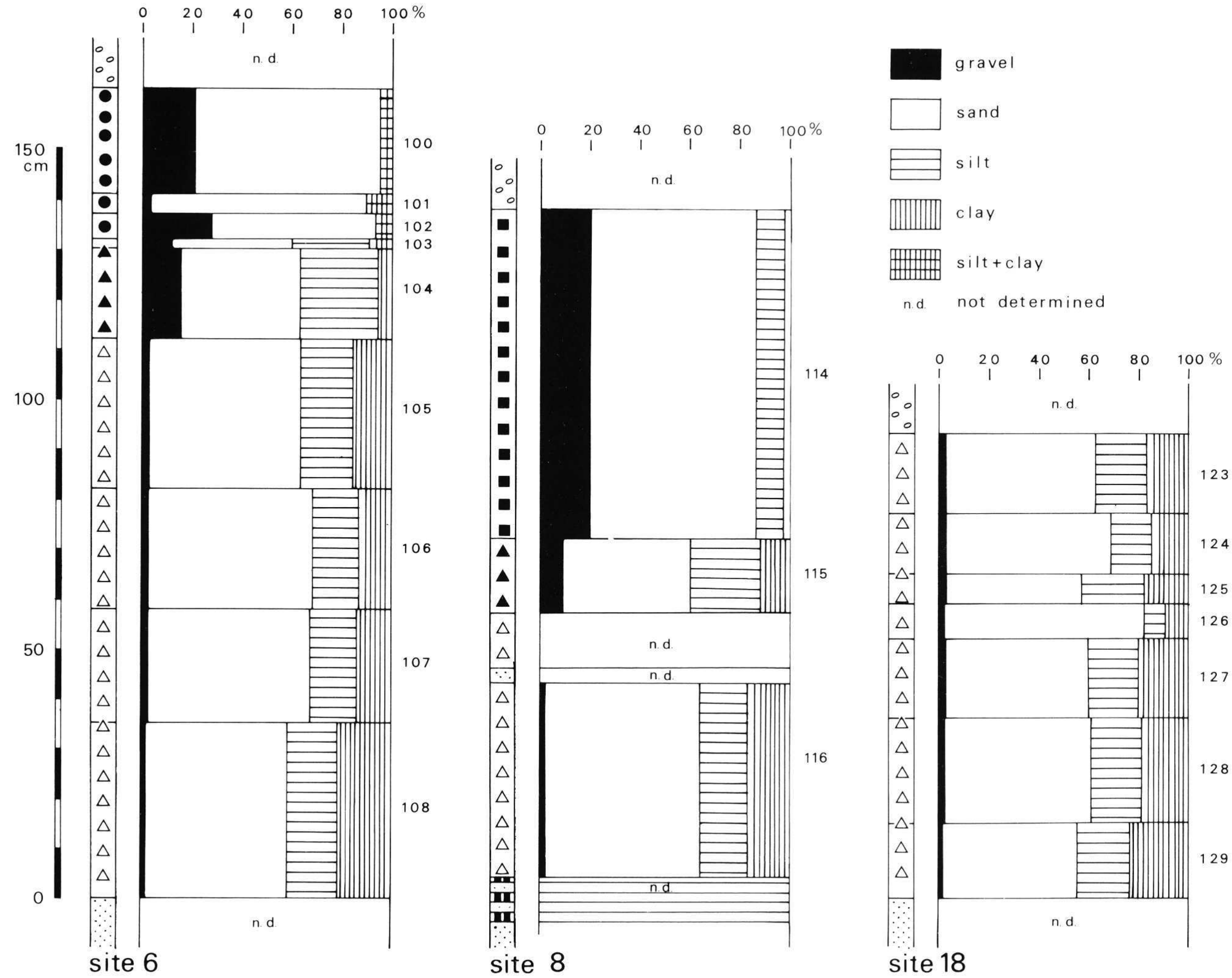
B. Recent ice-needle casts in puddle, observed in February 1981. Scale of B about the same as A.

schemes this might be called a "deformation till", (e.g. Boulton 1980): in almost all of its aspects, with the exception of its compositional characteristics, it is a till.

In the central part of the pit where this layer occurs at the greatest depth, silt/clay rhythmites are often present in its upper part. This layer of rhythmites reaches a maximum thickness of about 15 cm, and is



11. Lower till at site 18. The banding of the till clearly stands out. A frost crack cuts the till obliquely. Division of scale in dm (see also figs. 12 and 26). Note residual boulders at the till surface.



12A. Recorded lithology at a number of sites. Note the variable position of rhythmites and sand layers. Boundaries between sampled units based on differences in colour and/or texture.

also present under the steeper slopes of the till basin. Rhythmites have been observed (fig. 12A, B) in the upper part of the massive bed, directly at the base of the till, within the till and even in a doubled position. Sometimes they are disrupted and partly incorporated in the lower till. Generally, the rhythmites are well preserved, although the lower and/or upper boundary is often strongly deformed.

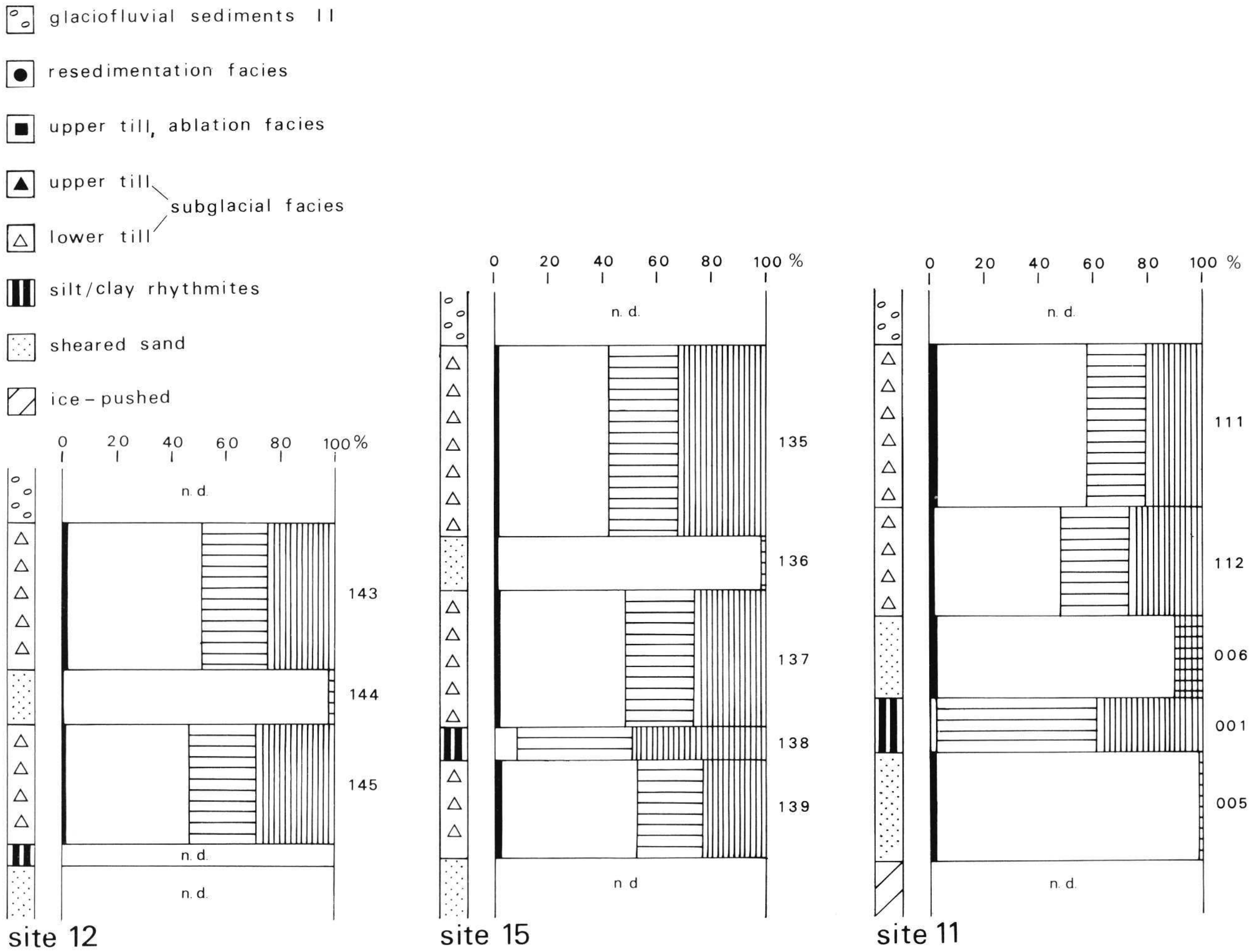
They were later dislocated by the glacier and incorporated in the shear zone. They may have been transported over quite a distance. The fact that in the pit they were mainly found underneath the lower part of the till basin, cannot be seen as evidence that they were deposited there. This is contradicted by their incorporation in the shear zone as well as by their occurrence under and parallel to steeply dipping parts of the till bed.

Within the rhythmites ice-needle casts have been observed a number of times (fig. 10A). These casts form sub-aerially on wet clay surfaces. During the investigation ice-needles and their casts were actually observed on thin clay drapes in shallow pools as well as on clayey till surfaces. These needles quickly melted when exposed to the sun, but leaving casts on the clay drapes only (fig. 10B). In the case of the fossil ice-needle casts these must have formed in shallow depressions in front of the advancing glacier. The depressions must have been filled regularly, each time loosing their water through drainage.

With respect to grain-size and sediment petrography, this unit resembles both units A and B (Appendix I). Comparison of figures 9A and 9B clearly shows that granulometrically unit C-1 cannot be separated from unit B, all samples also have their mode between 1 and 2 ψ. In the fine-gravel fraction occasional fennoscandian components are present, most probably these derive from unit B.

UNIT C-2: THE LOWER TILL

With a generally sharp transition, unit C-1 is overlain by a predominantly sandy diamicton, which, on account of its superposition on unit C-1, and characteristics to be discussed below, is interpreted as a till of subglacial origin. Granulometrically and petrographically, this subglacial till can be subdivided into two units (figs. 12, 13; Appendix III), an upper flint-poor till (F/C ratio 0.00-0.02) and a lower till comparatively rich in flints (F/C ratio 0.07-0.29).



12B. For explanation see Fig. 12A.

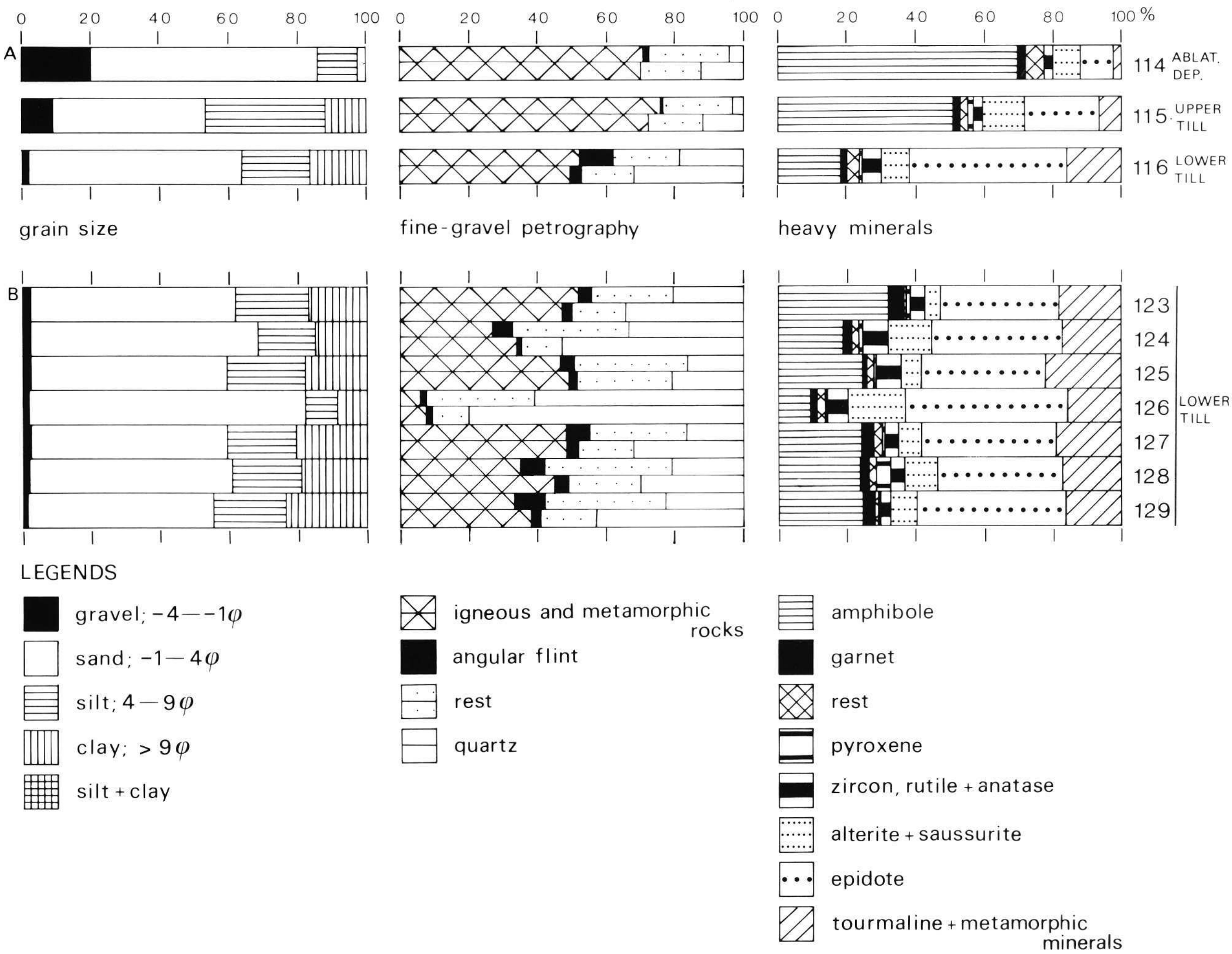
Throughout the pit the lower till has a relatively constant thickness between 0.5 and 1 m. Its characteristic compositional layering (fig. 11) shows in the field through differences in colour. This layering reflects differences in grain-size and petrographic composition (fig. 13). It is the result to differences in the amount of preglacial and/or fluvioglacial material incorporated in the layers by subglacial shear deformation. Clayey layers (over 30 % clay) are present that contain much material derived from the silt/clay rhythmites. This fine-grained material is mainly present in the form of small, rounded pebbles of silt and clay (up to several mm) in a more sandy matrix. These pebbles can easily be discerned in the field. Other layers may consist predominantly of sand and show a corresponding high amount of quartz grains in the fine gravel fraction (fig. 13, Appendix III). Especially near the base the till may also contain layers of clay or sorted sand, hardly contaminated with glacially supplied debris.

Stones are rather sparse in the lower till, and when present, occur mainly in the upper part. The largest stones observed *in situ* were slightly over 20 cm, although several larger stones were spread around in the pit. Most stones were seen to be concentrated on top of the till. These are interpreted as the resedimentation facies of the upper till however (see below). At one site a rounded clast of unconsolidated sand was observed.

As mentioned above, the till is associated with deformation structures (fig. 17) which are characteristic for subglacial shear deformation e.g. dragfolds. At site 4 (fig. 14) subhorizontal shear-planes were observed, these indicate glacier movement towards the SE. This is conform the orientation of elongated clasts (Rappol, 1982, 1983). At four sites the elongated clast fabric was determined (fig. 18). These are in good agreement, all pointing in a NW-SE direction, which together with the other evidence, indicates glacier movement towards the SE. Another example of this, a combination of faulting and folding affected both till beds (fig. 15). A number of times high-angle faults were observed. These are interpreted as being due to gravitational forces (fig. 16).

At site 10 several small flute-like forms were observed at the surface of the till. These were about 10 cm high and about double in width. In one of these an about 10 cm long stone was observed. Orientation of the flutes was NW to SE.

Some sites were sampled for grain-size analysis and fine gravel and heavy mineral composition. Because Zandstra (1974) mentioned the occurrence of calcareous till (his Lunteren till type) some ten samples were taken from the base of the till throughout



13. Compositional characteristics of two profiles: A - site 8, B - site 18 (see also fig. 12A). For the fine gravel analysis the upper part of the bars gives the composition of the 3-5 mm, the lower part that of the 2-3 mm fraction.

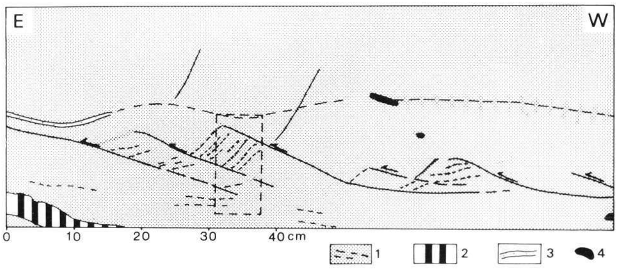
the pit. The calcareous till must have had a limited extension, as no carbonates were detected in the laboratory. One limestone particle was detected in one of the samples (no. 126)

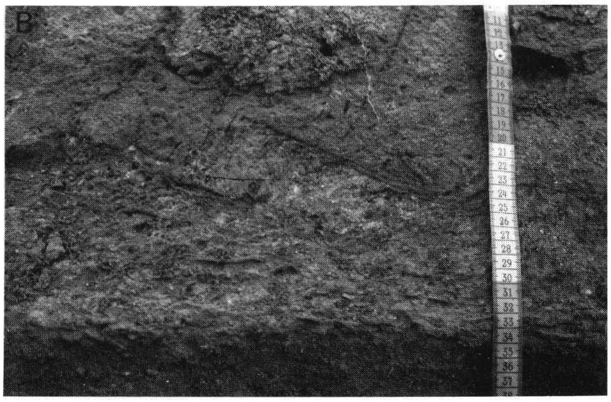
Fig. 13 shows the strong relation between the various compositional elements, e.g. sandy layers (samples 124 and 126) contain a high amount of quartz in the fine gravel fraction and a comparatively low amphibole and high epidote amount in the heavy mineral fraction. A high amphibole content is a characteristic feature of upper flint-poor tills in the Netherlands (Zandstra, 1983; Rappol & Stoltenberg, 1985), indicating relatively pure erratic material. With increasingly more local material being incorporated in the till, amphibole content tends to decrease while epidotes and metamorphic and stable minerals tend to become more important (see also Riezebos, 1983). Likewise, quartz content in the fine gravel fraction can be taken as an indication of the amount of local material present in the till.

A simple relation between quartz content and sandiness of the till at Lunteren is obscured through the incorporation of clayey and silty material from the silt/clay rhythmites in part of the till. At sites 12 and 14/15 the lower till contains a band of well-sorted sand (see fig. 12), of relatively uniform thickness (around 10 cm), showing a laminar structure which is interpreted to be the results of shearing (fig. 19). Grainsize composition of this sand layer differs from that of the sub-till shear-zone by a uniform and well-sorted composition (fig. 9C) and a modal fraction of 1.5-2 ψ.

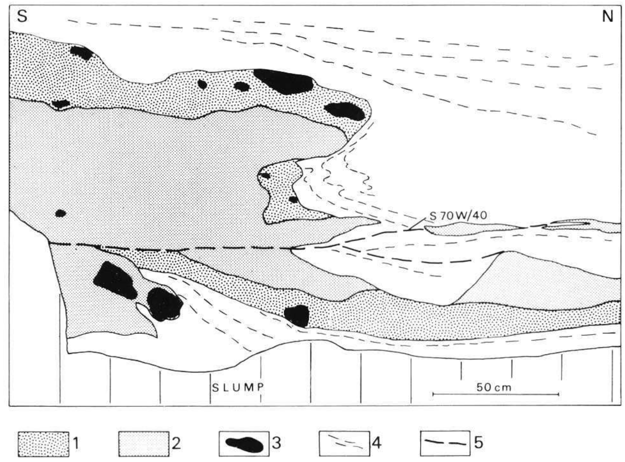
Fig. 20 gives the mean composition and standard deviation for 27 lower till samples. The modal fraction of 2-3 ψ is a characteristic feature of most till deposits of the Netherlands, and seems to be a characteristic of the glacial and erratic debris of the tills (Rappol, 1983). The large standard deviation in the fraction 1-2 ψ is characteristic for the till at Lunteren, and results from sandy till bands with the modal fraction shifted towards coarser sand fractions. Till bands containing the highest percentage of sand have modal fractions between 1.5-2 ψ, and a similar distribution as the intra-till sand layer. This coincidence strongly suggests a local origin for the excess of sand in these layers.

The influence of the amount of local material on the grain-size characteristics of the till layers is also well illustrated by the plot of mean size against inclusive graphic standard deviation (fig. 21). It shows a strong

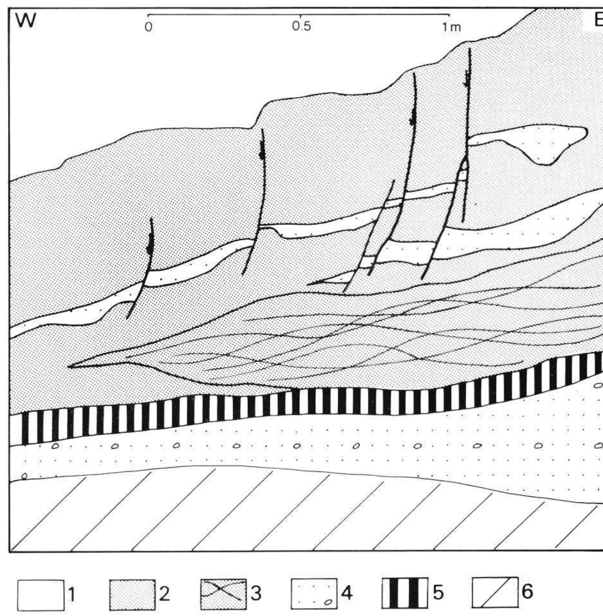




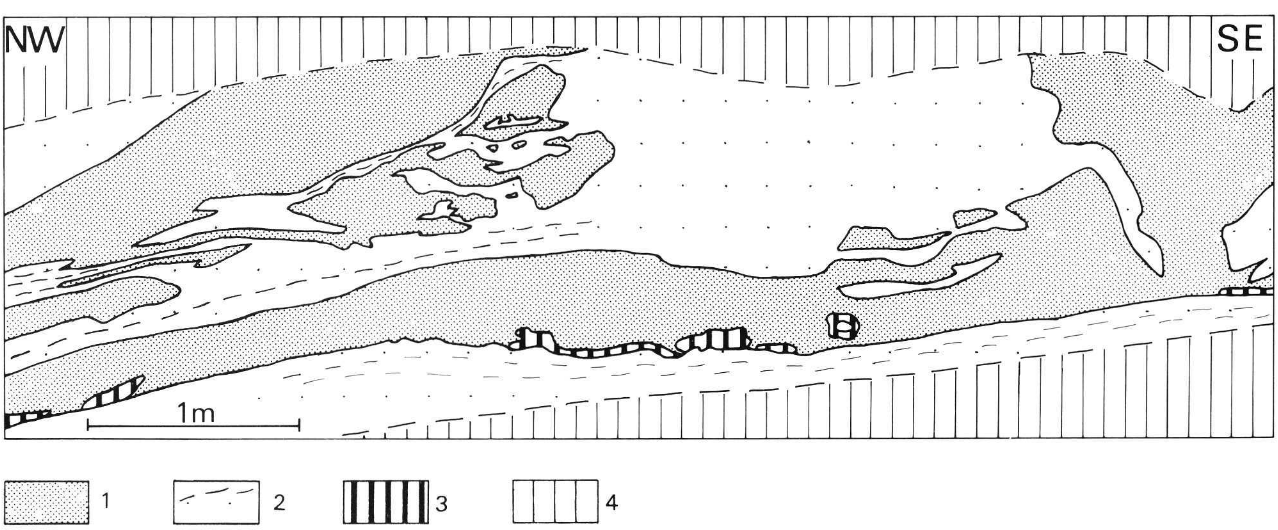
14. A. Low-angle shear planes in the basal part of the lower till (site 4, rectangle indicates fig. 28).
1 - lower till with lineations, 2 - rhythmites, 3 - sandy parting, 4 - clasts.
High-angle features in central part are joints.
B. Detail of central part.



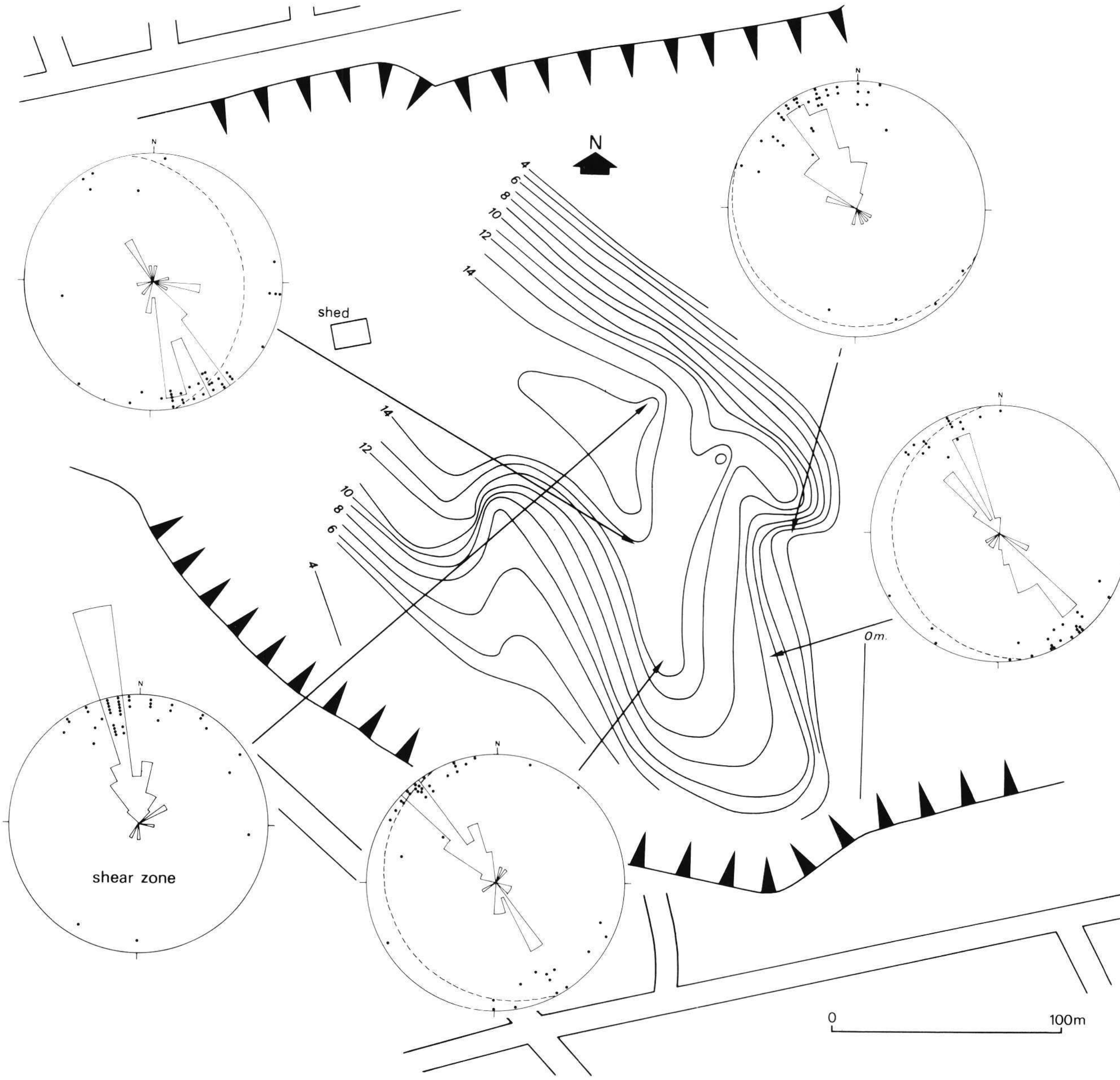
15. Deformation of both upper and lower till, involving shear faulting and recumbent folding. 1 - upper till, 2 - lower till, 3 - clasts, 4 - sand with bedding structures, 5 - faults.



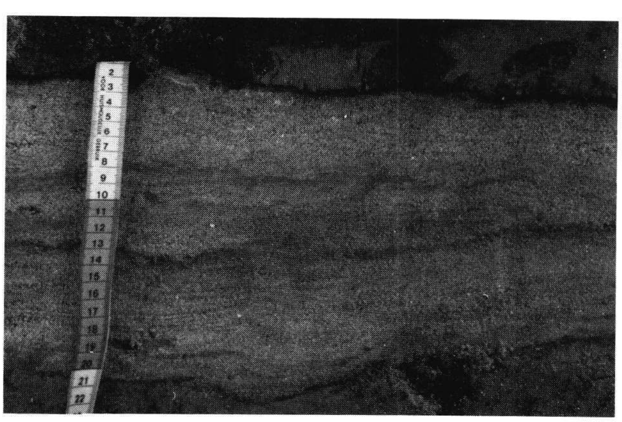
16. High-angle, slightly concave normal faults in lower till. Note that the faults do not continue through the base of the till and the layer of rhythmites. 1 - upper fluvioglacial deposits, 2 - lower till, 3 - lower till with sand lenses and partings, 4 - sheared sand, 5 - rhythmites, 6 - ice-pushed sediments (near site 19).



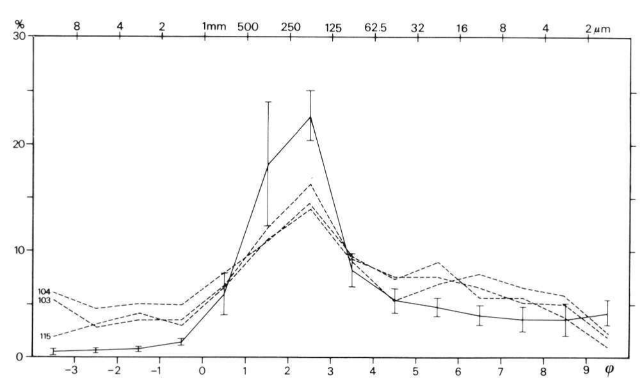
17. Deformation pattern of till and intra-till sand at site 13.
1 - lower till, 2 - sheared sand with lineations 3 - rhythmites, 4 - obscured.



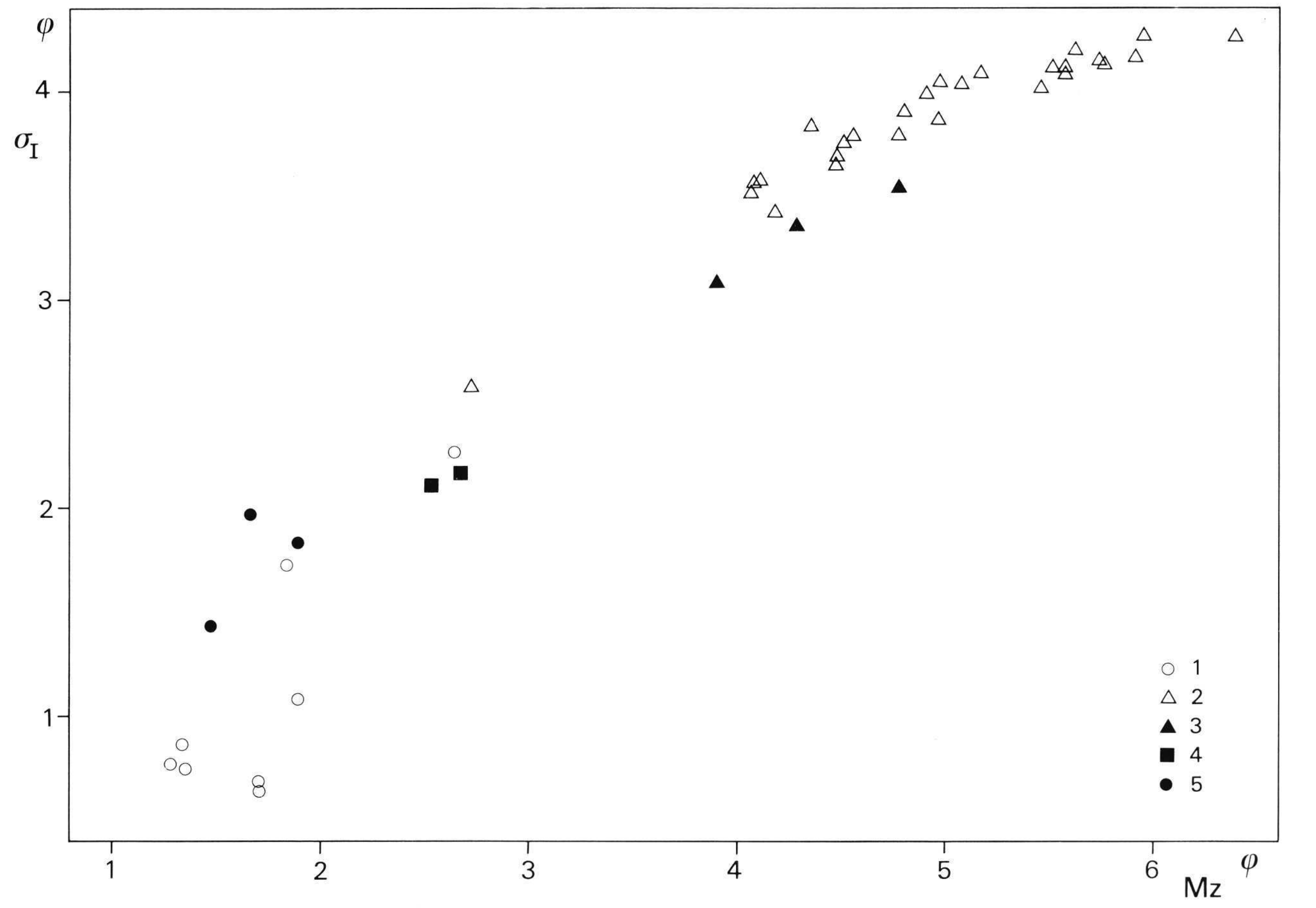
18. Elongated clast fabrics for the shear zone and the lower till. Broken lines give the dip of the site's till bed, circle represent 9 clasts. Note the correspondence between fabric orientation and till bed morphology.



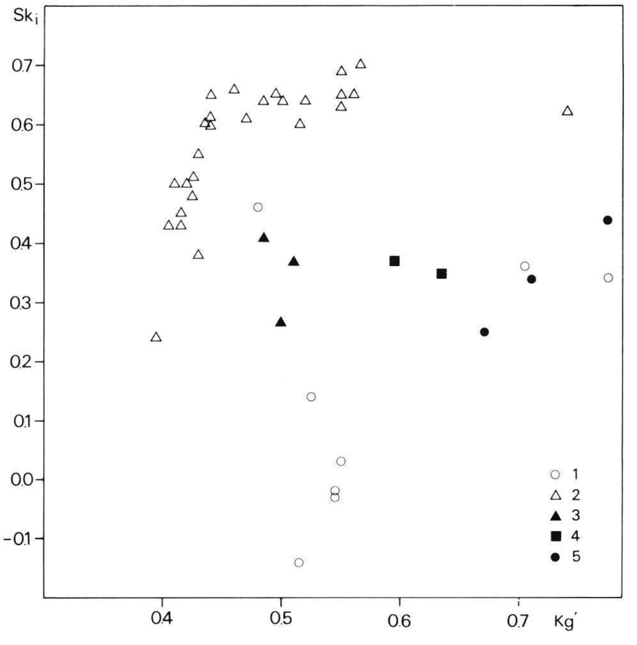
19. Parallel laminated intra-till sand layer of the lower till (near site 13).



20. Frequency curve of the mean grain size (per 1 ψ interval) with standard deviation (vertical bars) for 27 samples of the lower till. Broken lines give frequency curves for upper (basal) till samples.



21. Plot of mean size (M_Z) against inclusive graphic standard deviation (σ_I) for 1. intra-till and sub-till sheared sand, 2. lower till, 3. upper till, subglacial facies, 4. upper till, ablation facies, 5. upper till, resedimentation facies.



22. Plot of normalised graphic kurtosos (Kg^1) against inclusive graphic skewness (Sk_I). Legend as in fig. 21.

relation between mean size and sorting, where better sorting is accompanied by an increasing mean grain-size, and thereby an increasing amount of local material incorporated in the till.

The petrographic composition of the fine gravel (3-5 mm) fraction of the till bands is as variable as their grain-size composition (Appendix III). Flint particles in the gravel fraction of unit C-2 are characteristically very angular in which they differ with those from unit A. They are of fennoscandian provenance. Sandy layers contain large amounts of quartz grains, again suggesting that this variability in composition is mainly caused by the incorporation of local material.

UNIT C-3: THE UPPER TILL

In the eastern part of the pit a more stony till bed of more reddish colour overlies the lower till (fig. 12). Besides these obvious differences there are differences in grain-size and petrographic composition (see below). Because of its limited extent and bad exposure no elongated clast fabric could be determined in this till. As mentioned above, subglacial deformation of both the upper till and the lower till showed in only one locality (fig. 15).

It should be noted that Zandstra (1983: p. 373) sta-

23. Lower till overlain by blocky ablation facies of upper till, in turn overlain by the upper fluvioglacial deposits. Note the relief of the ablation deposits. Division of scale in dm.

tes that: 'The till (...) is composed of two beds, separated by boulders or gravelly sand'. This might refer to a section as illustrated in fig. 25, where we interpret a subglacial till overlain by an erosive lag and debris-flow layers. Our upper till is directly overlying the lower till, and both are interpreted as of subglacial origin.

Only a few samples of the upper till could be collected. With respect to grain-size composition, the upper till differs from the lower till by containing more gravel and silt, and less sand and clay. On a log-probability plot cumulative frequency curves of upper till samples are almost perfect straight lines, while the lower till samples would be S-shaped. Unlike the plot of Mz against σ_i, the plot of Sk_i against Kg' gives a good separation of the till types (fig. 22).

Petrographically, the upper till is characterised by the absence of flint, a hight amount of crystalline components, and a high amount of amphibole in the heavy mineral fraction. These are characteristic for Zandstra's (1983) Rhenen till type.

It should be mentioned that texturally unit 3 of Riezebos (1983) belongs to the lower till, and probably also with respect to fine gravel composition. Mineralogically however, this unit resembles more the upper till. It must be considered that possibly no sharp transition exists between the two till types; if formed under conditions of continuous ice cover and sedimentation, till bands of a transitional composition can rather be expected.

UNIT C-4: THE UPPER TILL, ABLATION FACIES

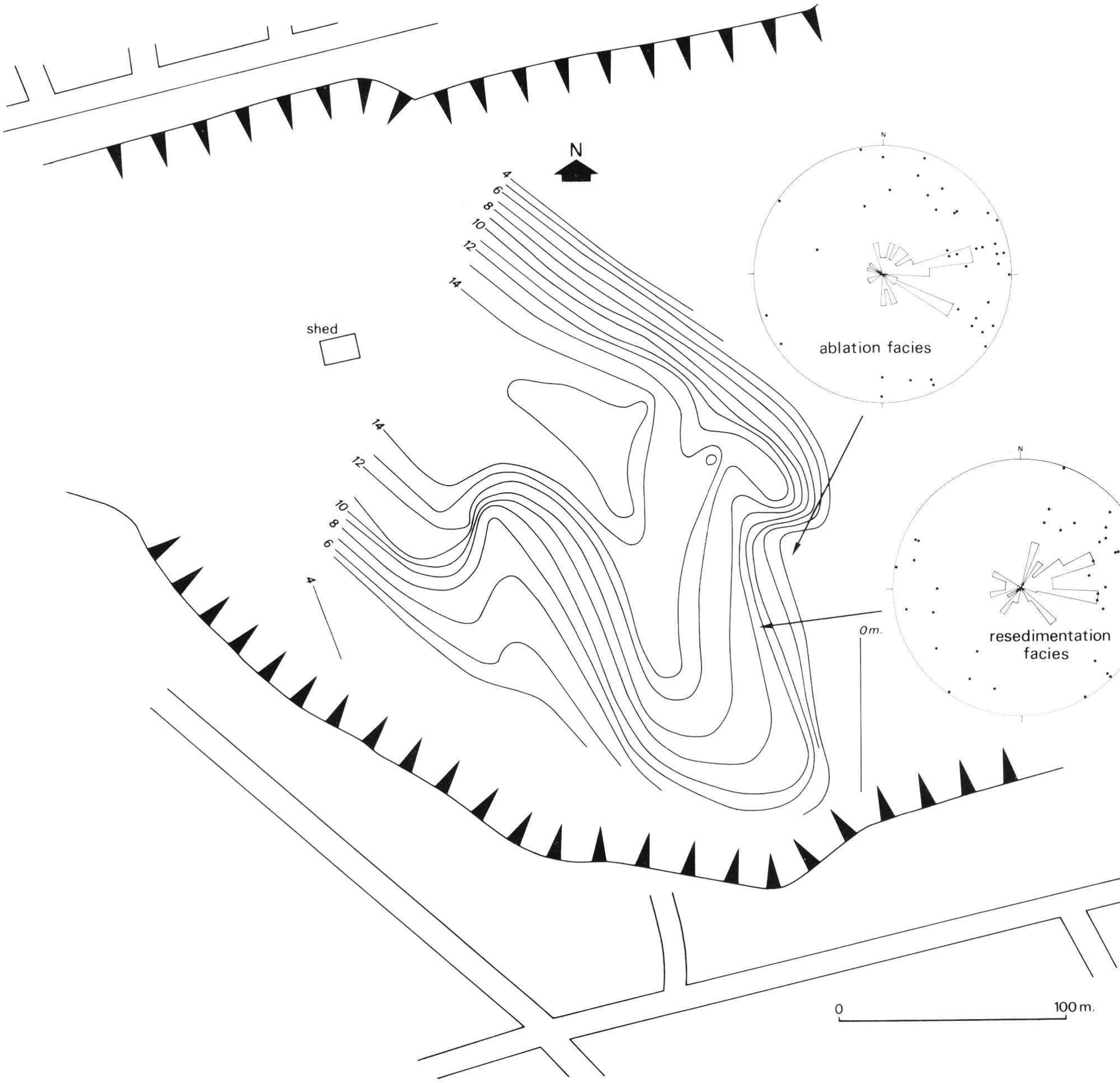
Close to the surface in the NW part of the pit, an up to 1 m thick bouldery deposit occurs (fig. 23), which directly overlies the till. Contrary to both till beds this is a clast-supported deposit. Petrographically however, it is similar to the upper till. Boulders are in general much larger than those in both the upper and lower till beds. Besides, they are predominantly imbricated in a N tot W direction. At one locality clast fabric was determined (fig. 24). This shows a much more variable orientation and higher dip values than the fabrics from the lower till. Nevertheless it clearly shows two maxima, one slightly N, the other slightly S of E.

Texturally, the samples from this unit (025/114) differ from the upper till by a deficiency of fines and by a high concentration of boulders.

The upper limit of this unit is highly irregular, which is considered to be a primary feature. Together with its general nature it suggests deposition from melting ice, hence ablation till.

UNIT C-5: THE UPPER TILL, RESEDIMENTATION FACIES

In many places the till is overlain by a bouldery lag deposit resulting from erosion of the till by meltwater (fig. 25). It seems predominantly to be derived from the upper till (both facies). In several places boulders occurred in concentration. These could hardly be studied, however, because they were invariably distur-

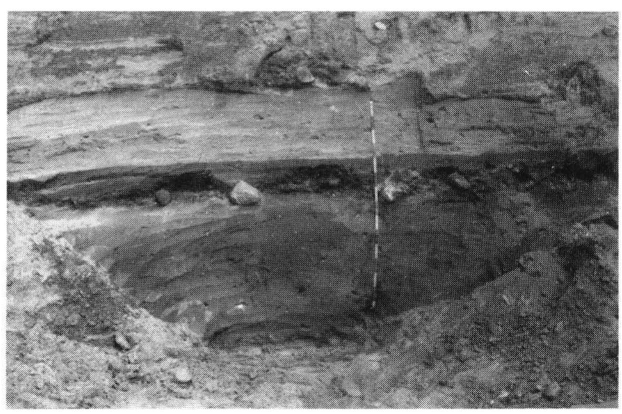


24. Elongated clast fabric of upper till, ablation facies (near site 7) and resedimentation facies (site 21). Compare with fig. 19.

bed by amateur archeologists looking for artefacts. At one locality a clast fabric could be determined (fig. 24). Like the fabric determined in the ablation facies of the upper till (see above) it shows much more random orientation and higher dip values than the fabrics from the lower till. It also shows two small maxima, which may be related to local slope during deposition.

Because of the existence of rather steep slopes of the till surface, some of the till material became unstable, which resulted in the deposition of diamict layers intercalated in fluvioglacial material ('flow-tills'), a feature also mentioned by Ruegg (1977) from a highway construction pit near Delden.

Strictly speaking this is not a glacigenic unit, but because of its compositional characteristics it is treated as unit C-5. Moreover, it is often very difficult to distinguish between units C-4 and C-5. Its thickness



25. Lower till overlain by a bouldery lag deposit, debris flows (dark layers above boulders) and upper fluvioglacial deposits (site 17).

seldom exceeds 30 cm. Texturally, this facies is characterised by a high gravel content and a deficiency of fines (fig. 12), which must be due to washing.

As the resedimentation facies is mainly flint-poor, most of it is probably derived from the upper till, especially the ablation facies. Consequently it is mainly found in the eastern part of the pit.

UNIT D-1: THE UPPER FLUVIOGLACIAL DEPOSITS

The till-floored basin has been filled in by fluvioglacial deposits. In the central parts of the pit these reach a thickness exceeding 10 m. Because of the shape of the basin this unit quickly decreases in thickness in all directions. The S extension of these deposits outside the pit has been dealt with by the third author in his doctoral dissertation (Semeijn, 1983).

Unit D-1 consists of an alternation of gravel, sand and silt beds, which are predominantly horizontally to subhorizontally bedded. The bed limits are in general sharp and erosive.

An up to 3 m thick rhythmically alternating set of loamy and sandy layers directly overlying the till was observed in the SE part of the pit. Within this unit poorly sorted layers (debris-flow deposits, sample 007) are frequently interstratified. Mud curls - indicating desiccation – from similar deposits have been described by Ruegg (1977). In the central part of the pit an about 25 cm thick lense of clayey laminated material occurred. It included thin sand lenses and gravel strings. No ice-needle casts have been found in this layer. Above this zone, parallel bedding predominates, although a few channels have been observed. Some of these were quite large with a maximum width of 20 m and 1 m depth. Their filling was characterised by sets of large-scale cross-stratification. Higher up in the sequence several smaller channels (maximum width 1 m) occur, these showed small-scale trough cross-bedding. In accordance with Ruegg (1977) a more or less S directed stream-flow during deposition is inferred.

Fining upward as well as coarsening upward sequences of small scale were observed at different places in the pit, but a consistent sequence in textures and structures was not found. In the S part of the pit a load cast structure was observed.

In the middle and lower part of this unit several sets of syngenetic frost cracks have been described (Van der Meer & Semeijn, 1981). Most of the cracks occur within the fluvioglacial deposits, but the lowermost set penetrates unit C. The largest cracks are about 1.5 m long, with widths varying between 1 and 10 cm. Frost cracks of this kind do not necessarily indicate permafrost. According to Dylik & Maarleveld (1967) they are an indication of severe winters with abrupt changes in temperature and little or no snowfall. Augustinus & Riezenbos (1971) mention the occurrence of frost cracks in fluvioglacial deposits near Soesterberg without stating their exact position in the sequence. According to Maarleveld (pers. comm.) these are much wider (fossil ice wedges) and thus not comparable to the frost cracks at Lunteren. Frost wedge casts of Saalian age have also been mentioned by Zagwijn (1973). But these are much larger, overlain by till and are thus older than the glaciation.

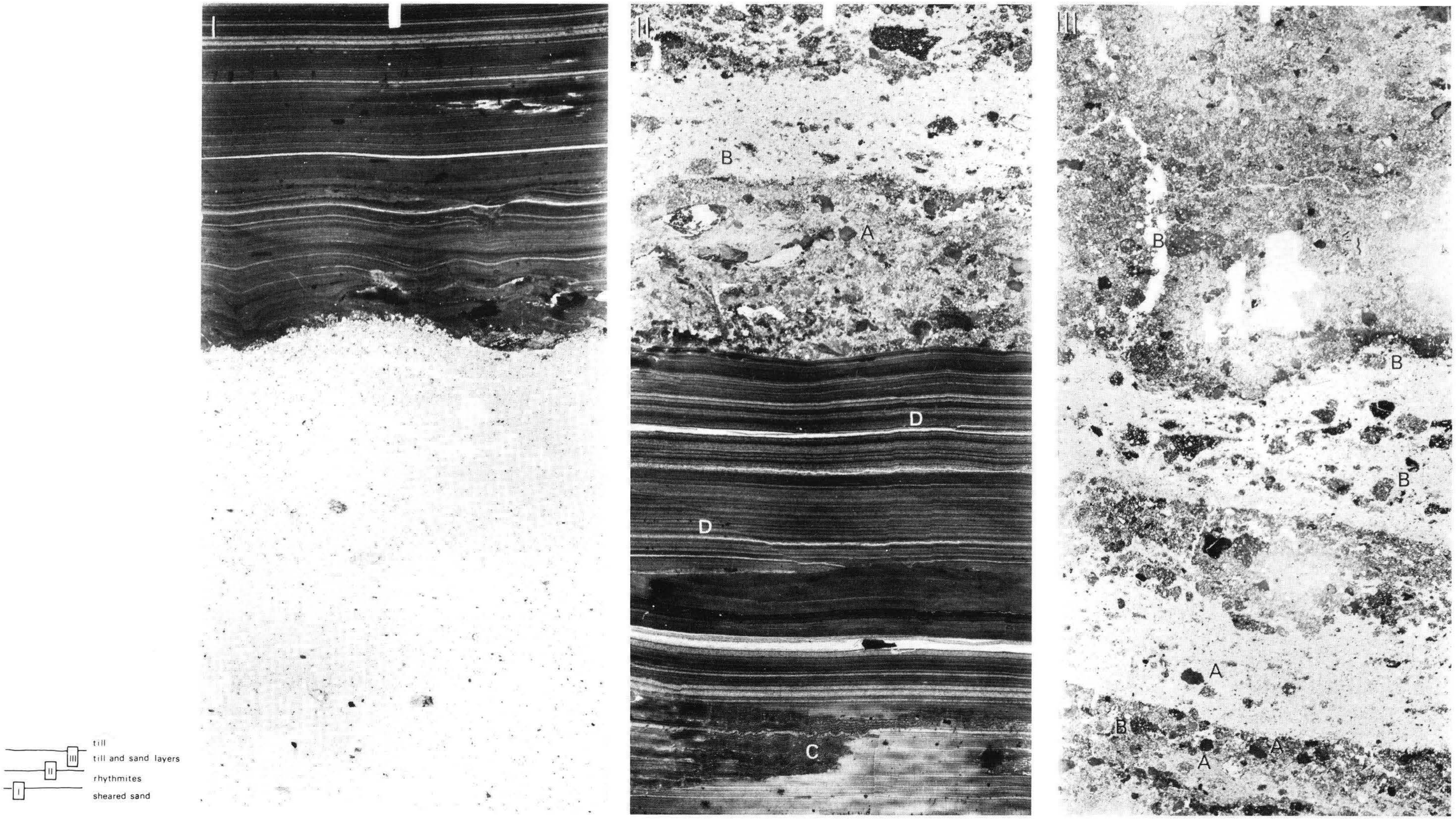
Ruegg (1977) could distinguish between at least four phases of sedimentation separated by angular unconformities. During our surveys we did not observe structures that indicated dislocation by active ice-pushing in the upper fluvioglacial deposit. Bedding structures in the upper fluvioglacial deposits are in many places off-set by high-angle reverse and normal faults with displacements being only in the order of dms at the most, and which are due to minor gravitational setting after deposition, in part possibly due to melting of sustaining ice.

Although the modal fraction is rather variable (fig. 9D), hardly any of our samples showed a bimodal distribution as was found by Ruegg (1981), who sieved at 0.25 ψ intervals. As thread sieves may have deviations of as much as 0.15 ψ (Folk, 1966), one must be careful with detailed interpretations of such results.

Petrographically, the upper fluvioglacial deposits differ from the lower fluvioglacial deposits by a more distinct fennoscandian component (Appendix I).

In general unit D-1 is interpreted as the infilling of a small basin by lacustrine deposits which regularly de-

26. Thin section of banded till at site 18, depth 24-37.5 cm from top of till bed (see figs. 11, 12, 13).



27. Set of 3 thin sections (actual size) collected from the base of the lower till and the underlying shear zone, including rhythmites. Position of the three sections has been indicated in sketch. A - clay and fine silt pebbles, B - till pebbles, C - wavy zone, processing artefact, D - faults.

siccated (mud curls and frost cracks) alternating with coarser fluvioglacial deposits.

UNIT D-2: THE CRYOTURBATED LAYER

This unit follows via a gradual transition on D-1. The extension of this unit both inside and outside the pit is mainly limited to the fluvioglacial deposits. Its thickness is variable (up to 2 m) and seems to depend on the thickness of the fluvioglacial deposits. In the pit its appearance is mottled and made up of smudges of grey, brown and yellow. The grey material consists of fine sand and silt, and is found between two sandy, gravelly layers. In texture unit D-2 differs from the underlying unit D-1.

Frost wedges are commonly found extending down the base of this layer. These are in general larger than the syngenetic frost fissures in the upper fluvioglacial deposits.

Two examples of the grain-size distribution from this unit are given in fig. 9E. The grey material consists of fine sand as well as abundant silt-sized material, by which it differs from the fluvioglacial deposits. Possibly, fine-grained material was added through solifluction and/or eolian processes.

The unit is, by its chaotic character, interpreted, as a cryoturbation zone, presumably of Weichselian age as is the case with the associated frost wedges.

MICROMORPHOLOGICAL OBSERVATIONS

At a number of sites samples for the preparation of mammoth sized thin sections were collected, with the objective to study special features, such as banding, or shear planes in greater detail. As part of the results of this specialised study are presented in a separate paper (Van der Meer et al, 1983), we will here only give a short description of the main results.

Besides looking at the special features for which the samples were collected, they were also studied for phenomena they have in common. It was found that the till in all of the samples has a weak to moderate skelsepic fabric in Brewer's (1964) classification. This means that the orientation of the plasma in the till is predominantly parallel to the surface of the skeleton grains. Larger plasma separations as described by Sitler & Chapman (1955), which they termed microfoliation, have not been observed.

Most of the samples contain mud pebbles, although these are not evenly distributed. Zones containing many pebbles alternate with those with hardly any (fig. 26). Two types of pebbles could be recognised. The first type consists of clay and fine silt only (fig. 27,A). In most cases these are mixed and the whole pebble is strongly birefringent. In some pebbles their origin as part of the rhythmites underlying the till could be recognised. The second type consists of a mixture of clay, silt and coarser grains (till pebbles, fig. 27,B). Internally the latter also have a skelsepic fabric. Their presence is interpreted as evidence of continuous reworking of the till by subglacial shearing.

One of the special features that was studied were the rhythmites, of which several samples were taken. They appeared to consist of very thin graded beds with very few coarse grains. The lamination is disturbed especially at the base of the set of rhythmites. Here a zone of up to 1 cm thick was found to be devoid of laminations. Instead this zone showed a high birefringence, indicating reorientation of the particles due to stress. The birefringence observed here was stronger than that in the clay laminae. The top zone was only slightly disturbed by normal faulting (fig. 27,D) and there seemed to be a general increase in birefringence.

28. Thin section of low-angle shear planes at the base of the lower till (see fig. 14A). At the base strongly deformed rhythmites, which have been incorporated in the till. Above this alternating more of less kinked, sandy till bands (actual size).

The last feature that was studied was the till-banding. The thin sections made clear that this is due to the texture. Some bands mainly consisted of sand (figs. 26, 27), while others had a distinct fine-grained matrix. The latter invariably contain much more clay pebbles than the sandy bands in which they are rather rare. Under the microscope it appeared that the banding was much finer than observable in the field, with variations in the amount of mud pebbles and sandiness of layers on a mm-scale.

DISCUSSION AND CONCLUSIONS

As indicated before it is necessary to establish the nature of the till at Lunteren if more is to be said about glacial events in the SW Veluwe. After studying the till for a number of years we conclude that the Lunteren till is not a 'flowtill' but a basal till. There are a number of reasons for this:

1. Throughout the pit an up to 1.5 m thick shear zone is found underneath the till. Flowing of the till alone could not have given this result. Besides, shear planes within the till, deformation of the till together with intra-till sands, and dragfolds and -faults in the top of the underlying sediment, cannot be explained as the result of a debris flow. In itself they are not unique to subglacial processes, but the observed scale and especially the fact that these deformations indicate dislocation in an up-slope direction, strongly point to a subglacial origin.
2. – Elongated – clast fabric in the lower till is characterised by a strong unimodal distribution, and at different measurement sites, the orientation of this mode is the same. This agrees with results generally obtained in subglacial lodgement and melt-out till in modern as well as Pleistocene environments; resedimentation by till flow ('flowtills') on the other hand are often characterised by poorly developed primary modes or apparently random orientations, without consistency in the orientation of modes (Marcussen, 1975; Lawson, 1979; De Jong & Rappol, 1983).
3. The presence of two superimposed petrographically different diamictons seems highly unusual for proglacial resedimentation environments. In many respects similar till sequences have been described from many places in the Netherlands (de Waard, 1949; Zandstra, 1976, 1983; Rappol, 1983). A similar sequence of the same till types has been exposed at pit 'Monnickenbosch' near Amersfoort (Zandstra, pers. comm.). The regionality of the phenomenon in the Gelderse Vallei suggests regionally constant conditions, hence subglacial formation. Because in the Netherlands there are no indications for different directions of ice movement during deposition of two till sections, nor for glacier retreat, these are interpreted as having been formed under conditions of continuous ice cover and deposition, where the petrographic stratification in the erratic debris is inherited from the englacial position (Rappol, 1983). Besides, the upper till was found to consist itself of three different facies: a basal, an ablation, and a resedimentation facies.
4. The till bed is of relatively constant thickness throughout the pit. Deposition as a debris flow should have occurred prior to the actual pushing of the ridge, because deposition on the steep slopes of the basin is very difficult to envisage. A constant thickness of a 'flowtill' bed can only be the result of a fast moving, liquid debris flow. This would mean however, that all stones should be found at the base of the till. In the Vink pit most stones were found to the top.
Banding in the till is due to differences in composition. Granulometric and sediment-petrographic analyses indicate that the layering is mainly due to differences in the amount of incorporated local material. Moreover, the layers never show erosional contacts, as could be expected by deposition as a (series of) debris flow(s).

Concluding that the Lunteren till is a basal till still leaves part of the question unanswered. It could still be either a lodgement till or a melt-out till.

Up to now no convincing criteria for the differentiation between lodgement tills and melt-out tills have been produced. It is doubful whether they ever will for Pleistocene tills, because in our opinion there seems to be a continuum in the processes of lodgement and melt-out (see also discussions by Virkala, 1952, and Lavrushin, 1980). Lodgement is either viewed as particle by particle plastering of till from active ice or as deposition through stagnation of debris-laden basal ice to the bed of the glacier (see INQUA Comm., 1981). The latter process however can also be looked upon as melt-out, because final deposition of till occurs through the disappearance of interstitial ice. This is supposed to happen underneath active ice. Basal melt-out on the other hand is traditionally and recently also by definition, considered as the deposition of till from ice neither sliding nor deforming internally (Shaw, 1982). It is not clear how tills deposited through either the second lodgement process or through melt-out can be separated from each other.

Recently Haldorsen and Shaw (1982) in a paper on the problem of recognising melt-out tills suggested that the criteria for interpreting a till as a melt-out till are a combination of: "1. the presence of unlithified, sorted and stratified sediments within or interstratified with the till(s), 2. the presence of a statistically preferred orientation of stone axis closely related to ice-flow condition, and 3. a configuration of till with a recognisable textural or lithological property closely related to the configuration of englacial debris with the same property". If we now try to relate these three properties with the properties of the till section at Lunteren, we find that property 1 does not apply, because intra-till sands at Lunteren originate through shearing. Only one clast of unconsolidated sand (see e.g. Stephan & Ehlers, 1983, fig. 257; or Rappol, 1983, fig. 53) was observed.

Property 2 is present, but is not exclusive for melt-out tills.

Direct evidence for property 3 is not available. It is true that Rappol (1983) used the compositional variability of tills for reconstructing the configuration of englacial debris in the Saalian ice-sheet, but using this as evidence would introduce an element of circularity.

We may thus conclude that at this stage it is impossible, if not undesirable, to distinguish between the two modes of till formation as mentioned above.

Interpretation of the Lunteren till as a basal till leads to the following reconstruction of events.

In the Middle Pleistocene the Rhine and Meuse deposited the Urk formation in the central part of the Netherlands. During the last stadial of the Saalian the Scandinavian ice sheet reached these latitudes. A lobe of this ice sheet first pushed the Ede ridge as part of the system bordering the Gelderse Vallei (Maarleveld, 1981) and subsequently the same or another lobe pushed the Oud Reemst ridge. As the pushing came from N-NE, while ice movement – as reconstructed from deformation structures and elongated clast fabric in the till – was in SE direction, it can be concluded that the Oud Reemst ridge originated through lateral pressure of the ice lobe. When the ice later overrode the ridge it continued in the same direction resulting in the already mentioned elongated clast fabric. The basin as observed in the Vink pit could be the result of glacial and/or fluvioglacial erosion. But it can also be a primary feature resulting from pushing by the ice lobe. From present-day ice-pushed ridges it is known that the surfaces of these ridges are not flat, but that they are characterised by ridges and furrows as well as closed depressions (Gripp, 1929; Kälin, 1971). Since the basin of the Vink pit also seems to be a closed depression, an origin through glacial erosion is still possible, but the ice should then have retreated to enable the sedimentation of the lower fluvioglacial deposits. This makes this origin less likely as well, which leaves us with an origin as a primary feature due to pushing.

As stated above the ice lobe continued to move SE-wards after the formation of the ridge and in doing so (partly) overrode it (for ice limits see Semeijn, 1983). In doing so its meltwaters deposited the lower fluvioglacial deposits, while underneath the ice a shear zone was formed. Continued movement of the ice led to deposition of the till. Upon melting of the ice part of its supraglacial debris was deposited as an ablation till, partly washed by meltwaters which resulted in the stony lag deposits found on top of the till. At the same time deposition of the upper fluvioglacial unit started. At first in a low energy environment as evidenced by the lowest part of the deposits, lateron in a higher energy environment. This deposit desiccated several times, because during cold periods (winters?) frost cracks developed. Fluvioglacial deposition continued until the basin had been completely filled in.

No evidence of any activity whatsoever of Eemian age has been found. During the Weichselian the upper part of the (upper) fluvioglacial deposits was cryoturbated, maybe with the admixture of some coversands. Planation of the ridge surface may also have occurred during the Weichselian.

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APPENDIX I (for captions see p. 26)

unit	fraction	n	C	F_t	Q	R
D	20-30	151	13.0	6,5	29,0	51,0
D	13-20	300	9,5	2,0	45,5	43,0
D	8-13	301	5,0	3,5	58,0	33,5
D	5-8	300	5,0	1,0	62,0	32,0
D	3-5	300	4,0	1,5	63,0	31,5
D	2-3	298	5,0	0,5	64,5	30,0
C5	8-13	124	67,5	2,5	3,0	26,5
C5	5-8	324	70,0	3,0	7,5	19,5
C5	3-5	405	59,0	0,5	17,0	23,0
C5	2-3	300	65,0	2,5	18,0	14,5
C4	8-13	126	65,0	–	1,5	33,5
C4	5-8	347	65,0	1,5	3,5	30,5
C4	3-5	200	71,0	1,5	4,0	24,0
C4	2-3	297	70,0	–	12,5	16,5
C3	5-8	167	61,5	x	1,0	36,5
C3	3-5	300	67,5	–	5,5	26,5
C3	2-3	200	72,5	–	12,0	15,5
C2	20-30	247	40,0	15,0	2,0	42,5
C2	13-20	297	38,5	14,5	9,0	38,0
C2	8-13	310	38,5	10,5	17,5	35,0
C2	5-8	296	41,0	9,5	19,0	29,5
C2	3-5	298	41,0	3,5	25,0	30,0
C2	2-3	300	28,5	4,0	41,0	27,0
C1	5-8	106	x	–	60,5	39,5
C1	3-5	300	–	0,5	66,5	32,5
C1	2-3	300	–	–	78,5	21,5
B	5-8	673	1,0	1,0	52,5	45,5
B	3-5	1164	x	–	66,5	33,0
B	2-3	618	0,5	x	75,5	24,0
A	20-30	176	1,5	7,0	47,0	44,0
A	13-20	295	–	2,5	56,0	40,0
A	8-13	299	–	3,0	55,5	41,0
A	5-8	300	x	x	63,0	36,0
A	3-5	299	x	–	61,0	38,5
A	2-3	299	–	–	73,0	27,0

APPENDIX II

Sample no.	Unit	Fraction (in mm)	n	C	Ft	Q	R
K_2	D2	2-3	107	x	–	68.0	31.0
F_1	D1	2-3	122	–	–	67.0	33.0
F_2	D1	2-3	350	1.0	–	73.5	25.5
$F_2$1	D1	2-3	446	x	–	77.0	23.0
$F_2$1	D1	3-5	168	2.0	–	66.0	32.0
F_3	D1	2-3	185	1.0	–	69.5	29.0
$F_3$1	D1	2-3	228	1.5	–	71.5	27.0
F_4	D1	2-3	300	3.0	–	66.5	30.5
F_4	D1	3-5	132	18.0	x	42.5	38.5
F_6	D1	2-3	300	2.0	–	74.0	24.0
F_6	D1	3-5	298	5.5	–	54.5	40.0
F_7	D1	2-3	122	x	–	69.5	29.5
F_8	D1	2-3	385	1.5	–	66.0	32.5
F_8	D1	3-5	101	x	–	57.5	41.5
F_9	D1	2-3	300	0.5	–	71.5	28.5
F_9	D1	3-5	300	0.5	1.0	65.0	33.5
F_{11}	D1	5-8	316	7.0	–	43.5	47.5
–	C1	5-8	665	x	–	57.0	42.5
B_1	B	2-3	299	x	–	69.5	30.0
B_1	B	3-5	259	x	–	58.5	41.5
B_1	B	5-8	589	1.2	–	55.0	43.5
B_2	B	2-3	300	–	–	73.5	22.5
B_2	B	3-5	299	–	–	60.0	40.0
B_2	B	5-8	298	1.7	–	54.5	44.0
B_3	B	2-3	247	1.2	–	75.5	23.0
B_3	B	5-8	1156	0.5	–	59.0	41.0
B_4	B	2-3	618	0.5	–	75.5	24.0
B_4	B	3-5	164	x	–	66.5	33.0
B_4	B	5-8	673	1.0	x	52.5	46.0
B_5	B	5-8	1403	0.5	–	58.0	41.0
B_6	B	5-8	1160	0.5	–	59.0	40.5
B_7	B	5-8	682	0.5	x	55.0	44.5
P_{11}	A	5-8	302	x	–	41.5	58.5

APPENDIX III

Fraction 3-5 mm

Sample nr.	*Site nr.*	*unit*	*n*	*C*	*Fa*	*Q*	*R*	*F/C*
002	11	C2	64	42.0	9.5	9.5	39.0	0.22
003	11	C2	105	45.0	5.5	27.5	22.0	0.13
004	24	C2	200	30.0	3.5	39.5	27.0	0.12
025	7	C4	174	72.0	0.0	5.5	22.5	0.00
026	7	C2	312	54.0	5.0	15.5	25.5	0.10
100	6	C5	550	56.0	1.0	17.0	26.0	0.02
101	6	C5	72	62.5	0.0	18.0	19.5	0.00
102	6	C5	405	59.0	0.5	17.0	23.0	0.02
103	6	C3	74	55.5	0.0	9.5	35.0	0.00
104	6	C3	171	89.0	0.0	3.5	7.5	0.00
105	6	C2	171	51.0	4.0	18.5	26.5	0.08
106	6	C2	159	29.5	5.5	23.5	41.5	0.19
107	6	C2	136	22.0	2.0	29.5	46.5	0.10
108	6	C2	160	37.0	5.5	23.0	34.5	0.15
111	10	C2	192	57.0	5.0	10.0	28.0	0.09
112	10	C2	99	46.5	9.0	19.0	25.5	0.20
114	8	C4	200	71.0	1.5	4.0	24.0	0.02
115	8	C3	159	76.0	0.5	3.0	20.0	0.01
116	8	C2	233	52.5	9.5	18.5	22.5	0.18
118	3	C2	173	45.0	6.0	15.0	34.0	0.13
120	16	C2	159	45.5	5.5	24.5	24.5	0.13
121	17	C2	149	19.0	2.0	43.5	35.5	0.11
123	18	C2	251	52.0	3.5	20.5	24.5	0.07
124	18	C2	141	27.0	5.5	33.5	34.0	0.21
125	18	C2	120	46.5	4.0	16.5	32.5	0.09
126	18	C2	116	6.0	1.5	61.0	31.5	0.29
127	18	C2	238	48.5	6.5	16.5	35.5	0.15
128	18	C2	187	35.0	7.0	21.0	37.5	0.20
129	18	C2	155	33.5	8.5	22.5	35.5	0.25
133	14	C2	179	44.0	4.0	15.0	37.0	0.09
135	15	C2	133	41.0	7.5	24.0	27.0	0.18
137	15	C2	142	41.0	6.5	22.5	30.5	0.16
139	15	C2	137	57.0	5.0	17.5	20.5	0.09
143	12	C2	133	34.5	4.5	23.5	37.5	0.13
145	12	C2	114	54.5	5.5	15.0	25.5	0.10

APPENDIX III

Fraction 2-3 mm

Sample nr.	*Site nr.*	*unit*	*n*	*c*	*Fa*	*Q*	*R*	*F/C*
114	8	C4	297	70.0	0.0	12.5	16.5	0.00
115	8	C3	200	72.5	0.0	12.0	15.5	0.00
116	8	C2	200	49.5	3.0	32.0	15.5	0.06
123	18	C2	200	47.0	3.0	34.5	15.5	0.06
124	18	C2	200	34.0	1.5	53.0	11.5	0.04
125	18	C2	200	49.5	2.0	21.0	27.5	0.04
126	18	C2	200	7.5	2.0	80.0	10.5	0.27
127	18	C2	200	48.5	3.5	32.0	15.0	0.07
128	18	C2	200	45.0	4.0	30.0	21.0	0.09
129	18	C2	200	38.5	2.5	43.0	16.0	0.06

APPENDIX CAPTIONS

I. Fractionised gravel analyses for selected samples of the distinguished lithostratigraphic units.

Legend:
- n number of particles
- C igneous and metamorphic rock fragments
- F_t total flint
- F_a angular flint
- Q quartz
- R rest
- F/C flint coefficient (actually F_a/C)
- x less than 0.25 %

II. Gravel analyses of the fractions 2-3, 3-5, 5-8 mm, mainly of the fluvioglacial units. Legend as in Appendix I.

III. Gravel composition of the fractions 2-3, 3-5 mm, mainly of the glacigenic units. Legend as in Appendix I.

IV. Grain size composition and Folk & Ward parameters of all the lithostratigraphic units.

APPENDIX IV

percentage for fraction smaller than − 1ψ = 100 %

Sample no.	*Site no.*	*− 4/ − 3ψ*	*− 3/ − 2ψ*	*− 2/ − 1ψ*	*> − 1ψ*	*− 1/ − 0.5*	*− 0.5/0*	*0/0.5*	*0.5/1*	*1/1.5*	*1.5/2*	*2/2.5*	*2.5/3*	*3/3.5*
Unit D-2: the cryoturbated layer														
K1	–				1.0	0.2	0.3	1.0	6.5	8.0	9.5	13.0	2.5	3.0
K2	–				1.5	0.6	0.7	1.4	4.5	12.5	21.0	33.1	14.0	6.0
Unit D-1: upper fluvioglacial deposits														
F1a	–				0.2	0.4	0.5	3.0	10.0	24.0	26.5	24.0	6.0	1.4
F1b	–				1.2	0.5	1.2	7.5	18.5	33.5	26.5	7.5	1.3	0.5
F2a	–				4.5	2.5	5.5	7.5	18.0	18.5	8.0	11.0	4.5	3.5
F2b	–				18.5	2.5	4.0	6.0	24.0	18.0	18.0	17.5	3.0	0.8
F3a	–				5.0	1.2	1.7	3.5	32.5	14.5	20.5	20.5	3.5	0.4
F3b	–				4.5	1.4	2.5	3.5	11.5	25.0	13.5	18.0	6.0	3.0
F4	–				4.0	1.1	3.0	6.0	21.0	35.5	21.0	9.5	1.2	0.3
F5	–				3.5	0.2	1.0	3.0	25.5	23.0	25.0	17.0	2.5	0.7
F6	–				10.0	4.0	10.0	16.0	28.0	25.0	11.5	4.5	0.6	0.2
F7a	–				0.0	0.2	1.6	5.0	49.0	14.0	12.0	14.5	2.0	0.2
F7b	–				2.0	1.1	2.0	4.0	9.0	17.5	19.5	26.5	10.5	4.5
F8	–				3.5	0.7	1.6	4.0	36.0	14.0	11.5	10.5	3.0	0.7
F9	–				21.0	3.0	3.7	4.5	12.0	16.0	17.0	22.0	6.5	3.0
F10	–				0.2	0.2	0.7	2.5	10.5	23.0	24.0	25.5	7.0	1.9
020	–	0.9	0.6	0.6	3.0	0.3	0.8	1.9	6.0	14.0	25.0	27.5	17.5	3.0
021	–	5.5	4.0	2.0	12.0	1.4	1.9	3.0	7.0	13.5	22.5	25.5	17.0	4.0
141	–	4.0	5.0	6.5	17.0	3.5	5.0	6.5	13.0	21.5	29.0	15.0	5.0	0.8
204	–				1.0	3.5	6.0	8.0	18.0	26.0	21.5	10.5	3.0	0.7
007	–	0.4	1.9	3.4	5.5	3.0	4.5	6.0	7.5	11.0	14.0	11.5	6.0	2.5
Upper till, resedimentation C-5														
100	6	9.5	6.0	5.0		3.0	5.0	8.0	14.5	21.5	21.0	11.5	6.5	1.8
101	6	0.7	1.2	1.0		0.7	1.7	4.5	7.5	21.5	27.0	15.5	7.5	2.0
102	6	12.0	9.0	5.5	50.0	3.0	5.0	7.5	13.0	18.0	19.5	11.5	8.0	3.0
Upper till, ablation deposit C-4														
025	7	4.5	3.5	3.5	18.5	1.7	3.5	5.0	7.0	10.5	14.5	14.5	12.5	5.0
114	8	8.5	6.0	5.5.	42.0	2.0	4.0	4.5	7.0	11.5	15.5	14.5	13.0	5.5
Upper till, C-3														
103	6	5.5.	3.0	3.5	12.0	1.2	2.5	3.0	4.5	6.0	8.0	8.5	10.0	5.5
104	6	6.0	4.5	5.0	17.5	1.9	4.0	4.0	5.0	6.0	7.0	8.0	9.5	5.0
115	8	2.0	3.0	4.0	11.5	0.8	2.5	3.0	4.5	5.5	7.0	7.0	8.0	4.5

3.5/4	<4φ	4–5	5–6	6–7	7–8	8–9	<9φ	M_Z	σ_I	Sk_I	K_G'	Remarks
								Folk & Ward graphic parameters				
0.6	54.5						8.5	4.8	3.2	0.1	0.8	grey deposit
1.0	4.5						1.0	2.1	0.8	0.1	1.5	brown deposit
0.2	4.7						n.d.	1.7	0.8	0.1	1.2	
0.2	2.5						1.3	1.3	0.6	0.0	1.2	
0.3	19.5						1.9	2.4	2.5	0.6	1.6	
0.1	5.0						3.7	1.4	1.3	0.2	1.8	
0.1	1.1						0.7	1.4	0.7	0.1	0.8	
1.0	13.5						4.8	2.0	2.0	0.5	2.7	
0.1	1.0						0.5	1.3	0.6	0.0	1.2	
0.1	1.8						0.8	1.5	0.7	0.1	0.8	
0.0	1.2						0.9	0.8	0.8	-0.1	1.1	
0.0	1.2						0.6	1.2	0.7	0.5	0.9	
0.8	4.5						n.d.	1.9	0.9	-0.1	1.2	
0.2	16.5						3.3	2.3	2.4	0.8	2.2	
0.4	11.5						3.0	1.8	1.8	0.5	2.5	
0.5	3.5						1.5	1.8	0.8	0.1	1.2	
1.2	2.0							2.0	0.7	0.0	1.1	
1.9	3.0							1.9	0.9	-0.1	1.2	
0.3	1.0							1.4	0.8	-0.2	1.5	
0.5	1.5							1.3	0.9	0.0	1.3	
2.5	32.0	4.5	4.0	4.0	3.0	3.5	13.0	4.5	3.7	0.6	0.9	debris flow deposit
1.1	6.2							1.5	1.4	0.3	2.1	
1.2	11.0							1.9	1.8	0.4	3.4	
1.8	10.0							1.7	2.0	0.3	2.5	
4.0	19.0	6.0	5.0	3.5	2.5	1.3	3.5	2.7	2.2	0.4	1.5	
5.0	17.5						3.0	2.5	2.1	0.4	1.7	
5.0	46.5	8.5	8.5	7.5	6.0	5.5	10.5	4.3	3.4	0.4	1.0	
6.0	44.0	9.0	10.5	6.5	6.5	4.5	6.5	3.9	3.1	0.3	1.0	
5.0	49.0	6.0	7.5	8.5	7.5	6.5	13.0	4.8	3.5	0.4	0.9	

Sample no.	*Site no.*	*−4/−3φ*	*−3/−2φ*	*−2/−1φ*	*> −1φ*	*−1/−0.5*	*−0.5/0*	*0/0.5*	*0.5/1*	*1/1.5*	*1.5/2*	*2/2.5*	*2.5/3*	*3/3.5*
Unit C-2: lower till, diamict sediment layers														
002	11	0.3	0.3	0.4	1.0	0.3	0.7	1.4	3.0	5.0	8.5	10.5	11.5	5.0
003	11	0.3	0.4	0.4	1.1	0.5	0.8	1.7	3.5	5.5	8.5	10.0	11.5	4.5
004	24	0.2	0.5	0.7	4.0	0.4	1.2	2.5	5.0	8.0	11.5	12.0	11.0	4.5
026	7	0.6	0.7	0.9	2.5	0.6	1.0	2.5	4.5	7.5	12.5	15.0	11.5	7.5
105	6	1.0	0.8	1.0	3.0	0.4	1.1	2.0	4.5	7.5	12.0	12.5	13.5	5.0
106	6	0.8	0.5	0.9	2.0	0.5	1.3	2.5	6.0	10.5	14.5	13.5	11.5	4.0
107	6	0.7	0.9	0.8	2.5	0.6	1.3	2.5	5.5	10.0	15.0	13.5	11.0	4.0
108	6	0.3	0.7	0.7	2.0	0.6	1.0	1.7	4.5	7.5	12.0	11.5	11.0	4.5
111	10	0.7	0.7	0.8	2.5	0.6	1.0	1.6	3.5	6.5	10.5	11.1	12.0	5.0
112	10	0.2	0.3	0.5	1.0	0.5	0.8	1.3	3.0	5.0	8.0	10.0	10.5	4.5
116	8	0.4	0.7	0.9	2.0	0.7	1.3	2.0	4.5	8.5	12.5	13.0	12.0	4.5
118	3	0.6	0.6	0.8	6.0	0.6	0.9	1.5	3.0	5.0	8.0	9.5	11.0	5.5
120	17	1.1	0.5	0.7	2.5	0.5	0.9	1.5	4.5	7.5	11.5	13.0	12.0	4.5
121	16	0.3	0.7	0.7	2.0	0.3	1.3	2.5	6.5	11.0	16.0	14.0	10.5	3.5
123	18	0.6	0.9	1.1	3.5	0.3	1.6	2.5	4.5	8.0	11.5	12.0	13.0	4.5
124	18	0.9	0.6	0.8	18.0	0.4	1.0	2.5	6.0	11.5	17.0	13.0	11.0	3.5
125	18	0.8	1.1	0.8	5.0	0.2	0.8	1.6	4.0	7.0	11.0	12.5	13.0	5.5
126	18	0.5	0.6	0.8	2.0	0.2	1.6	4.0	9.5	16.5	21.0	16.0	9.5	2.5
127	18	0.8	0.7	0.9	2.5	0.5	1.2	1.7	4.0	7.0	12.0	12.5	12.5	4.0
128	18	0.4	0.7	0.9	2.0	0.3	1.0	1.5	4.0	7.0	12.0	13.0	13.5	4.5
129	18	0.3	0.4	0.7	1.5	0.4	0.9	1.6	4.5	7.0	10.5	11.0	11.5	4.0
133	14	0.7	0.7	0.6	2.5	0.4	0.8	1.6	3.5	5.5	8.5	9.5	9.5	4.0
135	15	0.2	0.4	0.5	1.1	0.3	1.1	1.2	2.5	4.5	6.5	8.0	9.0	4.5
137	15	0.3	0.3	0.6	1.2	0.3	0.7	1.2	3.0	5.0	8.0	9.5	11.5	4.5
139	15	0.7	0.9	0.7	2.5	0.3	0.8	1.2	3.0	5.0	8.0	10.5	12.0	6.0
143	12	0.4	0.7	0.9	2.0	0.4	1.0	1.6	3.5	5.5	8.5	10.0	11.0	5.0
145	12	–	0.2	0.7	0.9	0.3	0.7	1.2	2.5	4.5	7.5	9.5	11.0	4.5
Unit C-2: sorted inclusions in lower till														
136	15	–	–	0.7	0.7	0.5	0.9	2.0	8.0	23.5	36.0	20.0	6.0	0.9
138	15	–	–	–	–	0.4	0.1	0.3	0.5	0.6	1.1	1.7	1.9	0.8
140	14	–	0.2	0.8	1.0	0.6	0.7	1.6	5.5	20.0	35.0	19.5	7.5	1.9
142	12	6.5	5.0	2.0	15.0	2.0	4.0	6.5	16.5	27.5	26.5	12.0	3.0	0.4
144	12	–	–	0.3	0.3	0.5	1.4	3.0	9.0	20.5	34.0	21.0	6.5	1.2
Unit C-1: sediments of shear zone														
001	–	–	–	–	–	–	–	0.1	–	0.1	0.2	0.2	0.3	0.4
005	11	2.5	2.5	3.5	9.0	2.0	4.5	8.5	17.0	24.5	27.0	12.5	2.0	0.5
006	11	0.4	0.9	0.8	2.3	1.2	1.6	4.0	9.0	19.5	28.0	18.0	5.0	2.0
168	22	1.5	3.5	4.5	11.0	2.0	5.0	8.0	16.5	25.5	24.0	11.5	3.0	0.5
169	22	0.8	1.3	2.0	4.0	2.0	3.5	5.5	12.5	16.0	12.5	5.5	2.0	1.8
Unit B: lower fluvioglacial sediments														
1/2A					9.0	1.9	4.0	10.0	14.0	24.0	22.0	15.5	2.8	0.8
1/2B					8.5	2.0	3.5	9.0	16.0	25.0	23.0	14.0	2.5	0.8
3/4A					1.0	0.6	2.5	6.5	15.5	28.5	27.0	14.5	2.3	0.6
3/4B					4.5	1.5	4.5	11.0	19.5	29.5	21.5	9.5	1.1	0.3
203					1.0	0.5	0.9	3.0	11.0	25.0	29.5	22.0	7.5	1.0
Unit A: ice-pushed sediments														
P1					4.5	–	0.1	3.0	26.5	45.5	11.5	9.0	1.5	0.6
P3					0.6	0.6	2.5	7.0	15.5	29.0	22.5	13.0	2.5	1.5
P5					4.5	1.8	4.5	12.5	21.0	27.5	19.5	10.5	1.2	0.4
P7					0.1	0.3	1.7	6.0	15.5	27.5	24.5	15.5	3.5	1.6
P9					5.0	3.0	8.0	23.0	24.5	12.5	6.5	12.5	4.0	1.2

3.5/4	<4φ	4–5	5–6	6–7	7–8	8–9	<9φ	M_Z	σ_I	Sk_I	Kg^1	Remarks
4.0	49.0	3.5	4.5	5.0	5.0	5.0	26.0	5.6	4.1	0.5	0.7	
3.5	50.0	4.0	5.0	4.0	4.0	5.0	27.5	5.6	4.2	0.5	0.7	
3.0	39.5	3.5	4.5	6.0	5.0	5.5	16.0	4.5	3.7	0.6	0.9	
4.5	33.0	5.0	4.5	3.5	4.0	3.0	14.5	4.2	3.4	0.6	1.2	
4.5	37.5	6.0	5.0	4.5	2.0	4.0	16.0	4.5	3.6	0.6	1.1	
3.5	32.5	6.0	3.5	3.0	2.5	4.0	13.5	4.1	3.5	0.7	1.3	
3.0	33.5	7.0	3.5	3.5	3.0	2.5	14.5	4.1	3.6	0.7	1.2	
3.5	42.5	5.5	4.0	3.5	3.5	4.0	22.0	5.0	4.0	0.7	0.8	
4.0	43.5	5.0	4.0	3.5	4.0	4.5	22.0	5.1	4.0	0.6	0.8	
4.0	52.5	6.0	5.0	5.0	4.0	5.5	26.5	5.7	4.1	0.4	0.7	
4.0	37.0	5.5	4.0	3.5	3.0	3.5	17.0	4.5	3.8	0.6	1.0	
4.5	50.0	5.5	4.5	5.0	6.0	4.5	24.5	5.6	4.1	0.5	0.7	
4.5	40.5	5.5	5.0	5.5	2.5	2.5	19.5	4.8	3.9	0.7	1.0	
3.0	33.0	4.5	4.0	3.5	1.7	1.4	17.5	4.4	3.8	0.7	1.3	
4.0	39.0	6.0	5.0	4.5	3.5	2.0	17.5	4.6	3.8	0.6	1.1	
2.5	32.0	4.0	5.0	3.0	3.5	0.8	15.5	4.1	3.6	0.7	1.2	
4.0	41.5	6.0	5.5	4.0	4.0	3.5	18.5	4.8	3.8	0.6	0.9	
1.8	18.5	3.0	3.0	1.8	1.3	0.6	8.5	2.6	2.6	0.6	0.7	
3.5	42.0	4.5	5.0	4.0	4.0	3.5	21.0	4.9	4.0	0.7	0.9	
3.5	40.0	6.5	5.0	4.0	3.0	2.0	19.5	5.0	3.9	0.6	0.8	
3.5	45.5	6.0	5.5	4.0	4.0	2.0	23.5	5.2	4.1	0.6	0.8	
3.5	53.5	5.5	5.5	3.5	5.5	3.5	30.5	6.0	4.3	0.4	0.7	
3.5	58.5	5.0	6.0	4.5	4.5	6.0	33.0	6.4	4.3	0.2	0.7	
4.0	52.5	6.5	6.5	3.5	3.5	6.0	27.0	5.8	4.1	0.5	0.7	
5.0	48.5	8.0	5.5	3.5	3.0	5.0	24.0	5.5	4.0	0.6	0.8	
4.0	49.5	7.0	5.5	4.5	4.0	3.5	25.0	5.5	4.1	0.5	0.7	
4.0	54.0	6.5	6.0	5.5	4.5	2.5	29.0	5.9	4.2	0.4	0.7	
Unit C2: sorted inclusions in lower till												
0.5	2.0							1.7	0.6	0.0	1.2	
0.7	92.0	1.0	1.6	8.0	14.0	18.5	49.0	9.3	3.1	0.0	1.1	rhythmites
1.8	6.0							1.9	1.1	0.4	2.4	
0.1	0.8							1.4	0.7	0.1	1.1	
0.8	2.0							1.7	0.7	0.0	1.2	
Unit C1: sediments of shear zone												
0.5	98.0	3.0	7.0	18.0	18.0	13.5	40.0	8.9	2.7	0.3	0.5	rhythmites
0.2	1.1							1.28	0.77	-0.14	1.07	
1.1	10.0							1.8	1.7	0.3	3.4	
0.3	3.5							1.3	0.9	0.0	1.2	
5.0	33.0	12.0	14.5	0.4	3.5	0.3	2.5	2.6	2.3	0.5	0.9	sandy and silty shear lenses at base of shear zone
0.2	4.0						2.0	1.4	0.9	0.0	1.3	
0.3	5.0						1.8	1.4	0.8	0.0	1.2	
0.3	2.5							1.4	0.7	-0.1	1.1	
0.1	1.7							1.2	0.7	-0.1	1.0	
0.4	0.3											
0.4	2.0							1.3	0.6	0.3	1.4	
0.5	5.5						1.7	1.1	1.3	0.4	1.4	
0.1	0.9							1.2	0.7	0.0	1.0	
0.8	3.5						1.0	1.5	0.8	0.1	1.2	
0.3	3.5						0.9	1.5	0.9	0.1	1.4	

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