Elongated hills near Schönhorst, Schleswig-Holstein: Drumlins or terminal push-moraines?

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Examination of bore-holes, test pitting and surficial mapping of one hill belonging to the group of smooth, elongated hills by Schönhorst, Schleswig-Holstein reveals three geological units: the lower, fine-grained, massive and compact till; the glaciofluvial sand; and the upper, coarse-grained, compact till with minute stringers and lenses of sand and silt. The sequence is strongly glaciotectonically disturbed. A detailed analysis of thin sections of the till micro-fabric, and of radiographs from undisturbed, oriented cores shows a relatively strong NE-SW and NW-SE particle orientation in the lower till and a weakly clustered to random orientation in the upper till.

It is suggested that the field represents either drumlins (the more favourable hypothesis) or terminal push-moraines, formed during the first three ice advances of the Weichselian Glaciation.

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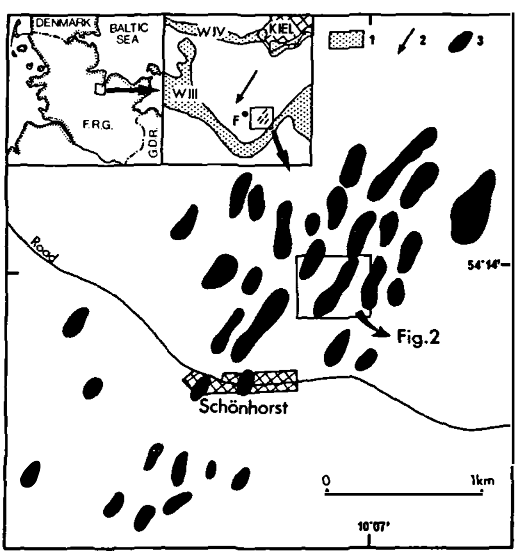


Fig. 1. The elongated hills near Schönhorst. 1-Weichselian end moraines (WIII – the Blumenthal ice advance, WIV – the Sehberg ice advance); 2-ice movement direction during the Blumenthal advance; 3-individual elongated hills as interpreted from a 1:25000 topographic map; F-Flintbek. 1 and 2 modified from Stephan & Menke (1977) and Stephan et al. (1983).

Introduction

An accurate interpretation of glacially derived landforms often poses difficulties because of the great complexity of glacial sedimentary processes, deposit facies and their geomorphic expression. This task is additionally complicated by field work constrains such as lack of exposures, inaccesibility of remote areas, etc. In many cases a precise reconstruction of the events leading to the origin of certain features verges on impossibility and the danger arises that evidence-based reasoning may give way to speculation. Furthermore, a rather limited terminology for glacial landforms often leads to simplifications in naming a given form, rather then describing the processes of formation.

This paper is an attempt to shed some light on the origin of an ambiguous group of elongated hills near Schönhorst, Schleswig-Holstein (fig. 1), with special emphasis on detailed till fabric analysis of thin sections and radiographs coupled with a geomorphological interpretation. Facing a lack of exposures, analysis of till micro-fabric from undisturbed, oriented drilling cores was used to elucidate a morphogenesis of the hills. The purpose of this study is to present geological and geomorphological evidence and to discuss the most likely mechanisms of formation, not to find definite answers.

Terrains south of Kiel have been the subject of numerous geomorphological and geological studies, most recently by Stephan & Menke (1977)

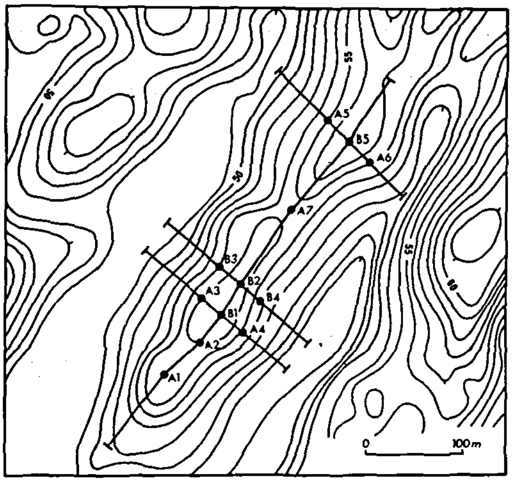


Fig. 2. Location of drilling sites and cross-sections. A1-A7 test-drillings; B1-B5 cored drillings. Contour interval 1m.

and Stephan, Kabel & Schlüter (1983). The study area lies within the range of the Weichselian Glaciation divided by Stephan et al. (1983) into five ice advances. During the first two advances (Brügge and Bordesholm advances) the area was under persistent ice cover and margin fluctuations took place approximately 5–20 km further to the south (see Stephan 1979, Fränzle 1981). At the time of its maximal extent, the ice sheet terminated at a zone marked by an extensive proglacial outwash plain and a transition from till to a marginal spillway. This zone, although not characterised by any end moraine ridge, also delineates the outermost position for the entire Weichselian Glaciation in the area south of Kiel.

After an initial retreat, the ice reactivated again and moved from NNE to SSW during the third Blumenthal advance to the position occupied today by the most prominent ridge in northern Holstein, the Blumenthal end moraine. This 3 to 6 km wide, hummocky zone just south of Schönhorst gently swings to the south creating an arcuate ice-tongue depression near Flintbek. The hills of Schönhorst, which formed at that time, occupy the eastern, marginal position of this depression in the transitional zone to the Blumenthal end moraine. At the time of the last two ice events in the vicinity of Kiel (the Sehberg and Fehmarn advances) the area remained ice-free and was subjected to periglacial processes.

The study area, 10 km south of Kiel, consists of some 35 elongated, parallel aligned, smooth hills occupying about 4 km². The hills reach a length of up to 650 m, width up to 250 m and height not exceeding 12 m above the surrounding terrain. The length/width axial ratio is usually about 2.5:1 giving the whole field a clear morphological trend in NNE-SSW direction. Individual hills are separated by depressions filled with bog deposits, occasionally cut by creaks.

The geomorphology suggests two possible origins for the hills; they are either drumlins or ice-marginal transverse features. According to Ashley, Shaw & Smith (1985), a drumlin is "a glacially formed, smooth hill usually elongate and aligned parallel to the glacier flow direction". As ice margin transverse features are considered all landforms originated as a result of glacial accumulation in ridges oriented roughly parallel to the ice margin.

The main paleogeomorphological question concerns the direction of the last ice movement over the area. Was it parallel to the longer axes of the hills (favouring a drumlin hypothesis) or perpendicular to it (favouring the origin as ice-marginal features)? Evidence supporting both possibilities is discussed in this paper.

Procedure and methods

To study the internal structure of the hills, a typical hill located centrally in the field was selected for drilling and test pitting. Initial test drillings were carried-out with a Pürckhauer drilling device (Ø 22 mm) at seven localities along the crest of the hill and along two section lines perpendicular to it (fig. 2). The depth of the boreholes varied between 4 and 6 m with one shallow hole of 2 m. All sediment layers encountered were analysed on site for texture, structure, color, genesis and stratigraphy.

Continously cored drillings were performed with an Eijkelkamp device at five other localities. The procedure consisted of driving a sampling unit with an up-to-50-cm long plexiglass tube (Ø 8 cm) into the sediment. The tube was firmly attached to the sampling unit and protected from damage during insertion by a drilling head. Extreme care was taken to avoid rotating and swinging the device. After driving a sampler 50 cm into the soil, the N-S direction was marked on the drilling device, then the entire device was pulled

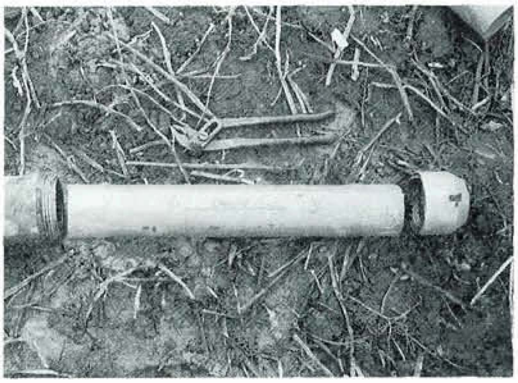


Fig. 3. Plexiglass tube with a till core disengaged from drilling device.

out of the bore-hole, the sampler opened, the N-S direction transferred onto the plexiglass tube and the tube with sediment core was disengaged from the device (fig. 3). In order to avoid the uppermost disturbed sediments (weathering, solifluction and anthropogenic processes) the first two metres were removed by hand augar. An exception was site B2 at which 1.9 m thick till horizon made deeper sampling impossible. Five drillings were performed and undisturbed, oriented till cores were aquired from depths between 1.5 and 4.5 m under the surface. The accuracy of core orientation with respect to the N-S direction is about ±10°. After sealing the plexiglass tubes with tape, they were transported to the laboratory.

Radiography

Oriented blocks of till were cut from the cores using plastic containers with dimensions of 57x41x9 mm. The samples were subsequently sealed with a plastic foil and subjected to a Röntgen beam at 35 kV for 25 minutes or 30 kV for 50 minutes in an Agfa Strukturix D4 device, perpendicular to the sample horizontal plane. The Röntgen negatives were then copied onto photographic paper and enlarged to dimensions of 275x200 mm.

Enlarged pictures were still sharp and of high contrast. Measurements on elongated particles whose long axes are 0.2 mm and longer were possible. A high-contrast picture was, however, possible mainly in case of heavy minerals, hornblend, lime and ore particles and drift fragments derived from basic rocks which, due to their black color on the R-images clearly differ from a gray background. Measurement of quarz and feldspar grains often posed difficulties caused by gray tones too light in contrast with the background. Because of the thickness of radiated samples (9 mm), the elongated particles are abundantly projected onto the negative and up to 100 measurements of grains some 2mm and longer per sample were made. Only particles with an axial ratio of at least 2:1 were measured. Particles located close to the sample edges were omitted because they could have undergone a slight reorientation during cutting of the blocks from the core.

Thin sections

Although considerably more laborous than radiographs, thin sections offer an advantage of determining orientation of significantly smaller particles, which is especially usefull when dealing with very fine-grained tills. In this study up to about 200 grains per sample were measured.

In order to find an optimal impregnation method, several techniques were tested. A flat-sided, oriented sample was rapidly frozen in liquid nitrogen to avoid a buildup of ice crystals and fabric disturbances. Then the sample was dried in a frozen state, soaked in polyester resin in a vacuum container at −20 Torr, and finally cured at 60°C for consolidation. The resin consisted of Vestopal Typ 150 (100 parts), monostyrol (25 parts), catalyst (2 parts) and cobalt accelerator (1 part). This method, succesfully applied to soft sediments (Richardson & Deane 1962, Werner 1966) did not provide good results on compact, highly consolidated till. The resin did not penetrate the specimen before hardening (12 hours). Also when softer (Vestopal 100 parts, monostyrol 100 parts, catalyst 1.2 parts, accelerator 0.8 parts, see Altemüller (1974)), samples remained unpenetrated except for a thin coating at the surface.

Good results were achieved by impregnating till samples with Polyäthylenglykol. Granules of Polyäthylenglykol (PEG) 6000 were liquified in a glass dish at 70°C and a sample was submerged in the resin. While in the oven, the PEG raises in capillary conduits replacing and removing the porewater. During this process (that lasted between 2 and 3 weeks depending on sample thickness, till texture and consolidation), the PEG was changed several times to remove the expelled porewater. At the end of the impregnation, PEG 6000 can be substituted by high-molecular-weight PEG 10000 thereby additionally consolidating the specimen.

Although not extremly hard, samples impregnated with PEG can be carefully oil-polished without damaging the original texture, but the temperature at the working surface should not exceed 40°C.

Internal structure

Based on drilling, test pitting and surficial mapping, three major geological units were delineated on the hill: lower till, outwash sand, and upper till (fig. 4).

Lower till was found only in two bore-holes (B4 and A6 in fig. 4B, C) and on the surface as a discontinuous layer along the south-eastern side of the hill. This till is very fine-grained (silty clay till with occasional admixture of sand, pronouncly massive and very compact. When overlain by outwash, its uppermost section is in places more silty (B4) and grades into a layer of fine sand few cm thick. Minute balls of this till are occasionally found in the basal parts of the upper till as well.

The next youngest member of the sequence is a medium to coarse, poorly sorted glaciofluvial sand with single gravel grains. It covers a large portion of the southern end of the hill's central region (A7 in fig. 4D). It also crops out along both slopes from under the upper till. This sand constitutes a major portion of the hill-building deposits particularly in the central and southern part.

The sequence is capped with the upper till, also highly consolidated. This till is generally coarse-grained (silty sand till) but it exhibits great local variations in texture. It is characterised by common intercalations of sandy and silty stringers varying in thickness from millimetres to centimetres. Typical there are abundant flints and tertiary lime fragments, the latter responsible for the high carbonate content of this layer. The above characteristics, particularly the texture, enable a clear distinction between the upper and lower tills.

A typical feature of the upper till is the sharply undulating, partly discontinuous body carved into the underlying sands along the crest of the hill. In the southern part of the hill, this till builds a local elevation at B1 and is trough-like cut into the outwash deposits to a depth of at least 4.2 m (fig. 4A). Some 30 m to the south-west the till wedges out completly and is substituted by the underlying sand (A1, A2 in fig. 4D). The till can again be traced about 30 m to the north-east from B1 where it covers the whole western side of the hill and is still present along the crest (fig. 4B). It wedges out again some 20 m further to the north-east and is also absent in the local sag in the crest at site A7. It appears for the second time at the foot of the next hump and can be traced continously to its highest point (fig. 4C) where it reaches a thickness of at least 3.5 m. Here, too, this till is carved into the sand and constitutes a major portion of the western part of the hill.

Till fabric

Since the pioneering work of Holmes (1941) till fabric is regarded as an important indicator of the ice movement direction during the deposition and possible later deformation of till. According to the theoretical explanation of orientation phenomena presented by Rusnak (1957), elongated particles immersed in the flowing medium will always tend to assume a position where all forces acting on them are in equilibrium, i.e., where torque equals 0. The torque (T) is expressed by the following equation:

$$T = -\pi \varrho(a^2 - b^2)u \sin\beta \cos\beta$$

where a and b are, respectively, the major and minor axes of the ellipse (an elongated pebble), ϱ is the density of fluid, u is the velocity and β is the angle between the major axis and the direction of motion. The particle reaches a stable position when β equals 0° (when the long axis is parallel to flow) or when β equals 90° (when long axis is perpendicular to flow).

Stanford & Mickelson (1985) pointed out that, lone, elongated particles in a till with little pebble content will be preferentially oriented transverse to ice flow, whereas in pebble-rich till with frequent collisions a longitudinal allignment is more stable. A transverse fabric occurs also in sheared debris bands in ice under a compressive flow regime (Boulton 1971) and an extensive flow with a positive velocity gradient between the down-ice and up-ice ends of a spindle-shaped particle will probably result in its rotation to the position parallel to flow. Therefore, fabric alligned parallel to ice flow is expected to occur in debris-laden basal tills in an extending regime and transverse fabric is likely to be found in fine-grained tills with lone stones under a compressive regime.

Numerous studies on till fabric in drumlins and in till sheets (micro- and macro-fabric analyses) show prefered orientation parallel to ice flow. Wright (1957) found a very strong orientation of elongate pebbles parallel to drumlin long axes in the Wadena field in Minnesota. Similar observations were made by Evenson (1971) for micro- and macro-clasts in drumlins from Wisconsin, and by Piotrowski & Smalley (1987a) for macro-clasts in the Woodstock drumlin field in southern Ontario. Hill (1971), Walker (1973) and Krüger & Thomsen (1984) reported till fabric oriented parallel to the contour direction of drumlins and attribute this pattern to deflection of ice around the growing mound. Johnson (1983) analysed microfabric of the Lake Superior red clay (till) and concluded that, of the major modes of sand grain trends, about half are oriented transversely, and about half parallel to ice flow. This pattern was attributed to varying sand content and the degree of microfoliation development. Shaw & Freshauf (1973) examined micro- and macro-fabric in flutes and reported a convergence of elongated particles towards the flute axes: possibly a result of helicoidal flow in the basal part of ice. Stanford & Mickelson (1985) found most of the fabric was parallel to the drumlin axes in the Waukesha field, but fabric perpendicular and oblique to ice flow was not uncommon. The latter was attributed to flow within previously deposited, remobilised till.

Sediment gravity flows such as sub-aerial flow tills and mudflows normally exhibit a strong fabric (Boulton 1968, 1970, 1971; Lindsay 1968), but randomly oriented and weakly clustered maxima are also known (Dowdeswell & Sharp 1986, Dreimanis 1988). Random orientations are expected in sub-aqueous "drop tills" (Evenson, Dreimanis & Newsome 1977; Lunkka 1988) where deposition proceeds from floating icebergs or ice shelves through a water column.

Till fabric from push-moraines is rarely reported because there investigations usually concentrate on glaciodynamic structures such as folds or faults which are more certain means for determining ice movement direction. In contorted sequences both parallel and perpendicular fabric could be expected (Berthelsen 1978). Houmark-Nielsen & Berthelsen (1981) demonstrated a till fabric interpretation in conjunction with glaciotectonic structures where a differentiation between parallel and perpendicular fabric was based on small intrafolial folds associated with the latter. Fabric of a dislocated till from the Weichselian Main Stationary Line at Bovbjerg, Denmark, reveals a strong up-ice dipping trend (Pedersen, Petersen & Rasmussen 1988). A similar trend is evident in pebble fabric of one push-moraine in the Karakoram Mountains (Owen & Derbyshire 1988).

Due to textural, structural and spacial differences between the lower and upper tills on the hill near Schönhorst implying their different stratigraphic and possibly genetic position, the tills will be considered separately.

Fabric of the lower till

For the lower till a total of 7 levels from the core of B4 (fig. 4B) located between 3 and 4.4 m below the terrain surface were investigated. Four fabrics were measured from radiographs and five from thin sections (from two levels there were prepared two thin sections per level). Although the sampled interval represents only a 1.4 m thick till section, a significant but systematic spread of fabric maxima was determined. In the lowest level (B4-7-R) the trend lies in the NE-SW direction. The next level just 15 cm above has a clear maximum lying NW-SE, i.e. perpendicular to the previous one. Measurements carried out on two thin sections from this level (B4-6.1-S and B4-6.2-S) exhibit a similar picture with mean directions lying 17° apart. Also the next higher level (B4-5-S) 10 cm further up has a peak at roughly NW-SE. The only level in the lower till without a relatively well-defined maximum is the next one (B4-4-R) located 15 cm above the previous one. Still higher in the sequence, level B4-3.1-S and B4-3.2-S have a peak of roughly NE-SW orientation which is at the next level (B4-2-R) substituted by a NW-SE fabric with a high strength of a circular variance (c.v.) = 0.54 (c.v. = 0 by uniform distribution and c.v. = 1 by random distribution). Direction NE-SW appears once again in the uppermost level (B4-1-R) located a considerable distance of 34 cm above the previous one.

With one exception, all samples from the lower till possess a relatively high fabric strength with c.v. values between 0.54 and 0.77. In some levels a second, oblique peak is also visible, but an obvious perpendicular one has not been observed.

Therefore, at least four direction changes from NE-SW to NW-SE and back are recorded within a 1.4 m thick section of the lower till. Based on the very fine-grained texture of this till, its high degree of consolidation, and its seemingly homogene and massive character, it seems resonable to interpret this unit as a lodgement till, probably deposited during the first two Weichselian ice advances over the area. Consequently, fabric changes should be interpreted in terms of ice movement changes, changes in ice flow character (compresive vs. extensive) and local variations in till coarseness. Bearing in mind the homogenity of the till in question and accepting a regional geology precluding repeated variations of ice movement directions in the range of 90° a plausible origin is that till fabric with a NE-SW maxi-

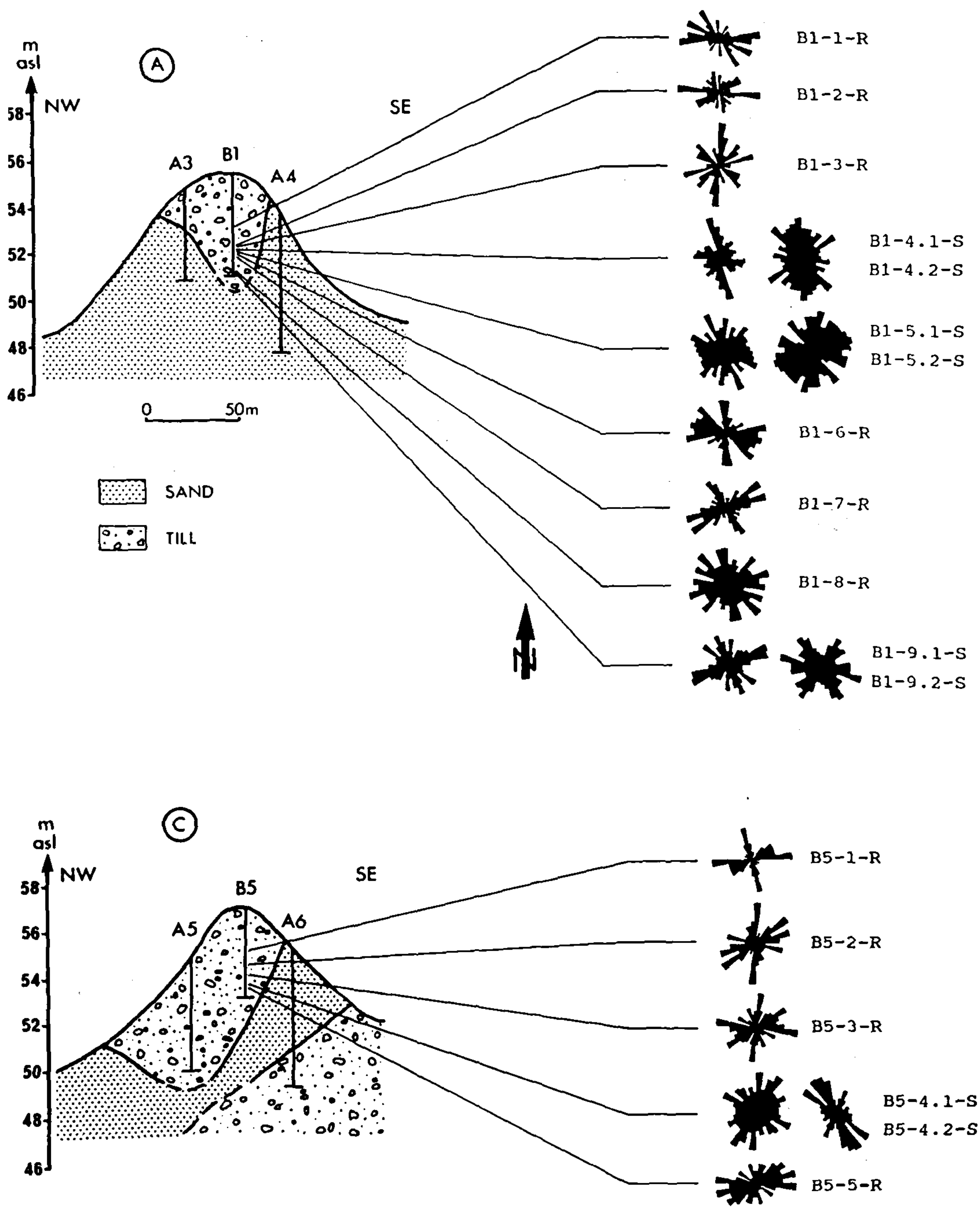
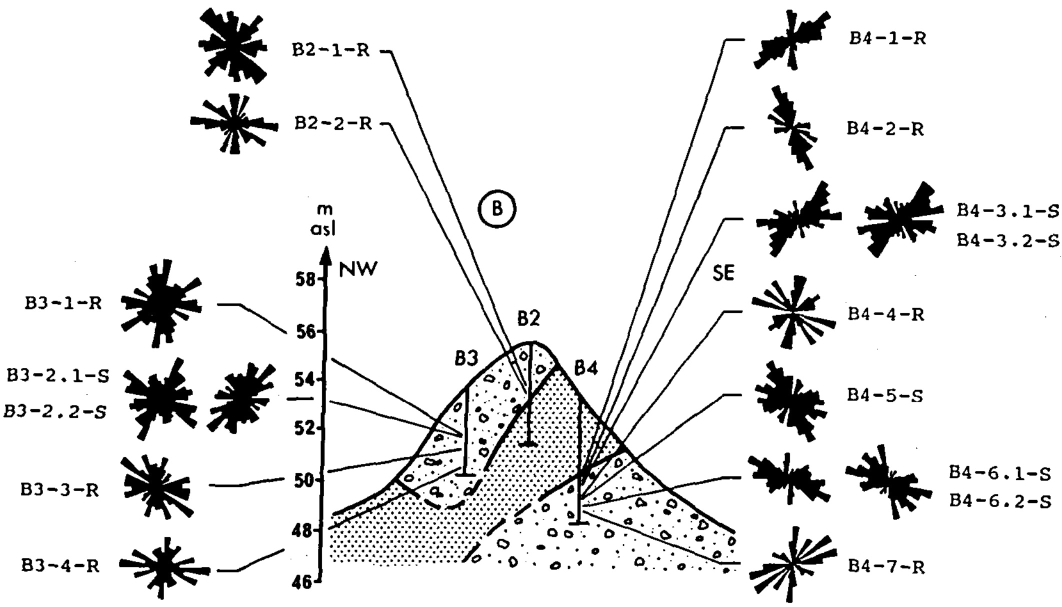


Fig. 4A-D. Internal structure of the examined hill with till fabric from the cores of the lower and the upper till. For location of cross-sections see fig. 2 and for explanation of till fabric see table 1. Vertical scale is enlarged 12.5 times.


B2-1-R
B2-2-R
B
m
asl
NW
SE
58
56
54
52
50
48
46
B2
B3
B4
B3-1-R
B3-2.1-S
B3-2.2-S
B3-3-R
B3-4-R
B4-1-R
B4-2-R
B4-3.1-S
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B4-4-R
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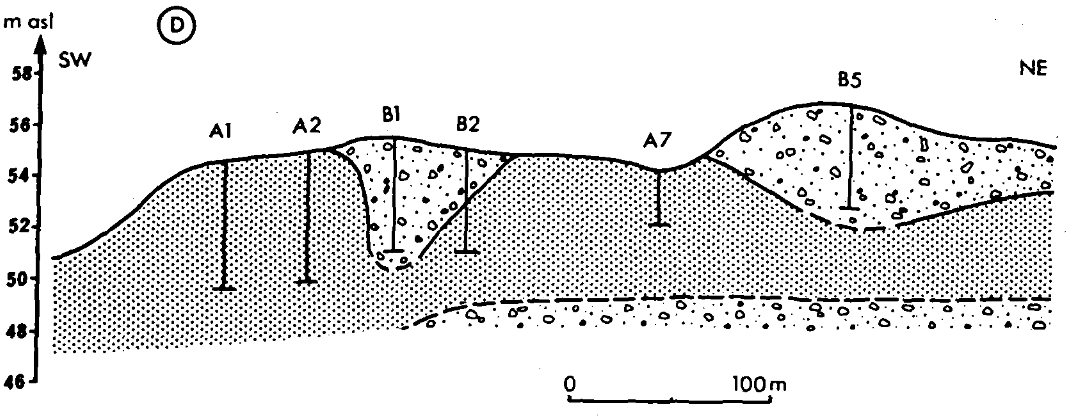
m asl
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56
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B5
0
100m

mum originated during the periods of extensive ice flow and that of a NW-SE maximum at times of a compressive flow regime with ice advancing in both cases from NE. It is possible that a change in flow regime from compressive (B4-6.1-S, B4-6.2-S and B4-5-S) to extending (B4-3.1-S and B4-3.2-S) is recorded as a chaotic fabric of the intermediate level B4-4-R. This interpretation seems to be supported by the fact that the area of the hills by Schönhorst layed, during the first two Weichselian advances, only a short distance to the north from the pulsating, active ice margin, i.e. in the zone where frequent changes in flow regime are likely to have taken place.

Fabric of the upper till

The upper till fabric was investigated using material acquired from 4 bore-holes: 15 radiographs and 10 thin sections. Eighteen till levels were analysed: 9 levels from borehole B1, 2 levels from B2, 4 levels from B3 and 5 levels from B5 (fig. 4A, B and C). The measured intervals varied from 35 cm (B2) to 1.7 m (B1).

The fabric of the upper till is by far more complicated and variable than the one of the lower till. The most irregular arrangement was found in drilling B1 (fig. 4A) located at the crest of the hill at its southern portion.

The lowest level of B1 is characterised by two, roughly perpendicular directions (ENE-WSW and NNW-SSE) in B1-9.1-S and a highly scattered fabric with three maxima in B1-9.2-S. This level is succeeded by a completly dispersed fabric in the next higher level (B1-8-R). Two peaks at roughly WNW-ESE and ENE-WSW with a secondary, oblique N-S orientation appear in B1-7-R and B1-6-R, but these are again substituted by a random distribution in the next level (B1-5.1-S and B1-5.2-S). Level 4 has a random distribution in thin section B1-4.2-S and a NNW-SSE peak in B1-4.1-S taken only a few cm apart from each other. Several peaks are visible at level B1-3-R. In the two uppermost fabrics (B1-2-R and B1-1-R) a tendency toward E-W clustering is apparent. Even if only the measurements with well defined peaks are taken into consideration, till fabric of the sampled section of B1 is characterised by several, randomly distributed maxima without any clear, dominant direction.

From bore-hole B2, also located on the crest of the hill about 35m away from B1, two levels were analysed (fig. 4B). The lower level (B2-2-R) has a slight tendency to ESE-WNW and NNE-SSW clustering, and the upper one (B2-1-R) has a main NW-SE direction with a secondary, perpendicular one.

The last site on the crest of the hill is borehole B5 (fig. 4C) located on the highest elevation. The lowest level (B5-5-R) and one section from the second lowest level (B5-4.2-S) are characterised by a relatively well-developed fabric maxima at ENE-WSW and NNW-SSE respectively. Section B5-4.2-S has additionally a secondary, oblique peak lying in NNE-SSW direction corresponding to the major trend of the second section of this level (B4-4.1-S). Further up in the sequence, level B5-3-R has three maxima with N-S and E-W directions dominating. Two oblique trends appear in level B5-2-R and two perpendicular trends (NNW-SSE and ENE-WSW) are seen in the uppermost level B5-1-R. Therefore, the fabric of B5 has no consequent allignment, but a weak clustering at NE-SW and NW-SE directions is detectable, similar to B1.

A comparison between all three sites along the morphologic axis of the hill does not allow any explicit site-to-site till fabric correlation with the exception of a tendency to NE-SW and NW-SE orientation of elongated particles in B2 and B5.

Bore-hole B3 (fig. 4B) is the only one in the upper till situated on the slope of the hill, some 30 m away from the crest. The lowest level (B3-4-R) has a major peak running WNW-ESE, accompanied by a smaller, perpendicular peak. In the next level (B3-3-R, 65 cm higher up) the dominant direction is NW-SE with two minor, oblique maximas. A relatively strong fabric appears at level 2, where section B3-2.2-S is clustered in a NE-SW direction, and two main peaks of section B3-2.1-S run NE-SW and NW-SE. The uppermost level (B3-1-R) exhibits, on the other hand, a high scatter of particle orientations with several trends intersecting at oblique angels. On the whole the measured portion of B3 can be characterised by a preferential though attenuated NE-SW and NW-SE till fabric.

Interpretation of fabric phenomena and depositional history of the upper till is even more complicated than in case of the lower till. A highly scattered orientation of elongated particles (often exhibiting no preferred direction or more

Table 1. Summary of till fabric statistics. In the sample designation (e.g., B1-1-R), the first number refers to the bore-hole number, the second number to the level, and the last letter to the analysis method (R-radiography, S-thin section). Cm.b.s = centimetres below surface, n = number of particles measured, X = mean direction, c.v. = circular variance (a measure of fabric strength: 0 = uniform, 1 = random).

Sample	Cm.b.s	n	X°	c.v.
B1-1-R	240	95	106	0.66
B1-2-R	305	68	80	0.82
B1-3-R	307	55	38	0.89
B1-4.1-S	315	197	169	0.92
B1-4.2-S	315	197	170	0.88
B1-5.1-S	320	197	96	0.97
B1-5.2-S	320	197	52	0.90
B1-6-R	337	97	112	0.82
B1-7-R	340	65	79	0.82
B1-8-R	400	99	99	0.96
B1-9.1-S	410	197	73	0.93
B1-9.2-S	410	197	106	0.92
B2-1-R	165	99	158	0.91
B2-2-R	200	47	118	0.90
B3-1-R	200	100	26	0.95
B3-2.1-S	215	197	83	0.95
B3-2.2-S	215	197	27	0.86
B3-3-R	245	109	124	0.87
B3-4-R	310	72	89	0.96
B4-1-R	301	110	54	0.67
B4-2-R	335	32	143	0.54
B4-3.1-S	345	197	62	0.63
B4-3.2-S	345	197	70	0.77
B4-4-R	400	48	166	0.89
B4-5-S	415	197	135	0.83
B4-6.1-S	425	197	102	0.70
B4-6.2-S	425	197	119	0.67
B4-7-R	440	40	58	0.74
B5-1-R	201	29	63	0.81
B5-2-R	245	96	61	0.88
B5-3-R	300	101	64	0.83
B5-4.1-S	330	197	37	0.94
B5-4.2-S	330	197	147	0.74
B5-5-R	345	53	66	0.70

than two, mutually oblique peaks) coupled with high variability in till texture and the presence of intercalations of sandy stringers do not permit a conclusion that the layer in question is a lodgement till deposited in a fashion similar that of the lower till. A common depositional process is also precluded by the spatial geometry of the upper till, especially the outline of its undulating underside which differs greatly from the flat, erosional undersides of lodgement tills. This geometry, together with a high consolidation, precludes a subaerial origin as morainic mudflows as well: the till is clearly carved into the underlying sands in a manner which required great dynamism at the time of formation. Because such dynamism was provided by the impulse of the glacier overriding the area during the third Weichselian advance, it seems reasonable to suggest that the last process leading to final deposition of the upper till and at least a portion of the underlying glaciofluvial sediments was a glaciotectonic squeezing, pushing or pressing that led to contortion and probably folding of these two units. During glaciotectonic deformation, the original till fabric was partly distorted and a new one was superimposed on it, often causing a somewhat chaotic and multimodal pattern.

The lack of evidence as to the presence of any extensive proglacial lake enabling till deposition from icebergs or ice shelves, precludes the interpretation of the upper till as a "drop till".

Because of no apparent systematic fabric change in a vertical profile in any bore-hole from the upper till, it is impossible to judge whether the weak trend NE-SW and NW-SE noticed in B2, B3 and B5 marks the remains of the original fabric imprinted on till at its deposition, or whether it should be assigned to the direction of a subsequent glaciotectonic deformation. Till fabric reorientation by an overriding glacier has been reported by numerous authors (e.g., McClintock & Dreimanis 1964, Prange 1983). Small scale fabric variations visible in some parts of sections taken from the same level only a few cm apart can be explained by locally different remoulding directions caused, for example, by stone collisions in the deforming till. Intercalations of sand and silt probably represent sheared-up stringers derived from the underlying glaciofluvial unit.

The lack of correlation between orientation of till particles and till texture precludes the possibility that local variations in grain size could have decisivly influenced particle orientation. At the same time it is apparent that a stronger fabric derives from the lower, finer-grained till.

Discussion and conclusions

Although till fabric data (see table 1) together with a knowledge of the internal structure of the hill indicate its glaciotectonic origin, the main paleogeomorphological factor (the direction of ice movement during the shaping of the hill) still has to be considered. Two ice advance directions are theoretically possible: parallel (NE to SW) or perpendicular (NW to SE) to the hill axis. Consequently, the hill has two plausible origins: as a drumlin or as a terminal push-moraine. Due to the geomorphic relationship of the hill in question to the whole field of elongated hills near Schönhorst, the origin of the examined hill can be extrapolated onto the whole field.

Data to support the drumlin origin can be summarised as follows:

1. The hills possess well-defined, clearly discernible, smooth, elongated forms with axial ratios varying from 2:1 to 4:1 and more.
2. They are aligned parallel to one another.
3. The long axes are oriented roughly parallel to the ice movement direction assumed for this area by Stephan & Menke (1977) and Stephan et al. (1983).
4. This group of hills makes up an isolated field without any obvious continuation in either direction. If the hills were formed by pushing parallel to the ice margin, such a continuation should exist, delineating the outline of the former ice margin in a lobate form south of Flintbek.

Data in favour of the origin as a terminal push-moraine are:

1. In this area the Blumenthal end moraine runs roughly parallel to the features in question and allows the suggestion that the hills are actually a continuation of the ice marginal landforms associated with a frontal deglaciation from the main still-stand zone.
2. Although elongated and parallel-aligned, the hills do not have a consistant stoss-and-lee side assymetry typical for drumlins; they are either symmetrical along the long axis or have a steeper and wider end, but these steeper and wider ends occur randomly either on the NE or SW side.

The highly variable upper till fabric, and its undulating underside and obvious overconsolidation, can be interpreted as a result of glaciotectonic disturbances. Together with the presence of a glaciofluvial core, these characteristics support both a drumlin hypothesis or a push-moraine hypothesis.

The genesis of the hills near Schönhorst can be summarised in three stages. During the combined first two Weichselian ice advances over the area, a fine-grained till was deposited with a relatively strong fabric indicating ice movement from NE to SW. This till, interpreted as a lodgement till, constitutes the basis and lowermost part of the investigated hill. At that time frequent transitions from extending to compressive flow regime and back are documented by two, mutually perpendicular and time-transgressively fluctuating fabric maxima. The second stage consisted of ice retreat and deposition of coarse-grained glaciofluvial sediments, probably as kame-like features in a proglacial environement rich in dead-ice blocks. At this time layers of flow till could also have been deposited on top of the glaciofluvial core. The final stage consisted of a new ice reactivation and its advance to the position marked today by the Blumenthal end moraine (the third Weichselian ice advance) and the accumulation of the upper till associated with glaciotectonic disturbances. Based on the data presented above, the scenario favoured is that the ice moved from NE to SW, overriding and streamlining the sandy hills which constituted obstacles on glacier's path. In this process of interfingering erosion, accumulation and glaciotectonism (expressed as till fabric variable in strength and orientation, contorted till-sand contact, high consolidation of till, presence of local patches of the lower till at the base of the upper till and a complex texture and structure of the upper till) the drumlin formation near Schönhorst was achieved. Deposition of the somewhat attenuated Blumenthal end moraine east of Schönhorst probably took place during a lobate ice disintegration, after ceaseation of ice movement.

Location of the study area at close proximity to the end moraine is typical for numerous drumlin fields throughout the world and fits well with the models suggested by Fränzle (1981, p. 21), Smalley & Piotrowski (1987a and 1987b), Piotrowski (1987) and Mooers (1989), in which drumlins form preferentially at the outermost peripheries of the ice sheet. It should be emphasized, however, that although the majority of evidence seems to support the drumlin interpretation, the origin as a terminal push-moraine can not be entirely discarded.

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Summary

The paper discusses the origin of a group of elongated hills in the vicinity of Schönhorst, Schleswig-Holstein, with special reference to a detailed till micro-fabric analysis by means of thin sections and radiographs from undisturbed, oriented till cores. Test pitting, surficial mapping, and a total of 12 drillings performed on a selected hill reveals the presence of three geological units: the lower till, the glaciofluvial sand and the upper till. The lower till is massive, fine-grained, compact and has two relatively strong fabric maxima at NE-SW and NW-SE. It is overlain by medium to coarse-grained sand with occasional gravel grains. The upper till is also compact, but has a coarse texture, intercalations of sandy and silty stringers and weakly-clustered to random fabric. This till is carved into the glaciofluvial sands along the crest of the hill in a manner related to glaciotectonic disturbations.

Extrapolating the data onto the whole field, it is suggested that the elongated hills are either drumlins (formed during ice advance parallel to to their present long axes) or terminal push-moraines (formed during pulsation of the ice margin perpendicular to their axes). The first possibility is favoured. The formation took place during the first two (the lower till) and the third (the upper till) ice advances of the Weichselian Glaciation.

Dansk sammendrag

I artiklen diskuteres oprindelsen af en gruppe aflange bakker i istidslandskabet omkring Schönhorst i Slesvig-Holsten. Ud fra prøvegravninger, geologisk jordbundskartering og analyser af 12 boringer i en udvalgt bakke, kunne den stratigrafiske opbygning erkendes. Især detalierede mikrofabric analyser af orienterede till kerner har været medvirkende til erkendelse af lagfølgen.

Nederst er en massiv, finkornet, kompakt till med relativt stærke fabric-maksima i NØ-SV og NV-SØ retning. Herpå følger mellemkornet til groft vandaflejret sand med enkelte gruskorn. Den øvre till er massiv med en markant erosiv og glaciodynamisk undergrænse. Den har grov textur og indeholder slirer og bånd af sand og silt. Fabric er svag eller uden foretrukken orientering.

Denne lagfølge er sandsynligvis afsat i forbindelse med de tre kendte Weichel isfremstød i området. Således henføres den den nedre till til de to ældre isdække, mens den øvre formodes afsat af det yngste isdække.

To mulige dannelsesmåder synes at gælde for hele bakke feltet. Den mest sandsynlige, at bakkerne er drumlins, hvis form er dannet ved isoverskridelse parallelt med bakkeryggene. Der kan imidlertid også være tale om randmoræner, proglacialt opskudt af en gletscher, hvis rand lå vinkelret på de nuværende bakkerygge.

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