Signature of the Baltic Ice Stream on Funen Island, Denmark during the Weichselian glaciation

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Ice streams are major dynamic elements of modern ice sheets, and are believed to have significantly influenced the behaviour of past ice sheets. Funen Island exhibits a number of geomorphological and geological features indicative of a Late Weichselian ice stream, a land-based, terminal branch of the major Baltic Ice Stream that drained the Scandinavian Ice Sheet along the Baltic Sea depression. The ice stream in the study area operated during the Young Baltic Advance. Its track on Funen is characterized by a prominent drumlin field with long, attenuated drumlins consisting of till. The field has an arcuate shape indicating ice-flow deflection around the island's interior. Beneath the drumlin-forming till is a major erosional surface with a boulder pavement, the stones of which have heavily faceted and striated upper surfaces. Ploughing marks are found around the boulders. Exact correspondence of striations, till fabric and drumlin orientation indicates a remarkably consistent flow direction during ice streaming. We infer that fast ice flow was facilitated by basal water pressure elevated to the vicinity of the flotation point. The ice movement was by basal sliding and bed deformation under water pressure at the flotation level or slightly below it, respectively. Subglacial channels and eskers post-dating the drumlins mark a drainage phase that terminated the ice-stream activity close to the deglaciation. Identification of other ice streams in the Peribaltic area is essential for better understanding the dynamics of the land-based part of the Scandinavian Ice Sheet during the last glaciation.

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Ice stream is 'a region in a grounded ice sheet in which the ice flows much faster than in regions on either side' (Paterson 1994). It has been demonstrated that these zones of fast ice flow, bound by sluggish or stagnant ice, are fundamentally important in controlling mass balance and the stability of ice sheets. Typically, modern ice streams are up to a few tens of kilometres wide, hundreds of kilometres long and move at velocities of several hundred metres per year (e.g. 827 m/a Ice Stream B in West Antarctica and 8360 m/a Jakobshavns Glacier in West Greenland; Clarke 1987). About 90% of ice drainage from West Antarctica and Greenland into the oceans occurs through ice streams (Morgan *et al.* 1982; Hughes 1992), which emphasizes their importance as sediment redistribution agents. Indeed, huge accumulations of glacial deposits are found at the mouths of both modern (Alley *et al.* 1989) and past (Vorren & Laberg 1997) ice streams. Subglacial geology clearly has a strong influence on ice-stream dynamics (Anandakrishnan *et al.* 1998; Bell *et al.* 1998), but specific mechanisms of ice movement are contentious with hypotheses ranging from pervasive basal sediment deformation (Alley *et al.* 1986; Blankenship *et al.* 1987) to enhanced sliding and ploughing (Engelhardt & Kamb 1998; Tulaczyk *et al.* 2001).

Although much data from direct observations is available on contemporary ice streams (e.g. Bentley 1987; Benn & Evans 1998), identification of past ice streams from geomorphological and geological records is much more difficult. Recent research demonstrates, however, that determining position, age and duration of activity of palaeo-ice streams is imperative if we are to better understand the dynamics of past ice sheets, their coupling with climate and, ultimately, the course of glaciations (Stokes & Clark 1999, 2001; Boulton *et al.* 2001). Useful criteria for identifying palaeo-ice streams were recently synthesized by Stokes & Clark (1999) and include (1) characteristic elongated shape and dimensions of the ice-stream trunk bounded by abrupt lateral margins with marginal moraines, (2) convergent flow patterns evident from the orientation of subglacial bedforms such as highly attenuated flutes and drumlins, (3) Boothia-type erratic dispersal trains (Dyke & Morris 1988), (4) pervasively deformed till, and (5) concentrated accumulations of glacial material on continental slope, if the ice stream was marine-based.

Over the past few years, evidence has grown rapidly about numerous ice streams that drained all major ice sheets during the last glaciation, notably at the Last Glacial Maximum and later. The Laurentide Ice Sheet had major ice streams draining through the Hudson Strait (Andrews *et al.* 1985), James Bay (Veilette 1997), Des Moines Lobe area (Patterson 1997), St. Lawrence Bay (Denton & Hughes 1981) and numerous smaller ice streams operating in the Canadian Arctic. Several major ice streams were likely active in the British and North Sea Ice Sheets, in particular in the North Sea (Eyles *et al.* 1994), in NE Scotland (Merrit *et al.* 1995), in north

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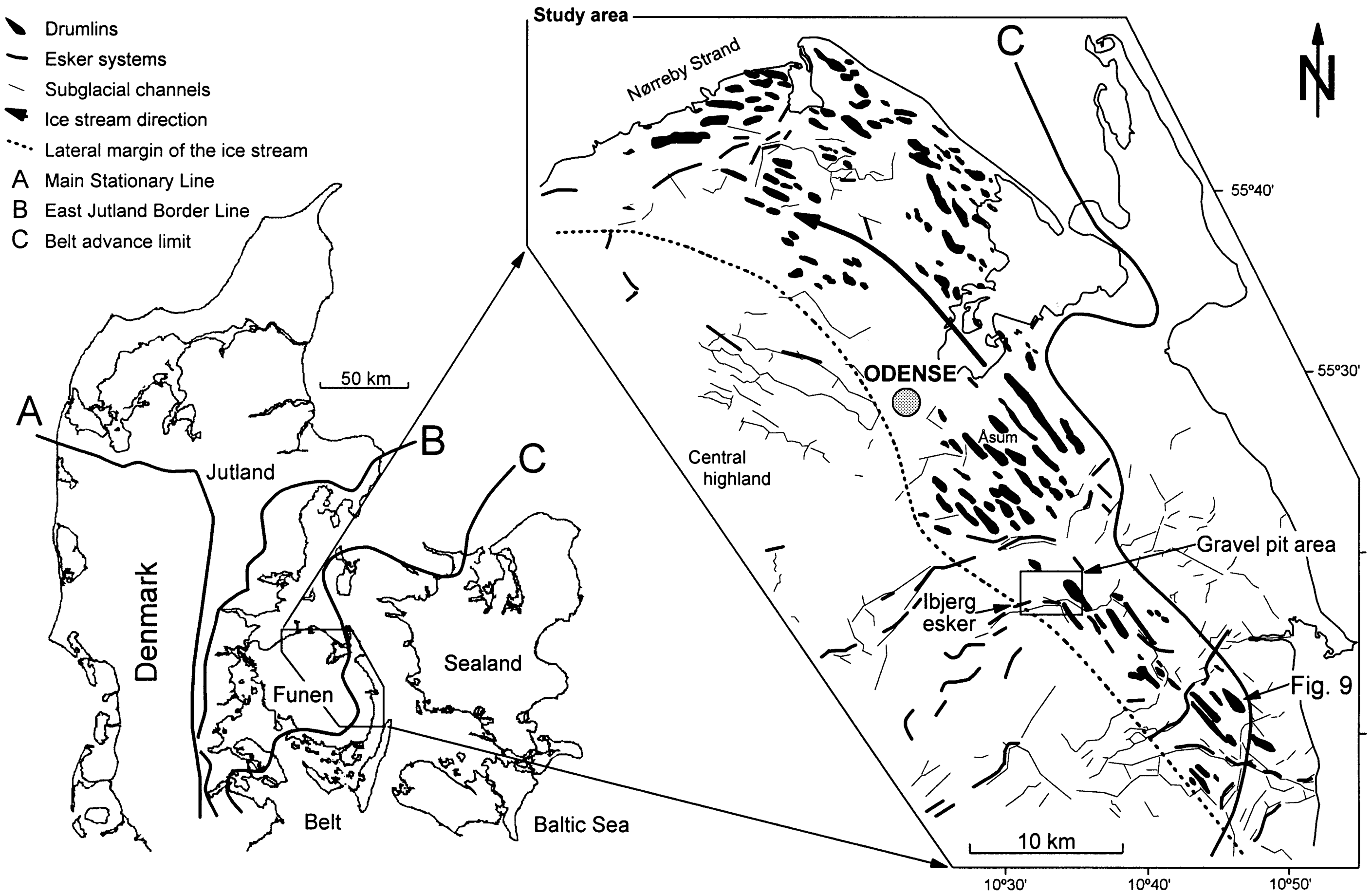

Fig. 1. Major geomorphological features of the study area on Funen Island with respect to ice-marginal positions of the Late Weichselian glaciation. Subglacially moulded features in the NE of the island indicate an ice stream of the Young Baltic Advance which reached the East Jutland Border Line. The study area is the outermost position of the Baltic Ice Stream detected thus far. Esker systems are generalized and simplified to fit the map scale. Ice-marginal positions A, B and C modified from Kronborg *et al.* (1990), Lagerlund & Houmark-Nielsen (1993) and Houmark-Nielsen (1999).

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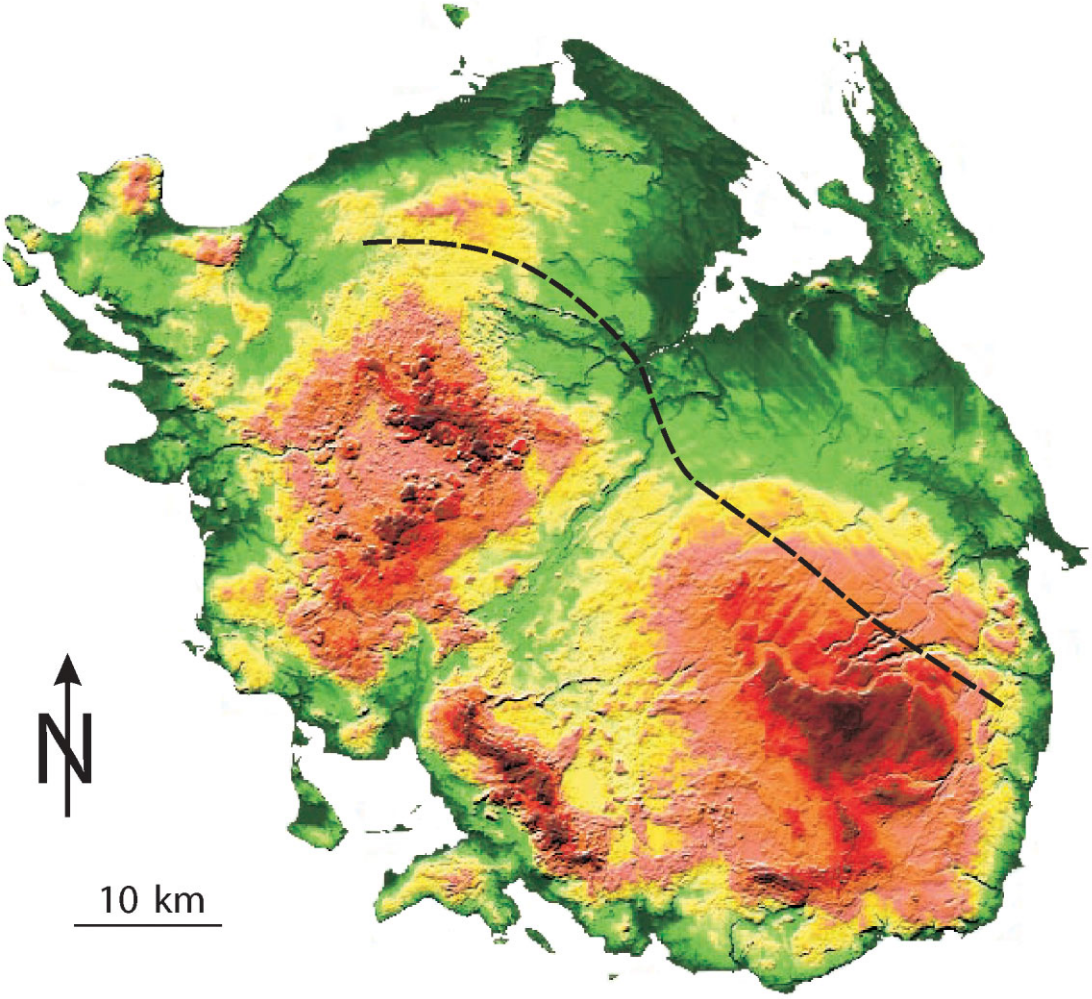

Fig. 2. Digital terrain model of Funen Island. Note the ice-stream area with attenuated drumlins. Major ice-flow direction from SE to NW. A gradual swing in ice-stream track towards the west is evident in the northern part of the island. Broken line marks the border between the ice-stream area and the highlands in the interior of the island. Altitudes are between 0 m and 130 m a.s.l., resolution (pixel size) is 50 × 50 m. Source: Fyns Amt with data from Kort og Matrikelstyrelsen.

central Ireland (Knight *et al*. 1999) and in the Irish Sea Basin (McCabe & Clark 1998). Two major ice streams of the Scandinavian Ice Sheet advanced along the Skagerrak–Norwegian Channel trajectory (Punkari 1995; Sejrup *et al*. 1998; Longva & Thorsens 1997) and the Baltic Sea basin (Holmlund & Fastook 1993; Stephan 2001), and numerous other marine and land-based ice streams have been inferred (Boulton *et al*. 2001). Less is known about the Eurasian Arctic and Icelandic Ice Sheets but there, too, ice streams have been reconstructed (see synthesis in Stokes & Clark 2001). Given that these ice streams operated at different times, their cumulative influence on the course of the entire last glaciation was significant.

In this paper we elaborate, for the first time, evidence from Funen Island in central Denmark indicating that an ice stream (in the sense of Paterson 1994) operated at around 14 ka BP. The area is located at the periphery of the Scandinavian Ice Sheet at the westernmost extension of the Baltic Sea, and we suggest that the reconstructed ice stream represents the terminal part of the major land-based Baltic Ice Stream (B^1 of Punkari 1997 and Boulton *et al*. 2001). We focus especially on the characteristics of a prominent drumlin field and other associated features of glacial and meltwater erosion to infer fast-flowing ice indicative of streaming.

Study area

The study area is located in the NE part of Funen Island in Denmark (Fig. 1). The island is surrounded by the Belt Sea *c*. 40 m deep, and is characterized by contrast-

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ing landscapes. The northern and NE parts are low (mostly less than 30 m a.s.l.), with gently undulating areas with a clear streamlined pattern of drumlins striking generally SE–NW, while the remaining part of the island is a diversified hummocky landscape rising to *c.* 130 m a.s.l. (Fig. 2). The hummocky area is divided into two uplands by a wide and shallow depression stretching NE–SW through the central part of the island. The drainage system includes oversized, partly dry valleys typically extending radially from the island interior towards the coasts, and numerous creeks and troughs following the same pattern. In parts of the streamlined area, however, the drainage network follows the general SE–NW landscape trend.

During the Weichselian glaciation, Funen was overridden by ice sheets several times. Houmark-Nielsen (1999) postulates three major ice advances with the first two from the Middle Weichselian and the third from the Late Weichselian. During the Late Weichselian, a period most relevant to the landscape formation of Funen, the island was covered by ice at least twice. The first advance reached the outermost limit of the entire Late Weichselian glaciation at the Main Stationary Line in Jutland (A in Fig. 1; Ussing 1903, 1907; Andersen 1933; Houmark-Nielsen 1987) at around 20 ka BP (Petersen & Kronborg 1991). During this Main Advance, Funen was overridden by ice from the NE. Following a retreat, the ice covered the island again during the Young Baltic Advance (Andersen 1933; Smed 1962; Houmark-Nielsen 1981, 1987, 1999). This ice came to a halt at the East Jutland Border Line (Harder 1908; B in Fig. 1) at around 14 ka BP (Petersen & Kronborg 1991), some 40 km from the northern margin of the study area. During this advance the ice followed the Baltic Sea depression towards W and NW, and formed the streamlined relief on Funen Island (Smed 1962). Subsequent ice retreat was succeeded by the final, short-lived re-advance of ice lobes that covered the Belt areas and the marginal parts of the island (C in Fig. 1; Rørdam 1909; Andersen 1927, 1933; Smed 1962; Houmark-Nielsen 1987).

Some have argued that the Young Baltic ice did not cover the central highlands of Funen Island, which formed a large nunatak. Milthers (1942) and Smed (1962) suggested that dead ice left by the Main Advance created an obstacle for the Young Baltic Ice which was then diverted along the low-lying flanks of the island. This was based on (1) the presence of NE–SW-striking morphological features such as tunnel valleys, eskers and drumlin-like hills interpreted as remnants of the Main Advance, and (2) stone counts from surficial deposits indicating the dominance of NE erratics on central highlands in contrast to SE erratics abundantly found in the coastal areas. However, Andersen (1963) and, more recently, Houmark-Nielsen (1987) pointed out that such an obstacle would not prevent the Young Baltic ice from entirely covering the island. The highest point of Funen (131 m a.s.l.) lies about 60 km down-ice from the East Jutland Border Line at an altitude of *c.* 110 m a.s.l. Using the formula of Paterson (1994: p. 242), modified for a soft-bedded ice sheet with very flat surface profile as in Piotrowski & Tulaczyk (1999), it can be shown that the ice surface would have been at about 350 m a.s.l. around Funen highland, so a nunatak at *c.* 130 m a.s.l. appears unrealistic even though the highland was covered by remnants of dead ice. The Funen highlands, however, had a strong influence on ice movement direction during the Young Baltic Advance, as shown by till fabric measurements of Houmark-Nielsen (1987) indicating a roughly coast-parallel deflection of ice on its way towards Jutland. Also, a sharp border between the central highlands and the drumlinized zone clearly points to the influence of the older core of the island on the dynamics of last ice flow.

Methods

In the present study, drumlins, eskers and subglacial channels were determined from topographic maps at 1:20 000 and 1:25 000 scale with contour intervals of 2 and 2.5 m, respectively. Also, the geomorphological map of Smed (1962) was used to some extent. Special attention was paid to correctly delineating the base outlines of the drumlins, but a limited amount of subjectivity was involved where the contours did not enclose single drumlins entirely.

During the course of fieldwork, numerous coastal sections and inland exposures, especially in nine gravel pits in an area of *c.* 10 km^2 in the central part of the drumlin field (Fig. 1), were examined with special focus on sediment structure, texture, lithology, glaciotectonic deformations and striations on boulder pavements. Till fabric was measured on at least 50 elongated stones (orientation given as true north). The fabric plots are rotated back to horizontal if the till was tilted, following a standard tectonic procedure. Striation measurements were made on boulder pavements in several exposures according to the following (subjective) rules minimizing the operator variance and enhancing trends: (1) the stones' shortest axis must be larger than 15 cm, (2) striations spread must not exceed 25°, and (3) at least two distinct grooves are needed to define a direction. The dip of the striated surface was also measured. All available construction reports and logs from water wells penetrating drumlins were examined for information on thickness and spatial characteristics of glacial deposits.

Samples were taken from each till unit found in a section and analysed for fine-gravel composition on 2–4 mm fraction (method of Kronborg 1986), grain-size distribution (combined sieve and pipette analysis) and clay mineralogy (X-ray diffraction yielding the content of smectite, illite and kaolinite). These parameters were used to define lithostratigraphic till units.

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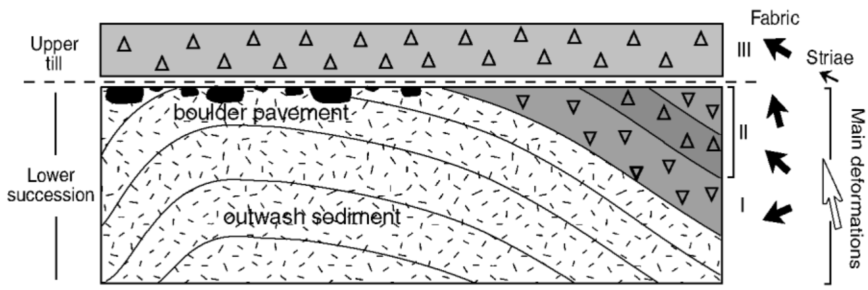

Fig. 3. Diagram showing sedimentary units and tectonic elements. Note the major erosional surface on top of the lower succession and the boulder pavement occurring as an erosional remnant of the tills from the lower succession. I – Main Advance till, II – Young Baltic tills (lower succession), III – upper Young Baltic till.

Glacial deposits and stratigraphy

The near-surface deposits are subdivided into the lower succession and the upper till, with a major unconformity and boulder pavement in between (Fig. 3). These deposits do not all occur in any single section, and are compiled from observations in numerous gravel pits.

Lower succession

At the bottom of the lower succession is an upwards-fining sandy–gravely outwash deposit with minor intercalations of silt. As documented by boreholes and numerous exposures, it occurs in an area of at least 20 km^2 and ranges between 10 m and 20 m in thickness. The outwash is overlain by two major till units with typically massive tills with different fabric signatures, without any intervening sediments (Fig. 3). The first (lowest) till, with 13% clay (I in Figs 3, 4), has a dominant ENE–WSW fabric (Fig. 5) and is interpreted as till of the Main Advance. The second till (II in Figs 3, 4, 5) is twofold. Its lower part is characterized by a very weak, variable fabric with some indication of ESE direction and relatively high clay content of 17%. Its upper part is slightly coarser-grained till (15% clay) with typically strong fabric from the SSE. In some sections these two parts have similar properties and are difficult to distinguish, and they are generalized into one unit (unit II) in Fig. 4. This till is ascribed to the Young Baltic Advance.

The lower succession is heavily deformed into several-metre-amplitude folds. In the gravel pit area, 22 fold axes have been reconstructed or measured directly (Fig. 6). Most axes cluster around the ENE–WSW direction with a secondary, approximately perpendicular trend. Comparison with the till fabrics indicates that the glaciotectonic deformations likely originated during the Main Advance from the NE direction, and during the Young Baltic Advance from the SE. The deformed lower succession is truncated by a regional disconformity, so that most of the three tills are only found locally.

Boulder pavement

The erosional surface truncating the folded lower succession along the base of the upper till is distinct and widespread. It can be seen in all gravel pits in the area, as well as in numerous other exposures in the drumlin field, which emphasizes its importance for process reconstruction. Where the tills of the lower succession are missing, a boulder pavement occurs at the erosional surface of the outwash deposit (Fig. 7A). The stones in the pavement typically range in size between *c.* 15 cm and 50 cm, with a biggest recorded boulder diameter of *c.* 1 m. In most cases their upper surfaces are flat and polished, and they either rest horizontally or dip slightly up-ice (to the SE). The mean dip direction of 18 surfaces is 110° and the mean dip angle 8°. The spacing between individual stones varies between a few centimetres and several-stone diameters,

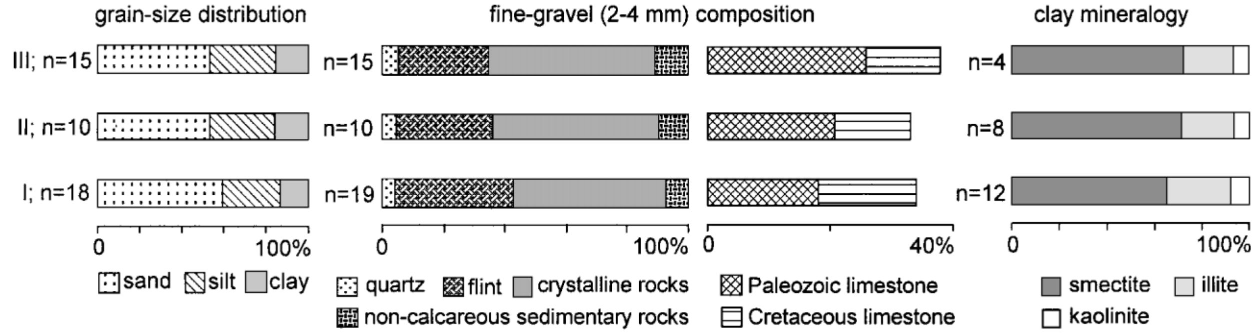

Fig. 4. Grain-size distribution and petrography of tills. Till units I–III as in Fig. 3.

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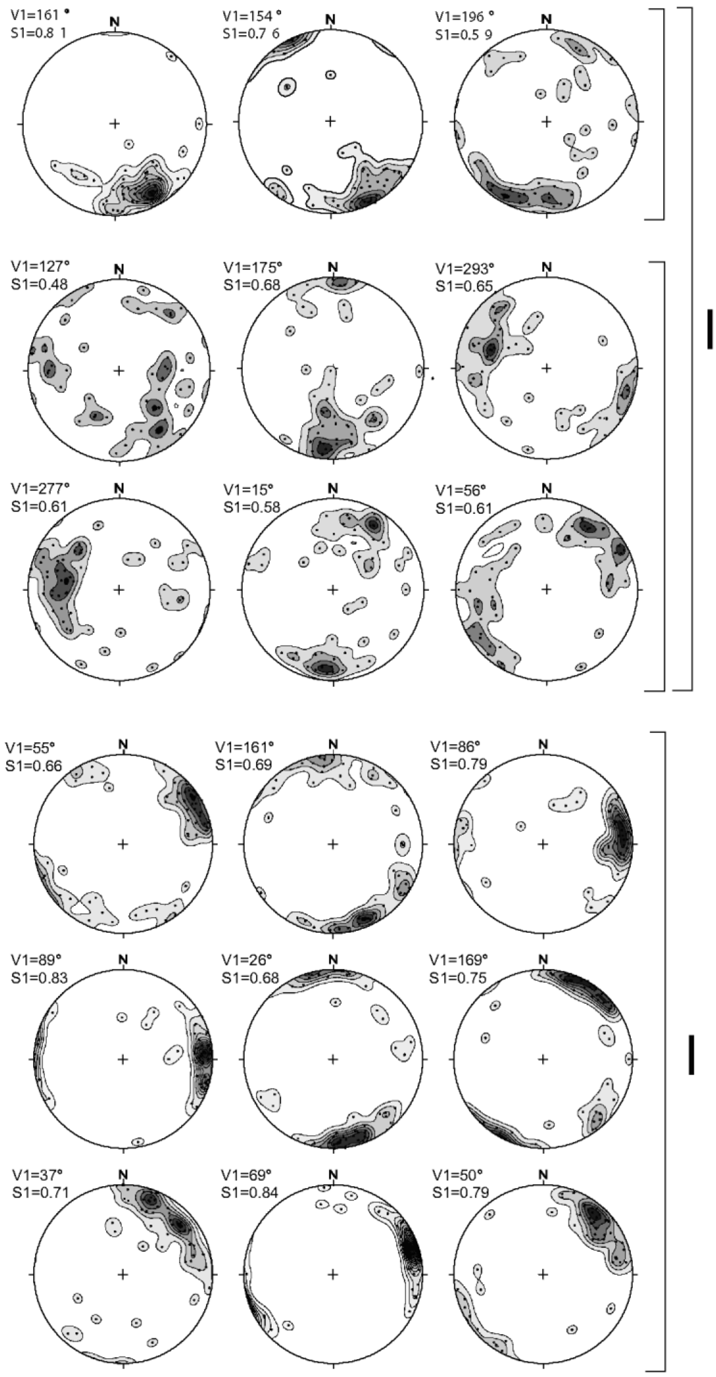

Fig. 5. Fabrics in the Main Advance till (I; see Fig. 3) and in two parts of the Young Baltic Advance till of the lower succession (II; see Fig. 3). Lower hemisphere projection, 2σ contour interval, $n = 50$ in each case.

and the average concentration is about 1 stone/m^2. Typically, the flat upper surfaces coincide directly with the erosional surface, i.e. the stones rest in the outwash. In sections striking parallel to ice flow, it is evident that stones ploughed through the outwash before they were lodged. This is shown by grooves and furrows stretching up to a metre from the bottoms of the stones in the up-ice direction, filled with the upper till. On the down-ice sides of the stones the outwash is often up-squeezed to form intensely deformed sediment prows (Fig. 7B). A similar association of grooves and prows was interpreted by Clark & Hansel (1989) as evidence of lodgement under a soft-bedded Pleistocene glacier in Illinois, USA.

Most of the flat upper surfaces of stones are distinctly striated (Fig. 7C). Striation orientations are unidirectional, with just a few single striations diverging from the main trend. Measurements from 6 gravel pits show

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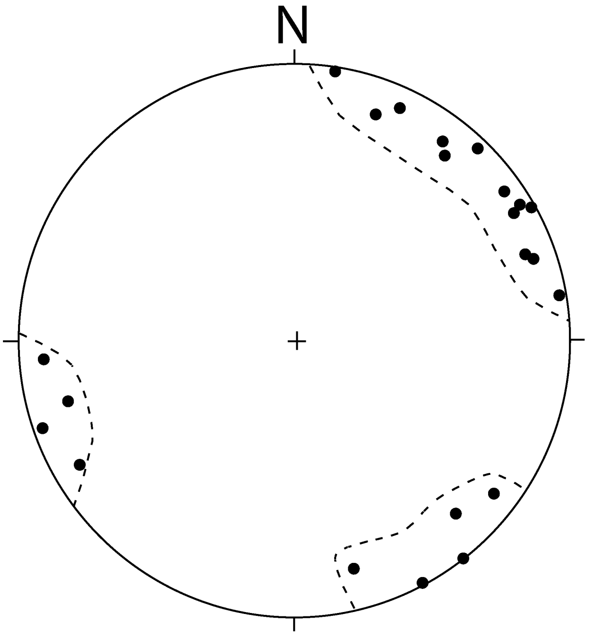

Fig. 6. Orientation of fold axes from the lower succession indicating folding first from ENE (Main Advance) and then from SE (Young Baltic Advance). Lower hemisphere projection.

very little dispersion, ranging from 105° to 128°. Mean directions calculated for each gravel pit separately vary between 118° and 128° (Fig. 8A).

Hansen (1942) has described the same boulder pavement in another part of the Funen drumlin field at Åsum, 10 km NW of the present gravel pit area (Fig. 1). The boulders at Åsum were pressed down into the outwash; they were heavily striated, their striated upper surfaces dipped 5–15° towards the SE, the main direction of the striations was 128° (with less pronounced other directions on some stones) and the boulders were overlain by a thin till cover. In the same area, Milthers (1928) found two large boulders striated in situ in an SE–NW direction. This is consistent with our observations and suggests that the boulder pavement with common characteristics may occur under a significant portion of the drumlin field. Another observation worth mentioning is that striations on boulders inside a Young Baltic till at Lindø, 15 km north of the gravel pit area also correspond to the orientation of drumlins (Smed 1962, 1997). Furthermore, it is interesting to note the occurrence of another boulder pavement at the base of the Young Baltic till at Heiligenhafen in Germany, about 90 km SSE of Funen Island (Gagel 1909; Seifert 1954; Stephan 1971). The Heiligenhafen pavement is similar to the one on Funen in that it has one dominant set of striations on upper, flat surfaces of the boulders, corresponding exactly to the fabric in the till above (Schlieker 1997), which also is drumlinized (Stephan 1987).

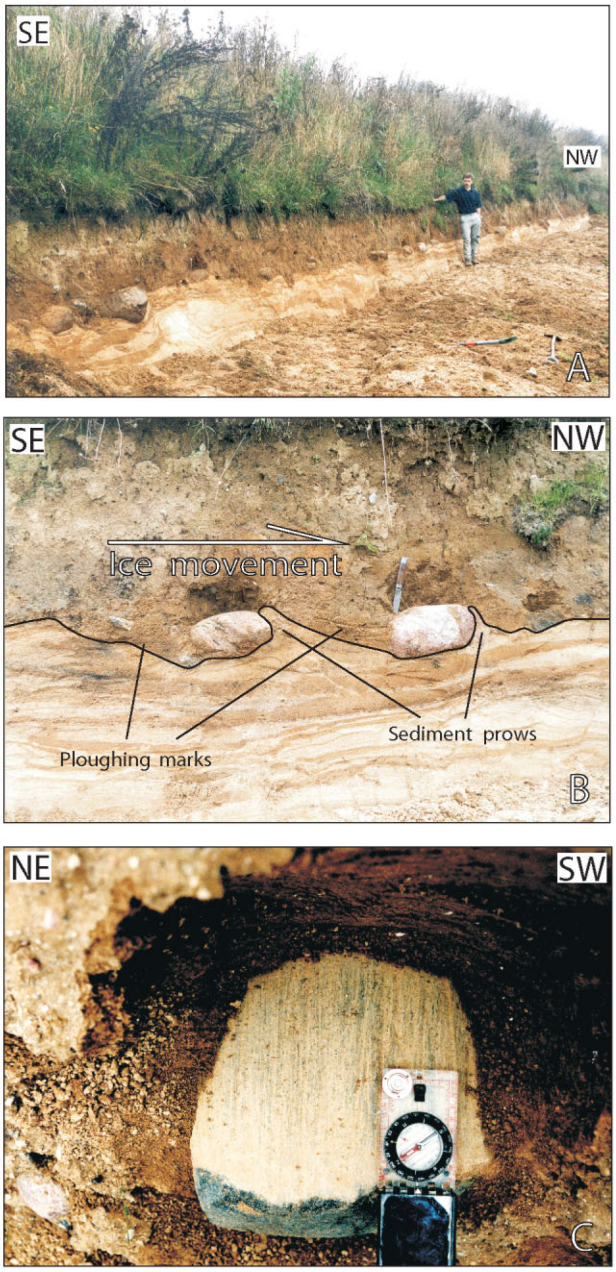

Fig. 7. Boulder pavement at the major erosional surface between the lower succession and the upper till in the gravel pit area (Fig. 1). A. Overview. B. Detail showing ploughing marks behind and upsqueezed sand (sediment prows) in front of two boulders. Both boulders are faceted and striated on top. C. Top view of a boulder with one set of striations on the upper surface at the base of a drumlin. Ice movement from the top of the page (strike 128°).

The upper till

The upper till (III in Figs 3, 4) occurs as a continuous, 1–4 m thick blanket in the entire gravel pit area on top of the discordancy, and it covers most of the Funen drumlin field. The till is a massive, homogeneous

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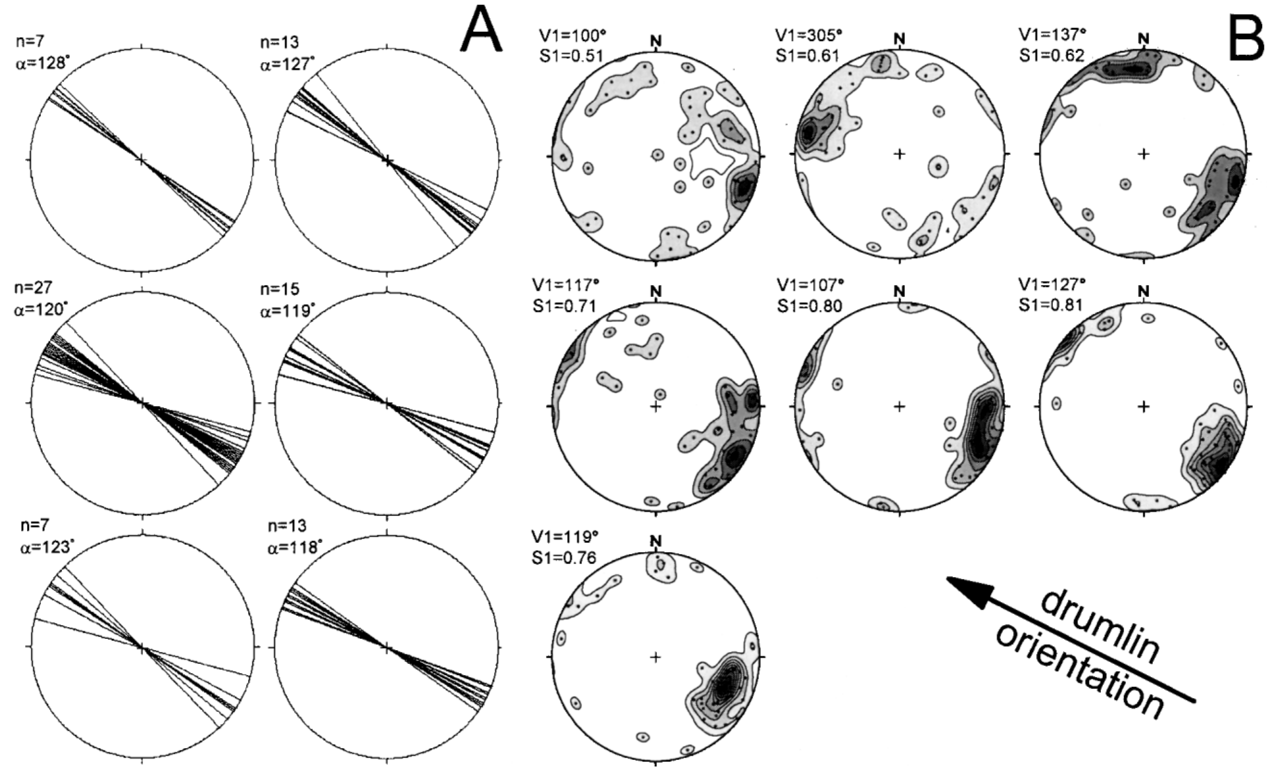

Fig. 8. A. Orientation of striations on the upper surfaces of stones in the boulder pavement (α is mean orientation and n is number of stones on which the striations were measured in each gravel pit). B. Fabric in the upper till overlying the pavement (lower hemisphere projection, 2σ contour interval, $n = 50$ in each case). Note close correspondence of striations, till fabric and drumlin orientation. Measurements from 6 sites in the gravel pit area (Fig. 1).

sandy-clay diamicton with average clay content of 16%. It contains more erratics from the Baltic area (Paleozoic limestones), less local material (flint and Cretaceous limestone), more smectite and less illite and kaolinite, and it is finer grained than the Main Advance till from the lower succession (Fig. 4). The upper till is similar to the two younger tills of the lower succession, with an exception for different limestone content in the fine-gravel fraction. Seven fabric analyses in the upper till have variable strengths (S1 eigenvalues between 0.51 and 0.81), but all show ice movement direction from the SE (120° on average) and a dominant up-ice dip of the clasts (Fig. 8B). This is consistent with a high percentage of Baltic lithologies and the orientation of drumlins, so that this till is attributed to the Young Baltic Advance.

Subglacial landforms

Drumlins

The northern and eastern lowland of Funen has a distinct active-ice morphology, as indicated by drumlins constituting the largest drumlin field in Denmark (Fig. 1). The drumlin field was described in detail by Smed (1962) and attributed to the Young Baltic Advance. Followed along the ice-flow path, the drumlins first strike towards *c.* 310° in the SE and central parts of the field and then bend towards 260–270° in the NW. This gives the northern part of the field an arcuate shape parallel to the coastline. The field covers an area of about 500 km^2. It is at least 60 km long and between 5 km and 15 km wide. However, its dimensions cannot be determined precisely, since some drumlins are below the present sea level and the eastern part of the field was remoulded by a late re-advance of the Belt ice. The change between the drumlinized and non-drumlinized landscape is distinct and occurs over a distance of less than 1–2 km. In all, 161 drumlins were delineated. Most are between 0.5 km and 2 km long and between 100 m and 500 m wide. The mean length is 1111 m and the mean width is 298 m. The longest drumlin is 6 km long, and the maximum elongation ratio (length/width) is 12.5:1. This ratio typically varies between 2 and 6.7, with a mean of 3.2. There is a clear difference in the length/width ratio for drumlins longer than about 1100 m (4.2) compared to shorter drumlins (2.8). This indicates that the drumlins increase less in width when they reach the critical length of about 1100 m, in

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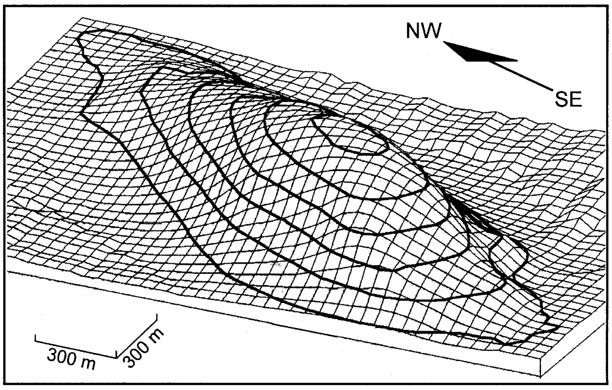

Fig. 9. Morphology of a drumlin from the proximal part of the ice-stream area (location in Fig. 1). Ice movement from SE to NW as indicated by an arrow. Elevation contour interval 2 m (50–60 m a.s.l.).

accordance with Heidenreich (1964), who first suggested a certain limit on drumlin-width growth based on observations from several drumlin fields. There is an increase in drumlin length away from the lateral margin of the field. Shorter and more oval ones are found close to the border with the hummocky topography. The drumlins are typically between 5 m and 10 m high with a maximum of *c.* 15 m. Using the shape categories of Piotrowski & Smalley (1987), the Funen drumlins can be classified as (1) typical drumlins with asymmetrical shapes with stoss ends facing up-ice (e.g. Fig. 9), (2) symmetrical drumlins, including both small drumlins and very long and narrow drumlins, and (3) tilted drumlins resting on down-ice inclined surfaces.

A 6-m-high drumlin in the NE part of the gravel pit area consists of the upper till resting on the regional erosion surface beneath the drumlin base. The till has a strong fabric in exactly the same direction as the striations on the boulder pavement (128°; Fig. 7C) and the drumlin orientation. Also, another drumlin dissected along a cliff in the northern part of the drumlin field at Nørreby Strand is composed of till with fabric orientation again corresponding to the drumlin orientation.

Based on surface mapping, water-well construction reports and logs of 9 boreholes penetrating drumlins (DGU 1991, 1992a, b), and evaluation of old geological maps (Madsen 1900, 1902), it is evident that the Funen drumlins are typically composed of the Young Baltic Advance till.

Eskers

Eskers occur both within the drumlin field and on the neighbouring part of the hummocky area, where they are most conspicuous. Esker paths are typically oriented radially away from the drumlin field towards the island's interior, where they often strike almost perpendicular to the drumlin trend (Fig. 1). Single eskers are short-segmented features a few hundred metres long. Some of them are relatively narrow and distinct ridges with heights exceeding 30 m, while others are wide and flat with irregular shapes, difficult to identify with certainty. The eskers sometimes occur in association with subglacial channels (Smed 1962). The palaeo-meltwater flow in the eskers was from NE towards the central and SW parts of the island (Madsen 1900, 1902; Andersen 1931, 1933; Smed 1962, 1978; Houmark-Nielsen 1987). Numerous eskers in the study area have diapiric cores consisting of till (Madsen 1900, 1902; Andersen 1931, 1933; Hansen & Nielsen 1960; Smed 1978) formed due to intrusion of bed material when water pressure in the channel dropped. According to Smed (1962), the eskers situated inside the drumlin field originated during the Young Baltic Advance, while these in the interior of the island were attributed to the older Main Advance from NE.

The Ibjerg esker is a short segment of a several-kilometres-long ENE–WSW oriented esker system that can be traced as discontinuous ridges traversing both the drumlin field and the central upland (Fig. 1). The Ibjerg esker is around 800 m long, 15 m high and 100–150 m wide. A section shows that the esker has a diapiric core consisting of till mantled with outwash sediment (Madsen 1902; Smed 1978; Jørgensen 1996). Fine-gravel composition, grain size and clay mineralogy indicate that the till is most likely the Young Baltic till.

Subglacial channels

A large number of subglacial channels of various sizes occur in the study area, within both the streamlined and the hummocky terrain (Fig. 1). The deepest channels are incised to 40 m below the surrounding terrain and can be traced for over 10 km. Their orientation corresponds to the esker trend. They have undulating longitudinal profiles with frequent thresholds and hollows. A distinct network of channels west of Odense is oriented at 10° to the nearby drumlins, giving a down-ice opening radial pattern of subglacial features in this area.

Smed (1962) postulated that the NE–SW oriented valleys originated due to meltwater erosion under the ice sheet of the Main Advance, and suggested that their survival in the drumlin field during the subsequent Young Baltic Advance can be attributed to preservation with dead ice. Other valleys oriented in accordance with the drumlin trend have been assigned by Smed (1962) to the Young Baltic ice.

Evolution of the area under the ice stream

The age and depositional environment of outwash deposits at the bottom of the lower succession are unknown, but judging from the upwards-fining grain size they likely represent glaciofluvial sedimentation in front of a retreating glacier. The outwash was subse-

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quently overridden by the Main Advance ice from the NW direction and locally deformed to SSE–NNW striking folds.

Following an ice-free phase, the study area was overridden by the Young Baltic ice. Since there are no independent data on multiple ice advances and retreats at that time, we consider all remaining tills as deposits of this glacier. First, the two remaining tills of the lower succession were deposited from the SE and SSE. As ice overriding continued, the tills, along with all underlying sediments, were deformed into major folds with axes oriented ENE–WSW. Subsequently, the processes of deposition and glaciotectonism were succeeded by intensive erosion of the substratum that led to truncation of the folds, partial removal of tills, excavation of outwash sediments and formation of the boulder pavement. The fact that the pavement occurs exclusively where tills are lacking indicates that it represents an erosional remnant of the tills. The stones from the pavement were dragged for a short distance along the ice/bed interface before they were lodged, as indicated by the ploughing marks preserved behind them, and the up-squeezed sand in front of them. After the boulders were emplaced, they experienced intensive abrasion that truncated their upper surfaces and imposed a distinct set of striations. From this stage on, the ice movement direction was stable, and the glacier flow was deflected by the central highlands of the island, including old dead-ice fields from the Main Advance. In the interior of the island, ice flow must have been much slower than in the ice-stream trunk. Lack of streamlined features in the upland suggests a limited movement along the ice/bed interface there, and the ice thickness probably increased due to a gradual creep into the area between the major lobes surrounding the island. It is possible that ice was cold-based over the centre of the island during much of the Young Baltic Advance.

As ice advance continued, basal till covered the discordancy on top of the lower succession. Since the drumlin morphology only results from variations in the upper till thickness and the discordancy clearly predates formation of the drumlins, we believe that the drumlins originated at a relatively late stage of the ice advance. Their formation can most likely be explained by non-uniform deformation of the basal till with more resistant patches acting as nuclei that were streamlined by more mobile till and the ice sole. This model corresponds to one common hypothesis of drumlin formation elaborated among others by Menzies (1979), Boulton (1987), Smalley & Piotrowski (1987) and Piotrowski (1987).

A late event recorded by the field data is the formation of subglacial meltwater channels and eskers. These features post-date the upper till, and may be related to channelized drainage of large meltwater volumes just before the deglaciation. Channels and eskers that cross the border between the drumlin field and the hummocky topography in the island's interior indicate a regional hydraulic gradient away from the ice-stream area, which could have been caused by a lobate configuration of the ice margin during the retreat, driving water radially towards a thinner ice. This is consistent with the orientation of the channel network west of Odense just outside the ice-stream trunk. The hypothesis of Smed (1962) that eskers and valleys oblique to the drumlin trend are remnants of the Main Advance is unlikely, given (1) their geomorphic freshness, (2) high erosion/deformation intensity in the ice-stream area, and (3) correlation of the till core of the Ibjerg esker with the Young Baltic till. However, some eskers and channels oriented approximately NE–SW in the island's interior may indeed derive from the Main Advance and survived the Young Baltic Advance due to low subglacial dynamics in this area.

Bed deformation and enhanced basal sliding

Because the Funen Island drumlin field possesses a number of features that originated at the ice/bed interface, it is tempting to elaborate the possible ice-movement mechanisms. As mentioned above, it has been shown that fast movement of modern ice streams may be facilitated by deformation of water-saturated, soft subglacial sediment, by basal sliding on a thin basal water film, or a combination of these mechanisms. In any case, high basal water pressure in the vicinity of the flotation point is required to weaken the strength of overridden sediments and ultimately to reduce the strength of basal coupling and initiate sliding. Since the basal shear stress typically varies within a relatively narrow range of values (Menzies 2001: p. 82), we believe that water pressure fluctuations were of crucial importance in controlling the ice-flow mechanism according to the Coulomb model in which the sediment strength $\tau = c + (p_i - p_w)\tan\varphi$, where c is cohesion, p_i is ice overburden pressure, p_w is porewater pressure and φ is angle of internal friction. Increase in p_w facilitates sediment deformation until the flotation point is reached. Then the glacier is lifted from the bed by a pressurized water layer; shear stress is not transferred to the bed and the glacier moves by sliding.

In the present study area, the sediment-landform assemblage indicates that both deformation and sliding occurred under the Young Baltic ice, although with varying intensities. Initially, two basal tills were deposited under relatively low water pressures (A in Fig. 10). A high percentage of far-travelled clasts, including east Baltic lithologies, suggests primarily lodgement of englacially transported material. Subsequently, porewater pressure rose sufficiently to cause localized, non-pervasive deformation of the substratum and the generation of folds (B in Fig. 10). This deformation style does not indicate fast ice flow at this stage yet.

Further weakening of the bed by increasing porewater pressure initiated penetrative erosion and hori-

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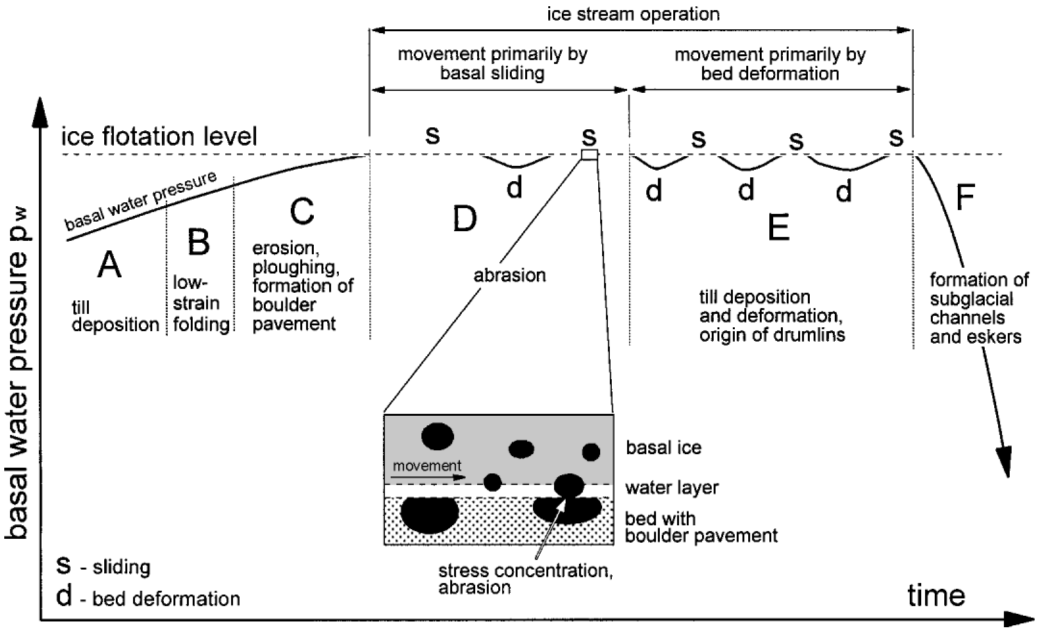

Fig. 10. Sequence of subglacial processes (A–F) in the ice-stream area interpreted in relation to basal water-pressure changes. We envisage that water-pressure conditions decisively influenced the mechanisms of ice movement, sediment deposition/erosion/deformation, and the generation of landforms. During ice streaming, water pressure was in the vicinity of the flotation point, and its fluctuations resulted in switching between basal sliding due to hydraulic decoupling at the ice/bed interface (s) and bed deformation (d). Highest ice-flow velocity is expected at stage D with minimum basal friction due to enhanced sliding on a water film.

zontal truncation of the folded sequence (C in Fig. 10). Significant volumes of sediment were removed under water pressure high enough to weaken tills and outwash, but generally not exceeding the flotation point which would otherwise decouple the ice from the substratum and terminate erosion. We believe that the pavement was either formed immediately beneath the ice sole or under only a thin deforming bed. A thicker deforming bed consisting of weak, dilated material would most likely have prevented ploughing of stones by acting as a buffer between the ice sole and the outwash. This would happen because a deforming till would have lower strength than the underlying outwash and would therefore absorb shear stress rather than convey it downwards to cause outwash deformation by ploughing.

When the ice sole was just above the boulder pavement, the bed was generally stable. This is indicated clearly by one dominant set of striations on the stones and by the fact that they have just one (upper) faceted side. Adversely, stones embedded in a deforming layer would tend to rotate (Hart & Boulton 1991; van der Meer 1997) or otherwise change their orientation, resulting in much more complex abrasion signatures. It follows that ice moved now predominantly by basal sliding due to water pressure at the ice/bed interface elevated to the flotation point (D in Fig. 10). We suggest that the peak of the Funen Island ice-stream flow velocity corresponds to this sliding event. Abrasion of the boulders can be attributed to debris projecting down from the ice sole through the water film, although some later erosion through the accreting (deformation) till is also possible. The thickness of this deforming bed during subsequent evolution of the area is constrained by the depth to the boulder pavement. Worth noting is that meltwater recharge to the subglacial system must have been substantial considering thick, permeable sand and gravel below, capable of evacuating large volumes of meltwater from the glacier bed. One important source of water was probably frictional heating, consistent with inferred high basal ice movement velocity.

As the advance proceeded, the upper (basal) till was deposited. Its accretion was accompanied by some deformation, as indicated by long, attenuated drumlins especially in the more central part of the ice-stream area. Water pressure fluctuated around the flotation point (E in Fig. 10), a condition necessary for pervasive till deformation (Paterson 1994: p. 169). Under such high water-pressure conditions, even slight pressure variations around the flotation threshold can lead to fundamental changes in the ice-movement mechanism between bed deformation (just below) and sliding with ploughing (at the flotation level); thus a combination of the two mechanisms is suggested during the drumlin formation in the study area. Local differences in till rheology, caused by heterogeneous grain-size distribution, could have created a patchy appearance of the bed with areas of more stable and more mobile till, leading to initiation of the drumlin landscape.

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At the final stage of ice streaming, meltwater channels of both R-type (Röthlisberger 1972) and N-type (Nye 1973) drained large volumes of meltwater from the subglacial environment, leading to a water pressure reduction well below the flotation point (F in Fig. 10). Enhanced bed deformation and sliding ceased, and the ice stream was shut down. The fact that the active-ice landscape is not concealed by ice disintegration features, and that the channels in places dissect the hummocky dead-ice relief of central Funen, indicates that the ice stream remained active until shortly before the deglaciation.

It is tempting to suggest that similar mechanisms were involved in fast ice flow also on the southern periphery of the Baltic Ice Stream at Heiligenhafen, where the same association of striated boulder pavement, till fabric and drumlinized landscape occurs, and where Piotrowski & Kraus (1997) determined very high subglacial water pressure in the vicinity of the flotation point.

Conclusions

Based on the data presented, we suggest that northern and eastern parts of Funen Island experienced ice streaming during the Young Baltic Advance of the Weichselian glaciation. Fast ice flow was due to enhanced basal sliding and bed deformation, the mechanisms whose relative importance varied through time. Ice streaming was initiated after a phase of glaciotectonism relatively early during ice overriding and continued until the deglaciation. The postulated ice streaming is supported by the following evidence:

- Drumlins covering the proposed ice stream area are attenuated features with length/width ratios partly above 10. Drumlins seem to increase in length away from the lateral border of the drumlin field, which corresponds to a predicted velocity increase towards the centre of an ice stream. The entire drumlin field occupies the terrain at an altitude *c*. 50–100 m lower than the island interior, i.e. the area where the topography-controlled accelerated flow would be expected.
- The lateral margin of the drumlin field is distinct. It separates the streamlined landscape from the entirely different, stagnant ice hummocky relief on most of the remaining parts of the island.
- Till deformation during drumlinization and enhanced basal sliding over a boulder pavement indicate basal water pressures elevated to the vicinity of the flotation point, implying fast ice flow. Excess meltwater at the ice/bed interface capable of accelerating ice flow is also indicated by the presence of subglacial channels and eskers.
- Close correspondence of three active-ice features, i.e. striations on the boulder pavement, till fabric pattern and drumlin orientation, indicates a remarkably constant flow direction during the Young Baltic Advance. This is consistent with the dynamics of an ice stream, which is laterally confined by nearly stagnant ice, possibly frozen to its bed.

Identification of the fast-flowing ice track on Funen Island confirms the presence of the Baltic Ice Stream at the periphery of the Baltic Sea basin during a late stage of the last glaciation around 14 ka BP. The older highland in the interior of the island was not affected by fast ice flow, which suggests that this major ice stream was split into smaller branches controlled by local topography close to the ice-sheet margin. Positive identification of these second-rank outlets will be difficult, since most topographically low areas are now under the sea. Also, it will be difficult to estimate their lifetime in relation to the duration of the Young Baltic Advance, but at least this branch was active until shortly before ice retreat. The evidence from Funen Island emphasizes the importance of land-based ice streams for the behaviour of the southern part of the Scandinavian Ice Sheet during the last glaciation.

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