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Glacial geology and palaeo-ice dynamics of two ice-sheet margins, Taymyr Peninsula, Siberia and Jameson Land, East Greenland

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Abstract

The North Taymyr ice-marginal zone (NTZ) on the Taymyr Peninsula, Arctic Siberia and the Ugleelv Valley on Jameson Land, East Greenland, have been investigated with the aim of reconstructing the glacial history, including depositional processes and environments. Geomorphological, sedimentological, stratigraphical and remote sensing methods have been combined to give a comprehensive view of developments in the two areas. Optically stimulated luminescence (OSL) and radiocarbon (^{14}C) dates provide the chronological control.

The Kara Sea shelf was glaciated three times during the Weichselian, each time with a smaller ice cover than before. The ice sheets caused a reversal of the fluvial drainage towards the south on the Taymyr Peninsula and, during the Early-Middle Weichselian, also the damming of proglacial lakes. The youngest ice-advance, but probably also the older ones, was warm-based and 'surge-like'. After it had reached its maximum position, the margin froze to its base and compressional flow took place there. The North Taymyr ice-marginal zone (NTZ) was initiated during an Early Weichselian retreat stage (c. 80 ka BP) and added to during the Middle (c. 65 ka BP) and Late Weichselian (<20 ka BP) ice advances, thus revealing a complex history. It comprises ice-marginal and supraglacial landsystems dominated by 2-3 km wide thrust-block moraines. Large areas are still underlain by remnant glacier ice and a supraglacial landscape with numerous ice-walled lakes and kames is forming even today. The proglacial landsystem is characterised by subaqueous or terrestrial environments, depending on altitude and time of formation.

The sedimentary succession in the Ugleelv area comprises three tills, glaciolacustrine, glaciofluvial and aeolian sediments. The depositional history started in the early Saalian with a prograding delta in a lake dammed by an outlet glacier in Scoresby Sund. Soon thereafter, and also once during the Weichselian, Jameson Land was inundated by glaciers emanating from Liverpool Land in the east. These glaciers were warm-based and deposited glaciofluvial sediments, local tills and small end moraines. Conditions were less dynamic later in the glacial cycles. During most of the Weichselian the Ugleelv area was ice free and aeolian activity took place, but in the late Saalian the Greenland ice sheet expanded eastwards over the area. This ice was mainly cold-based but in places temporarily warm-based, where a lodgement till was deposited. During deglaciation there was substantial glaciofluvial erosion.

The Kara Sea ice sheet and the Greenland ice sheet behave differently through a glacial cycle. The shelf-centred Kara Sea ice experiences large shifts in areal extent and disappears completely during interglacials. 'Individual' ice advances seem to be governed by internal ice dynamics rather than by climatic changes. Contrary to this, the Greenland ice sheet is relatively stable and the climatically driven expansion or retreat of its outlet glaciers through the fjords represents the major changes.

Key words: sedimentology, geomorphology, glacial history, ice-marginal processes, ice dynamics, Pleistocene, Arctic Siberia, East Greenland

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II: **Alexanderson, H.**, Hjort, C., Möller, P., Antonov, O. & Pavlov, M. 2001: The North Taymyr ice-marginal zone, Arctic Siberia – a preliminary overview and dating. *Global and Planetary Change 31(1-4)*, 427-445.

III: **Alexanderson, H.**, Adrielsson, L., Hjort, C., Möller, P., Antonov, O., Eriksson, S. & Pavlov, M. 2002: Depositional history of the North Taymyr ice-marginal zone, Siberia – a landsystem approach. *Journal of Quaternary Science 17(4)*, 361-382.

IV: Adrielsson, L. & **Alexanderson, H.**: Two cycles of ice-sheet and coastal mountain glaciation in central East Greenland. Manuscript submitted to *Boreas*.

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by

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'To see a world in a grain of sand'
William Blake

This thesis is based on four papers listed below as appendix I-IV and referred to in the text by their Roman numerals. The papers are reprinted with the permission of the Polish Geological Institute (paper I), Elsevier (paper II) and John Wiley & Sons, Ltd. (paper III). Paper IV has been submitted to *Boreas*.

App. I: **Alexanderson, J.H.** 2000: Landsat mapping of ice-marginal features on the Taymyr Peninsula, Siberia – image interpretation versus geological reality. *Geological Quarterly 44(1)*, 15-25.

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Folded glacier ice below a thin layer of melted-out diamicton, exposed in a slump headwall at White Lake, the Taymyr Peninsula, Siberia.

Introduction

Landscapes in high northern latitudes are largely shaped by ice sheets, which have repeatedly grown and decayed during the Quaternary. Sediments and landforms hold information about these events and can be used to reconstruct past environments and climate. This reconstruction is an ever ongoing work and our views are constantly changing as new data are brought forward.

Ice sheets grow and decay due to external and internal mechanisms. The ultimate driving force behind extensive glaciations is believed to be the Milankovitch astronomic orbital cycles (Berger *et al.* 1984). Repeated ice-lobe advances alternating with periods of ice-front stagnation or retreat during a single ice age are also generally considered to be driven by climatic events. However, this is only partly true, as other factors, such as topographic setting and subglacial conditions (substrate, temperature, hydrology) may hamper or facilitate individual glacier advances (e.g. Clark 1994) and even affect ice-sheet behaviour (Oerlemans 1982; Clark *et al.* 1999). Thus, to interpret the geological record correctly it is necessary to know whether an ice-lobe advance was caused exclusively by climatic changes or was mainly triggered by other mechanisms.

Two distinct modes of ice-sheet behaviour through a glacial cycle are indicated by the striking differences between the glacial records from northern Eurasia and Greenland. The Greenland ice sheet has long remained stable with only relatively small oscillations (Funder *et al.* 1998), while during the same time a build-up of ice sheets and large-scale rapid advances of low-gradient ice-sheet lobes seem to have occurred along the coast of arctic Eurasia (e.g. Tveranger *et al.* 1999).

Sedimentological data from southern Scandinavia (Adrielsson 2001), North America (Clark 1994) and the northern Siberian coast (this study), indicate that special physical and hydrological conditions, occurring at the base of the ice sheet, caused instabilities that resulted in the rapid spread of ice masses. This suggests a complex connection between climatic factors and ice-sheet dynamics, and highlights the importance of comparative glacial-geological studies of areas with contrasting ice-dynamic behaviour.

The spatial distribution of ice sheets influences the oceanic and atmospheric circulation, as well as the hydrology of surrounding continental areas. For example, depending on the ice-sheet distribution in arctic Eurasia, several large, north-flowing rivers may become blocked, leading to the creation of large proglacial lakes and to reversed (southward) drainage (Arkhipov *et al.* 1995; Mangerud *et al.* 2001). Ice-sheet limits are also important input parameters in computer models of climate, isostasy and rheology (e.g. Lambeck *et al.* 1998; Siegert & Marsiat 2001).

Several contradicting hypotheses have been put forward regarding the spatial and temporal extents of Eurasian ice sheets, and also about their geographical origins, especially for the Late Weichselian – the Last Glacial Maximum (Rutter 1995; Svendsen *et al.* 1999). The propositions have ranged from a marine-based panarctic ice sheet (Grosswald 1980; Grosswald & Hughes 2002) to limited local highland glaciation (Velichko *et al.* 1997; Pavlidis *et al.* 1997). Astakhov (1992, 1997, 1998) incorporated a temporal aspect and suggested that the large ice sheets occurred in the Early Weichselian or Saalian and that the Late Weichselian glaciation in Siberia was restricted.

Work within the QUEEN (Quaternary Environment of the Eurasian North) and 'Eurasian Ice Sheets' programmes, of which this study is a part, has led to a revision of the view on glaciations in the Eurasian Arctic (Larsen *et al.* 1999; Thiede *et al.* 2001). We now believe that the greatest ice extent was during the Saalian, and during the Weichselian the maximum glaciation was successively displaced towards the west, occurring in the east (Kara Sea region) during the Early Weichselian and culminating in the west (Scandinavia) during the Late Weichselian.

The glacial history of East Greenland is better known, in large part due to the results of the PONAM (Late Cenozoic Evolution of the Polar North Atlantic Margins) programme in the early 1990's (Funder *et al.* 1998). Most work has, however, been concentrated on outlet glaciers in fjords and less has been done in the highland areas in between.

The aim of my work has been to reconstruct the glacial history, including processes and environments, at former ice-sheet margins, in this case at the eastern flanks of the Kara Sea ice sheet and the Greenland ice sheet (Fig. 1). The more specific objectives have been to describe sediments and landforms, map ice-sheet limits, recognise the depositional processes and, from all this, deduce the nature of the ice sheets and glacial cycles.

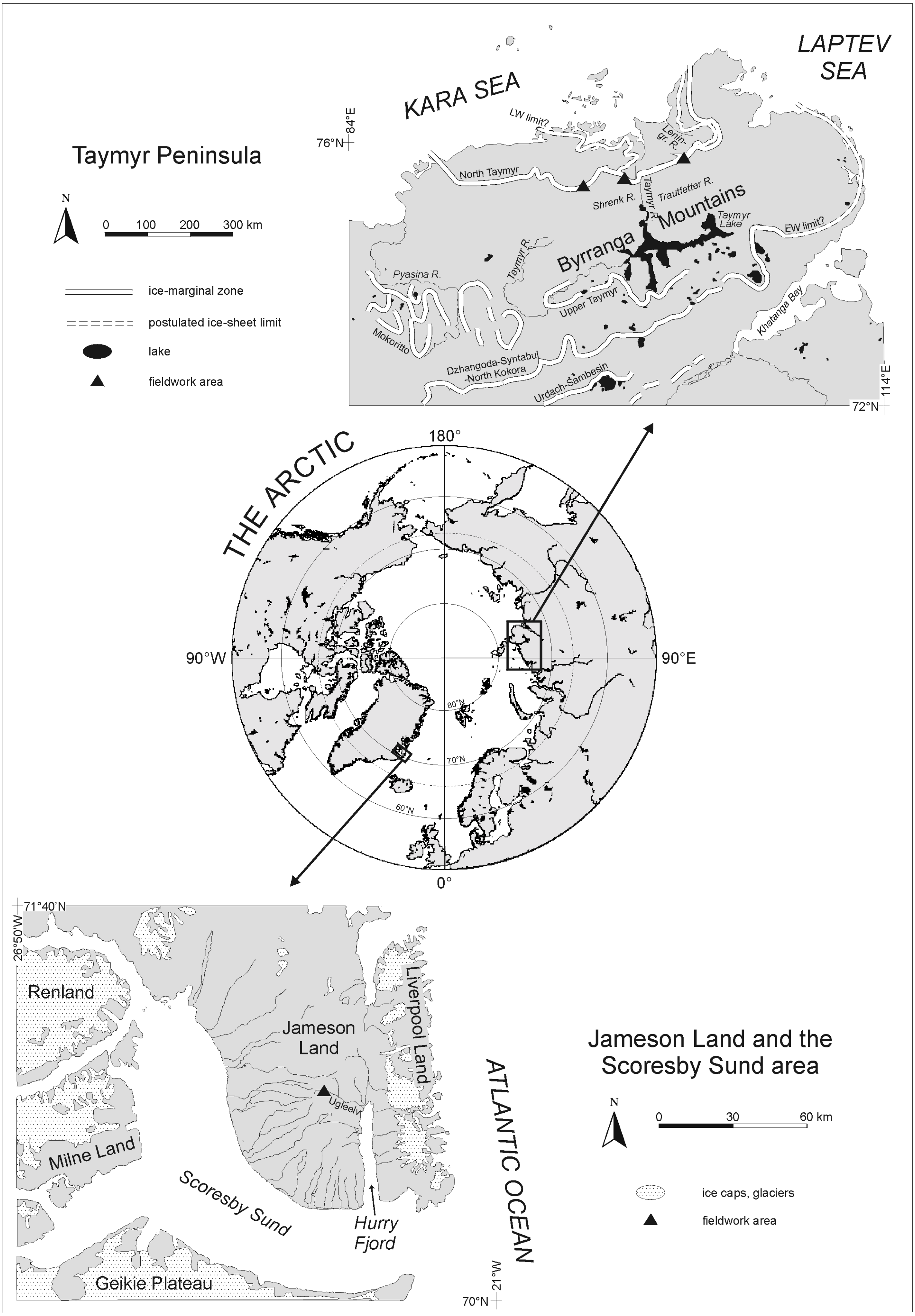

Fig. 1. Map of the Arctic with insets of my study areas: the Taymyr Peninsula, Siberia and Jameson Land, East Greenland. On Taymyr the fieldwork areas are, from left to right, the Astronomical Lakes, Barometric Lake and White Lake. EW is Early Weichselian, LW is Late Weichselian and R is river. Positions of the ice-marginal zones south of the Byrranga Mountains are mainly from Kind & Leonov (1982).

Study areas

My main fieldwork area has been the Taymyr Peninsula in north-central Siberia. The major target there was the North Taymyr ice-marginal zone (NTZ), which is the northernmost of several ice-marginal zones on Taymyr (Fig. 1). During two summers, in 1998 and 1999, the 750-km-long NTZ was extensively studied in three areas: the Astronomical Lakes (Ozera Astronomicheskye; 76°17'N, 96°19'E), Barometric Lake (Ozero Barometricheskoe; 75°35'N, 98°24'E) and White Lake (Ozero Beloe; 75°57'N, 101°54'E) areas. These sites are located 80-100 km apart on a SW-NE transect (Fig. 1). In the summer of 2000 I worked in the inner-most parts of the Ugleelv Valley on Jameson Land in East Greenland (Fig. 1), where more than 100 m of Quaternary sediments are exposed.

Methods

To get an overview of the northwestern Taymyr Peninsula and the NTZ, I studied a suite of satellite images (Landsat, Corona, KATE; see Table 1 in paper III) and analysed them both visually and digitally (paper I). I did the latter analyses by using the GIS programmes IDRISI (Eastman 1997) and ArcView (Environmental Systems Research Institute). Aerial photographs were available for the fieldwork areas on both Taymyr and Jameson Land and have been used to map sediments and landforms.

Digital elevation models (DEM's) of the Taymyr Peninsula and of Jameson Land have been extracted from the Global Land One-km Base Elevation (GLOBE) data set (GLOBE Task Team *et al.* 1999). I have also created more detailed DEM's of the fieldwork areas from digitised topographic maps (scale 1:100,000; 1:250,000). The DEM's have, for example, been used to estimate the extent and drainage-ways of ice-dammed lakes.

I have mapped landforms both in the field and by remote sensing. Detailed logging of sediments, including bed contacts, lithology, grain size and structures in sections along lake shores, rivers and valley sides formed a basis for interpreting depositional processes and environments. Palaeocurrent measurements and fabric analyses were also made and samples were taken for dating, laboratory analyses and documentation. The radiocarbon (^{14}C-) dating was done at the Radiocarbon Dating Laboratory in Lund, Sweden and the optically stimulated luminescence (OSL) dating at the Nordic Laboratory for Luminescence Dating at Risø, Denmark.

Latitude/longitude coordinates were measured with a Magellan GPS Pioneer. Altitudes are either taken directly from topographical maps or were measured by a Thommen HM30 digital altimeter, calibrated at fix-points on the topographical maps. I have investigated many more sites than are presented here, so the original site numbers have been kept to aid correlation with the public PANGAEA database (http://www.pangaea.de), from which all sedimentary logs from Taymyr can be retrieved.

Results – summaries of papers

Fieldwork and authorship contributions

The work behind the co-authored papers (II-IV) has been shared as follows: For papers II and III, the greater part of the fieldwork along the NTZ was done by Christian Hjort and me, with contributions from Oleg Antonov, Saskia Eriksson, Per Möller and Maksim Pavlov. I did most of the sedimentological logging and interpretation, a large part of the geomorphological mapping and also the bulk of the remote sensing. I was responsible for writing and received input from Lena Adrielsson, Oleg Antonov, Christian Hjort and Per Möller. For paper IV, Lena Adrielsson and I contributed equally to both fieldwork and writing.

Paper I

Alexanderson, J.H. 2000: Landsat mapping of ice-marginal features on the Taymyr Peninsula, Siberia – image interpretation versus geological reality. *Geological Quarterly 44(1)*, 15-25.

The aim of this paper was to survey fieldwork localities and to acquire a regional geological overview of the North Taymyr ice-marginal zone on the Taymyr Peninsula, Siberia (Fig. 1). I did this by visually and digitally studying a Landsat 5 Multispectral Scanner (MSS) image (153/006; 8 Aug. 1992). The computer-based analyses were mainly made in IDRISI (Eastman 1997).

The ice-marginal zone, which is >2 km wide and many kilometres long, is clearly visible on the satellite image and I could also distinguish different ground types by classifying spectral signatures. Two areas were ground-truthed during fieldwork and this helped in interpreting the ground types geologically. A supervised classification method ('Maximum likelihood'), based on Bayesian probability theory, proved to give the result which best corresponded to reality. Seven ground types (spectral classes) were distinguished, described and interpreted:

• *Dark-coloured bedrock and peat*. The bedrock includes dolerites and greenschists and is found on topographic highs. The peat areas are dominated by dark moss with sparse grasses and herbs and are located mainly within topographic depressions.

• *Light-coloured bedrock*. This class is made up of limestones, shales, sandstones, granites and, locally, also unconsolidated Cretaceous sand.

• *Unvegetated cobbles, gravel and sand*. This ground type has no or very sparse (<20%) vegetation cover. It is a diverse class that encompasses, for example, fluvial bars, beaches, boulder fields, windblown hilltops, sediment cliff sections and even some frost-shattered bedrock outcrops.

• *Vegetation-covered fine diamict and coarse sorted material*. This class is the most common on the satellite image and predominates in high, relatively dry terrain. The ground is >90% covered by vegetation. It consists mainly of thin silty till and, concentrated in some areas, of glaciofluvial and glaciolacustrine sands and gravels.

• *Tussocky and dry silt*. This ground type corresponds to a hummocky tundra landscape with frost-boiled silt and gully formation. In lowland areas, it consists of glaciolacustrine silts and in higher terrain of silty till.

• *Well-vegetated silt*. This is a very patchy ground type where moss-tussocks dominate and it forms large undulating areas. The class has been interpreted as silty glaciolacustrine sediments.

• *Waterlogged mud*. The class occurs on damp to wet grasslands on floodplains, recent deltas and around lakes. It consists of muddy alluvial sediments, mainly Holocene in age.

Satellite image analysis is advantageous in that it is relatively low-cost, covers large areas and can be done quickly and systematically. However, there are some disadvantages, such as poor spatial and spectral resolution. In this case the results were largely satisfactory, but to correctly interpret the identified spectral classes geologically, it was necessary to consider individual areas and their topographic position, relative size and association with other classes.

Paper II

Alexanderson, H., Hjort, C., Möller, P., Antonov, O. & Pavlov, M. 2001: The North Taymyr ice-marginal zone, Arctic Siberia – a preliminary overview and dating. *Global and Planetary Change 31(1-4)*, 427-445.

This paper gives an overview of the geographical extent and the general geomorphology and sedimentology of the North Taymyr ice-marginal zone (the NTZ), a c. 750 km long ice-marginal zone built up in front of an ice sheet emanating from the Kara Sea shelf area (Fig. 1). It also presents a preliminary chronology. The NTZ is most prominent and continuous in its central parts, on which this paper concentrates. For the rest of its length, west of the Astronomical Lakes and north of the Leningradskaya River, the zone is less distinct.

The NTZ is a complex physiographic feature, composed of several glacigenic elements of differing age. It marks a distinct change in the landscape, from a distal weathered terrain to a proximal, fresh landscape littered with crystalline erratics. Morphologically, the base of the NTZ is made up of large, arcuate ice-marginal moraines with a silty till cover. These moraines are ice-cored and pitted with lakes. Superimposed are smaller ice-marginal hills and ridges, which consist of sand, gravel or diamict sediments and occur mainly on the southern (distal) side. Distal to the moraines are sandur plains and valley trains, and also deltas related to two different glacial-lake levels, at 120-140 m a.s.l. and at c. 80 m a.s.l. Other shoreline indicators, such as beach ridges, corresponding to these levels have also been found. In the low-lying areas just outside the NTZ are large expanses of laminated, fine-grained glaciolacustrine sediments.

Ice-dammed lakes were formed when ice sheets, advancing from the north, blocked the normal, northward drainage and also supplied increased volumes of meltwater. The lakes occupied the Lower Taymyr, Shrenk and Trautfetter river valleys and were linked to the Taymyr Lake basin south of the Byrranga Mountains. From Taymyr Lake, the drainage was either westward, through the Pyasina River valley out onto the southern Kara Sea shelf, or eastward to Khatanga Bay and the Laptev Sea. South-directed glaciofluvial and glaciolacustrine sediments at, for example, Lake Engelgardt support the reversed, southward drainage through the Byrranga Mountains.

The depositional history of the NTZ can be divided into three major events (Fig. 2). The

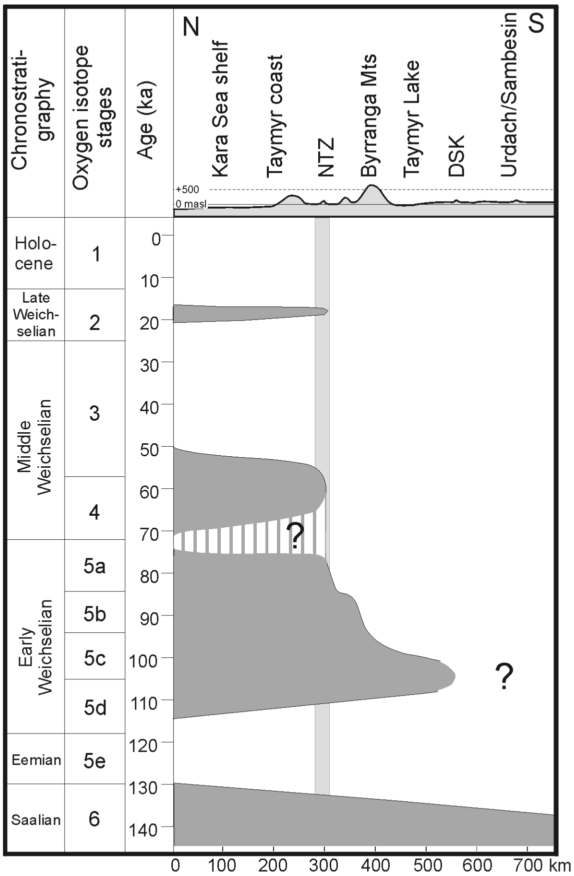

Fig. 2. Glaciation curve for the eastern flank of the Kara Sea ice sheet. The vertical, light grey shading represents the NTZ area. For locations see Fig. 1.

chronology is based on optically stimulated luminescence (OSL) and radiocarbon (^{14}C) dating.

1. Early Weichselian, c. 80 ka BP. A retreating ice-sheet front made a temporary halt at the NTZ and the large moraines and some superimposed ridges were formed together with deltas and glaciolacustrine sediments in the 120-140-m lake. During the early stage of the ice-dammed lake, a brief marine incursion may have occurred. After deglaciation, a detached debris-rich ice-margin body was left and it was gradually covered by its own melt-out till and incorporated into the permafrost. This event is most likely rather closely preceded by an earlier retreat stage, the 'Ledyanaya event' (Möller *et al.* 1999a, b), with glaciomarine delta sedimentation south of the Byrranga Mountains.

2. Middle Weichselian, c. 65 ka BP. The ice front once again stood at the NTZ and most of the superimposed ridges belong to this phase. Deltas and glaciolacustrine sediments were deposited in the 80-m lake, which was fed both by rivers and directly from the ice sheet. The lower lake level may be attributed to a lowered threshold, a new opened-up passage or simply to reduced isostatic downloading. There is also at least a 10 ka time difference between Events 1 and 2.

3. Late Weichselian, <20 ka, >9.5 ka BP. A rather thin ice sheet from the Kara Sea shelf inundated some coastal lowlands and large river valleys and dislocated and deformed older sediments. The central parts of the ice sheet melted away earlier than the frontal areas, where remnant glacier ice is still left under a thin (<1 m) till cover. No glacial lake of any consequence was dammed by this ice.

Paper III

Alexanderson, H., Adrielsson, L., Hjort, C., Möller, P., Antonov, O., Eriksson, S. & Pavlov, M. 2002: Depositional history of the North Taymyr ice-marginal zone, Siberia – a landsystem approach. *Journal of Quaternary Science 17(4)*, 361-382.

In this paper the North Taymyr ice-marginal zone (NTZ) is described in more detail and the processes responsible for its formation and the nature of the ice sheets involved are discussed. Information from satellite imagery, geomorphological mapping and sedimentological logging has been combined in a landsystem approach. The NTZ landsystem (Fig. 3), consisting of the sediment-landform associations mentioned below, has many similarities to subpolar ice-marginal landsystems, but there are some differences, such as the lack of subglacial landforms. It is concluded that:

- *The ice-marginal association* consists of large thrust-block moraines, two types of small push moraines, kames, subaqueous fans and large-scale deformation of sediment and ice. It formed where debris was concentrated and moved to the ice surface due to compressive flow at a margin frozen to its base. The push moraines, kames and subaqueous fans occur on the distal side of the large moraines, and the latter two are in places arranged in concentric or reticulate patterns.
- *The supraglacial association* is underlain by remnant glacier ice and is characterised by an ablation terrain with numerous glaciokarst lakes and kames. There is a zonation reflecting the relative abundance of sediment and ice, from a sediment-dominated distal zone to an ice-rich proximal zone. The surface cover is a supraglacial melt-out till, mostly consisting of redeposited shell-bearing marine sediments. The landscape is still under development by back and downwasting processes, which eventually should lead to topographic inversion.
- *The proglacial association* is either subaqueous or terrestrial, depending on altitude for different areas and times of deposition. It consists of ice-

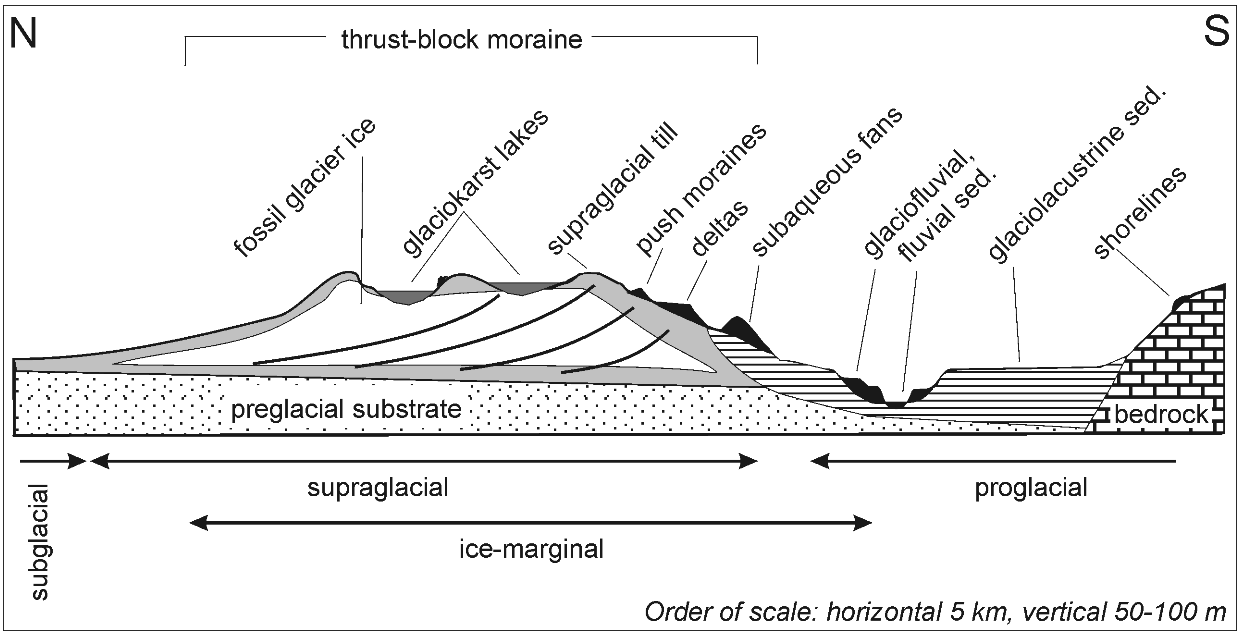

Fig. 3. A schematic representation of the landsystem of the North Taymyr ice-marginal zone.

contact deltas at two levels (c. 130 and 80 m a.s.l.), fine-grained glaciolacustrine sediments, glacial lake shorelines, sandar and valley fills.

- *The subglacial sediment-landform association* has not been studied in any detail. It seems, however, as if the subglacial drainage system was a distributed one, but that a switch to a channelised system may have taken place at the margin.
- *The paraglacial association*, consisting of alluvial and aeolian sediments, thaw lakes, patterned ground and palsas, has formed since the active ice retreated from the NTZ.

A schematic model, divided into four phases, for the dynamics of the Late Weichselian ice advance onto the Taymyr Peninsula has been constructed. In phase 1, cold ice was formed on the Kara Sea shelf. As it advanced over the permafrozen shallow shelf, much debris was incorporated and the subglacial drainage also became blocked (phase 2). Then the porewater pressure under the ice increased until the ice was lifted and started to slide over subglacial water and a deforming bed (phase 3). The ice moved on to present land areas until the driving force at the margin was reduced and the ice slowed down. The margin then froze to its bed (phase 4) and a compressional-flow regime was developed since ice from behind still pushed on.

The formation of the NTZ derives from three successively smaller glacial events during the Weichselian (Fig. 2). The oldest parts of the NTZ were formed c. 80 ka BP and represent a stagnation or readvance phase during the deglaciation of an Early Weichselian ice sheet that at its maximum reached far south of the Byrranga Mountains (Hjort *et al.* 2002). New deposits and landform segments were added to the NTZ during the Middle Weichselian, around 65 ka BP. Proglacial lakes were dammed by the ice during both these phases, at c. 130 and 80 m a.s.l., respectively. During the Late Weichselian, after 20 ka BP, a comparatively small, thin ice sheet advanced on to the northwesternmost Taymyr Peninsula. Like its predecessors it caused a reversal of the drainage towards the south, in this case, however, only leading to an elevated level and increased sedimentation rates in the Taymyr Lake basin (Möller *et al.* 1999a; Hjort *et al.* 2002). This last event was of short duration and the ice had collapsed by c. 12 ^{14}C ka.

Paper IV

Adrielsson, L. & Alexanderson, H.: Two cycles of ice-sheet and coastal mountain glaciation in central East Greenland. Manuscript submitted to *Boreas.*

This paper presents the glacial history of the Ugleelv Valley on central Jameson Land, East Greenland, as inferred from sedimentological and geomorphological data. Stratigraphy gives a relative chronology and optically stimulated luminescence dates provide some absolute age control. Correlations with the Jameson Land succession (e.g. Funder *et al.* 1998) and with regional ice-core and IRD-records (Johnsen *et al.* 1992; Stein *et al.* 1996) are discussed.

Three tills have been identified, differentiated by their lithological content and stratigraphic position, but the thickest deposits are

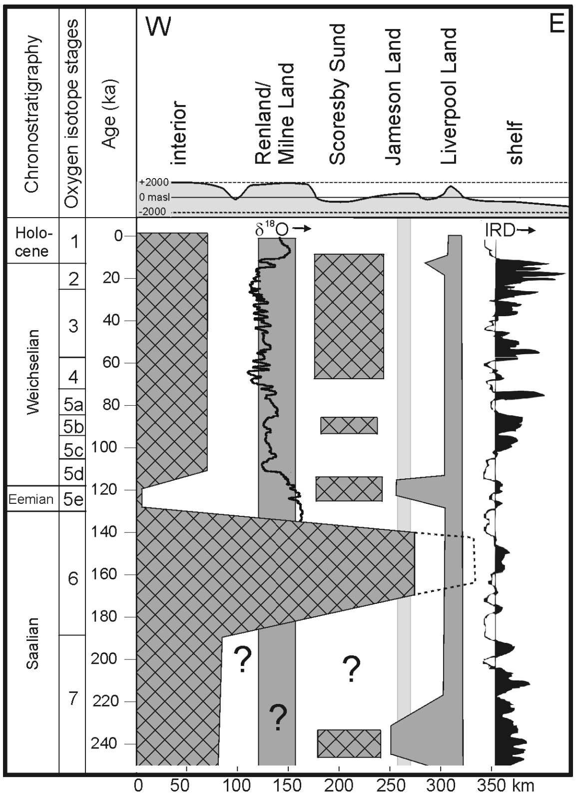

Fig. 4. Glaciation curve for the Scoresby Sund area. The hatched areas represent the Greenland ice sheet and its outlet glaciers, in contrast to local ice caps (grey). The vertical, light grey shading shows the location of the Ugleelv area. The $\delta^{18}O$-record is from the Renland ice core (Johnsen et al. 1992) and the ice-rafted debris (IRD) record from core PS1726 on the continental slope off Scoresby Sund (Stein et al. 1996; stretched to fit a linear timescale). Additional data also from Funder et al. (1998) and Hansen et al. (1999; Scoresby Sund).

glaciolacustrine deltaic and ice-marginal glaciofluvial sediments. Ice-free intervals are primarily represented by aeolian deposits. The depositional history in the Ugleelv Valley is as follows (Fig. 4):

• *A glacial lake dammed by an outlet glacier in Scoresby Sund, early Scoresby Sund glacial (Saalian).* A delta prograded from southwest into an ice-dammed lake on central Jameson Land, implying a debris-rich, warm-based glacier in Scoresby Sund.

• *Liverpool Land mountain glaciation 1, early Scoresby Sund glacial (Saalian).* Glaciers expanded from the Liverpool Land ice caps in the east and reached the Ugleelv area. A local lodgement till was deposited, showing that the glacier was warm-based. During deglaciation there was significant deposition of thick glaciofluvial sediments in subglacial and ice-marginal positions.

• *Periglacial conditions, Scoresby Sund glacial (Saalian).* At the end of deglaciation and during a following ice-free period, a cold and dry climate prevailed. Aeolian sediments were deposited and composite wedges and cryoturbation structures were formed.

• *Main ice-sheet advance, late Scoresby Sund glacial (Saalian).* The Greenland ice sheet overrode the area from the west, depositing lodgement till and crystalline erratics. Although mainly cold-based, spatial and temporal changes in basal temperature occurred. Meltwater eroded most of the present Ugleelv Valley, c. 135 ka BP.

• *Liverpool Land mountain glaciation 2, early? Weichselian, age <109 ka BP.* A glacier from the east (Liverpool Land) moved up the Ugleelv Valley while eroding its substrate and forming a U-shaped valley. It tectonised older glaciolacustrine sediments, as well as depositing a deformation till and small end moraines.

• *Aeolian activity, Weichselian, around c. 109, 27 and 10 ka BP.* On at least three occasions during the Weichselian, aeolian sediments have been deposited in the Ugleelv Valley. Both wind directions from the south (27 ka) and the north (10 ka) are recorded. Lee-side dunes within the valley are associated with the winds from the south and indicate arid conditions and no ice cover in the area at that time. The northerly winds are related to the formation of permanent snowpatches.

Two glacial cycles have thus been identified and they seem to follow a similar climatic pattern. Both glacial cycles began with the expansion of outlet glaciers from the main ice sheet and the growth of coastal mountain glaciers, caused mainly by relatively high precipitation. The glaciers were active, warm-based and contained much debris. Later, the climate got colder and drier, and the coastal glaciers probably became cold-based and retreated. Glaciers were less dynamic during the later parts of the glacial cycles. During the Saalian the main ice sheet advanced over Jameson Land. A drift limit southeast of the Ugleelv area, assumed to be erosional (Möller *et al.* 1994), may be explained by variations in basal thermal regime, either by spatial variation during the advance or by temporal variation at the ice-sheet margin during climatic warming. During the middle-late Weichselian the Ugleelv Valley was ice free, although a long-lasting glacier existed in Scoresby Sund (Hansen *et al.* 1999).

Discussion

Glaciations and landsystems

Three types of ice-dynamic behaviour, characterised mainly by basal thermal regime, have been recognised for the glaciations in my study areas. They are distinguished by different sediment-landform associations (papers III, IV). Climate and pre-existing topography initially control the type of glaciation, and thus the type of resulting landsystem, but as the ice sheet grows, subglacial bed conditions (substrate, hydrology) become increasingly important. For a single ice sheet, ice-dynamic behaviour may, and usually does, change with time and from place to place.

A warm-based 'surge-like' ice advance, with a margin that froze to its bed after reaching the maximum extent, has been inferred for the Late Weichselian Kara Sea glaciation on Taymyr, based mainly on the sediment-landform association of the NTZ (Fig. 3; paper III). An entirely cold-based ice would not have been able to reach that far inland without being very thick in its central parts on the shelf, and such a thick ice sheet is rejected by the lack of postglacial uplift (Lambeck 1995, 1996; Hjort *et al.* 2002). The older parts of the NTZ, older deformation tills elsewhere on Taymyr (unpublished data from this study; Funder *et al.* 1999; Möller *et al.* 2000) and the appearance of older moraines south of the Byrranga Mountains (Fig. 1; Kind & Leonov 1982) suggest that previous glacial events may have been similar. The southwestern sector of the Kara Sea ice sheet also seems to have been dynamic, at least partly warm-based and possessing a low-gradient profile during its maximum (Tveranger *et al.* 1999; Henriksen *et al.* 2001).

The present morphology of the NTZ is controlled by its buried glacier ice, melted-out supraglacial material and the glaciotectonic activity at its formation (Fig. 3). However, there are very few signs of glacial overriding north (proximal) of the NTZ (paper III). Landsystems similar to the NTZ are found in other parts of the Arctic (e.g. Sharpe 1988) and also along the former southern margins of the Laurentide (Mooers 1990; Ham & Attig 1996) and Scandinavian ice sheets (e.g. Wysota 1999), although in the latter areas the buried ice has melted long ago, leaving a hummocky moraine landscape. The interpretations from these other areas vary, but generally involve a warm-based ice-sheet lobe with compressive flow at its margin, located at the periphery of a large ice sheet in a relatively low-relief area and, at least partly, lying on top of permafrozen sedimentary bedrock or unconsolidated sediments. The conclusions drawn for the NTZ support the conception that transverse zones of hummocky moraines may not always represent passive marginal stagnation but could rather be the remnants of actively formed zones of ice-cored moraine (Dyke & Savelle 2000).

The Greenland ice sheet expanded onto Jameson Land during the Saalian, leaving scattered erratic boulders and lodgement till (paper IV; Möller *et al.* 1994). Most likely the ice sheet was cold-based on the Jameson Land plateau, as on other slightly higher areas between faster-moving outlet glaciers in the fjords (cf. England *et al.* 2000; Wilch & Hughes 2000). However, the deposition of lodgement till requires a warm-based ice and a thawed bed must have developed temporarily.

The main sediments and landforms resulting from this glaciation are characterised by glacial meltwater. On Jameson Land valley erosion, e.g. of the Ugleelv Valley, replaced the lateral meltwater channels most commonly associated with the retreat of cold ice (e.g. Kleman *et al.* 1992; Dyke 1993; Ó Cofaigh *et al.* 1999). This could be due to the flat topography of the area, with a broad ice-sheet front that mainly allowed frontal, not lateral, drainage.

The valley glaciers that extended to Jameson Land from the Liverpool Land mountains were active, erosive and carried much debris. These glaciers left small end moraines in the Ugleelv Valley and also glacially eroded their substrate (U-shaped valleys, local till). The pre-Saalian topography is largely unknown, but at least during the youngest advance, the glaciers were confined to valleys (paper IV). They do, however, differ from ordinary valley glaciers in that they moved upvalley on Jameson Land.

Ice-sheet limits

The maximum extensions of the Weichselian Kara Sea ice sheets are fairly well known on the Taymyr Peninsula (this study; Hjort *et al.* 2002), although two different moraines have been suggested as alternatives for terminal moraines of the most widespread glaciation, the one in the Early Weichselian (Kind & Leonov 1982; Astakhov 1998; C. Siegert *et al.* 1999). Evidence for both one and two Early-Middle Weichselian glacial advances from the Kara Sea shelf have been found on the mainland between the Taymyr Peninsula and the Pechora River (this study; Manley *et al.* 2001; Henriksen *et al.* 2001), on Severnaya Zemlya (Bolshiyanov & Makeyev 1995) and on the adjacent shelf (Knies *et al.* 2000, 2001; Kleiber *et al.* 2001). These Kara Sea ice sheets are generally assumed to have been confluent with the Barents Sea ice sheets (e.g. Svendsen *et al.* 1999) and the geographical limits are relatively well agreed upon.

The most questioned terminal ice margins are those for the Late Weichselian ice sheet and, especially, whether or not the ice was then confluent with the Barents Sea ice sheet. No evidence of inundation by a shelf-based ice has so far been recognised on Severnaya Zemlya (Bolshiyanov & Makeyev 1995; Raab *et al.* 2001; Berger *et al.* 2002; Per Möller pers.comm. 2002) or on the West Siberian and Russian mainland (Svendsen *et al.* 1999). Apart for Taymyr, the Late Weichselian ice-sheet limits are therefore believed to have been situated offshore (Fig. 1), and support for an ice sheet on the central Kara Sea shelf at that time is also provided by marine records (Polyak *et al.* 1997, 2002a, b). Recent marine-geological investigations seem to locate the southern limit of this ice sheet, based on till and moraine-ridge distribution, on the central shelf (Polyak *et al.* 2002a). So far the data are, however, inconclusive about whether the last Kara Sea ice sheet was separated from or confluent with the Barents Sea ice sheet to the west. Indications of glacial lakes and dammed north-flowing rivers are found in the southern Kara Sea and, thus, suggest a connection between the two ice sheets (Niessen *et al.* 2002; Polyak *et al.* 2002b). However, present-day land south of the Kara Sea does not seem to have been flooded (Mangerud *et al.* 1999; Svendsen 2001) and likely, the confluence was, if it existed, only brief, breaking up prior to 13 ka BP (Polyak *et al.* 2002b). The available data may favour a local ice mass on the central Kara Sea shelf, but are really too scarce yet to give a definite answer to this question.

As evidenced by western erratics and lodgement till, the Greenland ice sheet has, at some time, crossed both Jameson Land and Liverpool Land (Funder 1972). This glacial event is older than the Weichselian and has been placed in the Saalian (Scoresby Sund glaciation; Möller *et al.* 1994; Funder *et al.* 1998) and it has been proposed that the ice sheet terminated on the present shelf at this stage.

The boundaries between the till-covered plateau and the driftless areas on Jameson Land have been interpreted as caused by erosion (Möller *et al.* 1994). However, the eastern boundary may record a change from warm to cold basal conditions, or possibly, the terrestrial maximum limit of the main ice-sheet advance in Saalian time (Paper IV). If the latter is true, erratics on Jameson Land, Liverpool Land and other elevated areas along the East Greenland coast (Bretz 1935; Funder 1972; Funder & Hjort 1973) must have been brought there by one or several earlier, even more extensive glaciations. Evidence of such glaciations is found for example in IRD records off southeast Greenland, where the largest IRD peaks are 1-4 Ma old (St. John & Krissek 2002). It would perhaps also be easier to get the needed large increase in ice volume during longer cold periods and at a time before the efficient drainage system in the fjords was well developed.

The two advances from Liverpool Land have not previously been recognised and moraines in and along the Hurry Fjord have been thought to date from the Milne Land stade (cf. Table 3 in Paper IV), when glaciers briefly re-expanded along the East Greenland coast (Funder & Hjort 1973; Hjort 1979; Funder *et al.* 1998; Funder & Hansen 1999). Most of these moraines are undated and some of them, e.g. in the Gåseelv Valley (Lilliesköld & Salvigsen 1991) and at the mouth of the Hurry Fjord (Dowdeswell *et al.* 1994), may well belong to Liverpool Land mountain glaciation 2 (paper IV).

The nature of glacial cycles

Today both the Taymyr Peninsula and Jameson Land are situated in polar tundra environments (Köppen climate type ET; Henderson-Sellers & Robinson 1986), characterised by very low mean annual temperatures, little precipitation and continuous permafrost. During glacial periods the cold and the aridity were even more accentuated (Hahne & Melles 1999; Funder *et al.* 1998). For example, if precipitation is not reduced to almost zero during the Late Weichselian, ice-sheet models produce too much ice in the Kara Sea area to fit the geological record on the Taymyr Peninsula (M.J. Siegert *et al.* 1999; Siegert & Marsiat 2001). Due to the low temperatures, any ice that forms in these polar regions will initially be cold but may eventually, due to ice thickness, geothermal heat or friction, become warm-based.

The Weichselian glaciation in the Kara Sea region involved three glacial events of successively smaller amplitude (Fig. 2). The size reduction was a result of the successive westward shift of maximum glaciation with time, likely due to changes in atmospheric circulation (Velichko *et al.* 1997). Each glacial event called for the formation of an entire, new ice sheet, with the possible exception of the Middle Weichselian one (paper II; Hjort *et al.* 2002). During glacials the equilibrium line altitude (ELA) was probably lowered to sea level (M.J. Siegert *et al.* 1999; Grosswald & Hughes 2002) and ice sheets could form by ice accumulation on the exposed shelf (e.g. Barry *et al.* 1975) or from partly grounded, thickening sea ice (Grosswald 1980; Hughes 1986).

A glaciation on East Greenland, on the other hand, requires 'only' the expansion of pre-existing glaciers, ice caps or the main ice sheet. Increased ice cover may be brought about by northward (increased precipitation) or southward (decreased temperatures) shifts of climatic zones, both leading to lowered ELA's. The coastal glaciers and the Greenland ice sheet respond to different changes in climate and circulation and may expand and retreat out of phase (cf. Humlum 1999). A glacial cycle in the Scoresby Sund area may have started with both alpine glaciation in the coastal mountains and the expansion of outlet glaciers from the ice sheet (Fig. 4). During initial cooling there was still open water (a moisture source) close to the coast. Later, as sea ice expanded southwards, precipitation was reduced to glacial period levels and the coastal glaciers became less active, possibly changing to cold-based conditions. Similar switches in response to mass balance changes have been documented for glaciers on Svalbard (Glasser & Hambrey 2001). During the Saalian the ice sheet continued to expand, mainly due to low temperatures, while it remained relatively stationary during the Middle-Late Weichselian.

In both areas, Siberia and East Greenland, the early stages of a glacial cycle seem to have been the most dynamic, with extensive glacial advances of shelf-based ice, coastal glaciers and outlet glaciers from the ice sheet. Later, as the climate grew more severe (increased continentality and aridity), glaciations became more limited (Kara Sea) or static (Greenland). For example, the Late Weichselian ice advance onto the Taymyr Peninsula was probably caused by internal factors, rather than climatic (paper III), but nothing much happened with the relatively stable Greenland ice sheet in the Scoresby Sund area during the long Flakkerhuk stade (Hansen *et al.* 1999).

Deglaciations are usually more rapid than the growth of an ice sheet, mainly because accumulation is limited but ablation/calving is not (e.g. Letréguilly *et al.* 1991). The central parts of the Kara Sea ice sheets seem to have disappeared quickly, possibly aided by rising sea levels. In a strict sense, the marginal areas, e.g. the NTZ, have in fact not yet been deglaciated, as fossil glacier ice is still present under a thin cover of melted-out sediments (papers II, III). Glacier ice has also been reported from other areas covered by former Kara Sea ice sheets (Astakhov & Isayeva 1988; C. Siegert *et al.* 1999; Lokrantz & Ingólfsson submitted).

Conclusions

• The 750-km-long North Taymyr ice-marginal zone (NTZ) on the Taymyr Peninsula, Siberia, was formed along the front of ice sheets originating on the Kara Sea shelf. It records glacial events during the Early, Middle and Late Weichselian. The NTZ comprises large, ice-cored thrust-block moraines dotted with glaciokarst lakes, kames and small push moraines. At the distal margin are several deltas, subaqueous fans and sandur plains. Distal to the NTZ are laminated glaciolacustrine sediments deposited in lakes dammed by the ice sheets.

• The sedimentary record in the Ugleelv area on Jameson Land, East Greenland spans two glacial cycles. Glaciolacustrine sediments record a delta prograding from an outlet glacier in Scoresby Sund in the southwest. These sediments were later overridden by a glacier coming from the east (Liverpool Land) that deposited a local till and glaciofluvial sediments. After a period with periglacial conditions the Greenland ice sheet expanded over the area, depositing a till with regional distribution (Scoresby Sund glaciation). But the main impact was glaciofluvial erosion, including the erosion of the Ugleelv Valley, during deglaciation in the late Saalian. During the Weichselian a glacier advanced upvalley from the east, causing some erosion and deformation, and also depositing small end moraines. Aeolian sedimentation occurred in the Late Weichselian, showing there was no ice cover in the area at that time.

• Within my study areas, three types of ice-dynamic behaviour have been recognised. They are characterised by different sediment-landform associations, but share the trait of leaving few traces except for at their margins: (1) warm-based, 'surge-like' ice advance, with a margin that turned cold-based after reaching the maximum extent (the Kara Sea ice sheet); (2) mainly cold-based outer parts of an ice sheet, but with spatial and temporal changes in basal temperature (the Greenland ice sheet); and (3) mountain glaciation with valley glaciers (the Liverpool Land glaciers).

• The Kara Sea ice sheet was shelf/marine based and the ice advanced inward over land. It was unstable, experienced large shifts in areal extent and disappeared completely during interglacials. The glaciation of the Kara Sea had climatic causes, but internal ice dynamics may have governed 'individual' ice advances.

- The Greenland ice sheet is land-based and its ice advances towards the sea are strongly channelled by the fjords. Much due to the subglacial topography it is comparatively stable and the ice sheet remains during interglacials. The expansion or retreat of outlet glaciers in the fjords usually represents the major changes. Glaciations and ice advances are climatically driven.
- The most extensive Middle-Late Pleistocene glaciation took place during the Saalian in both the Kara Sea and Scoresby Sund areas. On Taymyr, three successively smaller glaciations occurred during the Weichselian, while the central Jameson Land plateau probably experienced only one minor Weichselian ice advance from the coastal mountains. See also Figs. 2 and 4.

Implications and ideas for the future

The work on Taymyr has delimited the eastern boundary of the Kara Sea ice sheet through time and, together with results from other QUEEN groups (Larsen *et al.* 1999; Thiede *et al.* 2001), disproved the idea of a great Late Weichselian Eurasian ice sheet (Peltier 1994; Grosswald & Hughes 2002). Another important part has been the documentation of the NTZ, which previously had only been outlined from satellite images (Kind & Leonov 1982; Isayeva 1984). So far, reliable absolute dates are relatively few and I would like to establish better chronological control of the glacial history of Taymyr. In determining the extent of the Late Weichselian Kara Sea ice sheet I find the recent results of marine-geological studies (Polyak *et al.* 2002a) very exciting and believe the combination of terrestrial and marine records will provide crucial answers. The sedimentary basins on Taymyr contain a long record of Quaternary environmental history (Kind & Leonov 1982) and it would also be possible to go further back in time and look at older glaciations, mainly south of the Byrranga Mountains, with a methodology similar to the one used in this study.

The Jameson Land results are roughly in agreement with previous studies (Möller *et al.* 1994; Funder *et al.* 1998) but provide more detail on the terrestrial glaciations in the otherwise fjord-dominated glacial record. To get a better idea of the ice-cover extent I would like to do detailed mapping of the plateau area, particularly of the glaciofluvial channels and till limits. It would also be interesting to look more closely at the late glacial–Holocene aeolian sediments and at what has usually been interpreted as 'historical' moraines. The possibilities of establishing a good chronology are promising, since the aeolian deposits are excellent for luminescence dating and I also think that cosmogenic isotope dating could be fruitful, for example for the older glaciations in the plateau area.

Taken together, my work has given some insights into the course of glacial cycles and into the dynamic behaviour of ice sheets in two different polar areas. It would certainly be interesting to further compare these results with those from other formerly glaciated areas in various parts of the world, and also with different glaciological models.

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Svensk sammanfattning

Glacialgeologi och isdynamik vid randen av två istäcken, på Tajmyrhalvön i Sibirien och på Jameson Land, Östgrönland

Arktis utgör en viktig del i Jordens miljö och vad som händer där har stor påverkan på det globala klimatet, samtidigt som området är mycket känsligt för förändringar. Under kvartärtiden har stora isar flera gånger täckt Skandinavien, Ryssland, Sibirien och Nordamerika och täcker än idag stora delar av Grönland. Isarna har lämnat spår (landformer och sediment) efter sig och genom att undersöka dessa kan man ta reda på var och när istäckena fanns och dessutom hur de fungerade.

Den grundläggande orsaken till varför istäcken växer till och sedan försvinner är klimatet som förändras med hur Jordens bana förhåller sig till Solen, det vill säga hur solinstrålningen periodiskt varierar. En isframstöt har tidigare i allmänhet tolkats som att klimatet blivit överlag kallare, men andra faktorer, t.ex. närheten till öppet hav (som nederbördskälla), topografi och förhållandena vid isens botten, kan också påverka var isen finns och hur den rör sig. För att kunna tolka de geologiska arkiven rätt är det därför viktigt att man förstår samspelet mellan landskap, is och klimat.

Inom mitt avhandlingsarbete har jag undersökt den så kallade Norra Tajmyrisrandlinjen på Tajmyrhalvön i arktiska Sibirien och Ugleelvdalen på Jameson Land, Östgrönland, två geografiskt vitt skilda områden men som båda har varit nedisade och legat nära randen av stora istäcken. Syftet med mitt arbete har varit att rekonstruera nedisningshistorien i dessa områden, inklusive de miljöer som funnits och de processer som varit inblandade. Jag har undersökt landformer och sedimentlagerföljder, studerat flyg- och satellitbilder samt använt mig av så kallade geografiska informationssystem för att få en helhetsbild av glacialgeologin i de två områdena. Åldersbestämningar har gjorts med hjälp av två olika metoder: optiskt stimulerad luminescens (OSL) och kol-14 (^{14}C).

Kontinentalsockeln i det grunda Karahavet, som torrläggs under istider då vatten binds i inlandsisarna, har varit nedisad tre gånger under den senaste istiden (Weichsel; 115 000 - 10 000 år före nutid). Varje is var mindre än den föregående. Istäckena ledde till att floderna på Tajmyrhalvön tvingades rinna söderut och, under de två äldre skedena, också till att sjöar dämdes upp söder om iskanten. Den yngsta isframstöten, men troligen också de äldre, skedde snabbt och var bottensmältande. När isen nått sitt yttersta läge fick den en bottenfrusen kant där is och sediment trycktes samman och deformerades. De äldsta delarna av Norra Tajmyrisrandlinjen bildades ursprungligen för ca 80 000 år sedan (Tidigweichsel), under isens reträtt från sin största utbredning. Senare isframstötar, för ca 65 000 år sedan (Mellanweichsel) och för mindre än 20 000 år sedan (Senweichsel), byggde på den ytterligare. Israndlinjen består av så kallade landformssystem bildade vid kanten av och ovanpå isen och den domineras av 50-80 m höga och 2-3 km breda moränryggar. Stora områden underlagras fortfarande av gammal glaciäris och ovanpå denna håller än idag ett landskap med otaliga sjöar och sandkullar (kames) på att bildas i samband med att isen sakta smälter. Landformsystemet framför israndlinjen karakteriseras av sediment och landformer avsatta antingen under vatten eller på torra land, beroende på höjdläget och tidpunkten då de bildades.

Sedimentlagerföljden i Ugleelvdalen på Grönland omfattar tre moräner, samt issjö- och isälvsavlagringar och vindavsatta sediment. De äldsta delarna utgörs av ett delta som byggdes ut i en sjö uppdämd av en fjordglaciär i Scoresby Sund i väster, tidigt under den föregående istiden (Saale; mer än 130 000 år före nutid). Något senare rörde sig en glaciär från Liverpool Land i öster in över Jameson Land. Glaciären var bottensmältande och avsatte isälvssand och morän, bestående av lokalt material, samt små moränryggar. Därefter, under den senare delen av Saale, följde "den stora nedisningen" då den grönländska inlandsisen överskred området från väster. Isen var bottenfrusen men blev tidvis och på vissa ställen bottensmältande. Dess största påverkan på landskapet var genom smältvattenserosion, bland annat nedskärning i Ugleelvdalen. Under större delen av Weichsel-istiden var Ugleelv-området isfritt, men vid ett tillfälle trängde en dalglaciär från Liverpool Land upp i dalgången. Förhållandena var mer föränderliga under de tidiga delarna av istidscyklerna än under de senare, då klimatet var extremt kallt och torrt.

Mina undersökningar tyder på att Karahavsisen och Grönlandsisen beter sig på olika sätt under en istidscykel. Karahavsisen, som är centrerad på kontinentalsockeln, förändras mycket i storlek och försvinner helt under värmeperioderna, då havet dessutom dränker sockeln. Enskilda isframstötar verkar styras av inre mekanismer snarare än av klimatförändringar. Den grönländska inlandsisen är däremot förhållandevis stabil, den finns av framför allt topografiska orsaker kvar under värmeperioderna (som idag) och reagerar främst på klimatförändringar genom utvidgning eller tillbakadragande av glaciärer i fjordarna.

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