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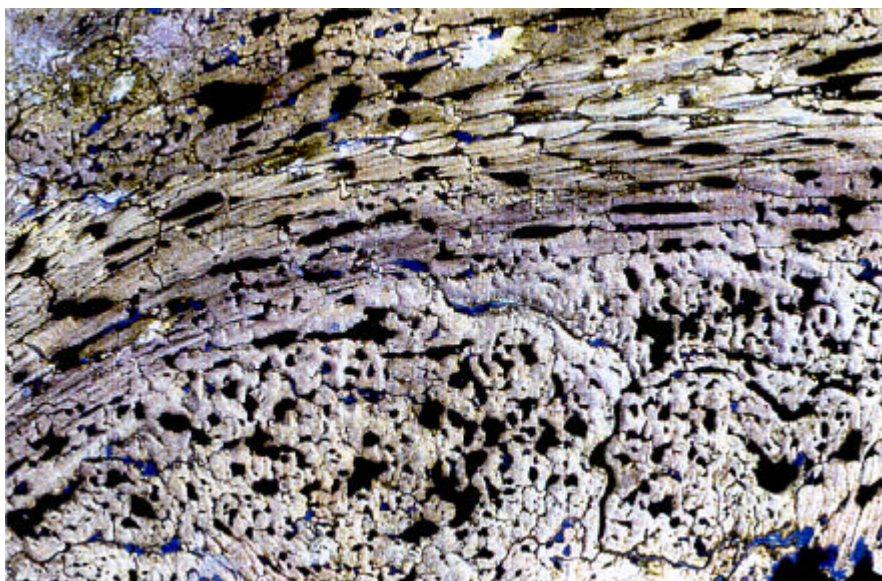
PAPERS AND POSTERS

PALAEO-ICE STREAM INTERNATIONAL SYMPOSIUM

17 – 20 October 2001, University of Aarhus, Denmark

INQUA Commission on Glaciation

D.J.A. Evans, J.A. Piotrowski, C.D. Clark



PALAEO-ICE STREAM INTERNATIONAL SYMPOSIUM

17 – 20 October 2001
Department of Earth Sciences
University of Aarhus
Denmark

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Abstracts are in alphabetical order and are as supplied by authors

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SUBGLACIAL HYDROLOGY AND BED DEFORMATION DYNAMICS DURING A LATE WEICHSELIAN ICE LOBE SURGE IN THE ÖRESUND STRAIT AREA, SOUTH SCANDINAVIA

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Repeated lobate ice advances, superimposed on overall retreat, characterize the early deglaciation phase in southwest Scandinavia. The uppermost of a series of Late Weichselian diamictos in the coastal areas of Öresund strait is easily recognized on geological maps, and corresponds to the distribution of a diamicton rich in clay and chalk. The diamicton forms a smoothly undulating plain and has a distinct depositional limit in the northern and north-eastern basin-ward slopes at altitudes between 65-90 m a.s.l., 20-25 km away from the coast.

Sedimentological investigations were performed in a 700 m long exposure, 3.5 km inside the eastern depositional margin. The lower boundary of the sediments, focused on in this study, is an extensive and undisturbed buried ground surface with sand-wedge casts, and a pavement of frost-shattered and wind-polished clasts. The periglacial surface is covered by glaciofluvial sediments dominated by a system of anastomosing ridges formed in submarginal Röthlisberger channels. The channel deposits grade into subglacial cavity sediments of stratified fine sand, silt and diamicton, which partly infill the depressions between the ridges and taper towards NE. A massive, matrix-supported clay diamicton interbeds the ridge sediments on the ice-proximal side, caps the ridges and cavity sediments, and continues up to the present ground surface along the entire exposure and into the smoothly undulating plain. Vertical and lateral facies variations within the diamicton indicate changes in stress, strain and sediment rheology.

The sedimentological interpretations provide a framework to reconstruct and explain environmental and sedimentological changes during an ice advance. The sedimentary sequence reflects a progressive migration and passage of distinguishable subglacial sedimentary environments over the investigated site, and shows gradual changes in subglacial drainage pattern and sediment transfer. The sedimentological interpretations suggest a glacier advance associated with soft bed dynamics and a glacier movement dominated by ice-coupled soft-bed deformation and by sliding on water and sediment slurries.

Subglacial hydraulic lifting and basal sliding on top of sub-marginal and extruded sediment slurries were the main conditions making the glacier advance over a hard, frozen ground easier. A strong dependence on landscape topography, shown by the halt against ascending slopes, and a subglacial hydraulic system associated with high basal water pressures support a model of ice-lobe behaviour related to low-gradient outlet or surging glaciers. Vertical facies transitions within the diamicton suggest changes in the nature, direction and pattern of subglacial sediment transfer, indicating characteristic changes related to alterations in ice flow dynamics during slow-down and cessation of a surging ice lobe emanating from the overall retreating Weichselian ice sheet.

FAST, ACTIVE ICE SHEETS IN ARCTIC SIBERIA

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The Taymyr Peninsula in central Arctic Siberia has been wholly or partly covered by ice sheets three times during the Weichselian. The ice sheets originated on the Kara Sea shelf and advanced southwards across the peninsula. The Weichselian glacial maximum in this area occurred during the Early Weichselian (100 - 90 000 BP) and the Middle and Late Weichselian ice sheets were successively smaller.

The extent of the different ice sheets is recorded by a number of pronounced ice-marginal zones. These zones are especially prominent in sedimentary basins, but not so conspicuous in elevated or crystalline bedrock terrain. Many of them are lobate, which indicate active, possibly surging ice fronts. Well inside the former ice sheets, there are few traces of the overriding. For example, within the area covered by the latest ice sheet, the only indication may be scattered boulders on top of older glaciolacustrine sediments. Most information on the ice-sheet dynamics and ages is therefore found at their former margins.

An example is given here from the northernmost of the zones, the North Taymyr ice-marginal zone (NTZ), a palimpsest feature that incorporates elements from all three Weichselian glaciations.

The NTZ can be followed for 700-750 km on the mainland, but is not continuous. It is prominent in the large river valleys, but disappears more or less in the coastal hills. In its central parts the NTZ consists of large glacial ridges, 75-100 m high and 2-3 km wide, which to some extent are ice-cored. Superimposed on the large ridges are small morainic ridges, kames, subaqueous fan complexes and ice-contact deltas. At the former ice margin there are also signs of (probably) proglacial deformation. Glaciolacustrine sediments have been folded and tilted and in one area, unconsolidated Cretaceous sands are found on top of remnant glacier ice. Just behind the former ice front there is a supraglacial landscape, where remnant glacier ice is covered by a metre-thick layer of silty melt-out till. For a supraglacial landscape to form, compressive flow with stacking of debris-rich ice is required and this could be caused by an ice-sheet margin frozen to its substrate or, in some areas along the NTZ, also when the ice sheet encountered a topographical obstacle, e.g. an older moraine or a bedrock cuesta.

The till associated with the NTZ frequently contains shell fragments and is interpreted as redeposited and deformed marine sediments. In sections, the till has the characteristics of a deformation till and boulders with short, scattered striae have also been found. The ice sheets were, at least at some point in time, moving on a deforming bed on the permafrozen (>500 m thick) substrate. However, the data is so far rather limited.

Datings indicate three build-up phases of the NTZ and sites along the zone were formed at different times and under diverse conditions. The Early Weichselian phase is most likely a

retreat or readvance stage, while during the Middle Weichselian the NTZ corresponds to the maximum extent. During both these events the ice sheets terminated into large ice-dammed lakes along the central parts of the NTZ. Theoretically, the presence of relatively deep lakes (80-120 m) in front of the ice sheets would have reduced the basal shear stress, lowered the ice-sheet profile and destabilised large subglacial conduits and replaced them with a distributed drainage system, e.g. linked cavities. For the NTZ, however, this appears to be only partially true, as the main melt-water and sediment outflows seem to have been concentrated to lateral and interlobate positions. Nonetheless, along parts of the former ice-margin complexes of subaqueous fans indicate a more distributed drainage system. In higher terrain proglacial drainage was subaerial, resulting in sandur plains or frontal and lateral terraces, depending on topographical conditions. Subaerial drainage was also the case along the entire front during the Late Weichselian, when a thin, rapid and topographically controlled ice advance inundated coastal lowlands and river valleys. Within some 8000 years the ice sheet had expanded (>200 km) and disappeared.

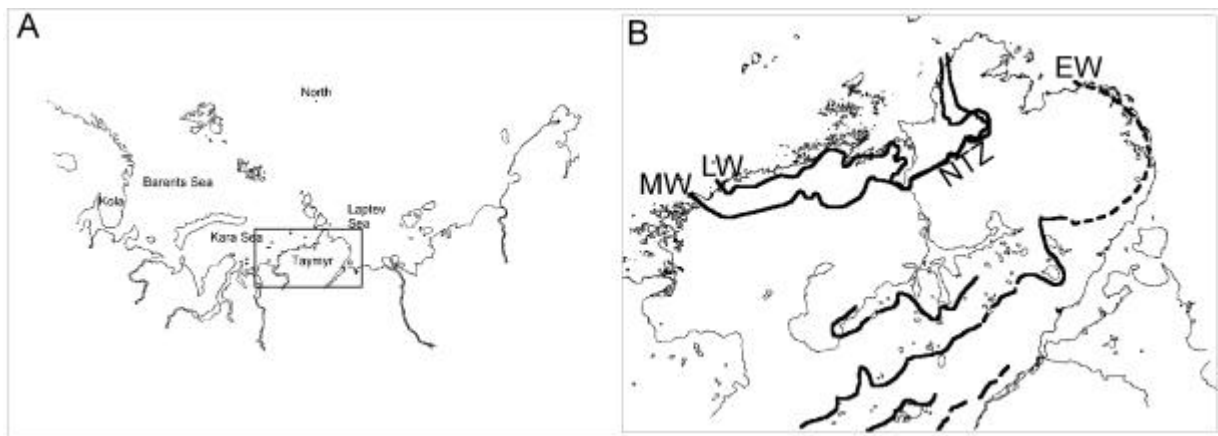


Figure 1. A) Location of the Taymyr Peninsula. B) Ice-marginal zones on Taymyr. EW is the Early Weichselian, MW the Middle Weichselian and LW the Late Weichselian maximum. NTZ is short for the North Taymyr ice-marginal zone.

LARGE-SCALE GLACIOTECTONIC THRUSTING IN THE SOUTH-EASTERN DANISH NORTH SEA, INDICATION OF A PALEO-ICE STREAM ADVANCE FROM THE EAST

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An extensive system of shallow thrust faults affecting Neogene and Quaternary sequences was recently discovered in the south-easternmost part of the Danish North Sea, just west of the Wadden Sea barrier isles Fanø and Rømø.

The offshore mapping of the thrust complex is based on an approximately 2 km by 2 km grid of relatively high-resolution (5-10 m) seismic reflection profiles.

The thrust complex is observed in a 40 km by 20 km wide area. The seismic data has delineated the western extension of the thrust complex, as an approximately north-south striking deformation front situated 35 km from the coast of Jutland. The eastern limitation of the complex is not detected, so the complex is assumed to continue eastwards of the study area towards the shore of Jutland. The thrust complex consists of disturbed, folded and up-thrusted sediment blocks with more than 17 thrust sheets. The direction of displacement is westward with a weakly inclined basal décollement plane, dipping approximately 0.5 degrees toward the west-southwest. On cross sections almost parallel to the direction of thrusting, the horizontal scale of the thrust blocks varies from 100 m to more than 1 km. The décollement surface is situated at depths of about 200 ms (~ 175 m) close to shore and down to depths of about 400 ms (~ 350 m) in the south-western part of the thrust complex. Preliminary correlation with wells in the North Sea indicate that the décollement surface is located in the Mid Miocene.

The thrust complex is tentatively interpreted as a glaciotectonic thrust complex. The transport direction of the thrusting indicates a direction of glacial pressure from the east towards the west. This westerly direction of glacial pressure and the position of the north-south striking deformation front situated in The North Sea, indicates that the glaciotectonic thrust complex have been formed by a Baltic paleo-ice stream of either Elsterian and/or Saalian age.

Thrusting of Miocene deposits is also seen on deep seismic sections in southern Jutland about 15 km east of Rømø. The décollement plane of these deformations is apparently at the same seismic marker in this area as it is in the North Sea. In this part of southern Jutland there is also a north-south striking ridge where Holsteinian deposits have been dislocated in a Saalian event by a Baltic paleo-ice stream.

It is likely that the disturbances of Miocene and Quaternary sequences, as observed in a recently made borehole on Rømø, forms part of the large-scale glaciotectonic complex situated in the South-eastern Danish North Sea. The same may be valid for the dislocations observed in the southern part of Jutland.

MORPHOLOGIC AND STRATIGRAPHIC EVOLUTION OF CONTINENTAL SHELVES AFFECTED BY ICE STREAMING: CONSTRAINTS FROM NUMERICAL MODELING OF WEST ANTARCTIC ICE STREAMS

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Geologic evidence such as deep erosional troughs and submarine 'till deltas' indicate that fast ice streams and outlet glaciers are capable of eroding, transporting and depositing large volumes of debris at high rates (up to $\sim 100 \text{ m}^3/\text{yr}$ per meter width, where ' \sim ' denotes 'the order of'). To sustain such high sediment fluxes, erosion of glacial substrata must be occurring at a rate of up to $\sim 1 \text{ mm/yr}$. Since there is a considerable current interest in the dynamics of ice streams and the geologic products of their activity, it is important to understand the physical mechanisms that control the rate of sub-ice-stream sediment generation and transport. Previously, a viscous model of deforming sub-ice-stream till beds was used to quantify these processes. In this model, debris-transport rates scaled with: (1) the thickness of the till layer squared, (2) the shear stress being applied to the till by the ice base, and (3) the inverse of the till viscosity. However, results of laboratory and field tests indicate that till rheology is nearly Coulomb-plastic rather than viscous. We propose a new mechanism that may be responsible for high rates of debris transport in weak subglacial till beds: till dragging by plowing ice bumps dominates the debris transport in a steady-state and is capable of producing transport rates of $\sim 100 \text{ m}^3/\text{year}$ per meter width. We have modified our numerical model of soft-bedded ice stream flow in West Antarctica. In the model, the till dragging is scaled with: (1) average amplitude of ice bumps, and (2) the ice velocity. The model predicts a zone of till erosion in the upstream areas of the West Antarctic ice streams, where the ice is accelerating. This is consistent with the observed presence of deep (ca. 100-1000 m) subglacial troughs beneath the interior sections of ice streams (also known as tributaries). As our simulated ice stream moves toward its grounding line, its velocity decreases, leading to cessation of erosion and gradual transition to till deposition near the grounding line. This model prediction is also consistent with the existing observations of modern and late Quaternary grounding-zone wedges (formerly known as 'till deltas'). Both erosion and transport rates occur at spatially averaged rates of $\sim 1 \text{ mm/yr}$ when a reasonable effective amplitude of basal bumps is assumed (about 1 m). The same bump size results in very reasonable till fluxes, $\sim 100 \text{ m}^3$ per m width of the ice stream, which is again consistent with the existing estimates of till fluxes during the last glacial maximum. Our model of till transport, erosion, and deposition involves just one adjustable parameter (the effective bump amplitude) and can be easily incorporated into numerical models of ice-stream flow. In the future such coupled models of ice and till flow can be used to infer the long-term history of the West Antarctic ice streams and ice sheets from the geomorphic and stratigraphic record existing on the West Antarctic continental shelf.

IDENTIFICATION AND MODELLING OF TIME DEPENDENT STREAMING BEHAVIOUR IN FORMER ICE SHEETS

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Ice streams are key dynamic components of modern ice sheets. Although they comprise only a small proportion of the area of an ice sheet, they discharge a disproportionate part of its mass flux and have an important influence on its form and mass. Modern ice sheets however only provide an ephemeral snap-shot in time of the long-term behaviour of ice streams.

Study of the large scale distribution of landforms produced by Pleistocene ice sheets permits reconstruction of the location of ice streams within them and the way in which they varied through time. The time dependent behaviour of ice streams in the Scandinavian ice sheet is deduced from geomorphological evidence and compared with time dependent results of numerical simulation of ice stream behaviour during the advance and retreat of the ice sheet. The study yields important conclusions about the locations of ice streams, the processes that govern their initiation and death, the dynamics of the ice sheet and its coupling with the lithosphere.

VOLCANO - ICE INTERACTIONS IN CONTROLLING ICE-STREAM LOCATION IN THE LGM ICE CAP OF ICELAND: AN ANALOGUE TO THE WEST ANTARCTIC ICE SHEET?

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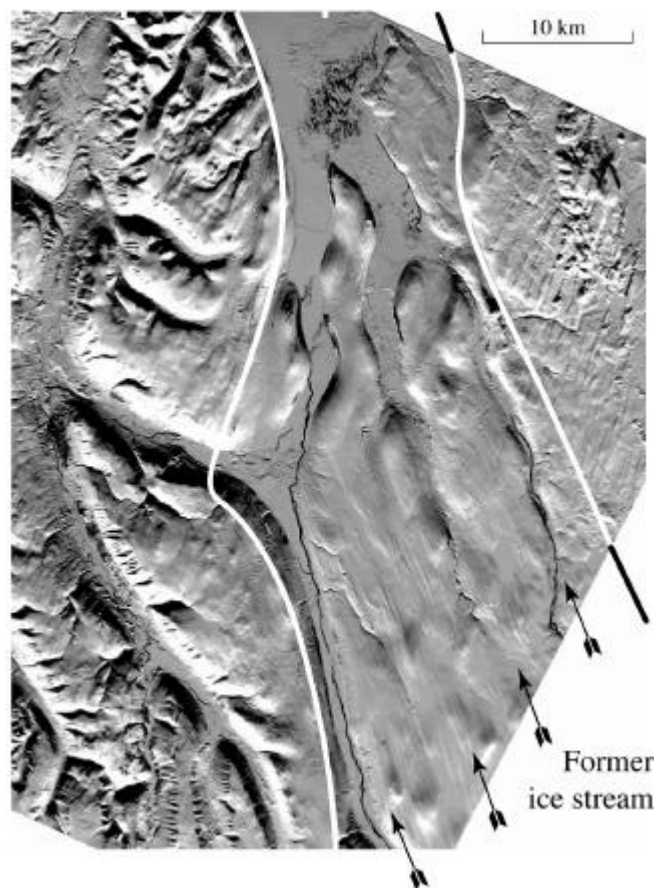
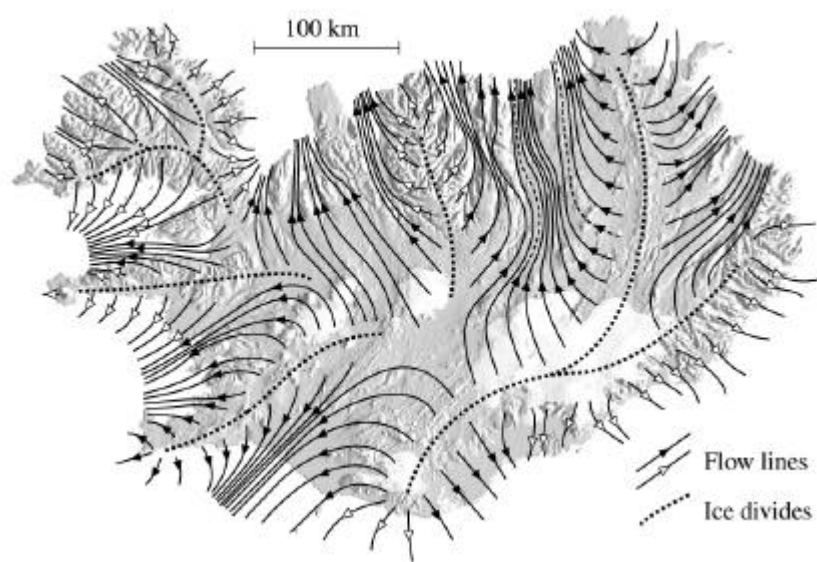
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Both Iceland and West Antarctica are volcanically active. The LGM ice sheet of Iceland therefore provides an analogue to understand the interplay between volcanism and present-day ice flow in West Antarctica. We reconstructed flow lines for the LGM ice sheet of Iceland from the geomorphic record [1]. The reconstruction shows that the ice sheet was partly drained through fast flowing streams (Fig. 1). Locations of the major drainage routes correlate with volcanic regions and with geothermal anomalies. The beds of the ice streams are composed either of heavily scoured basaltic rocks dissected by deep subglacial meltwater channels, or of mega-scale sedimentary flutes visible on SPOT satellite images (Fig. 2). The subglacial sediments are intensely deformed and are mostly composed of basaltic glass shards (hyaloclastite), which were produced by subglacial volcanic eruptions. This suggests that ice stream activity was favoured both by intense ice melting and by production of soft material by volcanoes.

Subglacial volcanic edifices have been preserved beneath the ice divides, whereas they have been removed beneath the ice streams [2]. The processes of removal include (1) incorporation of volcanic products into the ice and removal by ice flow, (2) catastrophic subglacial water and debris flows (jokulhlaups) and (3) long-distance subglacial lava flows. The subglacial volcanic products have been transported to the ice sheet margin and have been deposited in sedimentary fans around the island.

From a compilation of literature data, we investigate similar interactions between ice streams and volcanic activity in West Antarctica. The presence of subglacial volcanoes beneath the West Antarctic ice streams has been inferred from geophysical data [3]. The volcanoes are marked by magnetic anomalies but they do not appear in the subglacial topography, which indicates that their products have been removed by ice flow [4]. A topographic ridge (the 'Sinuous Ridge') however exists beneath the ice divide, close to a probable volcanic caldera [5]. On the basis of its magnetic signature, and by comparison with our work in Iceland, we suggest that the ridge be composed of volcanic edifices preserved beneath the ice divide. We also suggest that, as in the LGM ice sheet of Iceland, volcanism plays a role in controlling the formation of the West Antarctic ice streams.



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ICE FLOW DIRECTIONS DURING THE WARTANIAN IN CENTRAL POLAND

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The study area (300 sq. km) is located in central Poland, 40 km SE of Warsaw. The Wartanian ice sheet was the last one that occupied this region. Recession marginal features in this area, reflect distinct glacial lobes.

The geological structure of this area is characterized by common glaciotectionic deformations. The foregoing studies are an attempt to reconstruct the conditions in which these deformations occurred. Tectonic (mesostructural) investigations were performed for accurate determination of the ice-sheet push directions. Mesostructural measurements included the following: position of beds, lamination, fractures, cleavage, truncations, small faults and axial surfaces of folds. Measurements of directions recorded in tills were also investigated. The dominant of longer axes of pebbles is oriented NNE - SSW in the lower till, whereas it is nearly perpendicular in the upper till (NW-SE).

An outstanding relationship between the present relief and the sub-Quaternary geological structure can be observed. Tectonic structures are of a block character, and reflect the structural pattern of the older basement (predominant NE-SW and NW-SE fault trends).

Compression directions σ_1 , calculated on the basis of mesostructural measurements, vary from NW-SE in the western part of the area (Kuflew, Ko³acz), through N-S in the north (Grodzisk, Natolin), to NNE-SSW and NE-SW in the central and eastern part of the area (P³omieniec, Stoczek Łukowski). This regional variation in compression directions can indicate movement of ice streams within the same ice-sheet body.

CHANGES IN PROPERTIES OF SUB-ICE-STREAM TILLS INDUCED BY BASAL FREEZE-ON: THEORETICAL ANALYSIS AND TESTABLE PREDICTIONS

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Ice streaming under low driving stresses is typically associated with the subglacial presence of a lubricating layer of weak till. The physical properties of soft till depend on many factors that include the subglacial drainage system, the mechanics of loading, and the thermal characteristics of the bed. So far, theoretical investigations of soft bed mechanics have focused on the condition of basal melting. However, recent observations from beneath the West Antarctic Ice Sheet suggest that basal freezing may influence ice stream dynamics significantly. The basal temperature of the stopped Ice Stream C is below the pressure-melting point (Kamb, 2001), and freezing is also probable beneath the inter-stream ridges. A theoretical and observational framework may aid the understanding of how basal freezing change the physical properties of initially weak and porous till.

Here we present a theoretical basis for treating thermo-mechanic aspects of fine-grained till subjected to freezing bed conditions. The means to do so is provided by the theory of frost heave that has been developed and verified by permafrost engineers during the last several decades (O'Neill and Miller, 1985). Grain size characteristics dictate the response of subglacial sediments to basal freezing. Ice will intrude the pore spaces by regelation if the sediment is sufficiently coarse-grained. If the sediment is fine-grained and exhibits capillary characteristics, the response to basal freezing is by freeze-on and ice segregation. Freeze-on is analogous to the surficial frost heave phenomenon and it includes the processes whereby sediment freezing induces a moisture flow, beyond what is caused by the mere expansion of water. The flow of water is directed upward, towards the ice-till interface and the flow feeds the accretion of relatively clean ice. Basal accretion is substituted by ice lens formation when specific temperature and pressure conditions are met within the sediment itself. We have explored the evolution of till properties using a numerical model that couples the flow of heat, water, and solutes towards a freezing ice base. We are able to make testable predictions of sediment properties, sediment entrainment, ice segregation and ice-debris stratification. The model results compare favourably with observations from beneath the West Antarctic Ice Sheet.

This quantitative treatment of till evolution may provide a powerful tool for predicting the deformational signatures of palaeo-ice streams that affected the Laurentide and the Scandinavian Ice Sheets. For instance, characteristic profiles of till properties are found throughout the Great Belt in eastern Denmark. Thin layers of strongly consolidated till are commonly overlying more massive units of much softer till. This observation constitutes a geotechnical anomaly in the case of steady-state melting and drainage into a subglacial aquifer system. We are, nevertheless, able to reproduce such unique distributions of properties with the model of till evolution driven by basal freeze-on. Pore water would have been extracted from the upper-most till layer if the basal regimen of the Baltic Ice Stream at some point switched to freezing. Mean annual temperatures in this region were considerably higher during the Young Baltic Advance 15,000 Bp than the temperatures observed in West Antarctica today (approximately -20 to -30°C). Ice stream thinning to only several hundred meters may thus be required for a thermal transition into basal freezing. In any case, the theory of basal freeze-on seems to provide an appropriate explanation for the otherwise intriguing profiles of decreasing consolidation with depth.

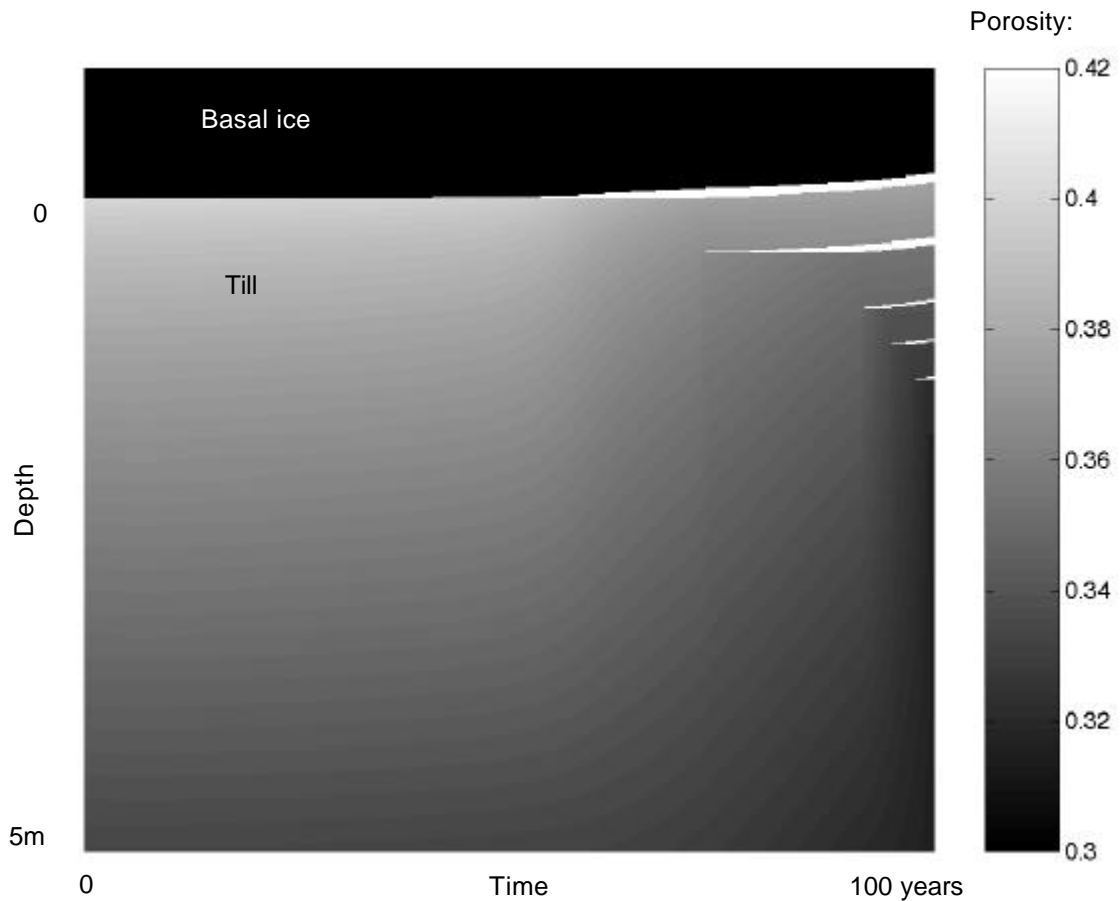


Figure 1. Porosity evolution of fine-grained sub-ice stream till subjected to basal freezing. Model configuration is for West Antarctic ice stream conditions. The ice base is outlined in black and the accretion of relatively clean ice is outlined in white. Grey scale outlines the changes in porosity of the till. Note development of ice lenses within the till and the associated property change. The gradient of porosity becomes negative below the last ice lens. (the results are preliminary).

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A REVIEW OF PALAEO-ICE STREAMS

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The location and behaviour of ice streams is one of the most important controls on ice sheet configuration and stability. In order to reconstruct former ice sheets we need to know ice stream location and timing. Once identified, palaeo-ice streams tracks hold much potential, not least because they provide an unprecedented opportunity to glean information about the basal environment of an ice stream, something which remains very difficult under contemporary ice streams.

This paper discusses palaeo-ice stream research and includes several fresh insights relating their activity to the evidence they leave behind. Evidence is often obscured or modified and there are several, often inherent, problems in identifying palaeo-ice streams. These include the ambiguous use of the term 'ice stream', a lack of diagnostic evidence of their activity, a lack of modern analogues and the problems of ascribing ice streams to solve glaciological problems involved with ice sheet modelling. The temporal context of bedform generation is discussed and we present a conceptual model of a 'rubber stamped' and 'smudged' bedform imprint resulting from isochronous and time-transgressive landform generation. In particular, we focus on the configuration of terrestrially-terminating ice streams, for which there are no modern analogues. We highlight advances made in the light of the most recent work and point to future developments which hold the most potential. It is suggested that marine geophysics from the fringes of contemporary ice sheets, (i.e. West Antarctica) can provide evidence that directly links the geomorphological record of palaeo-ice streams with their contemporary counterparts. Data from palaeo-ice stream beds is invaluable to ice sheet / stream modelling experiments and will help us understand ice stream operation and linkages between climate perturbations and both palaeo and contemporary ice sheets.

A GROOVE-PLOUGHING THEORY FOR THE PRODUCTION OF MEGA SCALE GLACIAL LINEATIONS, AND IMPLICATIONS FOR ICE STREAM MECHANICS

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Mega scale glacial lineations are landforms composed of drift which are produced subglacially. Typical lengths are 6 to 70 km, and widths of 200 to 1300 m. Their large size often requires satellite images or wide swath imaging to observe them, as they can appear too fragmented at the scale of aerial photographs or field investigation (figure 1). Their widespread occurrence was first reported for parts of the bed of the Laurentide Ice Sheet (Clark, 1993;1994) and have since been found elsewhere. It has been hypothesised that the generation of such long ridges with elongation ratios as high as 40:1 was by attenuation of ridges arising from sediment deformation, and that they record fast ice flow events, and can be thus be used as an indicator of palaeo ice stream location (Clark, 1993; Stokes and Clark, 1999). Swath bathymetry and high resolution seismic investigations on the Antarctic continental shelf have revealed drift landforms that have been interpreted as mega scale glacial lineations (Shipp *et al* 1999, Canals *et al* 2000). We take these remarkable finds as validation of the association between mega scale glacial lineations and fast flow as they are found to lie distal to positions of contemporary ice streams. In light of new information on their scale, form, and context we develop a qualitative theory of how they were produced.

An alternate view of a till sheet with parallel repetitive ridges, is that of an originally flat surface with many closely spaced grooves. In this paper we take the view that the appearance of ridges is misleading and a better visual model is that of a highly grooved till surface. Following from Tulaczyk *et al* (in press) a simple qualitative theory is developed and presented that may account for the carving of sub-ice stream grooves. Ice in contact with a rough (scale of 10 – 10³ m) bedrock surface will mimic the form of the bed. If flow acceleration and convergence occurs, as is the case for ice stream onset zones, then these bumps, or roughness elements, will experience strain, transforming them from irregular bumps into longitudinally-aligned keels of ice protruding down towards the bed. Where such keels slide across a soft sedimentary bed, their strength is higher than the bed and so they should ‘plough’ through the sediments, carving elongate grooves.

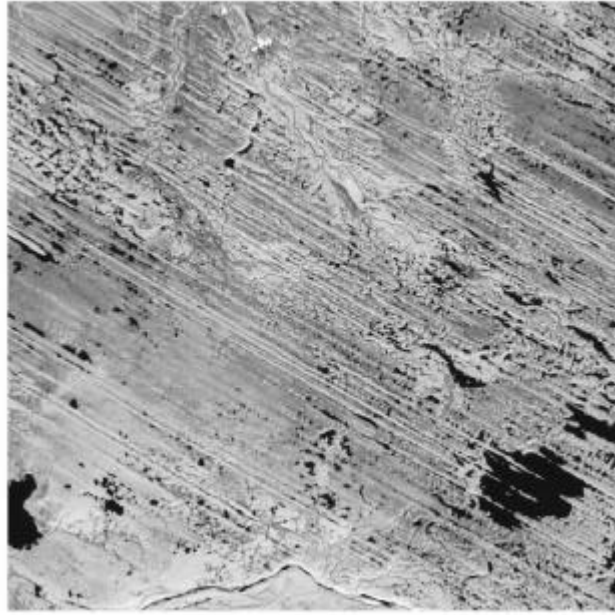


Figure 1.

Methods to validate or falsify this model are; geophysical observations of the real time process in operation; numerical modelling of the ice-bed system to assess the plausibility of generating keels and sustaining them down an ice stream; and development of predictions of the geomorphology that should arise from such a process, compared with actual geomorphology found on exposed ice sheet beds. This paper explores the latter method, and reports the predicted nature of landforms arising from the groove-ploughing process which are then compared to observations from Canada and the Antarctic continental shelf. Implications of this theory for the production of subglacial bedforms, sediment deformation and ice stream functioning are explored.

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GEOLOGICAL EVIDENCE FOR A DYNAMIC IRISH SEA GLACIER IN THE CELTIC SEA: INSIGHTS INTO SUBGLACIAL CONDITIONS AT THE MARGINS OF A PALAEO-ICE STREAM

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Around the terrestrial margins of the Celtic Sea, a shelly diamict facies exposed in coastal sections records deposition by the Irish Sea glacier, a major palaeo-ice stream of the last British Ice Sheet. This ice stream was fed by convergent flow into the Irish Sea basin from ice masses in Ireland and Britain. Along the south coast of Ireland, sedimentological data demonstrate that the shelly diamict facies is a subglacial deformation till and was deposited during the onshore advance of a grounded Irish Sea glacier, which glacitectonically disturbed and eroded pre-existing sediments and re-deposited them as deformation till. Subsequent glacier recession resulted in the formation of ice-dammed lakes in embayments along the south coast, into which glacialacustrine sedimentation took place. These lake sediments were then glacitectonised and reworked by overriding glacier ice of inland origin, which deposited deformation till on top of the succession. Stratigraphic and chronological data suggest that this advance of a grounded Irish Sea glacier along the south coast of Ireland occurred during the last glaciation.

Regionally, this interpretation is consistent with terrestrial and marine geological data from the Celtic Sea and the Scilly Islands. Extensive Dimlington Stadial ice in the southern Celtic Sea was proposed by Scourse et al. (1991) based upon till-like deposits recovered from offshore sediment cores. The maximum southerly extent of this Celtic Sea ice lobe is represented by the Devensian Scilly Till on the Scilly Isles (Scourse 1991a, b). The Scilly Till contains abundant siliceous sponges and Miocene glauconitic micrite derived from bedrock lying offshore to the north and is correlated with “till-like” material in the Devensian Melville Formation (Scourse et al. 1991; Cameron & Holmes 1999) lying in the southern Celtic Sea. The latter is interpreted as the deposit of an ice stream emanating from the Celtic Deep to the south of St George’s Channel and flowing southwestwards towards the shelf edge. A change in depositional processes at approximately 49°30’ is thought to represent either a grounding-line position or a change from proximal to distal glacialmarine sedimentation (Scourse et al, 1991). Wingfield (1994) suggests that the Scilly Till probably represents a short-lived advance by the Dimlington Stadial ice stream. We propose that collectively the evidence from the Celtic Sea and its terrestrial margins points to unstable behaviour or surging of the Irish Sea glacier into the Celtic Sea late in the last glacial cycle. Fast glacier flow would have been facilitated, at least in part, by a saturated substrate of readily-deformable, fine-grained, marine sediment.

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SUBGLACIAL BEDFORMS RECORDING PALAEO-ICE STREAM FLOW ACROSS THE ANTARCTIC PENINSULA CONTINENTAL SHELF

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Swath bathymetric and sub-bottom profiler data collected during Cruise JR59 of the RRS *James Clark Ross* to the western Antarctic Peninsula continental margin reveal a series of streamlined bedforms from the inner part of Marguerite Bay to the continental shelf edge (see also adjacent poster by Pudsey and Morris). Bedforms exhibit progressive elongation across the shelf, from drumlinoid ridges in inner Marguerite Bay, to more elongate mega-flutings on the outer shelf. These data are consistent with the former presence of a grounded ice stream draining the Antarctic Peninsula ice sheet through Marguerite Bay and across the continental shelf. Down-flow transition from drumlinoid ridges to more elongate mega-flutes is interpreted to reflect a progressive increase in ice-stream velocity along its flow path. Published seismic records suggest that diamict units thicken along the palaeo-ice stream path, pointing to advection of till towards the ice-stream margins, probably as a subglacial deforming layer.

SIGNIFICANCE OF HEAVY MINERALS ANALYSIS IN DETERMINING THE SOURCE OF MINERAL MATERIAL IN GLACIAL TILL

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The marginal zone of the Fláajökull glacier (SE Iceland) was researched in order to indicate heavy minerals content in contemporary formed glacial till. There were 11 samples taken from 6 different localizations: 1) 3 samples were taken from the surface of ablation cones located on the surface of the glacier and close to its front edge 2) 1 sample from the crevasse in the glacier ice, probably from the shear plane 3) 1 from the base of the glacier ice at the edge of the glacier, 4) 3 from the stoss side of the youngest and still formed ice-cored moraine ridge 5) 1 from the top of the youngest ice-cored moraine ridge 6) 2 from the bottom of a 1 m deep excavation hole at the top edge of the youngest ice-cored moraine ridge. Heavy metal analysis of the samples showed that surface moraine (localization 1) had a distinctive increase in biotite (over 70 % of total heavy mineral content). Other samples taken from basal and melt-out material were characterised by significantly lower biotite content as well as higher epidote and pyroxene content in comparison with the surface moraine material. Taking into account relatively low density of biotite and its lamellar structure it could be concluded that this mineral was transported by wind and incorporated into the surface moraine. Therefore the analysis of biotite content in glacial till can serve as an indicator of aeolian supplementary deposition onto the surface of the glacier.

PALAEO-ICE STREAMS OF WESTERN CANADA AND THE DYNAMICS OF THE SOUTHWEST LAURENTIDE ICE SHEET

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The understanding of ice streams is of fundamental importance in reconstructing and understanding the behaviour of ice sheets. While little enough is known about ice streams as a whole there seems to be an almost total lack of research on terrestrial terminating ice streams, despite evidence in the Quaternary record suggesting that such ice streams did occur. Alberta, Canada, contains a range of geological and geomorphological evidence believed to be indicative of fast flowing ice and such scenarios have been further substantiated in numerical models of the Laurentide Ice Sheet. A glacial landsystems approach has been employed to aid the interpretation of the glacial history of this region.

Previous research identified three major ice lobes that entered the province from Saskatchewan and the District of Keewatin and whose (coalescent?) lateral margins at the LGM are clearly marked by prominent moraine belts (Evans 2000) located on the higher topography. In the lower lying areas the sediment has been stripped off in places down to bedrock with till patches less than 0.5m thick underlain by extensive sand lenses. The largest of the ice lobes, the Central Lobe (Shetsen, 1984; Evans et al, 1999), produced mega-scale streamlined landforms greater than 90km in length (Evans 1996) taken as a significant indicator of fast ice flow. The interpreted termination of this lobe is the prominent Lethbridge moraine of southern Alberta. The moraine is composed of stacked sequences of multiple tills, glacitectorites and bedrock mega-rafts, comprising multiple ridges similar to push moraines produced by temperate glacier margins. This is interpreted to represent the thickening of tills towards the ice margin producing till wedges (cf. Boulton 1996a, b). The lack of sediment along the length of the Central lobe especially the large expanse of bedrock in the central section known regionally as the Torlea Flats present a convincing case for ice stream shut-down due to sediment exhaustion of a deforming bed driven fast ice flow. Alternatively, the ice stream could have been moving by fast flow due to sliding as high water pressures decoupled the ice from the bed. Evidence for large discharges of subglacial meltwater has been provided by Evans & Campbell (1995) and Evans (2000) based upon tunnel valleys located around Dinosaur Provincial Park. However such drainage entrenchment would tend to limit the areal extent of the sediment evacuation, which does not appear to be the case, and the tunnel valleys are located towards the ice lobe margin. The evacuation of sediment towards the Lethbridge moraine is interpreted to have occurred through sediment flux in a pervasive deforming layer in the region of 5-30cm thick. However, the marginal tills and glacitectorites display deformation signatures typical of low strains, indicating initial deposition towards the ice margin with subsequent reworking

Further to the north, the Lac La Biche ice lobe passed through Alberta and Saskatchewan and was responsible for the production of intense bed streamlining over a distance of more than 250km. Sediment thicknesses along the bed of the ice lobe tend to be greater than those found beneath the Central Lobe (Shetsen, 1987, 1990) and the streamlining terminates in a landscape of cross-cutting ridges (interpreted as crevasse-squeeze ridges) and thrust block moraines. This evidence has been taken to constitute a landsystem typical of surging glacier margins (Evans et

al. 1999; Evans & Rea 1999). The reduced level of sediment evacuation may indicate that ice movement was driven by high basal water pressures sufficient to produce significant ice-bed decoupling. The thrust block moraine provides further support for a surge type advance. Unlike the multiple ridged moraine found at Lethbridge, the Lac La Biche palaeo-ice stream geomorphology lacks evidence of minor push events, indicating that the glacier retreated from the outer thrust block moraine in a passive manner (stagnation).

At least two forms of fast ice flow ice streams appear to be represented in this part of the former SW Laurentide Ice Sheet, a deforming bed driven ice stream where shut down may have been the result of sediment exhaustion and a surge type ice stream where advance and retreat are interpreted to have been rapid. As the large Central Lobe ice stream shut down and the ice margin retreated further north it appears that it became more dynamic with significant amounts of cross-cutting by different flow sets and moraine systems relating to smaller ice streams, the Lac La Biche ice stream being an excellent example. It may even be the case that the evolution of the ice margin into smaller ice lobes resulted in the formation of a chaotic drainage system (i.e. the advance of one ice stream/lobe blocked the drainage of another, causing it to thicken and increase its basal water pressures etc.), that eventually broke out through the blockage and re-initiated the fast-flow cycle. Whatever the exact scenario, the evidence indicates a dynamic southwest Laurentide Ice Sheet margin as it retreated from its LGM at the end of the last glacial cycle. This may constitute terrestrial evidence for the binge-purge cycles previously proposed for the marine margins of the ice sheet and provide the means for rapid deglaciation as required by isostatic modelling.

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SUBGLACIAL-LAKE DRAINAGE AND ITS IMPACTS ON THE DEVELOPMENTS OF ICE-STREAMS: PREBOREAL SE CENTRAL SWEDEN

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Uncertainties on causes of the unbalanced deglaciation pattern of the Scandinavian Ice Sheet as observed in glacial records of the last deglaciation in SE central Sweden raise questions about timing and nature of the collapse of the Last Glacial Maximum ice sheet in Scandinavia. Based on current behavior of the Greenland and Antarctic Ice Sheets today, it seems that retreat did not occur evenly along all edges, but rather was concentrated to certain areas, presumably as ice streams emanated in a few well-defined areas for calving. Recent studies suggest a subglacial lake, presumably in the Lake Mälaren depression during the Preboreal. Sedimentology of esker deposits in the area supports sudden release (jokulhlaup) of this lake when under thin ice conditions prior to deglaciation of the area. This study, discusses impact of such sudden release of subglacial lakes on hydrological conditions of the ice sheet marginal zone and ice streams in adjacent areas. The suggested mechanism supports the proposed glaciological model for the area in which the formation of the Baltic Ice Stream during early Preboreal is considered as the most probable scenario.

RECONSTRUCTING FORMER GLACIAL BASAL THERMAL REGIMES IN A LANDSCAPE OF SELECTIVE LINEAR EROSION: GLEN AVON, CAIRNGORM MOUNTAINS, SCOTLAND

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The granite mountains of the Cairngorms represent a classic landscape of selective linear glacial erosion. A sharp contrast in the intensity of glacial erosion is evident between the deeply incised troughs and valleys and the undulating high plateau. This contrast has been attributed to the fundamental control exercised by the basal thermal regime of the ice sheets and glaciers that covered the Cairngorms during the Quaternary. The funnelling of ice along pre-existing valleys and over cols is thought to have raised basal ice temperatures above the pressure melting point and promoted sliding and linear erosion. On the plateau, however, ice was relatively thin and remained cold-based. This dry-based ice moved by internal deformation, rather than by sliding. Restricted erosion allowed the preservation on the plateau of a preglacial relief, including delicate features such as tors and chemically weathered rock. This model has widespread application to landscapes of selective linear glacial erosion. The Cairngorm landscape is directly comparable to more extensive landscapes of selective linear erosion from Baffin Island, the Torngat Mountains of Labrador, East Greenland and the Finger Lakes region of eastern North America.

This paper examines in detail the development of the landscape of upper Glen Avon, with its 300 m deep glacial trough set within the high plateau of the Cairngorms. Patterns of former high-level ice flow across this area are reconstructed for the first time. The aggregate basal thermal regime of the former glaciers is reconstructed from evidence provided by the mapping of bedforms indicative of wet-based sliding ice and dry-based ice frozen to its bed. This mapping shows that basal sliding is not confined to the trough but extends towards the valley head and to parts of the plateau adjacent to the trough. A survey of weathering pits formed on horizontal granite surfaces indicates that the extent of basal sliding was greatest beneath ice sheets before the Late Devensian. Basal ice temperatures are modelled for ice sheets covering the preglacial and the current topography of the area. The funnelling effect of the preglacial valley system is sufficient to induce basal melting and to initiate valley deepening. This effect is enhanced beneath the present topography. Comparison of results of bedform mapping and modelling reveals, however, significant differences between the actual and predicted extent of basal sliding outside the main valleys.

DRUMLINS AS INDICATORS OF PALAEO ICE STREAMS

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Ice streams are a key element of ice sheet stability, and are thought to be reflected in the Quaternary record by drumlins. This presentation investigates:

- a) the relationship between drumlins and other forms of subglacial deformation, and their relationship to ice sheet behaviour.
- b) an investigation of the drumlin structure continuum (i.e. *depositional*, *deformational* and *erosional* drumlins)
- c) the relationship between drumlins and “bed flow” surge geomorphologies
- d) the role of drumlins in the viscous vs. plastic debate concerning subglacial sediment deformation.

PLEISTOCENE ICE STREAMS IN CANADA: EVIDENCE FROM SUBGLACIAL TILL

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Over the last two decades the idea of palaeo-ice sheet draining by ice streams has become more and more popular. Understanding the underlying mechanisms is important because ice streams and outlet glaciers regulate the discharge and stability of modern ice sheets that have a profound influence on global sea level and climate.

Early arguments were based mainly on glacial dispersal trains of far-travelled erratics, theoretical reconstructions, and extrapolation of modern subglacial processes to Pleistocene ice sheets. Recently the idea has been increasingly based on remotely sensed images of glacial landforms, bedrock distribution (soft and hard beds), extrapolation of experimental results to continental ice sheets, and a great deal of computer modelling. While these techniques help us to imagine the shapes, flow patterns, and dynamics of palaeo-ice sheets, the most direct clues to what actually happened come from till deposited beneath the former ice sheets, especially in marginal areas where most activity was occurring.

With this in mind we will review field evidence for palaeo-ice streams and outlet glaciers from subglacial till in various parts of Canada - beneath the Laurentide and Cordilleran ice sheets. A common trend in several places is the occurrence of fine textured tills in glaciated basins and troughs that at first appear to have formed mainly by lodgement but on closer inspection are found to contain: disorganized stone fabrics and pavements, preserved soft bedrock and sediment clasts, delicate striae that follow stone curvature, and stone lee ends and striae that are inconsistently oriented among themselves and relative to other features. Such data indicate that stones frequently experienced Jeffrey-type rotation in till undergoing ductile deformation which in turn suggests that the till was saturated with pore water and had minimal shear resistance to overriding ice. Thus, the ice probably moved quickly over the slippery bed as an ice stream confined by slower moving ice (e.g. southern Ontario), in some cases over a plume of far-travelled erratics in fine till (e.g. northern Ontario, Canadian Arctic), or as a bedrock-confined outlet glacier from local accumulation areas (e.g. interior and west coast of British Columbia).

PHYSICALLY-BASED MODELLING OF GROUNDING-LINE PROCESSES AND DRAINAGE / TOPOGRAPHY / EROSION RELATIONSHIPS IN ICE STREAMS

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We consider the deformation of glacial sediment at and near the grounding line of ice sheets resting on a bed below sea-level. We use a scale-dependent model for the rheology of sub-glacial till; on small scales (less than about 1m) it is brittle, with most or all of the deformation occurring along shear planes. On the large scale the net brittle deformation aggregates to a viscous flow.

We investigate small-scale deformation by considering the superpositioning (i.e. glaciotectionic\ succession) of deformational events and how this affects the geological record. Observationally-motivated models relating faulting frequency to effective pressure are introduced, and the consequent appearance of geological sections computed. The effect of erosion, accretion and changing stress fields arising from translation of the grounding line are computed.

We consider the large scale erosional effects of ice streams, using models which account for lateral drag. Decoupling of glacier and bed near the grounding line leads to reduced ability of the glacier to move deforming sediment, leading to deposition well behind the grounding line. However, meltwater flux can lead to transport of sediment beyond the grounding line. These effects are demonstrated with an isothermal model. The assumed relationship between effective pressure and hydraulic transmissibility plays an important role in determining erosion patterns.

BASAL TEMPERATURES AND THE EXISTENCE OF AN BALTIC ICE STREAM DURING THE LAST GLACIAL MAXIMUM IN FENNO-SCANDIA

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Numerical modeling suggest that the ice sheet was drained by a "Baltic Ice Stream". The Ice Stream was steered by differences in basal conditions. Information on past thermal conditions are given by studies the deglaciated landscape of Sweden. The interior of Northern Sweden shows very little signs of glacial erosion while the coast of the Gulf of Bothnia and the Baltic show very clear signs of glacial erosion. In the Västerbotten area there is a sharp line wher drumlins change their direction from the inland south east to a much more southern direction, indicating high velocities in the Gulf of Bothnia. In Tornedalen tracers of survival of fragil landforms indicate cold based conditions. Preserved tor formations in tertiary sediments are found at Sydsvenska Höglandet, indicating extreemly little glacial eroison during the entire Quaternary. At the same time the cliffs of the Swedish east coast is one of the most beautiful examples of both large and small scale glacial erosion is clearly seen. Thus from a glacial morphological point of view we may conclude that there have been a mix of frozen areas and basal melting areas.

During a simulated termination it was shown that there was broad agreement about the marginal positions in Sweden and Finland if it was assumed that there was a general sliding zone for elevations below 100 m, with an enhanced sliding zone through the centre of the Baltic and the Gulf of Bothnia. Above 100 m it was generally below freezing. The good fit between these oversimplified levels, geologic evidence and modelled ice dynamics indicate a real relation between bottom topography and glacial basal temperatures, and most probably the existence of a former Baltic Ice Stream.

DID THE DES MOINES LOBE OF THE LAURENTIDE ICE SHEET MOVE BY DEFORMING ITS BED?

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Fluctuations of the Laurentide Ice Sheet may have driven climate change over several time scales during the Pleistocene by influencing the continental water balance, atmospheric and oceanic circulation, vegetation, and land-surface albedo. Fluctuations of the ice sheet may have been strongly related to its flow mechanisms, particularly to rapid basal motion facilitated by a thawed, unlithified substrate. Glaciers may move over such a substrate by two processes: decoupling of ice from the sediment bed and by shearing of the bed at depth. Decoupling involves sliding of ice past clasts that protrude from the bed into the glacier sole and plowing of such clasts through the bed surface. Shearing of the bed at depth occurs as pervasive deformation in a zone that is decimeters to meters in thickness beneath the glacier sole. Determining the relative importance of these processes would focus efforts to formulate a general constitutive relation for basal motion, a requirement for predictive models of ice-sheet motion. The dominant basal-flow mechanism also bears on glacial landform development and sediment transport. For example, pervasive deformation of till substrates may influence the formation of various landforms, including drumlins, eskers, and boulder pavements, and also may account for high sediment fluxes from some Pleistocene ice masses. A first step toward testing these hypotheses is assessing the importance of bed deformation in glacier flow.

The Des Moines Lobe, the most conspicuous of the lobes of the southern margin of the Laurentide Ice Sheet (see figure), underwent large fluctuations that may have been related to its thawed, unlithified substrate. The radiocarbon chronology of the lobe indicates that it flowed rapidly, and past reconstructions of the lobe's geometry indicated that it was thin and gently sloping with a commensurately small basal shear stress. The apparently high flow rate and low basal shear stress of the lobe have led some to compare it to the ice streams of West Antarctica. Our new reconstructions of the geometry of the lobe, based on terminal-moraine elevations and flow-direction indicators, show that it may have been two times thicker than indicated by past reconstructions if its terminal moraine were ice-cored during deposition. Nevertheless, the lobe was thin and gently sloping with basal shear stresses less than 6.0 kPa, indicating that internal deformation of the glacier was not significant. Motion, therefore, was at the till bed by some combination of sliding, plowing of particles through the bed surface, and pervasive deformation of the bed below the glacier sole. Consolidation tests on the basal till of the lobe yielded maximum preconsolidation stresses of 125 to 300 kPa, which indicate that basal water pressure was near the ice overburden pressure. A model of sliding and plowing indicated that at these low effective normal stresses, most particles gripped by the ice will plow easily through the till bed, resulting in too small a shear traction on the bed to deform it at depth. Consistent with this prediction, measurements of the alignment of clasts in the basal till of the lobe yielded a weak fabric, indicating a bed shear strain of less than ~ 2 . We concluded that rapid motion of the Des Moines Lobe was principally at the bed surface by plowing. This implies that transport of sediment must have occurred primarily in the basal ice of the lobe rather than in a shearing, water-saturated till layer beneath the ice.



Figure 1. Maximum extent of the Des Moines Lobe approximately 13,800 years before present.

LAND-BASED ICE STREAMS AT THE SOUTHERN MARGIN OF THE SCANDINAVIAN ICE SHEET: A DECISIVE FACTOR IN PLEISTOCENE GLACIATION PATTERNS IN DENMARK

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Stratigraphically controlled proxy-data on flow directions and the provenance of ice advances indicate that consecutive Late Pleistocene glaciers in Denmark operated in different modes. Possibly, ice streams in the southern margin of the Scandinavian ice sheet flowed from the Baltic and southern Norway onto the Danish lowland. These were, apparently, separated in time and space, by inter-stream areas of ice from Sweden. Though not expressed in modern terms, classical reconstructions by Andersen (1933), Milthers (1942) and Wennberg (1943) on glacier movement in southern Scandinavia operate with narrow and well-defined zones of glacier flow, which resemble ice streams. The theory of outlet surges and marginal domes was elaborated by Lagerlund (1987) in order to explain the same stratigraphical and morphological phenomena on ice sheet behaviour, which kept Ehlers (1990) to hold a more classical point of view. Several recent conceptual models by Boulton et al. (1985), Kleman et al. (1997) and Sejrup et al. (1998) on the dynamics of the Scandinavian ice sheet have been disputed and re-modelled by Boulton et al. (2001). A weakness of these models is an apparent lack of correspondence between morphology, stratigraphy and dating. Also, the combination of very different data sets and their uneven spatial distribution impede these models. In an oral presentation and a poster display we will present data that attempt to bridge some of those gaps.

The signature of land-based ice streams

In a recent overview on the palaeoglaciology of the Scandinavian ice sheet, Pleistocene land-based ice streams are empirically described as channelled and rapid flowing parts of the ice sheet bound by less active, inter stream areas. They are recognized in areas of low topographic relief and identified by longitudinal zones of strong lineations and show fan-shaped margins that extend further than the surrounding glacier (Boulton et al. 2001).

The glacial morphology in Denmark primarily reflects the withdrawal and deglaciation pattern of the youngest two Late Weichselian glacial phases. They show strong lobate marginal features on several scales which includes arch shaped terminal moraines and fanning, flow parallel streamlined terrain. Other evidence of Weichselian retreat and advance-phase glacier flow directions extracted from till stratigraphic studies include striations on boulder pavements, till fabric analyses and glaciodynamic directional elements may reflect similar fan shaped distributions. Pro-glacially formed tectonic structures indicating the position of former and now obscured end moraines are also included. Bed conditions favourable of generating fast flowing ice such as evidence for former proglacial lake basins and dead ice fields especially underlie the tills of Norwegian and Baltic provenance. These tills are characterised by specific contents of far-travelled erratics and the dispersal of exotic and local erratics also suggests weak interaction with the substratum indicating rapid flow for the Baltic glaciers and vice versa for tills deposited by glaciers of Swedish origin. The above-mentioned evidence has been combined with AMS ¹⁴C dating and luminescence age estimates.

Ice streams and their significance

Our data indicate that the Middle and Late Weichelian Baltic and Norwegian glaciers in Denmark were short lived (< 5 ka), they show a variety of features connected with land-based ice streams and they expanded up to several hundreds of kilometres beyond the main ice sheet. The glacier advance depositing till of Swedish provenance was of considerably longer duration (> 5 ka) and with more uniform and regionally dispersed flow patterns and its margins coalesced closer with those of the main ice sheet.

We conclude that an ice stream from southern Norway filled the Norwegian channel in Skagerrak and penetrated deeply into the Kattegat depression at the onset of the Late Weichselian, Jylland Stadial at c. 30 ka BP. An interlude with ice recession between 27- 24 ka BP was followed by the advance from Sweden of the Scandinavian ice sheet over a wide front reaching its maximum along the Main Stationary Line from northeasterly directions at c.22 ka BP. This stage possibly represents an inter-stream area, which could be contemporaneous with the peak in activity of the Norwegian Channel ice stream. This setting could have given rise to the characteristic V-shaped ice marginal configuration of the MSL in Jylland, which from many points of view has seemed enigmatic. Deglaciation and withdrawal towards the northeast was interrupted by smaller re-advances and marine draw down in Skagerrak left Denmark free of active ice at c. 17 ka BP. The Young Baltic glaciers streamed over vast dead-ice fields and split up into individual tongue shaped flows of ice spreading north, west and south. The ice streams created successively younger and time transgressive arch-shaped terminal moraines in eastern Denmark between 17 and 15 ka BP.

We postulate, that ice streams operating at the southwestern margin of the Scandinavian ice sheet have had a decisive impact on the directional pattern, the distribution and on the succession of glaciations in Denmark.

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EVIDENCE FOR PRE-LAST GLACIAL MAXIMUM ICE STREAMS IN CENTRAL LABRADOR-UNGAVA

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A prominent landform assemblage, the Ungava Bay landform swarm of ~100,000 km² south of the Ungava Bay, Canada, is defined by drumlins, crag-and-tails, horned crag-and-tails, and flutes, and indicates ice flow converging towards Ungava Bay. This landform assemblage has been difficult to interpret in terms of ice configuration, dynamics and age, and interpretations have previously included a Lateglacial event and a pre-Late Wisconsinan event.

One suggestion was that the Ungava Bay landform swarm (the areas west and east of the Ungava Bay included) is a mosaic consisting of five distinctly different segments, each formed during different glacial events. However, the southern part of the Ungava Bay landform swarm has been considered as formed during the Lateglacial Gold Cove advance at 9.9-9.6 ka, at which time the Laurentide ice sheet terminated on the southern part of Baffin Island (Kaufman *et al.*, 1993; Fig. 1). Previous explanations of the ice sheet configuration during the Gold Cove advance have, however, failed to explain the correlation between the pattern of till lineations south of Ungava Bay and the ice marginal evidence on Baffin Island. The problem that this explanation faces is that a modeled Lateglacial ice dispersal center in central Labrador and Ungava is situated over the Ungava Bay landform swarm (Pfeffer *et al.*, 1997; Fig. 1).

Air photo interpretations of the Labrador-Ungava region reveal a previously unrecognised level of complexity within the Ungava Bay landform swarm. Specifically, the area south of Ungava Bay consists of at least six well-defined segments, each interpreted to reflect a different ice flow event. We base this inference on observed angular unconformities and crosscutting relationships of till lineations between the six segments (Fig. 1). Because each segment is characterised by converging patterns at segment heads, attenuated till lineations and abrupt lateral margins, all of them previously used as diagnostic criteria for formation by fast flowing ice, we suggest that these segments are the remnant imprints of former ice streams. If true, these different segments could have been formed during a sequence of flow events that were closely spaced in time because they all require a similar ice sheet configuration.

Established relative chronologies on till lineations and striae south of Ungava Bay show that at least two regional ice-flow systems (ice flow towards northeast and east) postdate the Ungava Bay landform swarm. The oldest of these events is interpreted to be of Last Glacial Maximum (LGM) age, based on the location and extent of the inferred ice dispersal center. Both ice flow systems clearly demand that the Ungava Bay landform swarm (Figure 1) predates the Gold Cove advance at 9.9-9.6 ka.

An ice sheet configuration that is consistent with the six locations of the ice streams requires a dispersal centre which is >1100 km south of the ice margin during the Gold Cove advance on Baffin Island. The size of this ice sheet suggests to us that these ice streaming events occurred close to the Last Glacial Maximum. Furthermore, we agree with previous suggestions that Gold Cove advance ice marginal evidence on Baffin Island was transported either by ice from another

source area or by ice centred over southern Ungava Bay during Lateglacial time. The latter ice configuration is compatible with the outline of the ice marginal retreat required for the damming of the numerous glacial lakes that are known to have covered the Labrador-Ungava region during the last deglaciation.

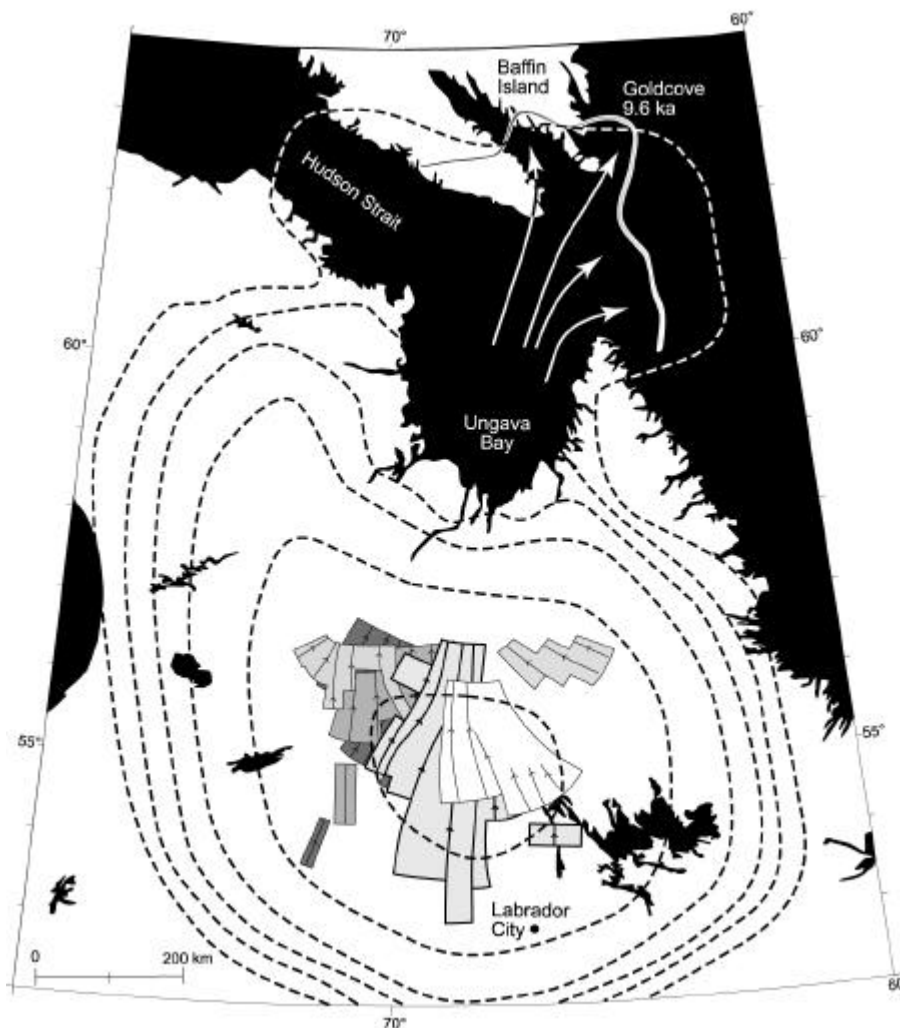


Figure 1. The six different segments (in gray scale) of the Ungava Bay landform swarm south of Ungava Bay, interpreted as the remnant traces of six ice streams. The broken line shows the modeled ice configuration during the maximum extent of the Gold Cove advance (9.9 ka ^{14}C) by Pfeffer et al. (1997). The solid line on Baffin Island and across the mouth of Hudson Strait shows the stipulated northeastern margin of the Labrador Dome during the Gold Cove advance (9.9-9.6 ka) by Kaufman et al. (1993). Arrows indicate associated ice flow direction.

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SIGNATURE OF THE YOUNG BALTIC ICE STREAM ON THE FUNEN ISLAND, DENMARK

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Denmark is situated in the area where Baltic Sea basin ice-streams of the Scandinavian Ice Sheet terminated during the Weichselian Glaciation. These ice streams, active during several glaciation phases followed the basin axis between Poland and Germany in the south and Sweden in the north.

At the Last Glacial Maximum, Funen was overridden by ice from ENE. Shortly after ice-retreat, the Young Baltic Ice advanced from SE and reached its outermost position about 80 km further. It is suggested that during this advance ice streams moved along the low-lying flanks of the island, whereas its interior was covered by more sluggish ice. One of those ice streams is indicated by a prominent drumlin field and other subglacial landforms and sediments in the northern and eastern part of the island.

The drumlin field has an arcuate shape gradually bending from SE-NW over E-W to ENE-WSW along the ice flow path (Fig.1). The field is at least 60 km long and 10-15 km wide, and it covers an area of about 600 km². About 130 individual drumlins were identified with unknown number of drumlins possibly covered by the sea at present. Most of the drumlins are 500-2000 m long and 5-10 m high. The width/length ratio varies between 0.2-0.5. Orientation of individual drumlins changes according to the shape of the entire field. There are also eskers and small subglacial channels oriented radially from the drumlin field towards the island's interior.

Funen drumlins are composed of till. Till fabric is strongly clustered parallel to drumlin axes, which suggests that the drumlin-forming till derives from the same ice advance that formed the drumlins. This till covers the entire field including the inter-drumlin areas, where it is c. 2 m thick. In the central part of the field a pavement of stones pressed down into the substratum occurs at the till base. The stones are heavily striated on their upper surfaces and striation orientation corresponds exactly to both till fabric and drumlin axes orientation. Below the boulder pavement are outwash sediments, often folded and truncated at the top.

The entire area has a distinct imprint of subglacial processes, both glacial and glaciofluvial that created the morphology and associated sediments. We believe that fast flow of the ice stream was facilitated by a combination of soft substratum deformation indicated by drumlin formation, and by basal sliding on a transient water film indicated by striated (ploughing) and undeformed boulder pavement. Subglacial water pressure would have been in the vicinity of ice flotation level, falling below it after water drainage events through the channels.

Identification of landform/sediment assemblages such as these on Funen Island and numerous similar assemblages in other areas of the Peribalticum indicate that ice transfer within the Scandinavian Ice Sheet during the last glaciation occurred primarily via ice streams, which suggests broader implications for the behaviour of land-based ice sheet margins at the periphery of the Baltic Sea basin.

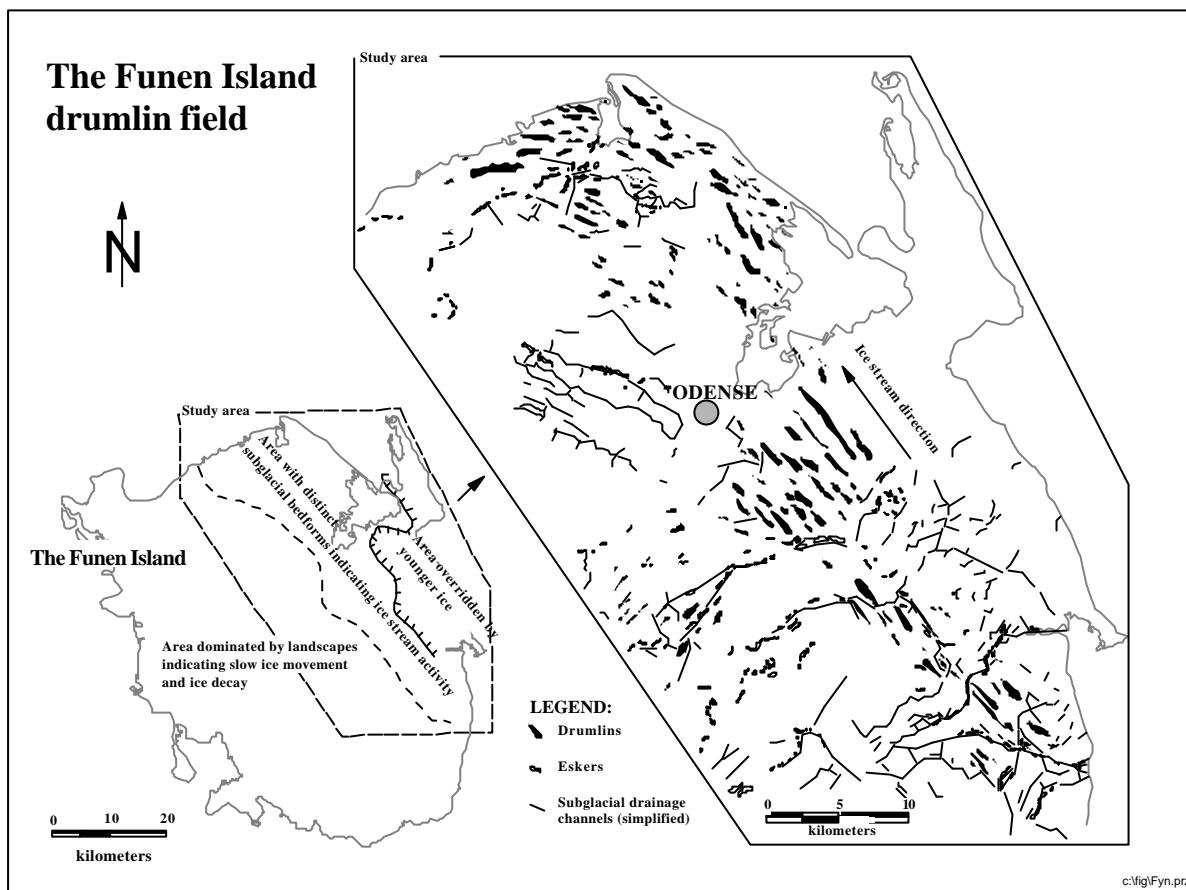


Figure 1. The Funen Island subglacial landform assemblage suggesting ice streaming.

LATE-GLACIAL (GOTIGLACIAL) PALAEO-ICE STREAMS OF THE SOUTHEASTERN SECTOR OF THE SCANDINAVIAN CONTINENTAL GLACIER

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The time interval between the maximum extent of the Weichselian glacier and final deglaciation in the Early Holocene is termed **Gotiglacial**. The period is characterized by active movement and rapid changes in the flow patterns of the glacier streams and lobes. The alternation of lobe depressions and interlobate formations (as plinth type uplands of glacial erosion and island-like accumulative heights) is characteristic of the area of the Gotiglacial morphogenesis.

Analysis of the morphology of the lobe depressions in the southeastern sector of the Scandinavian Ice Sheet shows that declination to the right from the geometrical (theoretical) radial lines of the ice sheet was typical of the ice streams and lobes in the area. The interlobate formations as the local ice divide zones also show an evident trend to be oriented from northeast to southwest. Declination to the right from the radial lines of the ice sheet resulted in asymmetry of glacial erosion: as a rule the west slope of a lobe depression in the bedrock is steeper than the eastern one (the depression of Lake Peipsi in Middle and Upper Devonian sandstones, the depression between Pandivere and Ahtme bedrock elevations of Silurian limestones and dolomites, the Riga lobe depression, cut by the glacier into Devonian sandstones, etc.).

The megadrumlins of the Gulf of Finland also show evident asymmetry in their cross sections. The same regularity can be traced in the morphology of the Saadjärve drumlin field. The eastern (northeastern) slopes of drumlins, in average, are remarkably steeper than the western (southwestern) ones.

The curving of the ice lobes to the right in the southeastern sector of the Scandinavian glaciation is evident. The problem of the origin of this phenomenon which has been discussed in several papers (Ehlers 1990; Matoshko and Chugunny 1993, p.145; Karukäpp 1996, 1999) is still open for further discussions.

INHOMOGENEOUS STRAIN DISTRIBUTION IN DEFORMABLE SUB-ICE STREAM TILLS?: OBSERVATIONS FROM WEST ANTARCTIC AND EXPERIMENTALLY SHEARED SAMPLES

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Micromorphology is a relatively recent technique that has been effectively applied to interpret genetic forming processes of glacial deposits, particularly subglacial till deformation. Despite many exciting recent developments associated with the technique, there is a strong need for systematic investigations of the promises and limitations of till micromorphology. Here, we present preliminary results of our study, in which we compared micromorphology of modern, sub-ice stream tills from West Antarctica with micromorphology of the same till material that was remolded and sheared in a ring-shear device to different total displacements. The principle objective of this work was to verify whether we can use micromorphological characteristics of the sub-ice stream tills to infer the magnitude of strain that they have experienced. To this end, the simulated deformed ice stream till is used for calibration.

Our sub-ice stream samples are derived from sediment cores collected by B. Kamb and H. Engelhardt at Ice Stream B, C, and D, West Antarctica. Texturally and compositionally, all of these cores contain remarkably similar, macroscopically structuresless, clay-rich diamicton (Tulaczyk et al., 1998; unpublished data). We impregnated our samples using an acetone exchange method and a very low viscosity (“Spurr”) resin. For our RSD tests we used remolded samples of Ice Stream B till with 40% porosity. The annular till sample that is subject to shear is 1 cm thick and 3 cm wide. The lower platen of the RSD, which holds an annular specimen, is rotated at the rate ranging from ~0.1 m/day to ~10 m/day, which corresponds to typical ice velocities. We conducted 8 tests that sampled the till in a range of states, including unloaded/unsheared to 770cm shear displacement. An undisturbed till sample was removed from each test, impregnated and thin sectioned in two planes (perpendicular and parallel to shear direction).

We performed qualitative microstructural and semi-quantitative microfabric analysis on the thin sections using a gridding technique (modified from Clark and Wilson, 1994), that maps spatial distribution of the particle orientation (developed with A. Ford, University of Utah). Initial investigations of the experimentally-sheared till show that at higher strain magnitudes, particle orientation in the RSD sample is distinctly inhomogeneous with small clusters of highly oriented grains (Figure 1). At the same time, a very strong plasmic fabric develops even at relatively low strain in this clay-rich material and remains similarly strong when shear continues to high strain. Somewhat surprisingly, samples of the real sub-ice stream tills do not show such strong plasmic fabric although they are likely to experience deformation of ~10 to ~100 strains per year (Alley et al., 1986; Engelhardt and Kamb, 1998).

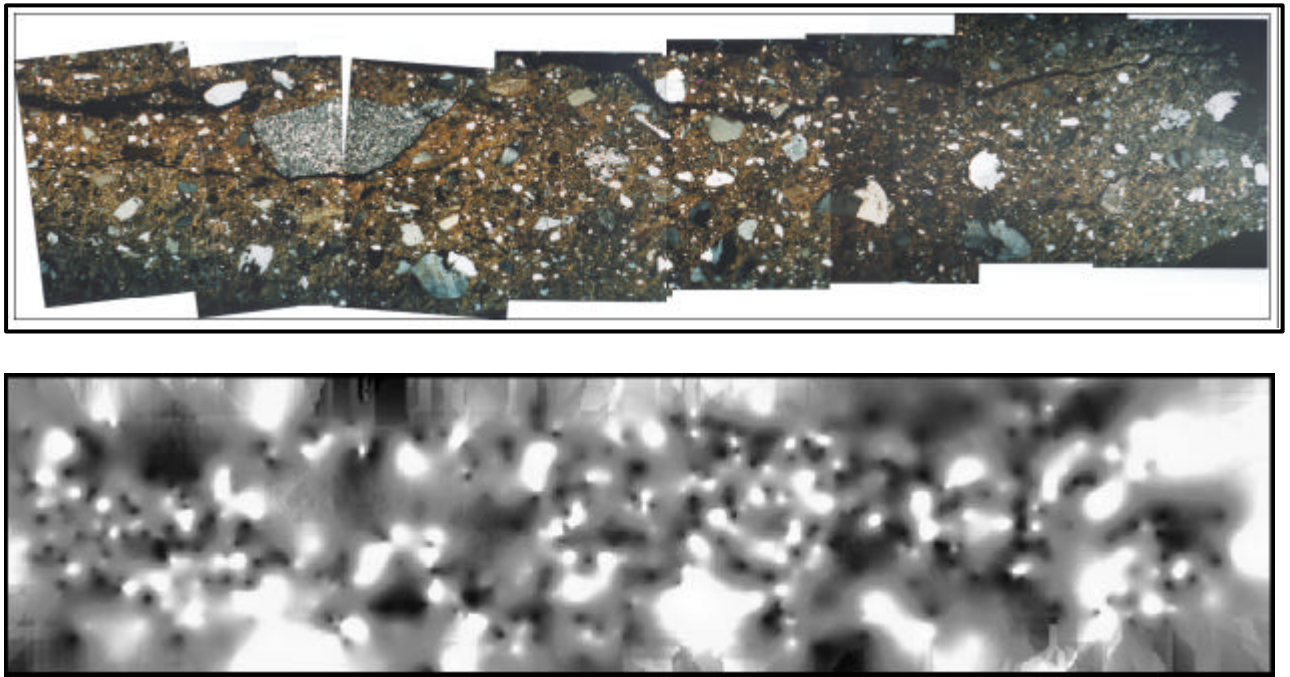


Figure 1. Inhomogeneity in particle fabric as illustrated by deviation of long particle axes from the general direction of shear (here horizontal.) Black designates areas where particles align perfectly with the direction of shear and white designates deviation of 90° from the direction of shear. The greyscale intensity is scaled linearly between the two end members. The image was prepared with data from the central part of Fig. 4 (thin section photomicrographs shown above).

Our interpretation of these preliminary results is that in the real sub-ice stream environment strain may be distributed in a much more inhomogeneous fashion than in the ring-shear experiments where simple-shear deformation predominates. An inhomogeneous subglacial strain field would result in local changes in the direction of shear till, which may be sufficient to disrupt the preferential alignment of clays that gives rise to the plasmic fabric.

Pending verification of our observations, we propose inhomogeneous strain distribution may be the predominant mode of deformation of weak subglacial tills. Such inhomogeneous deformation fields could arise from: (1) ploughing, (2) spatial variability of till properties, and/or (3) inherently chaotic interactions of till particles. This picture of subglacial till deformation is significantly different from the previous models of till kinematics, which focused on laminar (simple-shear) till deformation. More inhomogeneous ('turbulent') nature of deformation would have significant implications to the existing models of subglacial till transport and to interpretations of past till deformation from the glacial geologic record.

GLACIODYNAMICS AT THE SCANDINAVIAN ICE SHEET MARGIN: RECOGNITION OF PALAEO-ICE STREAMS AND INTER-STREAM AREAS

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When the last Scandinavian ice sheet terminated in the Late Weichselian, ice streams operating at its southwestern margin apparently had a strong influence on the glaciation pattern over Denmark. A hitherto unpublished event-stratigraphical model based on extensive litho- and chrono-stratigraphical investigations show that the ice sheet reached its first maximum extent in the Kattegat – Skagerrak region about 28 ka BP by glacier ice flowing southward from Norway. After an ice free period the second maximum along the main stationary line was reached at c. 22 ka BP by an advance from Sweden (Houmark-Nielsen, 1987, 1999). This is probably contemporaneous with an ice stream from southern Norway (Sejrup et al., 1998), which drained through the Norwegian Channel and consequently affected the general outline of the southwestern ice margin due to marine down draw. The succeeding deglaciation left Denmark free of active ice at c. 17 ka BP. Nevertheless, glaciers from the Baltic region subsequently invaded Denmark twice between 17 and 15 ka BP. For the time slice 22-18 ka our model embrace with a scenario where fast moving ice streams in the Norwegian Channel onto the shelf break and through the Baltic depression deeply into the Polish-German lowland, were separated by more slowly flowing ice from Sweden (Sejrup et al., 1998; Boulton et al., 2001). Between 17-15 ka BP Baltic ice streams invaded the former interstream area in central Denmark now occupied by vast dead-ice masses. The crucial question is, however, whether this configuration might be substantiated by field evidence. We address the question of distinction between ice streams and interstream areas on basis of geomorphology, directional patterns of former glaciers and till compositional properties. Also, we explore the possibility that stratigraphically controlled dispersal patterns or trains of distinctive lithologies in conjunction with ice-flow directions may provide insight into the dynamic behaviour of different parts of the margin in former Scandinavian ice sheet.

Data acquisition

Reconstruction of ice-flow and dispersal patterns is based on stratigraphical controlled proxy data i.e. fine gravel counts (3-5 mm grain-size fraction) from individual till units. Only well-documented sites with a significant stratigraphy were used. Stratigraphic units are defined by lithic properties other than compositional features i.e. clast fabric and other directional elements such as glaciodynamic structures and sub-till glaciotectonic unconformities (Krüger & Kjær, 1999). Well aware of the possible conflict in defining the stratigraphical units, directional elements as characterized in the principal of kinetostratigraphy by Berthelsen (1978) are collectively with geomorphological evidence used to provide an impression of ice flow patterns for ice streams and interstream areas.

Ice-flow and dispersal patterns

The Swedish interstream area under which the Mid Danish Till was deposited shows a general ice flow direction from the NE with a pronounced uniform ice-flow pattern. In

general, the Mid Danish till displays several well-defined areas of enrichments over local bedrock highs or in areas where thrust sheets and slabs of pre-Quaternary bedrock are present. Subsequent downstream loss occurs over relative short distances. Apparently, exotic rocks are dispersed rapidly after entrainment e.g. the proportion of crystalline rocks decreases from 85% to 50% over a distance of c. 100 km. Successively, two young Baltic ice streams reached Denmark; an older with a fan-shaped ice-flow pattern from E and SE which deposited the Eastjylland Till; a younger with a strongly lobate ice-flow pattern from SE and S, which deposited the Bælthav Till. Three separate lobes are associated with the youngest of the Baltic ice streams and, most likely time transgressive in nature, although their relative order is still uncertain. Moderate and non-uniform downstream loss is evident for the Baltic glaciers, but no enrichment over local bedrock highs occurs. However, some of the exotic rocks such as Palaeozoic sediments are transported progressively further (>200 km) to the maximum position of the ice streams. The dispersal pattern of sediments in the Bælthav Till shows a strong lobate distribution of Baltic rocks and a limited or moderate dilution from local glacial sediments. Thus, there is a difference in ice flow and dispersal patterns between the proposed ice stream and interstream areas.

The change in dispersal patterns of local material between our postulated ice stream and interstream areas indicate a gradual decrease in the interaction with the substratum i.e. strong interaction associated with the Mid Danish Till interstream area to weak interaction with the young Baltic ice streams i.e. Eastjylland Till and Bælthav Till ice-stream areas. Furthermore, it emerges that tills deposited by ice streams show distinct ice-flow parallel transport path, lobate distribution and reduced downstream loss of erratics. Therefore, the Late Weichselian change in mode of operation from an inter-stream area to an ice stream area over Denmark, reflects successively thinner glaciers, faster flowing ice and a stronger control exerted by the local bed topography. The dispersal patterns of sediment in the three tills are interpreted to reflect progressively faster flowing ice that retains the debris load in transport (Clark, 1987).

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HOLOCENE GLACIAL HISTORY OF DISKO BUGT, WEST GREENLAND; IMPLICATIONS FOR THE DYNAMICS OF THE JAKOBHAVN ICE STREAM

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The Jakobshavn ice stream is the largest ice stream in West Greenland, draining c. 7% of the Greenland ice sheet and a major source of ice bergs for Baffin Bay and the North Atlantic. The deglacial chronology for this section of the Greenland ice sheet has been relatively poorly studied, with a radiocarbon chronology provided by shells and other detrital carbonaceous material derived from a range of coastal, near-shore and sub-tidal settings. In this paper we present the results of a study designed to improve the deglacial history of the Jakobshavn ice stream in the wider context of the Disko Bugt portion of the West Greenland ice sheet. Our work relies on the collection of multiple high resolution relative sea-level (RSL) histories, which we use to constrain the regional glacio-isostatic field. Field sites lie north and south of the former ice stream, and together constitute a 150 km west-east transect from the outer coast to the inland sector of Disko Bugt, straddling the former route of the Jakobshavn ice stream. Stratigraphic, palynological and radiocarbon analyses from over 30 lake basins located from below present mean sea-level to 120 m above provide a regionally coherent chronology for deglaciation. These data suggest rapid collapse of the Jakobshavn ice stream between c. 10.4 ka and 9.2 ka cal. yrs BP. This is several thousand years later than previous models have suggested and implies the ice stream was able to maintain position on the continental shelf well into the early portion of the Holocene climatic optimum. A topographic high which extends across the western entrance to Disko Bugt appears to have had no significant impact on the deglacial chronology; rather we see rapid ice stream retreat to the position of the well developed “fjord stage” moraines dated to c. 8.2 ka cal. yrs BP in the eastern portion of Disko Bugt. The most plausible explanation for the late and rapid retreat of the Jakobshavn ice stream is that its collapse records the crossing of a stability threshold, triggered by the long-term upwards trend in relative sea-level and ice sheet / ice stream thinning due to climate warming. The Greenland ice sheet retreated perhaps 10's of km landwards of its current margin during the Holocene climatic optimum (up to c. 5 ka cal. yrs BP), and thereafter advanced to its current position during the neoglacial. Late Holocene RSL rise, amounting to up to 5 m since c. 2.5 ka cal. yrs BP, may record crustal flexure in response to this readvance. A key outstanding question is the degree to which the Late Quaternary dynamics of the Jakobshavn ice stream reflects the regional behaviour of the Greenland Ice Sheet, and to what extent it is a function of more specific set of controls related to the ice stream itself.

ICE-FLOW DIRECTIONS IN POLAND AND ADJACENT AREAS DURING THE LAST GLACIAL MAXIMUM

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Ice-flow directions during the Last Glacial Maximum can be determined by presence of direct and indirect features. Among the former there are streamlined landforms with drumlins as the most significant, till fabric and glaciotectionic deformations. Indirect features include glaciofluvial streamlined landforms with glacial tunnel valleys and eskers, but also petrographic indicators (erratics, trace elements, glacial rafts, etc.). Especially fabric analyses of tills, their varied clast petrography with indicator erratics included, give valuable data to distinguish ice-flow pattern during the Last Glacial Maximum.

Kliewe (1961) presented a general system of ice streams in the southern Baltic Basin. Basing on geomorphologic criteria Lencewicz (1927) was the first one who suggested a lobe-like pattern of ice sheet in central Poland during the Last Glacial Maximum. On the basis of occurrence of marginal features, an existence of ice lobes during the Pomeranian Phase has been postulated for the Lower Vistula and Lower Odra regions since the fifties of the previous century. Glaciotectionic structures in landforms of northern Poland suggest a lobe-like pattern of the ice sheet during the Last Glacial Maximum, similarly as in the adjoining part of Belarus. The general lobe pattern seems to reflect partly recent tectonic block movements of the Quaternary bedrock.

The southern limit of the ice sheet in the Polish territory has not been definitely synchronic at the Last Glacial Maximum. As indicated by different erratic assemblages in tills and their fabric, this limit was created by at least three main ice streams expanding from the Baltic Basin. They were the Odra, Vistula and Lithuanian ice streams and they reached the Polish territory *via* the Pomeranian, Gdańsk and Riga Bays. The main ice streams were supported also by the secondary ones, namely the Pomeranian and the Mazury ice streams that reflected a stream-like structure of the ice body flowing out from the Baltic Basin southwards. All the glacial lobes do not seem to have occurred simultaneously but their exact dating is still badly lacking.

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CHALLENGES FOR PALEO ICE STREAM PORTRAYAL IN ICE SHEET MODELS

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Ice streams present a challenge to ice sheet models because of their subgrid scale and their complex dynamics. Active ice streams on West Antarctica's Siple Coast and in Northeast Greenland flow through some combination of decoupled sliding over the bed and subglacial sediment failure, with relatively little ice flux associated with internal ice deformation. The spatial and temporal controls of these basal flow processes are not fully understood, but they involve subglacial thermal, hydrologic, geologic, and topographic conditions. While ice temperatures are internally predicted in ice sheet models, treatments of basal hydrology and subglacial sediment deformation remain essentially absent or oversimplified.

Garry Clarke and I have developed a continuum mixture framework of ice-sheet/ice-stream thermomechanics which creates the ability to portray ice streams in continental ice sheet models. This framework helps to overcome challenges of scale and it allows distinct treatment of ice sheet vs. ice stream dynamics (creep flow, dominated by vertical shear deformation vs. basal flow, with strain rates in ice streams dominated by longitudinal and horizontal shear deformation). Ice stream mechanics and ice-stream/ice-sheet interactions can be included in continent-scale models through this treatment. Important limitations and questions remain, however. When and where do ice streams arise? What mechanisms trigger and shut down ice stream activity? How do ice streams grow? How is basal shear stress (hence, ice stream vigour) regulated by subglacial hydrologic and geologic conditions? Can the subglacial hydrologic system be modelled with veracity? All of these questions require attention. I discuss these issues with numerical examples of the sensitivity and importance of these processes. This ongoing work is building towards a model-based analysis of paleo ice streams in North America.

SEDIMENT RECORD, BEDROCK EROSION AND SICHELWANNEN GENESIS IN SW SWEDEN: IMPLICATIONS FOR ICE DYNAMICS

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Bedrock and deposits: some regional characteristics. There are large areas with bare rock in SW Sweden, i.e. practically lacking the cover of Quaternary deposits, or with a very thin (<0.5 m) diamicton in patches on the outcropping bedrock. The zone of 'naked rock' is 50-80 km broad along the Skagerrak, 20-30 km along the northernmost Kattegat where it ends abruptly (Rudberg 1967, Fig.2). The explanation for this zonal pattern cannot be found in marine abrasion, lateglacial-periglacial mass movements or postglacial modifications. Crystalline rocks make up the bedrock in both types of land areas, and both have a nearby connection to the open sea. The retreat of the Late Weichselian ice sheet along the coast is marked by distinct marginal moraine ridges of diamicton and some stratified sediments. Otherwise, however, glaciofluvial deposits are scanty in the bare-rock region, lacking eskers etc., compared to the till-covered neighbouring areas. Glacial clay covers vast areas below the highest coastline. A number of large drumlinoid forms, containing sediments from different glacial and stadial epochs, occur in the Göta-älv valley but are mainly restricted to areas further south and east. Their top surface is sometimes occupied by small transverse moraines from a different ice-movement direction.

Bedrock morphology: some general characteristics. The northern part is characterized by a central high-level area of rugged plateaus (the 'fjälls' of Bohuslän), descending to the Lake-Vänern basin in the E, and to the skerries and the Skagerrak depression in the W. The southern part shows a step-by-step descending from the South-Swedish Highlands in the E (till area), to the coastal plain of Halland and the Kattegat in the W. One of the broad valleys cutting through Bohuslän terminates in the Gullmarn, a narrow fjord with a shallow threshold. The detailed rock sculpture is partly influenced by differences in rock type (granite, gneiss, metabasite). Roches moutonnées are very frequent in the whole area. They occur in different scales, and the surface of 'giant' forms is often strewn with smaller roches moutonnées and other glacial or glaciofluvial imprints.

Striae and p-forms. Striae from the NE quadrant occur all over the area, but with great variations in type and relative age. Striae from N-NNW-NW are also reported, sometimes attributed to a supposed older Norwegian ice movement, sometimes definitely the youngest striae set of the site. 'Plastic' bedrock sculpture is abundant in the northern (Bohuslän) part, but is less developed or totally missing in the southern (Halland) area. The p-forms (s-forms) of the bare-rock area are especially frequent in the broad central part and further eastward to the Vänern basin.

The sichelwannen case. Sickle-shaped rock depressions - sichelwannen - are shallow pots with two horns pointing in the ice movement direction, occurring alone or in clusters. These special p-forms vary in size from cm to many m in width, from cm to dm in depth, and occur on rock surfaces of all attitudes, even on precipitous rocks (descriptions in Ljungner 1930, Johnsson 1956; cf. Shaw 1988). The subglacial origin is indicated by their orientation parallel with the bedrock striae. But their genesis is still a controversial issue (sheet-flood water-erosion, cavitation-implosion erosion, ice-water, slurry-till, deforming-sediment erosion; Ljungner 1930, Hjulström 1936, Johnsson 1956, Gjessing 1965, Eyles and Boyce

1998, respectively.). Detailed studies of some sichelwannen sites indicate that these forms are shaped by glaciofluvial erosion but also some grinding activity. The cavitation-implosion hypothesis must be rejected. There are evidences of strong water-erosion but not of an once-only catastrophic flooding. Successive generations of sichelwannen, with stages of cm-dm-m scales, have formed and grown in size, as seen where granite plucking repeatedly generated successively new rock-surfaces. The iterative character with alternating fluvial and glacial dominance, points to differences over time in water and sediment supply (cf. Andersen and Sollid 1971). The striating till facies (slurry till, deforming till) may have accentuated some part of a sichelwanne already existing, but mainly reduced-erased such forms. The regional distribution of sichelwannen shows some analogies with the extension of bare-rock areas. Abundance of sichelwannen characterizes most of the Skagerrak-Bohuslän area, but there are zonal differences with higher or lower frequency.

Conclusions. The design and areal distribution of bedrock erosion and sediment deposition may have many explanations being a summing up of a long evolution with many shaping-overprinting-erasing phases. The distribution of bare bedrock and specific rock sculpture indicates different ice characteristics in different regions of SW Sweden, perhaps with (periods of) rapid *ice-streams* operating in the northern part (Bohuslän-Skagerrak area; cf. Boulton et al. 2001, ice-stream A), in contrast to more sluggish ice in the southern part (Halland-Skagerrak). The ice dynamics, determined by many factors in the ice-bedload-bedrock environments, may also be directly and indirectly related to regional differences in topography (e.g., the Lake-Vänern basin in contrast to the South-Swedish Highlands, the deep Skagerrak to the shallow Kattegat), with different possibilities to receive, produce, store, pond and evacuate subglacial water above the impermeable crystalline bedrock.

Field evidence implying ice-streams activities in other regions e.g., S Norway, Skåne, Bornholm, SE Sweden and Åland), are shortly noted, with relevance to the overall evolution of ice cover and ice movements during the Weichselian.

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GLACIAL DEPOSITS AND ICE SHEET DYNAMICS DURING THE LAST DEGLACIATION IN THE NORTH-CENTRAL BALTIC SEA

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Nine seismic stratigraphic units were distinguished, and their distribution mapped, in an 80x130 km submeridionally oriented area in the northern Baltic Sea, east of Gotska Sandön and Fårö. Analysis of these units revealed a great influence of the bedrock relief on the structure and distribution of the glacial deposits. Major glacially eroded valleys in the Baltic clint, connecting the Fårö Deep and the North Central Baltic Basin across a narrow saddle, form an extensive submeridional bedrock depression. The drumlinized surface of the basal till sheet indicates a concentration of the ice flow along this depression. Furthermore, the glaciofluvial upper portions of the southwards merging drumlins show that the valleys also drained the subglacial meltwater. The major subglacial meltwater conduits can unambiguously be traced by eskers. The eskers are clearly associated with the large bedrock valleys, particularly near the Baltic clint. The eskers end rather abruptly with large subglacial outwash fans. The deposition of the outwash fans along the northern margin of the Fårö Deep resulted probably from a pressure and subsequent velocity decrease in the subglacial meltwater conduits. The pressure decrease occurred most likely due to the existence of a floating, ice-shelf type, of glacier in the Fårö Deep. A characteristic seismic stratigraphic unit, limited to the bottom of the Fårö Deep, is interpreted as a subglacial aquatic melt-out till. This lends further support to the interpretation of the ice-shelf environment in the depression. A wedge-shaped glacial-marginal grounding-line deposit on the Silurian plateau south of the Fårö Deep suggests that the ice stream was floating in the marginal zone of low-lying areas during deglaciation.

Drumlins, merging southwards into large esker ridges, which in turn end with extensive outwash fans and glacial-marginal grounding-line deposits, reflect the continuum of subglacial to glacial-marginal processes and environments in the northern Baltic Sea.

GEOMETRY AND DISTRIBUTION OF GLACIGENIC SEDIMENTARY UNITS ON THE MÅLØY PLATEAU, NORTHERN NORTH SEA

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At the outlet of the Norwegian Channel the Måløy Plateau can be recognized as a large bank area on the eastern channel flank. The extent of the Måløy Plateau is limited by the Norwegian coast in the east, the Norwegian channel in the south and west, while the Møre shelf and the headwall of the Storegga slide defines the northern limits.

The Måløy Plateau consists of a sequence of glacial and interglacial sediments up to 400 m thick above the glacial unconformity, spanning the Late and most of the Middle Pleistocene. The present morphology of the Måløy Plateau is a result of several episodes of glacial erosion and deposition. The area has been influenced by westward moving glaciers from the Norwegian mainland, and from northward moving glaciers (Norwegian Channel Ice Stream) occupying the Norwegian Channel. On 3D seismic datasets several stratigraphic levels show strong directional elements, particularly in the lower part close to the glacial unconformity. The datasets provide possibilities to identify the remnants of different depositional and erosional regimes, comprising till units, marine units and delta-like units. The stratigraphy of the Måløy Plateau is correlated with the stratigraphy of the Norwegian Channel provided by the Troll core and new geological borings on the outer Møre shelf/upper slope. This allows a better understanding of the contributions different glacial regimes have made to the development of the large bank area, and how the outlet of the Norwegian Channel has migrated through the Middle and Late Pleistocene.

ICE STREAM DIRECTION INTERPRETED FROM TILL FABRICS, A STUDY OF THE WEICHSELIAN YOUNG BALTIC ICE ADVANCE OVER LOLLAND IN SOUTHERN PART OF DENMARK

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During the systematic mapping of the northern part of Lolland and the Smålandsfarvandet archipelago till fabrics have been measured in the Lolland Till Formation. The till represents the prominent lithostratigraphic unit deposited by the Late Weichselian Young Baltic Ice advance, which from its main centre in the eastern Baltic transgressed over the southern part of Denmark. The western limit of this ice sheet is situated in eastern Jylland and central part of Kattegat.

The till fabric analysis here presented are based on common principles known to the international glacial geologists as for instance outlined by Visser (1989). In the till fabric analysis the stereoplot program SSWIN was applied and the Kamb (sigma) counting was selected for the calculating operation. The direction of the fabric (large arrow in the stereograms presented in the Fig. 1) is given by the maximum density distribution, eigenvector 3 (E_3). The evaluation of the fabric is based on Volmer's Fabric Indexes in a cluster-girdle-uniform triangular distribution plot, hereafter referred to as the cgu-index. In this diagram a cluster distribution corresponds to one well defined direction, a girdle distribution corresponds to two or more directions in the same plane, and finally the uniform distribution represents no preferred direction. A girdle distribution in the till fabric analysis normally refers to fabric axes distributed in the horizontal plane or in a weakly plane tilted away from the direction of shear movement. From the girdle analysis it can not be seen whether the distribution of clasts is an A-axis or B-axis orientation, which is only interpreted from the contouring display in the stereogram.

Various aspects of interpretation of till fabric diagrams are discussed, and the main question to be addressed is the liability of interpretations based on a statistically not well defined cgu-index.

The interpretation for the flow of the Young Baltic Ice in the south-eastern Baltic and southern part of Denmark advocates a main stream from east towards west with a substantial northerly spreading vector during the progressive advance. It is inferred that a similar spreading towards the south affected northern part of Germany as also indicated by Stephan (1994).

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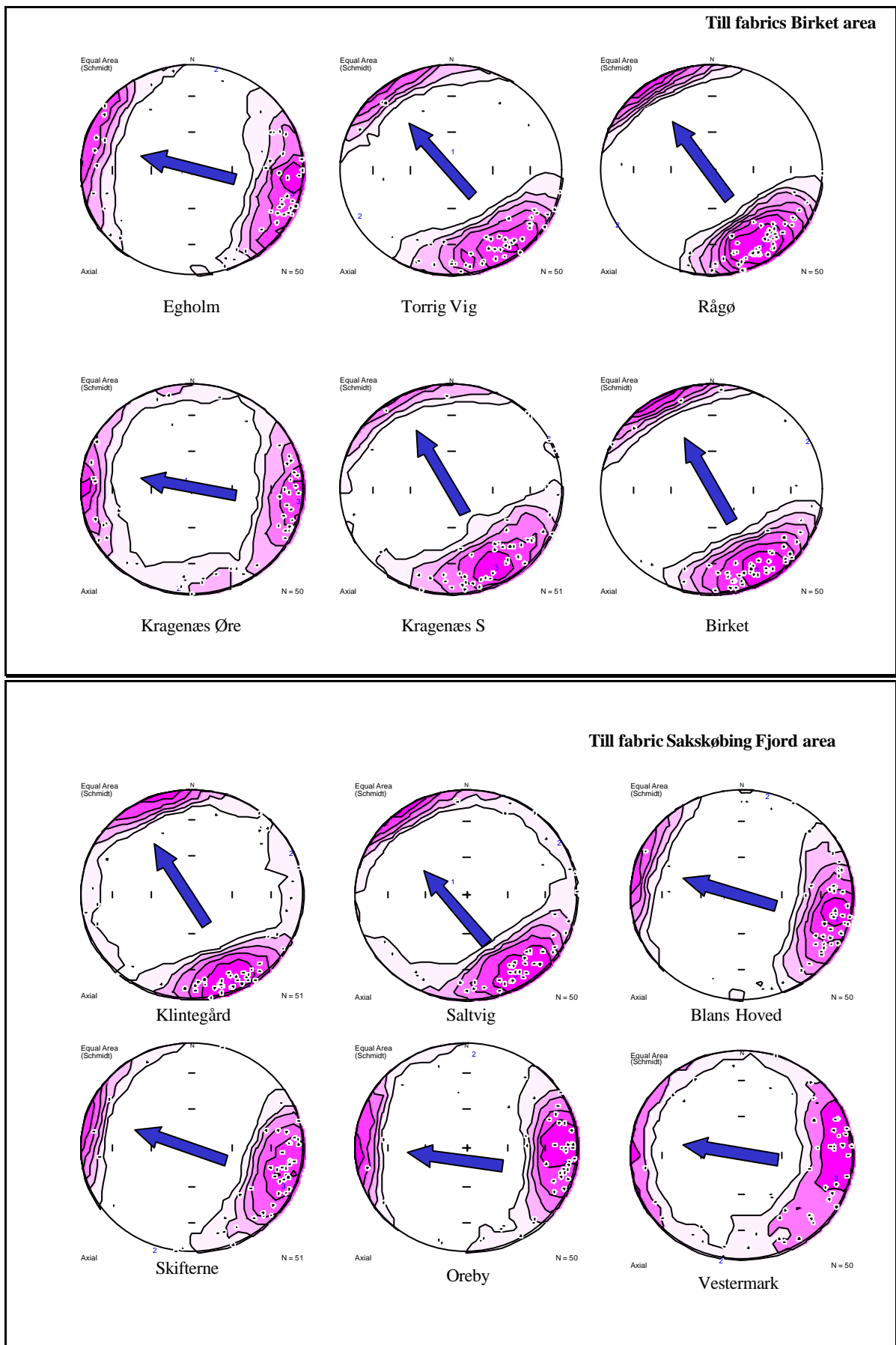


Figure 1. Examples of the till fabrics measured in the Young Baltic till at Lolland.

DID ICE STREAMS AFFECT THE WEICHSELIAN ICE SHEET CONFIGURATION IN POLAND?

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Ice flow patterns in the Noteæ area, NW Poland, are enigmatic. During the Weichselian the area has been subject to at least two ice advances. The last advance was directed towards the west. The penultimate advance was towards south- southwest. This poster presents preliminary results from investigations of the ice dispersal pattern, ice movement mechanism and ice extent during these events.

Along the E-W stretching Noteæ River valley (Torun-Eberswalde ice marginal streamway) there are excellent exposures where up to four different till beds may be studied. Earlier studies of these till beds (Kozarski & Kasprzak, 1987) revealed that the uppermost till bed was deposited by an ice moving from the east to the west. This, for this area, rather uncommon ice movement direction drew our attention and initiated the present study. An ice based on a rigid bed would within a rather short distance from the ice margin have such a thickness that the topography in this region would be unable to control the ice flow direction. The ice flow would then mainly be controlled by the position of the ice divide. In this region it would, with small deviations, flow towards south-southwest during the deglaciation. As this is not the case in the study area we have to look for another ice movement mechanism permitting very diverging directions. Hypothetical candidates are an ice stream moving over a deformable bed or a marginal ice dome.

In order to investigate the spreading pattern and mechanism for the last ice advance, sedimentological and lithostratigraphical investigations in open exposures and morphological studies of maps and satellite images has been undertaken.

Results so far:

- The last advance was rather complex and may be divided into two phases:
 - During the earlier phase the ice movement was towards south-southwest. The ice thrust the sediments in front of it, overrode the area and deformed its substrate. The resulting sediment is a stratified diamicton consisting of a mixture of deformed substrate and material released subglacially by the ice. During this phase there was deforming bed conditions beneath the glacier.
 - The later phase started with a shift of ice movement to a direct western direction. The clast lithology is of a more eastern provenance than the sediments from the earlier phase. The sediment is now homogenous and fissile. This is interpreted as a change towards more of brittle deformation.

In the sites eastwards, the sediments from the later phase are directly underlain by glaciofluvial sediments. Sediments from the earlier phase were either not deposited, were deposited and later eroded or are present in the unexposed sediments below the glaciofluvium. Thus, an alternative interpretation is that diamictons from the early and late phase represent two different ice advances separated by an ice-free period with glaciofluvial deposition. There is however no evidence to confirm this interpretation.

The results indicate that the earlier phase represents the maximum glaciation during the late Weichselian and the later phase represents a change in ice dynamics during the

deglaciation. The marginal zone attributed to the Chodzież sub-phase by Kozarski (1981) fits well with the presence of the sediment from the later phase and may represent its outer limit.

- The penultimate advance was towards south-southwest. It left a stratified diamicton interpreted as a deformation till. The sediments are exposed in a few sites along the Noteć River valley sides and the extent of the advance is still uncertain. Earlier work, mainly based on drillings, present different views. Dzierżek (1997) suggests that this is an early/middle Weichselian ice advance and that the till bed extends at least 30 km south of the Noteć River. On the other hand, Kozarski & Kasprzak (1987) suggests that it is the maximum glaciation during the late Weichselian and that it extends to the Leszno ice marginal zone.

The chronology of the ice advances is still unclear and contrasting views exist. The only opinions that have some support in datings are the ones expressed by Dzierżek (1997), who has TL-dated some exposures. The suitability of the sediments he has dated is, however, very questionable. There are also organic sediments from the Eemian in drillings in the area but correlation of the drilling sites with the exposures is very problematic.

To help solving the chronological problems, new OSL-samples of fluvial and glaciofluvial sediments have been submitted for dating.

The results suggest that the ice moved over a deformable bed during the two last glaciations in the area. This allows for a thinner ice, which would be more susceptible to topographical control of the ice flow. Sediments from the later phase of the last ice advance has only been found along the Noteć River valley, with a westerly directed ice flow, parallel to the valley. This suggests that the sediments were deposited by an ice stream controlled either by the topography or by the porewater conditions in a precursor to the Noteć River valley.

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FOOTPRINT OF AN ICE STREAM ON THE OUTER CONTINENTAL SHELF OF THE ANTARCTIC PENINSULA: ACOUSTIC FACIES AND HIGH-RESOLUTION SWATH BATHYMETRY

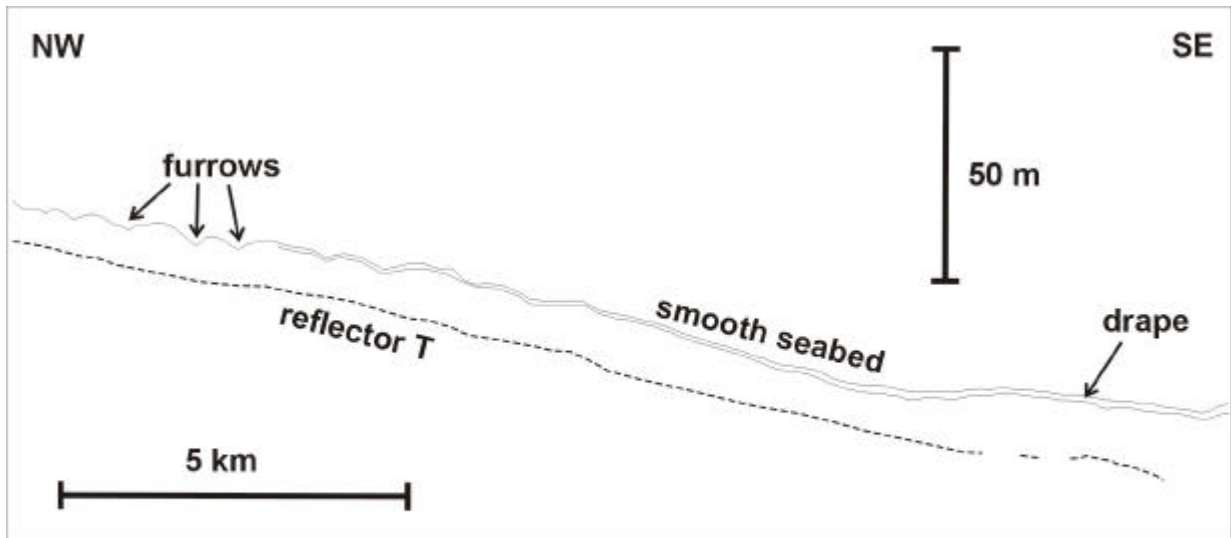
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In February-March 2001, RRS James Clark Ross conducted swath bathymetric (Simrad EM120) and TOPAS sub-bottom profiling along the path of an ice stream west of the Antarctic Peninsula. The survey extended 400 km from 69°30'S in King George VI Sound northwards along a deep trough in Marguerite Bay to the shelf edge. Subglacial bedforms on the shelf are described in the adjacent poster by O'Cofaigh et al.

The outer continental shelf slopes landward at 0.1°. The shelf break is at about 440 m depth with the outer part of Marguerite Trough incised some 100 m. The floor of the trough contains a clear linear fabric oriented 125°/305°. Five TOPAS profiles within the trough, and sidescan records from an earlier cruise, show the seabed is iceberg-furrowed from the shelf break down to 520 m depth, where it becomes smooth. Subsurface reflector "T", which is smoother and without furrows, lies 3-4 m below the seabed at the shelf break, increasing to 10-15 m below the seabed some 60 km landward where it becomes indistinct. On profiles 30-60 km away from the trough axis, the outer shelf is iceberg-furrowed but without a linear fabric, and reflector "T" is not present. Piston cores on the outer shelf recovered diamict (Pope & Anderson 1992). The unit of sediment above reflector "T" is interpreted as a till sheet, confined to Marguerite Trough and deposited beneath a northwest-flowing ice stream.

Farther inshore, i.e. below the depth of iceberg furrowing and including a few km where reflector "T" is present, a transparent or faintly stratified drape of sediment up to 6 m thick covers glacial topography. Cores in this drape consist of Holocene glacial-marine and biosiliceous sediment; the till sheet is thus pre-Holocene. In Marguerite Trough there is no evidence for a mid-shelf grounding zone or till deltas near the shelf edge (cf Bart & Anderson 1995, Larter & Vanneste 1995). During the most recent glaciation represented by the till sheet, the ice stream reached the shelf edge and subsequently retreated rapidly landward.



TOPAS profile in the outer part of Marguerite Trough.
The shelf break is 45 km to the northwest.

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3-D SEISMIC DATA FROM THE SOUTH-WESTERN BARENTS SEA PROVIDE PALAEO ICE FLOW PATTERN IN GLACIGENIC SEDIMENTS

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Three-dimensional seismic data with close line spacing have, combined with application of all data-points in the interpretation, increased the understanding of the palaeo-environment in different geologic settings. The preserved high lateral seismic resolution through the process to the final maps gives less room for subjective interpretation and thus provides more objective interpretation. The study area is located south of Bjørnøyrenna and covers an area of 2870 km². With a vertical and horizontal resolution of around 10 m, the 3-D data provide detailed maps of palaeo surfaces, revealing grooves of depths down to 2.5 m.

The morphology of the interpreted horizons reveals several types of sub- and pro-glacial features within the glacigenic sediments overlying the consolidated bedrock. Several generations of glacial grooves, observed on four different palaeo-surfaces, are interpreted to reflect ice flow patterns from palaeo glaciers. Earlier studies in nearby areas suggest that if large parts of the south-western Barents Sea were covered by ice, the ice flow direction in the Bjørnøyrenna would have been towards west. The main lineation pattern of grooves in our data set trends N-S on all four palaeo-surfaces, suggesting a dominant ice flow direction from south to north across the Barents shelf at least four times during the last 0.8 Ma. If our interpretation and the model from the literature are both correct, they imply that there has been a convergence-zone in the southern part of Bjørnøyrenna. Another possibility is that the grooves in our data-set were formed while the ice was retreating. In the latter case the N-S-trending grooves in our data-set may have been formed while Bjørnøyrenna was ice-free and acted as a major calving bay for the ice moving from south towards north. This suggests that evidence from the ice advances may have been obscured during the retreat of the ice.

DOES THE SAADJÄRVE DRUMLIN FIELD, ESTONIA INDICATE A WEICHSELIAN ICE STREAM?

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The Saadjärve Drumlin Field (SDF) in east-central Estonia comprises about 120 drumlins and drumlinoid ridges within an area of 1200 km² (Fig. 1). The length of the drumlin field is about 55 km, the maximum width is 27 km on the proximal (NW) end and less than 5 km on the distal end, giving the entire field a distinct shape of a down-ice tapering wedge. In accord with the regional Late Weichselian ice movement direction, the drumlins are oriented NW-SE.

The SDF can be divided into two regions. The NW region contains very large, yet relatively flat and wide drumlins, 7–13 km long, 2–3.5 km wide (mean L/W ratio of 3), and up to 60 m high. The SE region comprises smaller and more elongated drumlins with steep slopes. Their length is 2–6 km, width 0.2–1 km (mean L/W ratio of 7), and height 20 m on average. Furthermore, drumlins in the SE region are more densely spaced than in the NW region.

Under the NW part of the drumlin field the bedrock is Lower Silurian limestone and dolomite (S_{1rk} in Fig. 1). These rocks are, especially in the uppermost 30 m cavernous with abundant cracks, fissures and channels contributing to high permeability. Bulk lateral hydraulic conductivity in this zone is 1.2–5.8 x 10⁻⁴ m/s (Perens & Vallner 1997). In contrast, bedrock in the SE part of the drumlin field is Middle Devonian silt- and sandstone interbedded with clays (D_{2nr} and D_{2ar} in Fig. 1). Lateral conductivity is between 1.2 x 10⁻⁵ and 8.6 x 10⁻¹⁰ m/s or less (Perens & Vallner 1997).

Drumlins are composed predominantly of till from the last Weichselian ice advance. There is no difference in the mean grain size of this till in both regions, but smaller drumlins consist of finer-grained till and larger drumlins contain coarser-grained till.

These relationships indicate the influence of substratum and till rheology on the dynamics of the drumlin forming process. In the area of high-permeability substratum (NW), porewater drained efficiently from the subglacially deforming material increasing its strength and stabilizing the material into large, conspicuous drumlins. In contrast, in the area of high basal water-pressure caused by low-permeability substratum (SE) the material would be swept away more readily leading to much smaller and more elongated drumlins. Furthermore, a slightly coarser-grained till with higher shear strength would have also facilitated formation of larger drumlins, similar to the Woodstock drumlin field in Ontario (Piotrowski 1987).

Diversity of the substratum characteristics would have influenced the ice flow dynamics, possibly leading to higher flow velocity in the low-permeability (high water pressure) SE region, where the ice would be funneled into a narrow track at the most distal part of the drumlin field. Spatial characteristics of the entire drumlin field and large elongation ratios

of drumlins in the SE region indicate that an ice stream drained this part of the Scandinavian Ice Sheet during the Weichselian glaciation.

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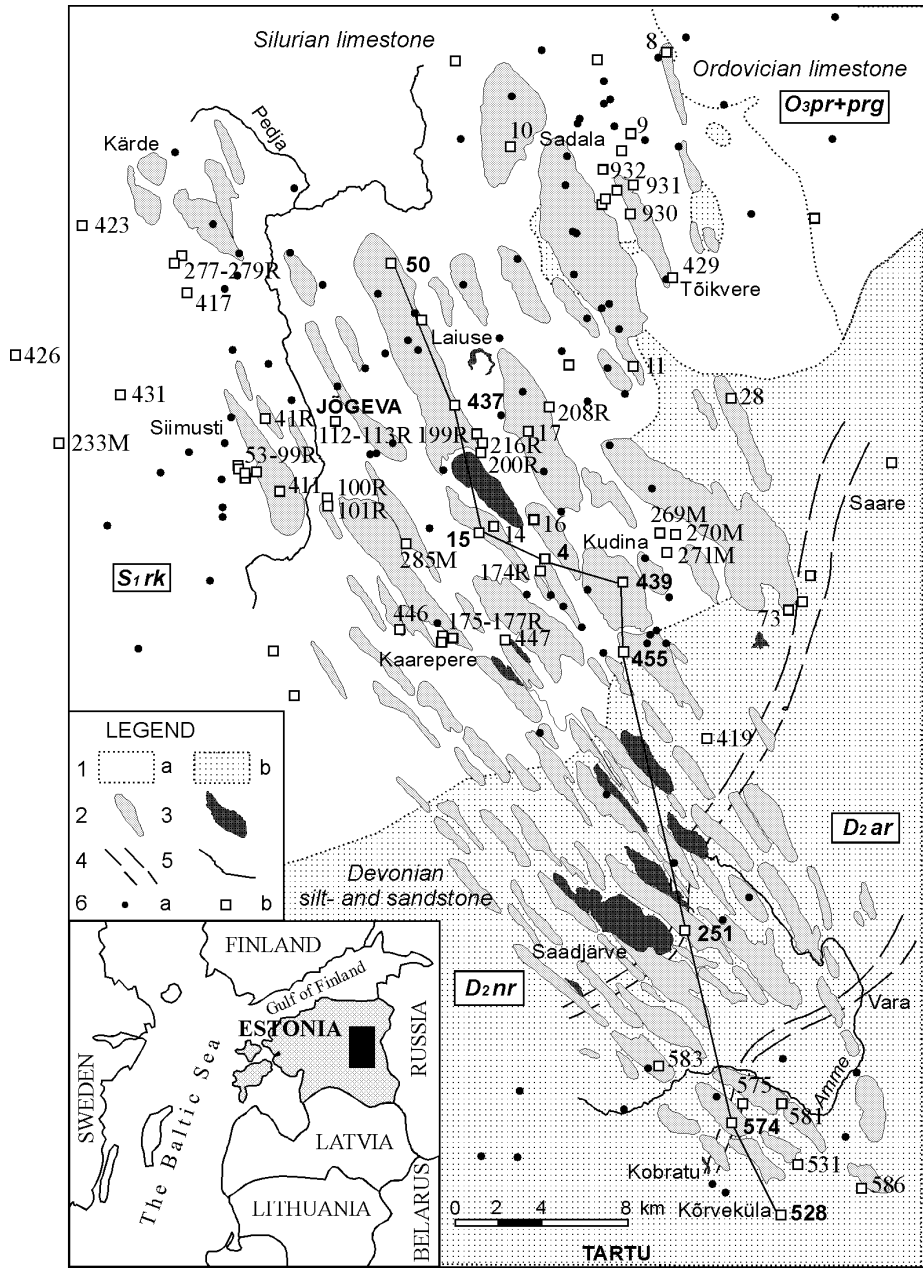


Figure 1. The Saadjärve Drumlin Field. 1 – bedrock lithologies with dominating (a) high-permeability limestone and dolomite, and (b) low-permeability silt- and sandstone; 2 – drumlin; 3 – lake; 4 – deep buried valley; 5 – river; 6 – boreholes with (a) not analyzed and (b) analyzed samples.

WEICHSELIAN SEA LEVEL CHANGES AND GLACIATION HISTORY OF JÆREN (SW NORWAY): INDICATIONS OF HIGHLY VARIABLE ICE CONFIGURATIONS

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Jæren is a low, undulating landscape in southwestern Norway with a thick cover of Quaternary sediments. The surface sediment is commonly a sandy till from the Late Weichselian. Below this there are a number of glaci-fluvial and glaci-marine units, indicating highly varying sea levels through the Weichselian. The postglacial marine limit at Jæren is less than 26 m a.s.l. This is in sharp contrast to older marine sediments, which are found up to 200 meters above present sea level. The high-lying marine sediments can be divided in three main categories; laminated glaci-marine clay, homogenous glaci-marine clay and glaci-marine diamicton. New ^{14}C dates from the marine sediments support the presence of an ice-free period at Jæren at about 31-34 ka BP, the Sandnes interstadial. There are also indications of an older interstadial with similar sea levels around 45 ka BP.

The anomalous high sea levels have been explained as a result of glaciostatic depression by an ice stream in the Norwegian Channel followed by a rapid deglaciation both of the ice stream and the inland ice. After the last deglaciation of the Norwegian Channel ice stream, the inland ice advanced rather than melted back, and thus most of the rebound after the ice stream took place before deglaciation.

High-resolution digital maps have been used to identify landforms formed during this late expansion of ice from central Norway. Flutings with a southwesterly orientation are common, and an area with transverse ridges interpreted as ribbed moraine occur in-between the flutings. The individual ridges of the ribbed moraine are up to 800 meters long and 10 meters tall, with a relatively steep southwestern slope and a gentler slope towards northeast. The ridges are dominated by sandy diamicton, but in the intervening depressions there is only a thin cover of sandy diamicton overlying clay-rich glaci-marine sediments.

The glaci-marine sediments at Jæren contain up to 78% clay, and the very fine-grained composition makes these sediments virtually impermeable. Glaci-marine sediments probably covered all of Jæren during the Sandnes interstadial, and they impeded drainage of subglacial melt-water produced during the following glacial phase. When the Norwegian Channel ice stream melted back about 15 ka BP, the inland ice advanced south-westwards over fine-grained sediments with high pore water pressure. At some localities, highly deformed glaci-marine sediments are cut by undeformed clastic dikes wedging down from the overlying sandy till. The clastic dikes are composed of sorted sand and silt, and they indicate a sudden drainage of subglacial melt-water. The preservation of the ribbed moraine indicates that the final deglaciation over large parts of Jæren was dominated by stagnant ice. It is possible that this stagnation was partly a result of a sudden drainage of subglacial melt-water.

MAXIMUM EXTENSION OF THE SAALIAN AND WEICHSELIAN GLACIGENIC DEPOSITS ON THE CONTINENTAL SHELF AND SLOPE OFF MID-NORWAY: BATHYMETRIC, SEISMIC AND BOREHOLE EVIDENCE FOR EXTENSIVE AND DYNAMIC GLACIAL SYSTEMS

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Several studies have confirmed that the present morphology of the mid-Norwegian continental shelf is mainly a result of glacial processes, and that the substratum commonly consists of till and glaciomarine sediments. King et al. (1987) and Rokoengen et al. (1995) made a comprehensive interpretation of the seismic stratigraphy, but due to poor chronostratigraphic controls, ages have only tentatively been assigned to the different seismic units mapped in the area. Interpretation of high resolution seismic data collected west of the shelf break and detailed investigations of long cores/geotechnical borings, have made it possible to tie "dated units / horizons" in the slope to the established stratigraphic framework on the shelf. The improved age control together with new lines showed that parts of the regional seismic grid had to be reinterpreted in order to obtain a consistent glacial model.

Bathymetry: A digital bathymetric data set from the northern part of the Norwegian Trench to Lofoten archipelago, gives a unique regional view into glacial processes and ice-sheet dynamics on the continental shelf west of Norway during the Weichselian glaciation (Ottesen et al. 2001). The study area is located where the shelf is widest (ca. 250 km E-W), and includes the huge Skjoldryggen ridge at the shelf edge. The ridge is ca. 150 km long, up to 150 m high and 10 km wide and is by far the largest end-moraine on the Norwegian continental shelf. The shelf includes the large bank areas (Røstbanken, Trænabanken and Haltenbanken), separated with depressions (Trænadjupe and Sklinnadjupe), which have acted as major drainage routes for ice in this area of the shelf.

Stratigraphy: A long seismic line from the slope to the middle part of the shelf illustrates the general seismic stratigraphy. The units mapped comprise Naust B (oldest), Naust A2 and Naust A1. The acoustically massive and thick unit Naust B is located mainly on the slope. It represents probably the depositional products of one or several severe glacial erosion cycles on the shelf (glacigenic debris flows?). The deposits are younger than the Brunhes/Matuyama paleo-magnetic boundary (730ka), and we tentatively propose that this unit was deposited during the Elsterian glaciation.

The unit Naust A above consists of layered sediments in the middle/lower slope and both acoustically layered and massive sediments in the upper slope. On the shelf, acoustically massive sediments dominate, although a 10-50 m thick sub-unit of layered sediments exist above the inferred "Elsterian" glacial erosion-surface (interpreted as the main unconformity). The massive units in the outer shelf continue as two wedge-formed massive units west of Skjoldryggen (Naust A1 and Naust A2), which terminate in the upper/middle part of the slope. Eemian sediments were detected in the IMAGES core 2289 and well

6404/5-GB1, coinciding at or very close to the Intra Naust A reflector, which can be followed within the layered sediments below the upper massive unit Naust A2.

Saalian glaciation (Naust A1): No direct age information of the layered sediments below the lowermost massive unit Naust A1 exists, but amino acid ratios west of where the unit pinches out indicate that the unit represents sediments from one or several extensive glaciations during the Saalian (c. 130-200 ka). In the Skjoldryggen area, unit Naust A1 coincides with the "Middle Till", which internally consists of 12 till tongues (King et al., 1987). The westernmost termination of the unit is c. 50 km west of the central part of Skjoldryggen, occurring at a depth of c. 1100 m below the present sea level. New data show that unit Naust A1 did not extend to the shelf edge just north and south of Skjoldryggen, and that a huge ice-lobate depositional system was active in the central-outer part of the shelf. The ice masses responsible for the progradation of stacked till-tongues flowed out between Haltenbanken and Trænabanken, with a focused ice drainage out a palaeo-trough extending westwards below the present Sklinnadjupet. The "Middle Till" was not deposited in the inner shelf area, or became eroded during the Weichselian glaciation.

The map of the Saalian glacial deposits indicates that separate and less active glacial systems occurred across the Haltenbanken and Trænabanken. Glaciomarine sediments were deposited in the "embayments" north and south of Skjoldryggen. Pronounced glacial erosion of older sediments at the flanks of Trænadjupet indicates that a huge and active ice-stream flowed out the Vestfjorden basin and Trænadjupet towards the shelf edge.

Weichselian glaciation (Naust A2): The map of the acoustically massive unit Naust A2 shows that the maximum extension of the Weichselian glaciation was beyond the present shelf edge. Unit Naust A2 is equivalent to the Upper Till of King et al. (1987), although some reinterpretations of till-tongues have been carried out south and north of Skjoldryggen. The Weichselian ice-sheet did not extend as far west of Skjoldryggen as the Saalian ice, but the westward extension south and north of Skjoldryggen is greater. The morphology east of Skjoldryggen is complex, comprising several depressions and ridges and interpreted to be a result of glaciotectonic deformation during a late stage of the Weichselian glaciation. This may indicate that a cold based ice-sheet existed for some time east of Skjoldryggen, and that the ice masses flowing out from Sklinnadjupet in this period was directed towards northwest. Several till-tongues deposited above the layered sediments in the "embayment" south of Skjoldryggen, indicate that there was an active flow of ice across or south of Haltenbanken during the Late Weichselian.

Pronounced megascale lineations as well as erosion of unit Naust A1 show that an active ice stream flowed out the Vestfjorden basin and Trænadjupet towards the shelf edge.

Dating of cores in the upper slope / outer shelf as well as on-shore samples indicate that the most extensive Weichselian ice-sheets on the shelf occurred during two late phases (c. 15-17 ka and c. 21-24 ka respectively). In the interstadial period between c. 17-21 ka, the ice margin was probably east of the Norwegian fjords (Olsen et al. 2001).

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THE KUANERSSUIT SURGING GLACIER, DISKO ISLAND, WEST GREENLAND: ICE MARGINAL SURGE DYNAMICS

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Since 1997 the Kuanerssuit glacier has surged 11km from its original position on the northwest edge of the Storbraen ice cap. The mechanisms that control Disko Island surging glaciers are not fully understood however, with possible driving mechanisms including shifts in mass balance and changes in basal thermal regime and subglacial hydraulics. This paper presents the initial results of an investigation into the ice marginal dynamics of this system, in order to understand the mechanisms controlling fast ice flow in this climatically sensitive region of West Greenland.

The Kuanerssuit surge resulted in the formation of an ice cored push moraine complex up to 30m high and 500m wide. Large ice cored thrust duplicates form 3 main moraine ridges. These resulted from initial open and recumbent folding, followed by listric thrust development and finally hydrofracturing. The hydrofractures indicate the existence of a syn- or post-tectonic high pressure hydraulic regime during or post the main surge phase(s). Between the 3 largest ridges lie smaller thrust features and 'avalanche' moraines formed by the accumulation of unconsolidated sands and gravels at the base of larger thrust moraine slopes. Bulldozing mechanisms are also prevalent with previous surge moraines partially overrun and displaced sandur rafts evident.

The thrust duplicates within the moraine complex are characterised by subglacially derived, banded, debris rich basal ice (BDRBI) units which exhibit extensional deformation structures and are coupled with over lying clean glacier ice. The coupling of basally derived ice and clean englacial/supraglacial ice during thrusting suggests thrust initiation and detachment from a subglacial position. This is the result of thrust stacking in the marginal zone as extensional subglacial stresses switch to a compressional regime. The widespread BDRBI facies may indicate the existence of a distributive subglacial water system characterised by cyclical regelation with evidence for 'surge' and 'quiescent' phase freezing. However, its spatial extent relative to the margin is unclear and its relationships to basal thermal regime, permafrost extent, subglacial hydraulics, proglacial icing formation and an upglacier ice dammed lake require further investigation if the nature of surge initiation and fast ice flow in this highly variable polar maritime region is to be understood.

MICROFOSSIL AND GEOCHEMICAL TRACERS OF PAST WEST ANTARCTIC ICE STREAMS ACROSS THE ROSS SEA, ANTARCTICA

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The geological setting of West Antarctica influences the position and configuration of the major ice streams that drain West Antarctica, and the subglacial lithology and physical properties influence the flow regime. Ice streams and slow-moving grounded ice, in turn, modify the subglacial deposits and landforms.

Here we report investigations of sediment cores from the Ross Sea and from beneath the Ross sector of the West Antarctic Ice Sheet. We are using geochemical and micropaleontological data to distinguish between diamicton packets emplaced under different glacial regimes and basal conditions. Our objective is to assess the glacial conditions that formed these deposits, as an aid to reconstruction of past ice stream and sheet configurations and the development of glaciological models of West Antarctic Ice Sheet behavior.

Detailed bathymetric maps of the Ross Sea floor have been constructed from seismic, side-scan sonar, and multibeam (CHIRP) imaging (Shipp et al., 1999). The sea floor is characterized by complex glacial structures, including drumlins, flutes, "washboard moraines," and various grounding-line features. It has been hypothesized that past ice streams followed troughs from the interior of West Antarctica toward the continental shelf break. Seismic stratigraphy and drilling during DSDP Leg 28 demonstrated that a massive volume of marine sediment originally deposited in the West Antarctic interior has been eroded, transported and redeposited near the continental margin.

Shallow sediment cores recovered from the central basin of the Ross Sea, near the ice shelf front, typically contain a diamicton overlain by hemipelagic mud (Domack et al., 1999; Kellogg et al., 1979). Despite textural similarity among Ross Sea diamictons, our geochemical and diatom assemblage analyses highlight considerable stratigraphic complexity within and among cores. Quantitative and semi-quantitative geochemical, textural, and micropaleontological data are reduced by principle component analysis (PCI).

Chemical analyses by plasma emission spectroscopy (ICP-AES) of stratigraphic samples from 8 Ross Sea piston and trigger cores included concentration of 10 major oxides, and 17 trace elements, and loss on ignition. We also have begun measurement of cosmogenic ^{10}Be . Additionally, we have, to date, analyzed one core and have initiated analysis of additional material recovered from beneath the southern Ross Ice Shelf as part of the Ross Ice Shelf Project (RISP) (Webb et al., 1979). We have initiated further trace and major

element analyses on material recovered from beneath the ice shelf and the grounded portion of the WAIS, including active and stagnant ice streams and inter-stream ridges.

The second major component of the study is micropaleontology. All sediments analyzed contain diatoms and/or diatom fragments, though absolute abundance of diatoms greatly varies. Diatoms and ebridians are characterized according to their known stratigraphic ranges. Although the investigated deposits are late Quaternary in age, they usually contain significant concentrations of reworked Tertiary diatoms. Stratigraphically-significant fossils present include representatives of Quaternary (dominantly Holocene), Pliocene, upper, middle, and lower Miocene, and Oligocene strata. These reworked diatoms are of variable concentration and preservation, and Tertiary age diatoms dominate the total assemblage of many samples. Identification of age-diagnostic fossils provides an accurate method of documenting mixing of upper Cenozoic strata, thus they provide a powerful tool for evaluating glacial erosion, mixing, and transport. Species data are analyzed by PCI and are cross-correlated with chemistry data.

As expected, diamictons containing a low concentration of diatoms are relatively enriched in elements characteristic of detrital grains. There is significant variance in the concentrations of trace elements such as Ba, Zn, Cu, and other trace elements in muddy facies. Ba concentration is high in Holocene diatomaceous mud, but is low in samples rich in exclusively Tertiary diatoms, such as the RISP cores. Zn is enriched in most samples, but especially in mud-rich, diatom-poor samples. Diamictons in cores from the central trough were emplaced by ice streams, with spatially and temporally variable facies. Diatoms in the diamictons tend to be highly stratigraphically mixed and mechanically degraded.

The stratigraphic, paleontologic, and geochemical complexity within and between diamicton units implies highly variable subglacial conditions, presumably including changing glacial configurations and basal conditions. Sedimentary particles have been transported and repeatedly mixed during glacial advance and retreat stages. In contrast, diamictons of the Pennell Bank display little stratigraphic mixing. They contain a significant concentration of Tertiary diatoms, but these are largely derived from age-restricted, local source beds not consistent with ice stream deposits. These interpretations are in accord with those of Shipp et al. (1999) and Domack et al. (1999) who suggested that the central trough held an active ice stream, and Pennell Bank was an ice-rise during the last glacial maximum.

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THE YOUNG BALTIC ADVANCE IN THE WESTERN BALTIC DEPRESSION

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The term „Baltic ice “ is used by Danish geologists (e.g. Andersen 1945; Houmark-Nielsen 1985) describing a glacier that had a main source area in northern Scandinavia and – flowing southwards - passed the Baltic depression between Sweden and the Baltic States, proved by the composition of its drift. The term “Young Baltic” is used for the last Weichselian glacier advance reaching Denmark and Schleswig-Holstein, in contrast to an early Weichselian, the “Old Baltic” and the latest Saalian, the “Paleobaltic” Advance.

The Young Baltic ice, forming a large ice stream, first flowed from its source area southwards along the eastern Baltic depression where it terminated in the Pomeranian uplands. The ice flow then turned west passing the depression between South Skane and North Germany, the main stream flowing through the “gate” between the islands of Bornholm and Rügen. It fanned out in the western Baltic region with strongly different flow directions (Sjörring 1981; Ringberg 1988; Stephan 1994).

For more than a hundred years geologists have tried to explain the different composition of tills in Denmark and North Germany by the existence of different ice streams in the glaciated Scandinavia. Early observations and interpretations were delivered by De Geer (e.g.1888:Tafl. 2/I, with a Baltic glacier advance in the western Baltic depression) and Gottsche (1883:63). Zeise (1889:16, 43) and Madsen (1898) - from their studies of the “Baltic moraine girdle” – inferred repeated glaciations with Baltic (E-W stream) ice masses separated by a N-ice. Torell (cit. by Zeise 1889:56) explained the E-W flow direction by the deflection of the normally southwards moving ice mass at the uplands at the southern margins of the Baltic depression and then by the leading of the ice along this depression towards W. This conception was again formulated by Gripp (1981). Eissmann (1967) and others later explained the dominance of Baltic ice masses during the late phases of glaciations by a shift of the ice shed or the main ice accumulation centre (ice dome) in Scandinavia from W to E. Such shift has first been mentioned by Enquist (1918:23).

Zeise (1889:56) thought a meridional ice flow to be restricted to the time of maximum ice in Scandinavia, preceded and followed by an E-W flow along the Baltic depression. This fundamental model again occurs in Wennberg (1949) and is modified by him in detail. He explained the late Baltic ice stream by a torsion of the primary main flow within the Scandinavian ice shield due to the decay of the Småland- and the Dalarna-ice during the melt phase. Baltic ice masses should have displaced therefore central and south Swedish ice masses in the western Baltic region. A very similar idea was published by Stephan (in Ehlers, Meyer & Stephan 1984:31; melting of blocking western ice masses). The similarity with the concept depicted by De Geer (1888, small map Tafl. 2/I) is striking.

The Young Baltic Advance can be correlated with the Sehberg Advance in Schleswig-Holstein and the Mecklenburg Advance in Mecklenburg-Vorpommern (Eiermann 1984). Its ground moraine wedges out north of the Rosenthaler Staffel (Cepek 1967). It is separated into three individual phases. During the oldest phase the ice reached the so-called East Jutland marginal line in Denmark, during the next younger phase the Belt Sea

marginal line, and a late re-advance terminated in the Baltic Sea depression between North Mecklenburg and Falster. Its marginal line embraces the Fakse Bight, the southern part of the Öresund and the southwesternmost area of Skane (Smed 1994).

Our recent knowledge allows the conclusion that during all larger Pleistocene glaciations or stadia there very probably existed a cyclic change of the main ice streams within the Scandinavian ice shield: Meridional to radial ice flow during the ice maxima, dominance of Baltic ice masses during the late phases of glaciations. From a theoretical point of view similar conditions as during the late phases (ice dome accumulation in the NE) should have existed also during the very early phases. Evidence for this view is the existence of the early Weichselian "Old Baltic" till (e.g. Andersen 1945). The reason that hitherto no early Baltic tills are known from older glaciations might be the erosion of such tills during the following main glaciations.

Yet some discussions regarding the behaviour of the E-W ice stream still continue. The striking composition of "red tills"(cf. Kabel 1982; Ehlers 1992; Stephan 1998) has been explained by an englacial transport of East Baltic material not mixed with other material at the glacier sole between the source area and the glacier margin. Also a movement over large fields of "dead ice" of the preceding glaciation phase without contact to the ground or a movement over an unfrozen water-oversaturated sediment or even a water sheet could be an explanation for a more or less pure East Baltic till facies found in the west. The second case is discussed by Boulton & Jones (1979). In their theory of such "deformable bed"-condition the ice could have been fast moving on a steadily and strongly deforming bed with little frictional resistance. In the third case the ice could have rapidly slid on the wet base with no or little contact to the ground (ice/bed-separation, Shaw & Kvill 1984), an assumption already principally published by Tyndall & Thomson (cit. by Haas 1890). Piotrowski & Tulaczyk (1999) postulated this for the last ice sheet in north-western Germany. Such behaviour of the ice sheet in the Baltic depression is all the more likely since the ice flow followed the main (melt)water discharge towards the Kattegat, Skagerak, and the Norwegian Trough. This movement could have temporarily culminated in a surge.

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THE DUBAWNT LAKE PALAEO-ICE STREAM: BEDFORM SIGNATURE AND ICE SHEET SIGNIFICANCE

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Investigating the evidence left behind by palaeo-ice streams considerably enhances our knowledge of former ice sheet dynamics and can contribute to our understanding of the basal processes that facilitate fast ice flow. In this paper we report evidence for a large terrestrial ice stream, describe and explain the significance of its bedform signature, and assess its importance at the ice sheet scale.

Our investigation focuses on a previously identified flow pattern trending in a north-westerly direction north of Dubawnt Lake, District of Keewatin, Canada. Using satellite imagery (Landsat MSS and ETM+) we mapped over 11,000 lineaments, mainly from the southern half of the flow-set and surrounding areas. These bedforms depict a large zone of convergence which narrows into a main trunk before diverging into a lobate terminus. The location of the flow-set and its abrupt southern margin lie irrespective of regional topography and we infer that the convergence is attributable to rapid ice flow.

Individual bedforms within the flow-set exhibit a remarkably coherent pattern. In the main trunk the standard deviation of bedform orientation does not exceed 3.8° over an area of 720 km^2 . These characteristics are typical of an 'isochronous' bedform pattern produced by rapid ice flow over a relatively short time-span. The presence of attenuated drumlins and mega-scale glacial lineations of great length (up to 13 km) and elongation ratios (up to 48:1) provide further evidence of fast ice flow. The extreme attenuation and parallel conformity of these bedforms gives the appearance of a ridge/groove pattern.

The characteristics of the flow-set (described above) are entirely consistent with an episode of rapid ice flow and we invoke the presence of a large ice stream – hereon called the 'Dubawnt Lake Ice Stream'. Its extent is reconstructed at over 450 km in length, with widths varying from 305 km in the onset zone, 140 km in the main ice stream channel and diverging to 190 km at the terminus.

Downstream variations in bedform elongation ratio reflect exactly what we would expect from a terrestrial ice stream. Lineament length increases from the onset zone and reaches a peak around 220 km downstream. After this point, the lineation length decreases and drumlins become smaller as the ice stream diverges at the terminus. Downstream variations in width peak much further upstream (between 140 and 180 km) indicating that the longest bedforms are not necessarily the widest and that an abrupt increase in streamlining takes place. This is confirmed by a dramatic increase in mean elongation ratios at around 200 km downstream from $<8:1$ up to $>14:1$ over a distance of around 20 km. This coincides with a slight drop in bed elevation and a change in geology from the 'hard' granitic shield rocks to a 'softer' sedimentary outcrop.

It is unlikely that the bed topography or sedimentology controlled the overall location of the ice stream or its marginal positions within the ice sheet, and their influence on ice stream initiation were probably limited. We speculate that the ice stream was driven by a change in the basal thermal regime of the ice sheet during deglaciation. Climate amelioration at this time probably resulted in excess meltwater and the formation of extensive proglacial lakes is well documented at the ice sheet margin. Increased temperatures may have triggered a change in the thermal state of the bed, possibly causing a switch from cold-based to warm-based conditions and leading to rapid basal sliding.

A number of dated ice marginal positions from other studies suggest that this ice stream contributed to the rapid retreat of the Keewatin Ice Sheet Sector between 10,000 and 8,400 yr. BP, probably after 9,000 yr. BP. The ice stream would have resulted in substantial thinning of the ice sheet and possibly a reversal back to cold-based conditions following its shutdown. This may be related to the development of numerous ribbed moraine which occur superimposed on the ice stream bedforms. The ice stream contributed significantly to the demise of one of the last major ice centres of the Laurentide Ice Sheet and hints at their unpredictable and catastrophic importance during deglaciation.

SUBGLACIAL ICE STREAM MARGINAL MORAINES

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The distribution and pattern of subglacial bedforms provides valuable insights into the configuration and behaviour of former ice sheets and recent work has begun to address the landform assemblages of palaeo-ice streams. In this paper, we focus on subglacial ice stream marginal moraines and provide a description of their characteristics and dimensions and explore their possible mode of formation. These relatively unknown landforms are thought to form in the shear zone between the fast-flowing stream-ice and slow-moving sheet-ice and have been documented from only a few locations (e.g. Dyke and Morris, 1988).

Using satellite imagery (Landsat Thematic Mapper), aerial photographs and ortho-photomaps, we identify four subglacial marginal moraines associated with the western margin of the former M'Clintock Channel Palaeo-Ice Stream, Victoria Island, Arctic Canada (Clark and Stokes, *in press*). The ice stream marginal moraines display lengths of between 11 and 22 km and maintain fairly constant widths of between 300 and 800 m along their length. They do not taper in the downstream direction and display a low degree of sinuosity. They are positive relief features whose crest heights range from <10 m to over 50 m above the surrounding terrain and vary by up to 30 m along individual ridges. Two moraines display a lateral offset of between 1100 m and 2750 m from the last inferred ice stream margin. Their position is thought to record minor migrations of the margin.

The moraines do not coincide with a change in geology and appear to be composed entirely of carbonate drift of a similar composition to the ice stream drumlins and mega scale glacial lineations. The moraines are unlikely to have formed by meltwater processes because they are not comprised of glaciofluvial sediments (Hodgson, 1993). The lack of topographic control on their location, and the fact that they climb in elevation in the downstream direction, indicates that they cannot be lateral moraines at the edge of an outlet glacier but were subglacially produced. In addition, younger eskers and other outwash features can be clearly seen crossing the ice stream margin, confirming that ice existed there after the ice stream had shut down.

We infer that the ridges are not merely heel-to-toe lineations at the edge of the ice stream bedform suite, but are distinctive ridges formed by another process. They are interpreted as subglacial accumulations of sediment formed in the shear zone between fast moving stream-ice and adjacent slow moving sheet-ice.

As a first attempt to explain their formation we suggest that they occur when erosion at the ice stream margin provides a surplus of sediment which is 'smeared out' in the downstream direction. We infer that as the ice sheet eroded down through a thick (>50 m) carbonate till it produced a step at the ice stream margin, and that the moraines are composed of sediment mined from here. The appeal of this mechanism is that it explains the intermittent nature of

the moraines, i.e. we would only expect them to exist downstream of areas of thick, erodible sediment. Sediment supply from upstream may be the primary control on their development and this would explain the large variability in their size and elevation above surrounding terrain.

The identification of other palaeo ice stream marginal moraines has probably been hampered by their interrupted continuity which can only be appreciated at the large scale. It is hoped that the descriptions presented in this paper will help to identify these landforms and increased detection of palaeo-ice streams will reveal other ice stream marginal moraines.

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WAS THERE AN ICE-STREAM OR SURGE ALONG THE EAST COAST OF ENGLAND DURING THE DIMLINGTON STADIAL GLACIATION?

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Previous palaeogeographic reconstructions of the Dimlington Stadial glaciation of Eastern England have tentatively suggested that unstable fast ice-streams and/or surging glaciers may have been evident during advance and retreat stages. Empirical evidence such as the development of hummocky topography and till diapirs have been offered to justify such hypothesised but these are not conclusive. Testing of ice-stream and/or surging for this region has been restricted previously due partially to the limited understanding of the glacial history of Eastern England, the inability to examine sediments and geomorphology which are presently covered by the North Sea and the lack of sedimentological and geomorphological criteria with which to recognise ice-streaming and/or surge events in the geological record. Stratigraphical, sedimentological and geomorphological evidence from Holderness, East Yorkshire, England is presented here with the intention of critically examining whether the ice-marginal landsystem assemblage of Holderness was the product of unstable ice streams and/or glacier surge events during the Dimlington Stadial glaciation. Attention is drawn specifically towards (i) the thick deformation till sequences throughout Holderness (ii) the development of a intrabeds and intrabeds of sands and gravels in the stratigraphy inferring possible linked cavity drainage system conditions during advance and glacial maximum conditions (iii) the creation of deglacial geomorphology in a lobate marginal setting (forming coalescing outwash fans and deltas) by the evacuation of abundant meltwater and subglacial sediment and (iv) the timing of glacial conditions in Holderness. A regional palaeogeography for the east coast of England is proposed in an attempt to further discussion and research on the question of whether there was an ice-stream or surge event occurred along the east coast of England during the Dimlington Stadial glaciation.

THE PALAEO-ICE STREAMS OF THE GULF OF RÎGA AND ITS EVOLUTION DURING THE RETREAT OF THE LAST ICE SHEET, LATVIA

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The ice streams of the Gulf of Rīga were wide spread and developed on a vast area of different regions in Central Latvia and had great moment significance in common dynamic of flowing ice on all space of southeastern slope of Scandinavian continental glacier cover during deglaciation of the Last Ice Sheet. The role of the ice streams in Central Latvia was not more little, than the role of the ice streams, which developed in a large depression of the Baltic Sea. The map of Quaternary compiled by V. Zāns in 1935 firstly allowed to suppose the existence of the ice streams in Central Latvia. Later basically significance had the important investigations of Veinbergs (1968, 1972) and Āboltiņš, Veinbergs, Stelle, Eberhards (1972) and Āboltiņš, Veinbergs, Eberhards (1974). These researchers not only drew separated ice streams but also connected its activities with problem morphogenesis and principally showed the origin of different types of frontal, radial and before frontal formations. The development of general ideas about distribution of the Last Ice Sheet on area of Latvia was shown by Danilāns (1965, 1972). The basically peculiarities influencing on movements of ice cover were repeatedly characterized by him also. According to mapping within the area of the Gulf of Rīga (Juškevičs, Talpa 1997) found rampart and like-rampart forms of glacial deposits, which are probably the marginal formations of different glacial stages.

The beginning of the existence of the ice streams of the Gulf of Rīga, which clearly are reconstructed by typical glacial landforms and formations originated during retreat of the Last Ice Sheet and as well orientations of elongated debris in tills had been started on area of Latvia from Pampāji-Ranka Stage. However not except that these streams existed earlier also.

The subglacial topography had been covering by Last Ice Sheet was hardly connected with position of sub-Quaternary surface of the bedrock and had been dominant factor in the distribution all palaeo-ice streams of the Gulf of Rīga known in a vast area of Central Latvia. There existed and developed a large Central Latvian or Middle Latvian Glaciodepression, which gradually decreasing in sizes in result of retreat the Last Ice Sheet within its space. This glaciodepression occupied following recent morphological regions: the Gulf of Rīga and surrounding Coast, Northvidzeme Plains with Idumeja Uplands, Zemgale Lowland, Southkurzeme Lowland and Middle Latvian Lowering. The area of the Gulf of Rīga and surrounding Coast had been characterized by lower surface both subglacial and sub-Quaternary topography than within other regions. These peculiarities and as well the locations of the basal elevations in bedrock topography, limiting Central Latvian or Middle Latvian Glaciodepression both western and eastern sides, determined the directions of the ice flow and drift also within common space of the glaciodepression. The lines of ice flow on a large area of the glaciodepression were stretched from N to S and from NW to SE, but within Middle Latvian Lowering - WNW to ESE and within Southkurzeme Plain -

from E to W and even from SE to NW. The ice flow realized in plastic conditions. Observed separate tills in cover of the Last Ice Sheet preferably to consider its as the basal tills of different stadial stages. The some differences in composition and color of outcropped tills, boundaries between its and sometimes occurring intertill sediments and sometimes different orientations in elongated debris contained in tills are known in sites of practical all regions of Central Latvian or Middle Latvian Glaciodepression. The ice flows of the Last Ice Sheet during all mentioned stages, which took place in the formation of glacial sediments in Central Latvia, had been characterized by great activity. The strength of the flowing ice was so much that in margin parts of ice cover were formed dislocated end moraines. The numerous inclusions from subglacial bed both in the basal till and in the composition of the sediments of marginal forms (Åboltiðs 1970, Veinbergs 1972) are the important signs of the great activity of the ice sheet too. The intermediate marginal formations behind frontal forms (ribbed and rogen moraines), which can formed in result of oscilatorical movements of the ice sheet and often distributed drumlins and drumlin-like radial forms are the clear signs of a great activity of the ice sheet also. The thickness of the ice cover at the time of retreat ice sheet from Central Latvian or Middle Latvian Glaciodepression precise not determined until, but can consist that it was some less than for Vaiðode-Gulbene Stage and probably varies from some ten to two hundreds metres. The retreat of the ice sheet from Central Latvian or Middle Latvian Glaciodepression began about 13500 years ago and had been finished pre-Palivere Stage. The relative small ice stream probably exist on northern area of the Gulf of Riga during Pandiveri glacial Stage.

The principal scheme of glaciodynamical evolution of Central Latvian or Middle Latvian Glaciodepression is demonstrated (Fig. 1) and discussed.

Evolution of glaciodepression and the directions of the ice flow within its area had been concluded (1) in gradual removal of the margin of the ice cover to side of it retreating in result deglaciation, what was connected with climatically warmings (interstadials) repeatedly took place at the time of the Late Glacial and (2) with new advancements of ice cover at the times of coolings (stadials) also. The common glacial curve of deglaciation ice cover of Central Latvian or Middle Latvian Glaciodepression is characterized by sequence in changeable of stadials and interstadials intervals (Savaitovs, Veinbergs 1996). New stadial advancements of the Last Ice Sheet covered only the part area as rule, which had been earlier freed from ice cover of previous stadial stage. The maximum distribution of new advancements of ice cover had been marking by band of marginal forms, which clear is observed in recent relief. Such advancements of ice cover in area of Central Latvian or Middle Latvian Glaciodepression are fixed by clear represented marginal bands of Pampâii-Ranka, Linkuva, Plieði, Valdemârpils, Staicele, Lejassalaca Stadial Stages. Therefore the forms of glacial relief and deposits in limit of this glaciodepression have different age, determined by areas of distribution stadial stages. Different age, which was connected with the time of retreat separate stadial stages and when maked subglacial and elongated forms, had ice streams also.

The intertill sediments represented by silts, clay and peat also occur in area of Central Latvian or Middle Latvian Glaciodepression and by results of biostratigraphical investigations are interstadial sediments. There are Raunis interstadial sediments located between Pampâii-Ranka and Linkuva tills, Mazsalaca interstadial (?) sediments - between Linkuva and Plieði tills (?), intertill clay near Upits and Bridags (Vitrupe River) - probably between Valdemârpils and Staicele tills. At present the silt found under till at Pabaþ i also. This site locates on beach near mouth of Pçterupe River. The age of outcropped silt

possible correspond to interval between Valdemârpils and Staicele Stages also. The intertill sediments between Pampâii-Ranka tills and represented by clay were found by Âboltiðð in 1963 in some sites of Zemgale (between the top of the Gulf of Riga and Linkuva end moraine) and later in these sediments was determined the pollen and spores of interstadial interval.

Discussed above data are serious ground for opinion that during retreat of the Last Ice Sheet within Central Latvian or Middle Latvian Glaciodepressionan took place the row sequence stadial independent advancements of the ice cover. The ice cover during each stadial advancement is characterized both itself sizes and glaciodynamical features. The largest sizes and more complicated system of ice streams existed during Pampâii-Ranka and Linkuva Stages and at the time of ice covers retreat had been formed more different glacial formations. Besides frontal and behind frontal marginal forms for these stages clear are fixed inner zones of morphogenesis, which represented radial forms and plains also. The bands of marginal forms fixing beginning from Plieði Stage the ice cover of the Last Ice Sheet within Central Latvian or Middle Latvian Glaciodepressionan had smaller sizes than at the time of previous stages and contours of Plieði ice cover in side of Northwestern Widzeme had been approached to recent shore of the Gulf of Rîga and the contours observed sequence younger stages are stretched along of the Gulf of Rîga nearer to it shore. The glacial forms of these younger stages in zones located on land represented both marginal band formations of maximum distribution of ice and probably behind frontal marginal forms only but inner morphogenesis zones of these ice covers located on area of the Gulf of Rîga.

The different age of glacial formations connected with advancements and retreat of ice cover during stadials and interstadials, which took place at the time of the common deglaciation of the Last Ice Sheet not allow to reconstruct the palaeodynamical and palaeographical schemes based only on sequence changes of glacial morphogenesis in different parts of common ice cover (kinetic stratigraphical method). Ice cover at the time both each stadial advancement and it retreat had itself gaciodynamical development and especial sign of morphogenesis. Besides, each new stadial advancement covered the area formations, which were formed during previous glacial stage. Therefore on common area development of the Last Ice Sheet, as clear observed in Central Latvian or Middle Latvian Glaciodepression, mechanical is breaked sequence in normal paragenetical location of the glacial formations characterizing different dynamical zones in homogenous by age ice cover.

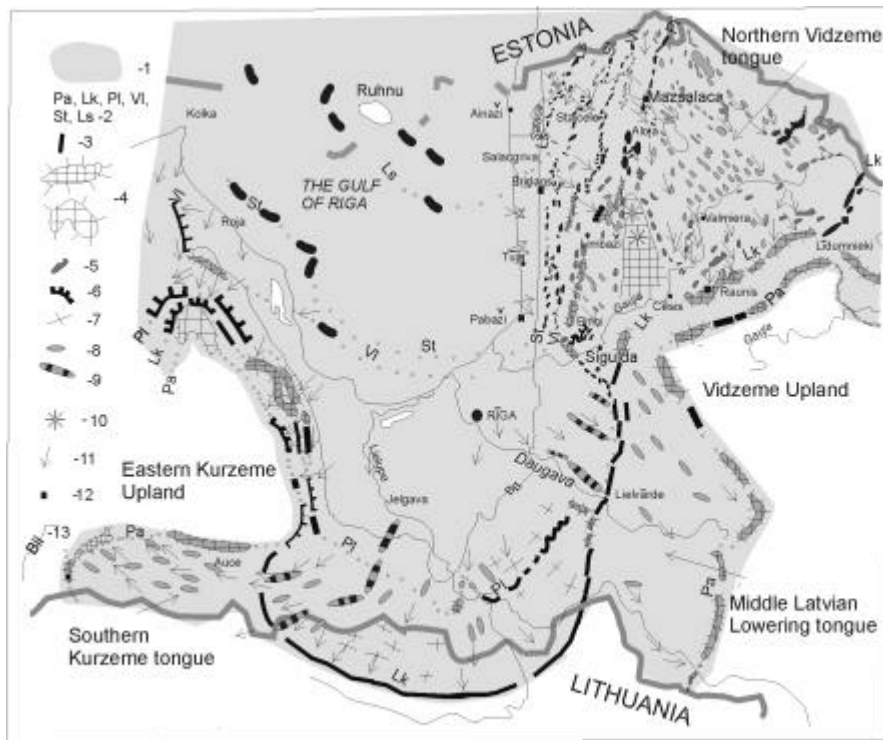


Figure 1. The principal scheme of glaciodynamical evolution of Central Latvian or Middle Latvian Glaciodepression, where had been developed the ice streams of the Gulf of Rīga during the retreat of the Last Ice Sheet. (took into account and used also the data of Zâns 1933, 1935, 1936/1937, Âboltiðð 1970,1998, Âboltiðð, Veinbergs, Stelle, Eberhards 1972, Veinbergs 1968,1972, Âboltiðð, Veinbergs, Eberhards 1974, Straume 1984, Zelès 1993, 1998, Dreimanis, Zelès 1997,1998, Zelès, Dreimanis 1997,1998, Juškeviès, Talpas 1997). 1- the area of Central Latvian or Middle Latvian Glaciodepression, 2-indexes of the glacial stages of the development of the ice streams of the Gulf of Rīga: Pa-Pampâii-Ranka, Lk-Linkuva, Pl- Plieði, Vi-Valdemârpils, St-Staicele, Ls-Lejassalaca , 3-ramparts and like-rampart forms of end and flank moraines, 4-marginal hilly ridges and massifs, 5- marginal ramparts and like-rampart forms, showing intermediate positions of the ice-sheet margin between basical glacial stages, 6-slope of glacial contact, 7-rogen and ribbed moraine, 8-drumlin and like-drumlin forms, 9-esker, 10-dauguīi, 11-orientations of elongated debris in the till, 12- the sites with intertill interstadial sediments, 13-shore line of Baltic Ice Lake of Bii stage.

RECENT GLACIAL HISTORY FROM THE CONTINENTAL SHELF OFFSHORE OF THE PENNELL COAST, NORTH VICTORIA LAND, ANTARCTICA

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During the 1998 and 1999 field seasons, geologic and geophysical surveys were conducted on the Antarctic continental shelf from North Victoria Land to Marguerite Bay. The data set includes sediment cores, high-resolution seismic data, side-scan sonar, and multibeam swath bathymetry data.

Glacial troughs were observed on the shelf offshore of each major drainage area. The troughs tend to be narrow and deep with irregular bathymetry on the inner shelf and broader and shallower on the outer shelf. This observed pattern correlates with patterns of geology and geomorphic features. Seismic data show that the inner shelf has a crystalline substrate and the outer shelf is composed of sedimentary strata. Multibeam swath bathymetry data reveal that the geomorphic signature of grounded ice varies from one side of the sedimentary-crystalline substrate contact to the other. In the area of crystalline substrate only erosional features such as roches moutonnees, meltwater channels, and grooves were observed. Mega-scale glacial lineations and iceberg furrows are observed in the area of sedimentary substrates and gullies occur on the upper slope. These features indicate a slow moving ice sheet eroding the inner-shelf crystalline bedrock and a relatively fast ice stream eroding the sedimentary substrate and forming a deformation till. This pattern is interpreted as evidence that a sedimentary substrate is required for rapid flow of ice by bed deformation. Evidence for subglacial meltwater was only observed on the crystalline substrate landward of the mega-scale glacial lineations. Gullies on the upper slope have been interpreted as evidence for the release of turbid sediment-laden water from the base of an ice sheet grounded at the shelf edge. Evidence for meltwater on both the landward and seaward side of the mega-scale glacial lineations may be evidence that deformation till is formed using any meltwater available. Drumlins were observed only at the contact between areas of crystalline substrate and erosion and areas of sedimentary substrate and mega-scale glacial lineations. Drumlins are thus interpreted to be indicative of ice acceleration.

The Pennell Coast region of North Victoria Land does not have the same pattern as the majority of the study areas. It is characterized by a glacial trough with rugged bathymetry formed in crystalline substrate on the inner shelf and a broad shallow trough in the sedimentary substrate on the outer shelf. However, despite evidence from core samples for ice-sheet grounding on the outer shelf during the last glacial maximum, there is no evidence for streaming ice on the sedimentary substrate. This study area serves as a reminder that despite being a requirement, a sedimentary substrate is by no means a guarantee of streaming ice. Possible reasons for the lack of evidence for streaming ice on the Pennell shelf include the relatively small drainage area, the relatively narrow zone of sedimentary substrate on the shelf, and the sandy nature of the majority of the sediment that may not be suitable for the development of deformation till.

ICE STREAMS, VALLEY GLACIERS AND PALAEO-ICE CAPS IN NORTH NORWAY

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Investigations in the Lyngen and Ksfjordjøkelen areas of north Norway have shown that there are large areas of plateaus covered with weathered blockfield material. These remnant plateaus sit in a dissected landscape with large, often fault guided, valleys that existed before the onset of Quaternary Glaciations. These weathered residua have not, apparently, been removed by active glacier ice, even though cold based glaciers are currently melting back from these surfaces. Only where the surface gradient has produced wet-based glaciers are glacially-smoothed bedrock surfaces exposed and the blockfield has been removed. The valleys cutting through the north Fennoscandian mountains clearly show evidence of ice flow. We have investigated the possibility the north Fennoscandian ice cap was not as thick over this area as has been predicted (2-3 km) but that much of the ice was moved out of major accumulation centres through the pre-existing valleys. The paper shows the results of simple modelling with various scale DTMs which suggests that ice streaming could indeed be responsible for high discharges of ice movement from the accumulation centre to the west and the production of a variety of landforms, both constructional and erosive, that resulted from these flows.