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Quaternary Science Reviews ∎ (∎∎∎∎) ∎∎∎–∎∎∎

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Late Quaternary ice sheet history of northern Eurasia

John Inge Svendsen[a,*], Helena Alexanderson[b], Valery I. Astakhov[c], Igor Demidov[d], Julian A. Dowdeswell[e], Svend Funder[f], Valery Gataullin[g,h], Mona Henriksen[a], Christian Hjort[i], Michael Houmark-Nielsen[j], Hans W. Hubberten[k], Ólafur Ingólfsson[l], Martin Jakobsson[m], Kurt H. Kjær[i], Eiliv Larsen[n], Hanna Lokrantz[o], Juha Pekka Lunkka[p], Astrid Lyså[n], Jan Mangerud[a], Alexei Matiouchkov[q], Andrew Murray[r], Per Möller[i], Frank Niessen[s], Olga Nikolskaya[t], Leonid Polyak[h], Matti Saarnisto[u], Christine Siegert[k], Martin J. Siegert[v], Robert F. Spielhagen[w], Ruediger Stein[s]

[a] *Bjerknes Centre for Climate Research & Department of Earth Science, University of Bergen, Allégaten 41, N-5007 Bergen, Norway*
[b] *Department of Physical Geography and Quaternary Geology, Stockholm University, SE-10691 Stockholm, Sweden*
[c] *Geological Faculty, St. Petersburg University, Universitetskaya 7/9, St. Petersburg 199034, Russian Federation*
[d] *Institute of Geology, Karelian Branch of Russian Academy of Sciences, Pushkinskaya 11, 125610 Petrozavodsk, Russian Federation*
[e] *Scott Polar Research Institute and Department of Geography, University of Cambridge, Cambridge CBZ IER, UK*
[f] *Geological Museum, Øster Voldgade 5-7, DK-1350 Copenhagen K, Denmark*
[g] *Oil and Gas Research Institute, Exporta Street 5, LV-1226 Riga, Latvia*
[h] *Byrd Polar Research Center, Ohio State University, Columbus, OH 43210, USA*
[i] *Quaternary Sciences, Department of Geology, Lund University, GeoCenter II, Sölvegatan 12, SE-22362 Lund, Sweden*
[j] *Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen, Denmark*
[k] *Alfred-Wegener Institut for Polar and Marine Research (AWI), Postfach 600149, 14401 Potsdam, Germany*
[l] *University of Iceland, Department of Geology and Geography, IS-101 Reykjavík, Iceland*
[m] *Center for Coastal and Ocean Mapping, Chase Ocean Engineering Lab, University of New Hampshire, Durham, NH 03824, USA*
[n] *Geological Survey of Norway, P.O. Box 3006, Lade, N-7002 Trondheim, Norway*
[o] *Geological Survey of Sweden, Box 670, SE-75128 Uppsala, Sweden*
[p] *Institute of Geosciences, University of Oulu, Linnanmaa, P.O. Box 3000, FIN-90014, Finland*
[q] *VSEGEI (National Geological Institute), Sredny proezd 74, St. Petersburg 199026, Russian Federation*
[r] *Nordic Laboratory for Luminescence Dating, Department of Earth Sciences, Aarhus University, Risø National Laboratory, DK-4000 Roskilde, Denmark*
[s] *Alfred Wegener Institute for Polar and Marine Research (AWI), Columbusstrasse, D-27568 Bremerhaven, Germany*
[t] *Institute of Remote Sensing Methods for Geology (NIIKAM), Birzhevoy proezd 6, St. Petersburg 199034, Russian Federation*
[u] *Geological Survey of Finland, Betonimiehenkuja 4, P.O. Box 96, Espoo, FIN-02151 Uusimaa, Finland*
[v] *Bristol Glaciology Centre, School of Geographical Sciences, University of Bristol, Bristol BS8 ISS, UK*
[w] *Academy of Sciences, Humanities and Literature Mainz and Leibniz Institute for Marine Sciences, East Coast Building, Wischhofstr. 1-3, D-24148 Kiel, Germany*

Abstract

The maximum limits of the Eurasian ice sheets during four glaciations have been reconstructed: (1) the Late Saalian (>140 ka), (2) the Early Weichselian (100–80 ka), (3) the Middle Weichselian (60–50 ka) and (4) the Late Weichselian (25–15 ka). The reconstructed ice limits are based on satellite data and aerial photographs combined with geological field investigations in Russia and Siberia, and with marine seismic- and sediment core data. The Barents-Kara Ice Sheet got progressively smaller during each glaciation, whereas the dimensions of the Scandinavian Ice Sheet increased. During the last Ice Age the Barents-Kara Ice Sheet attained its maximum size as early as 90–80,000 years ago when the ice front reached far onto the continent. A regrowth of the ice sheets occurred during the early Middle Weichselian, culminating about 60–50,000 years ago. During the Late Weichselian the Barents-Kara Ice Sheet did not reach the mainland east of the Kanin Peninsula, with the exception of the NW fringe of Taimyr. A numerical ice-sheet model, forced by global sea level and solar changes, was run through the full Weichselian glacial cycle. The modeling results are roughly compatible with the geological record of ice growth, but the model underpredicts the glaciations in the

*Corresponding author. Fax: +47-55583660.
E-mail address: john.svendsen@geo.uib.no (J.I. Svendsen).

0277-3791/$ - see front matter
doi:10.1016/j.quascirev.2003.12.008

Eurasian Arctic during the Early and Middle Weichselian. One reason for this is that the climate in the Eurasian Arctic was not as dry then as during the Late Weichselian glacial maximum.

1. Introduction

Vast areas of the northern parts of Russia and Siberia have repeatedly been affected by major glaciations during the Quaternary. Ice sheets that formed over Scandinavia spread eastwards across the NW Russian Plains and the White Sea area, whereas ice sheets in the Barents and Kara Sea region expanded southwards onto present-day land (Figs. 1–3). The timing and dimensions of these former ice sheets have been much debated over the past decades and, in particular, it has been difficult to form a consensus as to the extent of glaciations in the Russian Arctic during the Last Glacial Maximum (LGM). According to the most cited view, much of northern Eurasia was covered by an enormous ice sheet complex at the LGM (Grosswald, 1993, 1998) whereas others visualized more localized ice caps over the Arctic Islands, the Polar Urals and the Central Siberian Uplands (e.g. Velichko et al., 1997). It is now accepted that a sizeable ice sheet formed over the NW part of the Barents Sea shelf during the LGM (Landvik et al., 1998), but the southern and eastern extension of this ice sheet has been difficult to determine. A reconstruction of ice sheet limits post-dating the last interglacial was previously presented in an overview paper by Svendsen et al. (1999), showing that the Barents-Kara Ice Sheet during the LGM was smaller than expected. It is also evident that the glacier distribution in the Eurasian Arctic has been more variable through time than previously thought and that the largest ice sheets existed for a relatively short period. During the last 160,000 years as many as four major glaciations have been

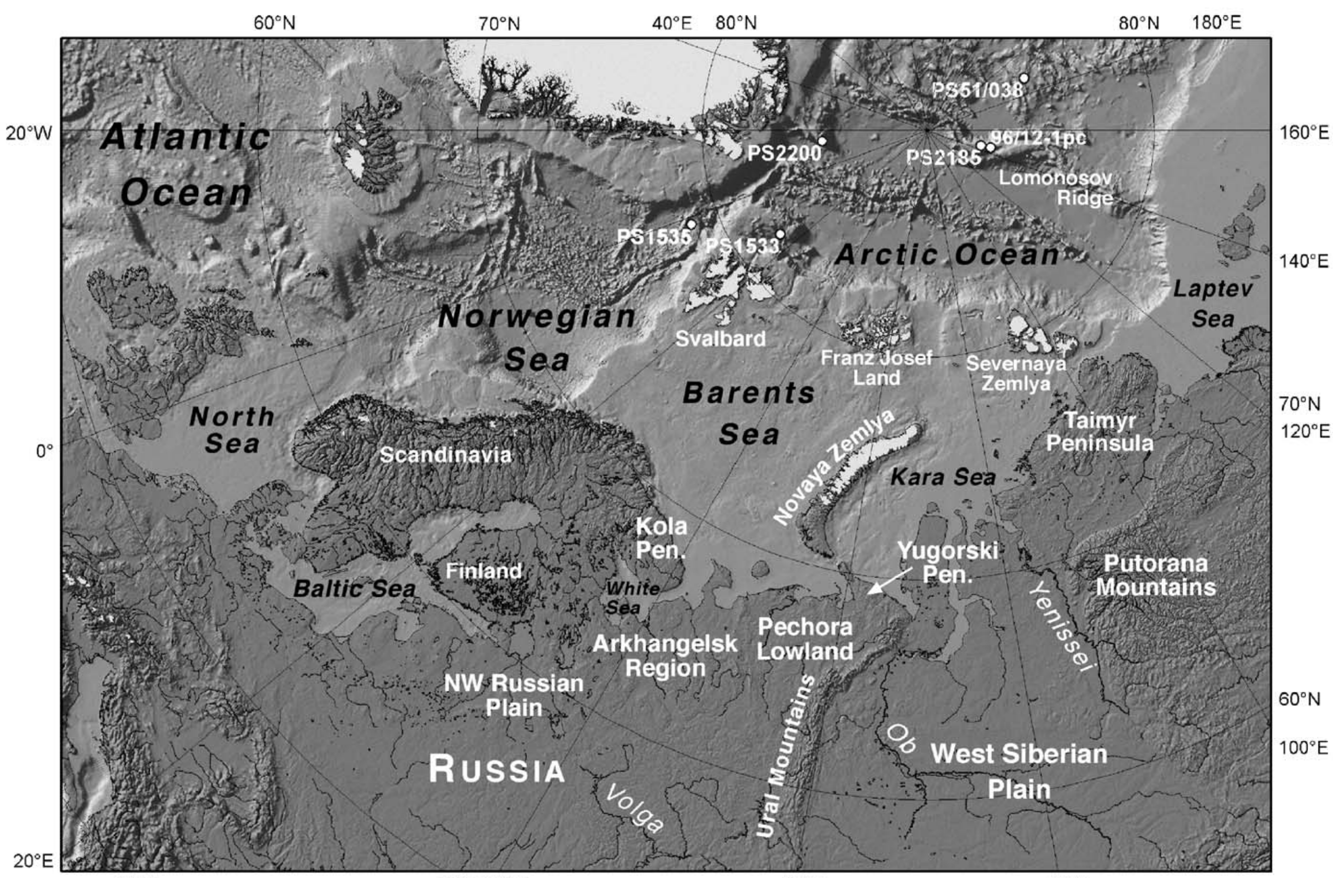

Fig. 1. Map of northern Eurasia with adjacent seas. The areas considered in this study include the Taimyr Peninsula, Severnaya Zemlya, Putorana Plateau, West Siberian Plain, Polar Urals,Yugorski Peninsula, Pechora Lowland, Arkhangelsk Region, Kola Peninsula, NW Russian Plain, Southeastern Barents Sea, Kara Sea and the Arctic Ocean. Core sites from the Arctic Ocean that are used for comparison with the continental records are shown (Jakobsson et al., 2001; Spielhagen et al., 2004).

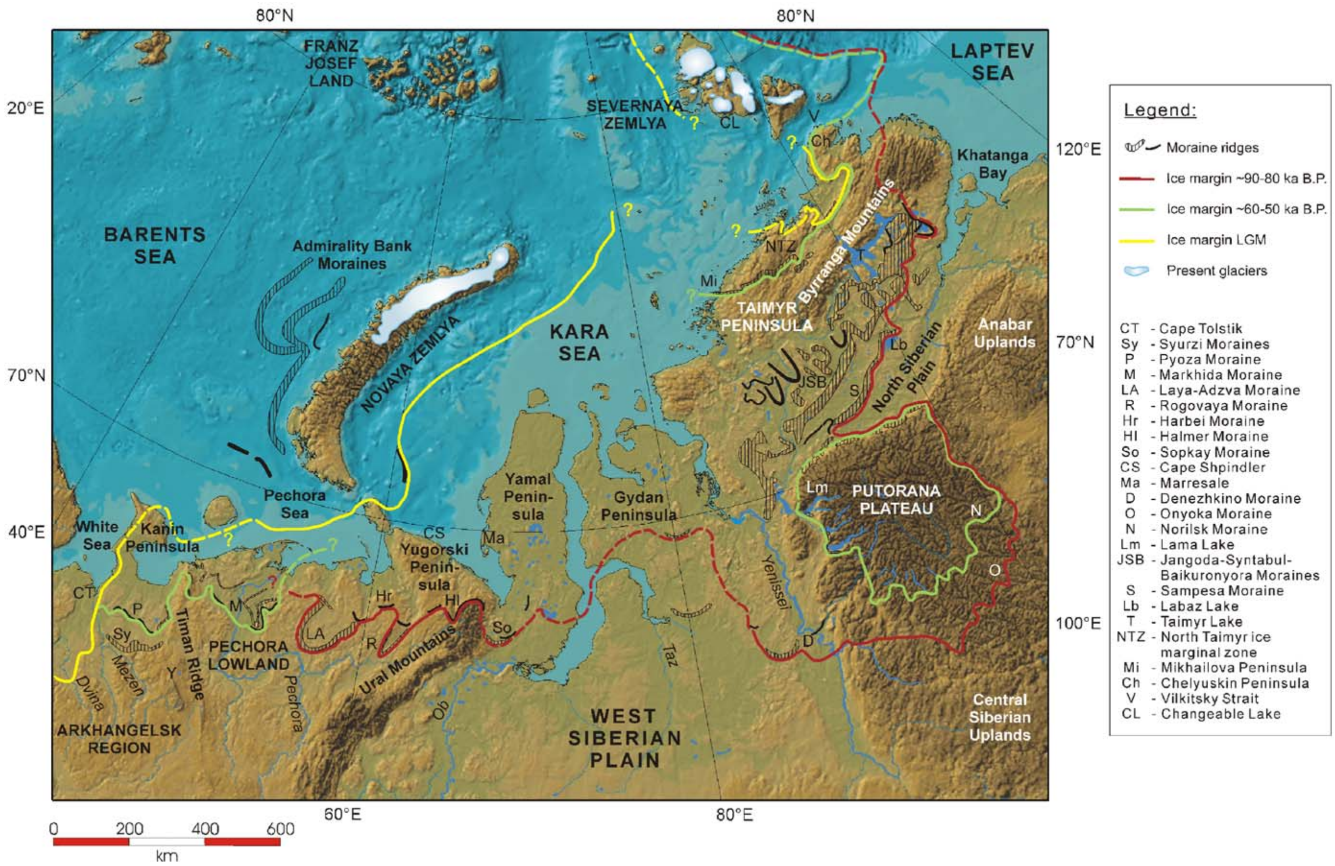

Fig. 2. Map of the area affected by the Barents-Kara Ice Sheets and by the ice caps over the Putorana Plateau. Some of the most prominent end moraines that were originally mapped by geological surveys and institutes in Russia are marked. The inferred maximum ice sheet extent after the last interglacial (Eemian/Kazantsevo) is marked with a red line. Middle Weichselian moraines are indicated with a green color and the LGM limit with a yellow line. Some key sites mentioned in the text are marked with letters.

recorded in the NW Barents Sea region, but the majority of this time was characterized by limited ice cover (Mangerud et al., 1998, 2001).

Here we present an updated synthesis of our current understanding of the chronology and dimensions of the Eurasian ice sheets during the last 160,000 years. The Saalian glacial maximum in Western and Central Europe that occurred during marine isotope stage (MIS) 6 is here considered to be equivalent with the Moscow glaciation in European Russia, the Taz glaciation in West Siberia and the Murukta glaciation in North Central Siberia. For the last interglacial (MIS 5e) and glacial (MIS 5d-2) periods we use the western European terms Eemian and Weichselian respectively, which correlates with the Mikulino and Valdai in European Russia, and the Kazantsevo and Zyryanka in Siberia. The Early Weichselian correlates with MIS 5d-a (117–75 ka), the Middle Weichselian with MIS 4-3 (75–25 ka) and the Late Weichselian with MIS 2 (25–10 ka). The reconstructions are based on comprehensive geological field investigations on the northern Russian and Siberian mainland and in the adjacent shelf seas, and are compared with data from the Arctic Ocean and with glaciological modeling. This is a compilation of results that were obtained within the framework of the European Science Foundation program ‘‘Quaternary Environment of the Eurasian North’’ (QUEEN) during the period 1996–2002. Inferred ice sheet limits are drawn over the entire northern Eurasia for the last four major glaciations: (1) the Late Saalian (before 130 ka), (2) the Early Weichselian (c. 90–80 ka), (3) the early Middle Weichselian (c. 60–50 ka) and (4) the Late Weichselian (20–15 ka). The empirical data are compared with the Arctic Ocean record and with a model simulation of the repeated growth and decay of the Eurasian ice sheets over the whole Weichselian period (117–10 ka). The reconstructed ice sheet limit for the Late Saalian glaciation is mainly based on a review of earlier published material.

We first review the regional glacial records from the continent and the adjacent sea floor. The work areas include: Taimyr Peninsula, Severnaya Zemlya, Putorana Plateau, West Siberian Plain, Ural Mountains, Yugorski Peninsula, Pechora Lowland, Arkhangelsk Region, Kola Peninsula, NW Russian Plain, Southeastern Barents Sea shelf and the Kara Sea shelf (Fig. 1). We

Fig. 3. Map showing the areas of Russia and Finland that were affected by the Scandinavian Ice Sheet during the Weichselian/Valdai glaciations. The LGM limit and some ice recessional limts are drawn. Note that the ages indicated on the map are calendar years (ka) and not radiocarbon years.

describe the glacial histories for each work area, as the "QUEEN-teams" have understood the available evidence. In the following section "Synthesis of the ice sheet history" we discuss the reconstructed ice sheet limits for the entire study area, utilizing the regional records. It is not a prerequisite to have read the regional reviews in order to grasp this synthesis. Finally, we present the modeling results and compare them with the empirical reconstructions.

2. Methodology

2.1. Geomorphologic and glacial geological investigations

Ice marginal zones, originally mapped by Russian geological surveys, have been re-analyzed using satellite imagery and air-photos (Figs. 2 and 3). Their stratigraphic position have been inferred from our own field research. The principal method employed in the field has been sedimentological and structural geological documentation of Quaternary deposits exposed in natural sections. In addition, sediment coring of lake basins, either from the winter ice or in open water using a raft, was undertaken. A number of seismic records and sediment cores from the sea floor off the mainland have been collected and interpreted.

2.2. Proxies for ice sheet fluctuations in the deep-sea sediments

Records of ice-rafted debris (IRD), microfossils and oxygen isotope ($\delta^{18}O$) measurements from high-resolution sediment cores from the eastern and central Arctic Ocean (Fig. 1) are used to detect ice sheet fluctuations on the Barents-Kara Sea shelves (Spielhagen et al., 2004). Abrupt freshwater discharges associated with deglaciation events in the Eurasian Arctic and/or drainage of ice dammed lakes are identified from the $\delta^{18}O$ records of plankton foraminifers. Furthermore, the content of planktonic foraminifers and coccoliths provide useful information about sea ice conditions and paleoceanographic changes in the Arctic Ocean.

2.3. Dating methods

The chronostratigraphy of the continental records is, to a large extent, based on optically stimulated luminescence (OSL) and radiocarbon dating, and to some extent on electron spin resonance (ESR) dating. The stratigraphic framework of the eastern and central Arctic Ocean cores is based on a variety of methods, including biostratigraphy (coccoliths), paleomagnetics, radioisotopes (^{14}C, ^{10}Be) and correlation with other dated cores. Details are given in Spielhagen et al. (2004).

OSL dating has enabled us to establish a reliable chronology of sediment successions that are beyond the range of the radiocarbon method. Most OSL dates were obtained from the Nordic Laboratory for Luminescence Dating, Risø, Denmark. As many as around 600 samples from Russia have been analyzed since 1996 as part of the QUEEN programme. The single aliquot regenerative dose protocol applied to quartz grains was used to estimate the equivalent dose (Murray and Wintle, 2000). The samples were analyzed for natural series radionuclide concentrations in the laboratory, using high-resolution gamma spectrometry (Murray et al., 1987). These concentrations were converted into dose rates using the conversion factors listed by Olley et al. (1996). Dates from Yamal and Yugorski peninsulas in West Siberia were obtained by using the infrared-stimulated luminescence (IRSL) and thermoluminescence (TL) by multiple aliquot additive dose procedures (Forman, 1999). A. Molodkov at the ESR Dating Laboratory, Institute of Geology, Estonia has carried out ESR datings on samples from the Taimyr Peninsula, using the method described by Molodkov et al. (1998).

2.4. Glaciological modeling

Numerical modeling experiments were carried out using a model that is centered about the ice continuity equation (Mahaffy, 1976), which relates the mass balance and flow of ice to the time dependent change in ice sheet thickness. Algoritms for ice deformation, basal slip and isostasy are included, as described by Siegert et al. (1999b). The model is forced by its climate input, which involves the air temperature and accumulation of ice, and their variations in time and space. The ice sheet limits are not numerically predetermined. The model uses an informal inverse approach, where ice sheet limits are forced to match geologically mapped and dated limits through adjustment of the climate. The result is a plausible scenario for ice and climate in the Eurasian Arctic at the LGM. The model is forced through the full Weichselian by linking climate to solar insolation changes, so that interglacial conditions are associated with values at 10 ka, and LGM conditions occur with minimum insolation values in the Weichselian.

3. Regional glacial records from northern Russia, Siberia and the adjacent continental shelves

This regional overview is, to a major extent, based on new observations and results obtained during the QUEEN Programme (1996–2002). We have, however, also reviewed and incorporated previously published observations relevant to this study. Below we summarize our current understanding of the glacial history for twelve key regions in northern Russia, Siberia and the adjacent continental shelves that were affected by the major Quaternary glaciations (Figs. 1–3). Documentation of the data is given in the cited primary publications.

3.1. Taimyr Peninsula

In some previous reconstructions the last major ice sheet that reached the southernmost part of the Taimyr Peninsula was called the Murukta glaciation (Kind and Leonov, 1982; Isayeva, 1984; Arkhipov et al., 1986). At this time the ice sheet coalesced with large ice caps over the Putorana Plateau and the Anabar Uplands (Figs. 2 and 4). The Murukta moraines in their stratotypic area east of the Putorana Plateau are covered by terrestrial sediments with flora indicating environments warmer than present, i.e. an interglacial type of climate (Bardeyeva, 1986). Even though we have not investigated the critical areas along the southern margin of the Murukta glaciation the stratigraphic relations suggest that this ice sheet existed during the Late Saalian

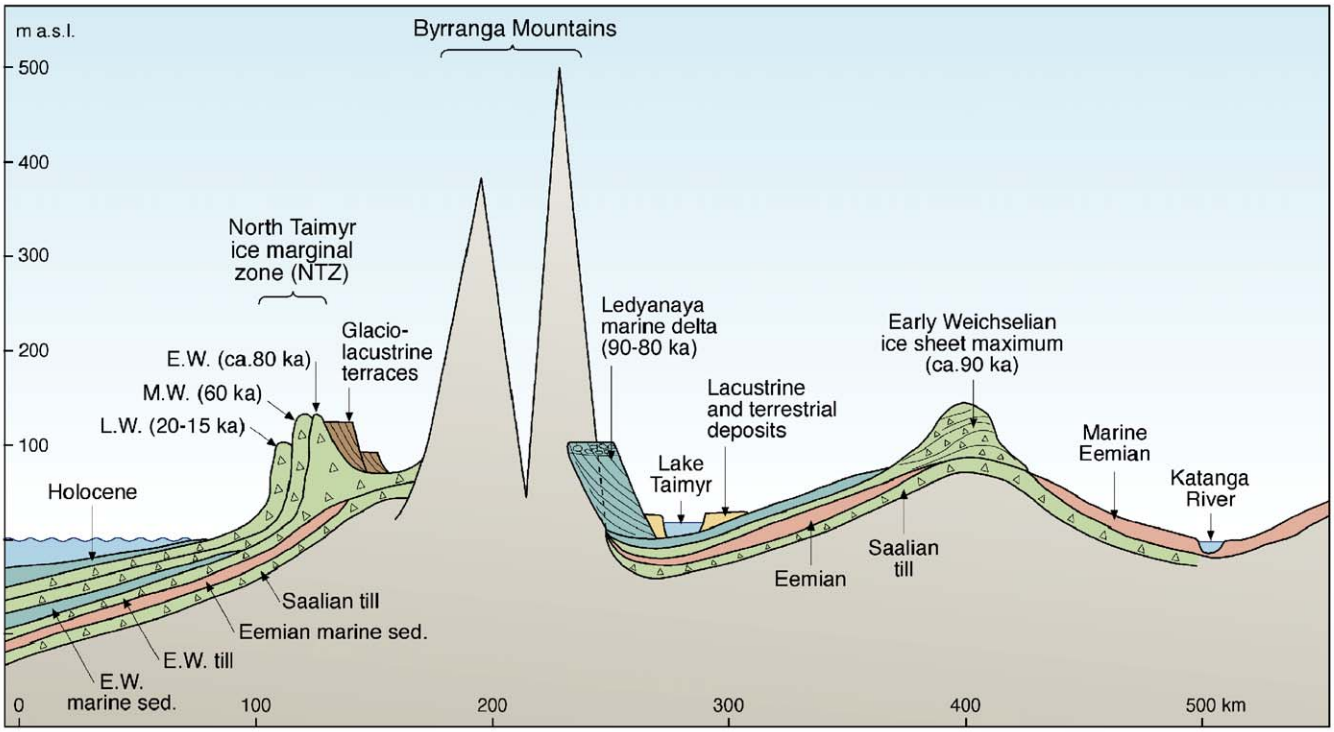

Fig. 4. Generalized sediment stratigraphy on Taimyr, showing the inferred relations between tills, marine sediments and the mapped ice marginal features.

(MIS 6) and that it corresponds with the Taz glaciation recorded in West Siberia.

Along the Khatanga River, the Murukta till is sometimes found directly above an interglacial marine formation containing the extinct mollusc *Cyrtodaria jenisseae (angusta)* and a foraminifer complex that is characteristic of the Siberian Holsteinian (Gudina, 1976; Kind and Leonov, 1982). The till is overlain by marine sediments with arcto-boreal molluscs (including *Arctica islandica, Macoma balthica*) and boreal foraminifers. A relatively warm sea seems to have flooded much of the North Siberian Lowland during this period (Fig. 4). In western and northern Taimyr, sediments from this transgression are found over 100 m a.s.l. (Kind and Leonov, 1982). Pollen spectra indicate dense forest vegetation, with spruce (*Picea*) and pine (*Pinus*) on what is today tundra. Diatoms from these strata also reflect an interglacial type of climate. These sediments were subsequently correlated with similar marine deposits at the well-known Cape Karginsky section in West Siberia, which became the type locality for this interglacial. Andreyeva (1980) and Kind and Leonov (1982) therefore called this period Karginsky, a widely used term in the stratigraphic framework for the Late Quaternary of Siberia. Based on several finite radiocarbon dates these strata were originally thought to be of intra-Weichselian age. However, subsequent investigations revealed that the Karginsky strata are beyond the range of the radiocarbon method (Fisher et al., 1990) and they are now considered to be equivalent with the Kazantsevo (Eemian) interglacial (Arkhipov, 1989; Sukhorukova, 1999; Astakhov, 2001).

The next ice sheet that inundated the Taimyr Peninsula left a continuous zone of wide push moraines about 850 km long that are called the Jangoda-Syntabul-Baikuronyora ridges (Fig. 2), the JSB Line (Kind and Leonov, 1982). South of this moraine belt interglacial marine sediments are not covered by till (Fisher et al., 1990). Most important is that in the foothills of the Byrranga Mountains there are many sites where interglacial marine sediments are found beneath a till (Urvantsev, 1931; Sachs, 1953; Kind and Leonov, 1982) and presently we suggest that this till-covered area stretches south to, and includes, the JSB zone. We therefore relate these moraines to the Early Weichselian ice sheet maximum. In our former reconstructions (e.g. Svendsen et al., 1999; Hjort et al., 2004) the Weichselian limit was drawn along the Sampesa ridge, some 50 km south of the JSB zone and south of the recently studied Lake Labaz. The upper till to the north of Lake Labaz contains ‘fossil’ glacial ice (Siegert et al., 1999a) and blocks of marine sediments with boreal foraminifers (Kind and Leonov, 1982), indicating that it postdates the Eemian transgression. However, southwest and northeast of this lake, especially on the river Bolshaya Balakhnya, there are many sites of interglacial marine sediments not covered by till (e.g. Fig. 29 in Kind and Leonov, 1982; Fisher et al., 1990). We therefore believe that only the northern shores of Lake Labaz should be located inside the ice sheet limit.

Our recent field investigations indicate that central Taimyr, south of the Byrranga Mountains, was affected by a major marine inundation after the Early Weichselian glaciation, following the northwards receding ice margin from the JSB-line (Fig. 2). Along the Ledyanaya River and at other sites south of the Byrrangas, Möller et al. (1999, 2002) investigated thick deltaic marine sediments not covered by any till (Fig. 4). These marine sediments accumulated up to 100 m a.s.l. and contain a mollusc fauna which is not significantly different from the present Kara Sea assemblages, but very different from the boreal Eemian mollusc fauna of Taimyr. The high marine limits reflect a significant glacio-isostatic depression when these sediments accumulated. It is inferred that the marine deltas were fed by melt-water rivers from ice fronts located in the valleys and along the northern slope of the Byrranga Mountains, most likely

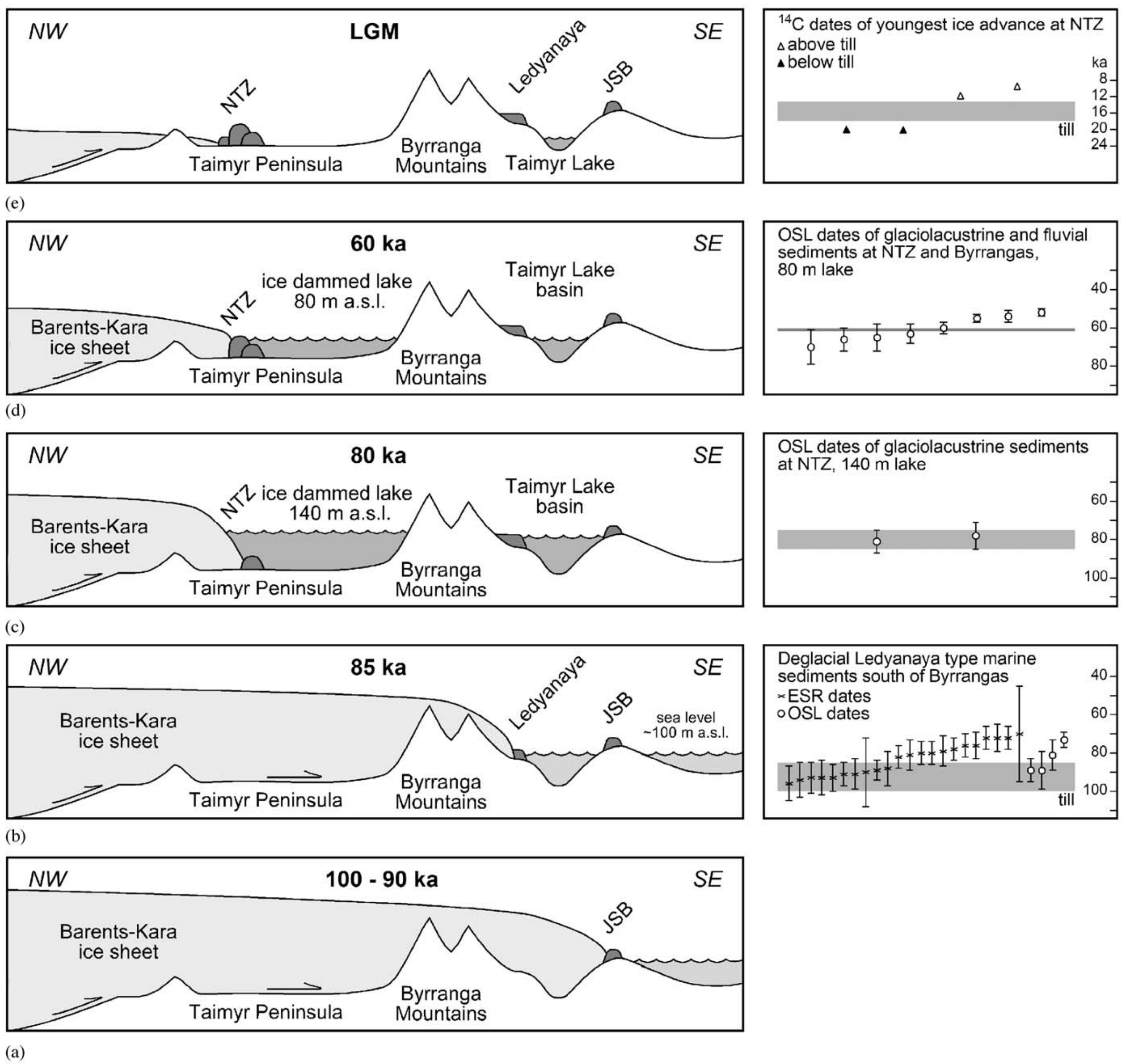

Fig. 5. Schematic northwest-southeast profiles across the Taimyr Peninsula showing: (a) the inferred ice sheet position during the Early Weichselian glacial maximum (c. 90 ka), (b) the Early Weichselian glacial retreat and marine inundation (90–80 ka), (c) the formation of ice dammed lakes on the NW Taimyr during the Early Weichselian (c. 80 ka), (d) the Middle Weichselian readvance (60–50 ka) and (e) the LGM (20–15 ka). Radiocarbon-, OSL- and ESR dates are plotted to the right.

reflecting a temporary halt of the ice front during its recession northwards. A series of 25 ESR dates on molluscs from these delta sequences (Hjort et al., 2004) yield ages in the range of 96–70 ka, with a mean value of 83 ka (when three outliers >110 ka are excluded). Four OSL dates from the same formation reveal ages in the range 89–73 ka (Fig. 5).

On the Chelyuskin Peninsula, the northernmost part of Taimyr, a till covering interglacial marine deposits reflects an ice sheet that flowed eastwards over mountains as high as 350 m a.s.l. This till is covered by another sequence of marine sediments that can be traced up to 65–80 m a.s.l. ESR dates (9) from mollusc shells in the interglacial sediments under the till yielded ages between c. 150 and 110 ka. The upper marine unit was dated to 93–80 ka, which roughly correlates with the Ledyanaya marine sequence south of the Byrrangas.

There are no indications that the areas south of the Byrranga Mountains have been glaciated after the Early Weichselian deglaciation. A continental polar desert environment seems to have prevailed throughout the Middle- and Late Weichselian (Siegert et al., 1999a; Hubberten et al., 2004). The section at Cape Sabler, on the shore of Lake Taimyr, features one of the best-dated formations in the Russian Arctic. It is over 30 m thick and includes a terrestrial–lacustrine sequence of laminated silts with peaty interlayers, large syngenetic ice wedges and a mammoth steppe fauna and flora (e.g. Kienast et al., 2001). This formation has repeatedly yielded finite radiocarbon dates, including values more than 39 ka at the base, with a continuous age and deposition record up to the Holocene (Kind and Leonov, 1982; Pavlidis et al., 1997; Möller et al., 1999). Pre-Late Weichselian lacustrine sediments were also found in cores from the lake bottom and from the adjacent Levinson-Lessing Lake (Ebel et al., 1999; Hahne and Melles, 1999; Niessen et al., 1999). As the present Lake Taimyr lays only 5 m a.s.l., the relative sea level in this region must have remained low for at least the last 40 ka.

North of the Byrranga Mountains there is another distinct belt of ice marginal features (Fig. 2), called the North Taimyr ice-marginal zone (NTZ) (Kind and Leonov, 1982; Isayeva, 1984). This zone, which is a complex of glacial, glaciofluvial and glaciolacustrine deposits, has been investigated and mapped in detail by Alexanderson et al. (2001, 2002). The NTZ contains a series of up to 100 m high and 2 km wide morainic ridges, consisting to a large extent of redeposited marine silt. These moraines remain ice-cored but, in most areas, the active layer only rarely reaches the ice surface. The ridge system can be traced for 700–800 km, from near the Mikhailova Peninsula in the southwest to the Tessema River in the northeast, but is most pronounced in a c. 300 km-long zone on both sides of the Lower Taimyra River, some 80–100 km inland from the Kara Sea coast (Fig. 2). When the outermost moraines were deposited along the NTZ the ice sheet, flowing from the Kara Sea, must have crossed the 300–500 m high range of coastal hills west of the Lower Taimyra River. Associated with this ice-marginal zone are shorelines and glaciolacustrine sediments from two generations of ice-dammed lakes that formed in front of the Barents Kara Ice Sheet (see further discussion in Mangerud et al., 2004). OSL datings suggest that the highest lake existed during the Early Weichselian ice recession around 80 ka whereas the lower lake system reflects a younger Middle Weichselian ice sheet advance that terminated at the NTZ around 70–54 ka (Fig. 5) (Alexanderson et al., 2001, 2002). Thick deposits of glaciolacustrine sediments at the coast north of the Leningradskaya River, that have been OSL dated to around 80–70 ka, may stem from the Early Weichselian deglaciation (Funder et al., 1999).

Well-developed marginal features along the NTZ define the youngest ice limit on NW Taimyr, west and east of the Lower Taimyra River (Fig. 2). They outline a thin ice lobe terminating at altitudes below 150 m a.s.l, up to 100 km inland from the coast. Around the Lower Taimyra River valley this stage is recognized by morainic lobes that partly onlap the Middle–Early Weichselian moraine system. Glacially distorted sediments, both marine Quaternary silt and sand and Cretaceous sands characterise the area inundated by this youngest ice advance. Remnants of glacier ice covered by a thin (c. 0.5 m) meltout till are found at many places behind the youngest ice front. Two AMS radiocarbon dates of mollusk shells (Fig. 5), sampled from glacially redeposited marine silt close behind the former ice front, yield ages around 20 ka, suggesting that the ice sheet reached this position later than this time (Alexanderson et al., 2001). A minimum age of the deglaciation is given by a radiocarbon age around 12 ka from in situ terrestrial plant material at the present coast (Bolshiyanov et al., 2000). Organic material retrieved from the sea floor off the coast has been radiocarbon dated (conventionally, bulk sample) to around 16 ka (Bolshiyanov et al., 1998). Based both on the shell dates and on the especially thin meltout till in this area, in combination with the much higher frequency here of exposures of the underlying ice than in other areas within the NTZ, we believe that the lowland on northernmost Taimyr was inundated by a restricted ice sheet advance from the Kara Sea shelf during the Late Weichselian. This ice was, however, much thinner than the preceding ice sheets in this area, and did not manage to override the coastal hills. It did however, reverse the drainage of the Lower Taimyra River as indicated by the increased sedimentation of the Taimyr lake basin around 19 ka (Möller et al., 1999).

3.2. Severnaya Zemlya

The occurrence of till beds with marine mollusks and of uplifted marine sediments of Quaternary age indicates that ice sheets several times have covered the entire Severnaya Zemlya archipelago (Bolshiyanov and Makeyev, 1995; Möller et al., in preparation). Sediment cores recovered from Changeable Lake (6 m a.s.l.) on October Revolution Island (Fig. 2) have provided minimum dates of the last major glaciation of the archipelago (Raab et al., 2003). This lake is located 4 km to the south of the Vavilov Ice Dome and occupies a structurally controlled basin. Two AMS radiocarbon dates of foraminifer shells, from a thin layer of marine sediments overlying a till at the base of the cored sequence, yielded nonfinite ages. Three luminescence (OSL) dates revealed ages in the range 86–35 ka. A series of AMS dates on plant and insect remains indicate that the overlying lacustrine sediments date back to at least 30 ka.

Based on the records from Changeable Lake it is concluded that the last major glaciation of Severnaya Zemlya occurred during the Middle Weichselian, when the ice front terminated on the shelf (Raab et al., 2003). The deglaciation was associated with a marine transgression that inundated the lake basin at around 60–50 ka, reflecting a strong glacioisostatic depression. Possibly, this marine inundation corresponds to raised shorelines up to 100 m a.s.l. that have been radiocarbon dated to 50–21 ka (Bolshiyanov and Makeyev, 1995).

The sediment sequence from Changeable Lake indicates that the Vavilov Ice Dome was small, or perhaps absent, during the Late Weichselian. This conclusion may be supported by radiocarbon dates on mammoth tusks from elsewhere on Severnaya Zemlya, indicating that mammoths were grazing close to the present day glaciers at around 25, 20, 19 and 11.5 ka (Makeyev et al., 1979; Bolshiyanov and Makeyev, 1995).

3.3. Putorana Plateau

At least once during the Quaternary an ice sheet advance from the Kara Sea inundated this mountain area (Fig. 2). The occurrence of granite erratics reflects ice flow across northern Taimyr and onto the Putorana Plateau and a very thick shelf-centered ice sheet at that time (Urvantsev, 1931). Even though this glacial event is poorly dated a major glaciation is thought to have occurred during the Saalian when the ice sheet terminated far south on the adjacent lowland in West Siberia.

Two younger moraine belts that encircle the Putorana Plateau indicate that the glaciations were more restricted during the Weichselian than during the foregoing glaciation (Fig. 2). The outer moraine system in northeastern Putorana was originally dated to the LGM on the basis of several radiocarbon dates from beneath the corresponding till (Isayeva et al., 1976). The same age was suggested for the Onyoka morainic belt along the southern slope of the plateau (Isayeva, 1984). The Onyoka moraines merge with the moraines trending east west across the Yenissei valley to the West Siberian Plain. This chain of moraines is therefore considered to be contemporaneous with the last shelf-centered glaciation that inundated the West Siberian Plain, which according to our interpretation occurred during the Early Weichselian (Astakhov, 1992).

The inner system of morainic ridges, termed the Norilsk Stage, is represented by horseshoe-shaped end moraines encircling the western ends of deep fjord-like lakes. Sachs (1953) and other geologists considered the Norilsk moraines products of alpine glaciation, whereas Isayeva (1984) thought that these spectacular features were deposited by outlet glaciers which drained a substantial ice cap covering the flat plateau. A Younger Dryas age was suggested for the Norilsk Stage (Kind, 1974), but more recent investigations indicate that it is older. Pollen diagrams from long cores retrieved from the bottom sediments of Lake Lama, situated on the proximal side of the Norilsk moraines (Fig. 2), suggest that lacustrine sedimentation started well before 17 ka (Hahne and Melles, 1997). Judged from seismic records there are more than 20 m of lacustrine sediments below the 19 m long cored sequence. Hahne and Melles (1997) therefore assume that the youngest till in these lake basins is of Middle Weichselian age, which implies that the Norilsk moraines predate the LGM. This is supported by geomorphologic observations, proposing that the maximum extent of the LGM glaciers is represented by moraines higher up in the valleys (Bolshiyanov et al., 1998).

3.4. West Siberian Plain

From the distribution of tills mapped by the Russian Geological Survey, it appears that the most extensive ice sheet expanded as far south as 60°N (Zarrina et al., 1961; Ganeshin, 1973). This glaciation is believed to be of Middle Quaternary age (MIS 8), based on several ESR and TL dates. This till is in places covered by another till unit (Taz till) that terminates 100–400 km to the north of the drift limit (Figs. 2 and 6), and is conventionally correlated to MIS 6 (Arkhipov et al., 1986; Arkhipov, 1989).

Marine sediments and tills containing remnants of warm-water marine fauna show that the West Siberian Plain was affected by at least two "boreal" transgressions (Zubakov, 1972). The youngest marine strata with shells of the boreal mollusks *Arctica islandica* and *Zirphaea crispata* have traditionally been termed the Kazantsevo formation (Sachs, 1953). Along the Yenissei River this marine formation has been described at

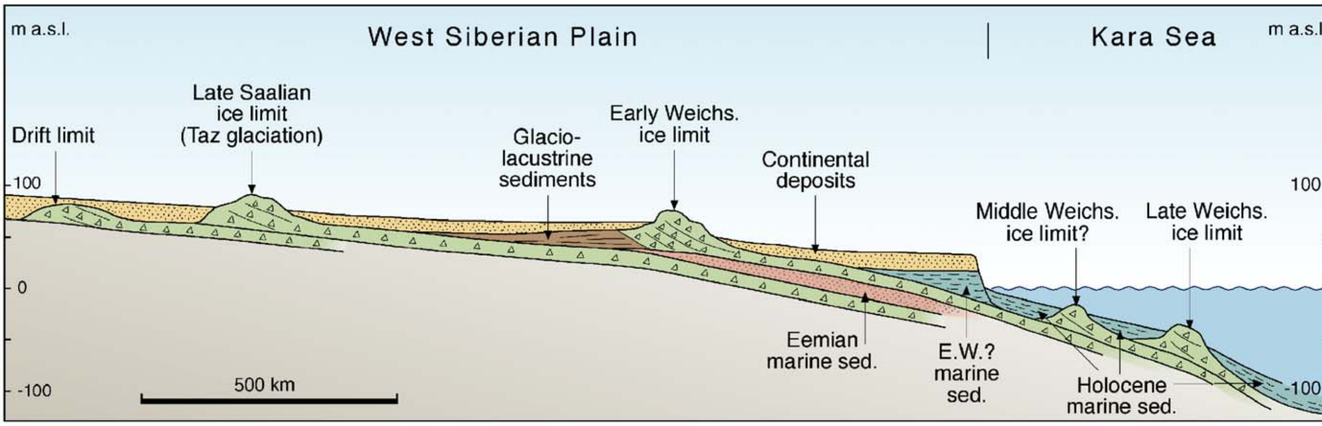

Fig. 6. Generalized stratigraphy from the West Siberian Lowland showing the inferred relations between tills, marine sediments and the mapped ice marginal features.

altitudes from 5 m a.s.l. at 67°N rising to 64 m at 72°N (Sukhorukova, 1999). It is difficult, however, to determine the upper limit of the transgression because the strata are often heavily glaciotectonized and covered by till (Fig. 6). Four ESR dates from marine mollusk shells gave ages in the range of 134–105 ka, suggesting that at least some of these strata are of Eemian age (Sukhorukova, 1999). We suspect, however, that several sequences traditionally ascribed to the Kazantsevo (Eemian) transgression may be much older.

To the north of the proposed ice-sheet limit on the West Siberian Plain there are many sites with interglacial sediments of the Kazantsevo (Eemian) formation that are covered by till (Zarrina et al., 1961; Troitsky, 1975; Astakhov, 1992). We adopt the traditional view of many Russian geologists that the maximum ice sheet extent during the Weichselian corresponds with topographically distinct ice-pushed ridges that can be traced across the Yenissei River valley near the Arctic Circle (Fig. 2). These ridges were formed by a lobe of the Barents-Kara Ice Sheet that flowed southwards along the river valley (Astakhov and Isayeva, 1988) and merged with the Onyoka glaciation on the Putorana Plateau (Isayeva, 1984). The southernmost ridges, described as the Yermakovo (Arkhipov et al., 1986) and Denezhkino moraines (Astakhov and Isayeva, 1988), can easily be recognized from satellite images. The ice marginal zone is a hummock-and-lake landscape that includes distinct ice-pushed ridges and prominent hill–hole pairs, locally displaying a relief of more than a hundred meters. Basal tills with blocks of fossil glacier ice are exposed in sections along the Yenissei River (Kaplanskaya and Tarnogradsky, 1986; Astakhov and Isayeva, 1988). The ice limit west of the river valley is drawn along a similar belt of glacial topography, including some large horseshoe-shaped push moraines (Zemtsov, 1976). The ice front position across the flat and swampy areas between the Ob Estuary and the Taz-Yenissei interfluves is hardly recognizable on aerial photographs and satellite images, but we suspect that it was located along ice marginal features on the Gydan Peninsula; the so-called Gydan Stage (Troitsky, 1975). Further to the west, the maximum ice extent after the last interglacial probably corresponds with a west–east striking belt of push moraines on the southern part of the Yamal Peninsula (Fig. 2), merging into the Sopkay Moraines on the Uralian piedmont (Astakhov, 1979, 2001).

Proximal to the moraines in the Yenissei River valley there is a plain built of glaciolacustrine varved sediments at altitudes up to around 60 m a.s.l. (Fig. 6). A former thermokarst sinkhole incised into this plain is filled with frozen silt containing well-preserved logs radiocarbon dated to more than 50 ka (Kind, 1974). This indicates that the latest ice advance in the Yenissei River valley occurred well before 50 ka and prior to a period when trees were growing in the Arctic (Astakhov, 1992, 1998). Two luminescence dates obtained on ablation sediments capping the thick fossil glacier in the core of a marginal moraine on the Arctic Circle yielded values 79 ± 20 and 78 ± 19 ka (Kostyayev et al., 1992). Recently obtained OSL dates from beneath and atop of a varved sequence at the Ob River mouth and on the southwestern Yamal Peninsula constrain the last ice advance in this area to the time span 80–70 ka (Astakhov, 2004).

On the western Yamal there is a well-studied section, Marresale, which contains a thick sequence of pro-deltaic marine sediments covered by a till, the Kara diamicton (Gataullin, 1988). The till is associated with large-scale glaciotectonic deformation, reflecting ice flow to the north. The till is covered by a well-dated sequence of undisturbed lacustrine, fluvial and aeolian sediments indicating that the last glaciation of this area took place before 40 ka, either during the Early Weichselian or early Middle Weichselian (Forman et al., 1999a, 2002).

At several places to the north of 70°N the upper till is covered by cold-water marine sediments (Fig. 6), indicating that a transgression inundated this northern region after deglaciation. On the northern Gydan and Yamal peninsulas there are several sites with fossil glacier ice that are directly covered by marine silt and clay containing mollusk shells of the cold water species *Portlandia arctica* or arctic foraminifers (Troitsky and Kulakov, 1976; Astakhov, 1992). Unlike the Kazantsevo formation the *Portlandia* strata are normally flat lying without any traces of being overridden by glacier ice. These deposits, aged beyond the range of the radiocarbon method, are only found below 30–40 m a.s.l. No warm-water faunas have been documented above the *Portlandia* strata (Troitsky and Kulakov, 1976). It is, however, unclear whether these sediments accumulated during the Early or Middle Weichselian.

In the Marresale section on western Yamal there was a break in deposition of continental sediments during the LGM, at which time large ice wedges formed (Forman et al., 1999a, 2002). On eastern Yamal a similar development was recorded in the well-dated coastal section Syo-Yakha that displays a 20 m thick sequence of icy silts of Yedoma type that accumulated during the period of 37–17 ka (Vasil'chuk and Vasil'chuk, 1998). This section is pierced by two generations of thick (syngenetic) ice wedges, which grew simultaneously with accretion of the predominantly aeolian sediments. On the extreme north of the Gydan Peninsula there are several finds of frozen mammoth carcasses that were buried in surface sediments not covered by till. Radiocarbon dates on mammoth flesh from three sites yield ages in the range 36–30 ka (Heintz and Garutt, 1965; Astakhov, 1998). These sites demonstrate that glacier ice did not intrude into the West Siberian Arctic during the Late Weichselian (Mangerud et al., 2002).

3.5. Ural Mountains

The occurrence of foreign boulders scattered over a flat summit more than 1000 m a.s.l. show that an ice sheet covered even the highest mountains in the Polar Urals at least once during the Quaternary (Yakovlev, 1956). From investigations in adjacent areas it is concluded that this event occurred prior to the last interglacial (see Astakhov, 2004).

Even though the Weichselian glaciations were more restricted than in the Saalian, south flowing inland ice inundated the foothills of the Polar Urals after the last interglacial. Glacial striae and till fabric measurements in these northern areas reflect an ice movement from N-NE; i.e. from the Kara Sea. Geomorphic features and the end moraine system indicate that both flanks of the Polar Urals were bypassed by an ice sheet flowing towards the south (Fig. 2). The well-expressed Sopkay Moraines to east of the Polar Urals have been traced from the southern part of the Yamal Peninsula and around the northern tip of the mountain chain (Astakhov, 1979), where the ice sheet flowed up-valley to deposit end moraines at 560 m a.s.l. (Astakhov et al., 1999). Local alpine glaciers did not overrun any of these moraines and there is nothing to suggest that major ice caps formed over the Urals after this glaciation. However, large arched end-moraines in the foothills in front of mountain valleys to the south of the Barents-Kara Ice Sheet margin show that piedmont glaciers of Alaskan type formed on the western flank of the mountain. At the western foot of the Polar Urals geomorphological mapping suggests that a piedmont glacier on the river Bolshaya Usa coalesced with a contemporaneous ice lobe from the Barents-Kara Ice Sheet (Astakhov et al., 1999). Glaciofluvial sediments that accumulated in front of this piedmont glacier yielded OSL ages in the range 82–62 ka (Dolvik et al., 2002), whereas a kame terrace that was deposited by a lobe of the Barents-Kara Ice Sheet to the north of the piedmont glacier gave somewhat higher ages (125–87 ka) for the deglaciation (Henriksen et al., 2003). We suspect that this age difference is related to dating uncertainties, but cannot exclude the possibility that the piedmont glacier is slightly younger than the ice sheet lobe.

Ongoing investigations in the mountain valleys of the Polar Urals suggest that the glaciers there were much smaller during the Late Weichselian than during the preceding Weichselian glaciations (Dolvik et al., 2002). It is concluded that only cirque glaciers or small valley glaciers existed in the highest mountain valleys during the LGM. However, the exact dimensions of these glaciers and their ages remain uncertain.

3.6. Yugorski Peninsula

The stratigraphy in the coastal cliffs of Cape Shpindler, Yugorski Peninsula (Fig. 2), record two glacial advances and two ice-free periods older than the Holocene (Lokrantz et al., 2003). During interglacial conditions, a sequence of marine to fluvial sediments was deposited. This was followed by a glacial event when ice moved southwards from an ice-divide in the Kara Sea and overrode and disturbed the underlying interglacial sediments. After a second period with fluvial deposition under interstadial or interglacial condition, the area again was overrun by ice, now moving northward, from an inland ice divide. Infrared-stimulated luminescence (IRSL) dates suggest that the older glacial event occurred during MIS 8 (300–250 ka), and that the underlying interglacial sediments might be of Holsteinian age (>300 ka). However, it should be mentioned that only a few dates are available from the lowermost stratigraphic units and the chronology for the pre-Weichselian strata is therefore more uncertain than for the upper part of the sequence. The younger glacial event recognized in the Cape Shpindler sequence is interpreted to be of Early- to Middle Weichselian age, and possibly correlates with the last regional glaciation around 90–80 ka. We propose that the last ice advance from the south over the western Yamal Peninsula (Forman et al., 1999a, 2002) correlates with the younger south-to-north directed glacial advance recorded in the Cape Shpindler sections. Possibly glacier ice was flowing from the hills in the Pai-Hoi uplands on the Yugorski Peninsula, 468 m a.s.l., which may have acted as an ice-sheet nucleation area during the Early Weichselian glaciation. At the onset of this glaciation ice grew on the highlands fringing the Kara Sea Basin and later coalesced to form a larger ice sheet in the Kara Sea. This larger ice sheet in its turn left most of the glacial fingerprinting recognized in the western Siberian record.

3.7. Pechora Lowland

As many as five tills, interbedded with marine sediments, have been recorded from boreholes in the Arctic part of the Pechora Basin (Fig. 2). The thickest till directly underlies marine sediments of assumed Eemian age (Lavrushin et al., 1989). South of the overlying Weichselian glacial deposits the surface till (Vychegda till) is conventionally correlated with the Moscow glaciation of Central Russia (Guslitser et al., 1986), which is presently thought to be of Late Saalian (MIS 6) age (Astakhov, 2004). The maximum ice sheet limit to the east of the Russian Plain is mapped in the Kama-Volga catchment close to 59°N (Krasnov, 1971). In the western part of the Pechora Lowland the Vychegda till contains frequent Scandinavian erratics, reflecting a dominant eastward ice flow across the Timan Ridge. East of the Pechora River it merges with a surface till of northeastern provenance, i.e. a till that was deposited from a shelf-centered ice sheet. In an exposure along the Seyda River in the northern part of the Pechora Lowland a series of OSL dates have been obtained from interglacial strata below a till that possibly corresponds with this glaciation (Fig. 7).

After the Late Saalian glaciation the northern part of the Pechora Basin was inundated by the Boreal Transgression (Yakovlev, 1956; Guslitser et al., 1986). Along the river Sula, a western tributary of the Pechora River, marine sediments with a rich mollusk fauna occur 40–50 m a.s.l. (Fig. 7), including boreal elements like as *Arctica islandica*, *Cerastoderma edule* and *Zirphaea crispata*. Palaeontologically, these strata are correlated with the Eemian, which is confirmed by OSL dates in the range 120–100 ka (Fig. 8) (Mangerud et al., 1999). Sediment cores recently retrieved from Lake Yamozero near the highest part of the Timan Ridge contain c. 20 m of lacustrine sediments below the Holocene strata (Henriksen et al., in preparation). Judging from the pollen stratigraphy and a series of 21 OSL dates with consistent ages in the range 120–15 ka, the basal lacustrine layers in this basin accumulated during the Late Saalian and the Eemian. There are no tills or other glacial sediments above the Eemian strata, suggesting that this area of the Timan Ridge remained ice free throughout the Weichselian and up to the present.

An east–west trending belt of glacial landforms (Markhida, Harbei and Halmer moraines) was mapped above the Eemian marine strata between the Timan Ridge and the Polar Urals (Astakhov et al., 1999). The

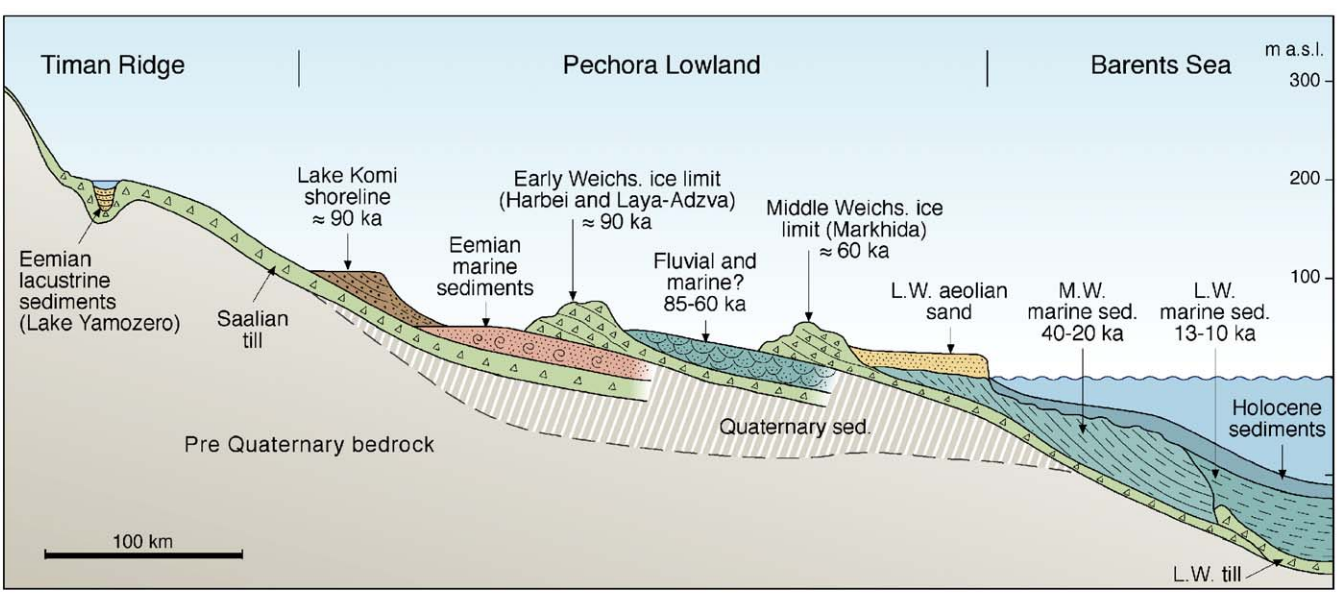

Fig. 7. Generalized stratigraphy of the Pechora Lowland and SE Barents Sea showing the inferred relations between tills, marine sediments and the mapped ice marginal features.

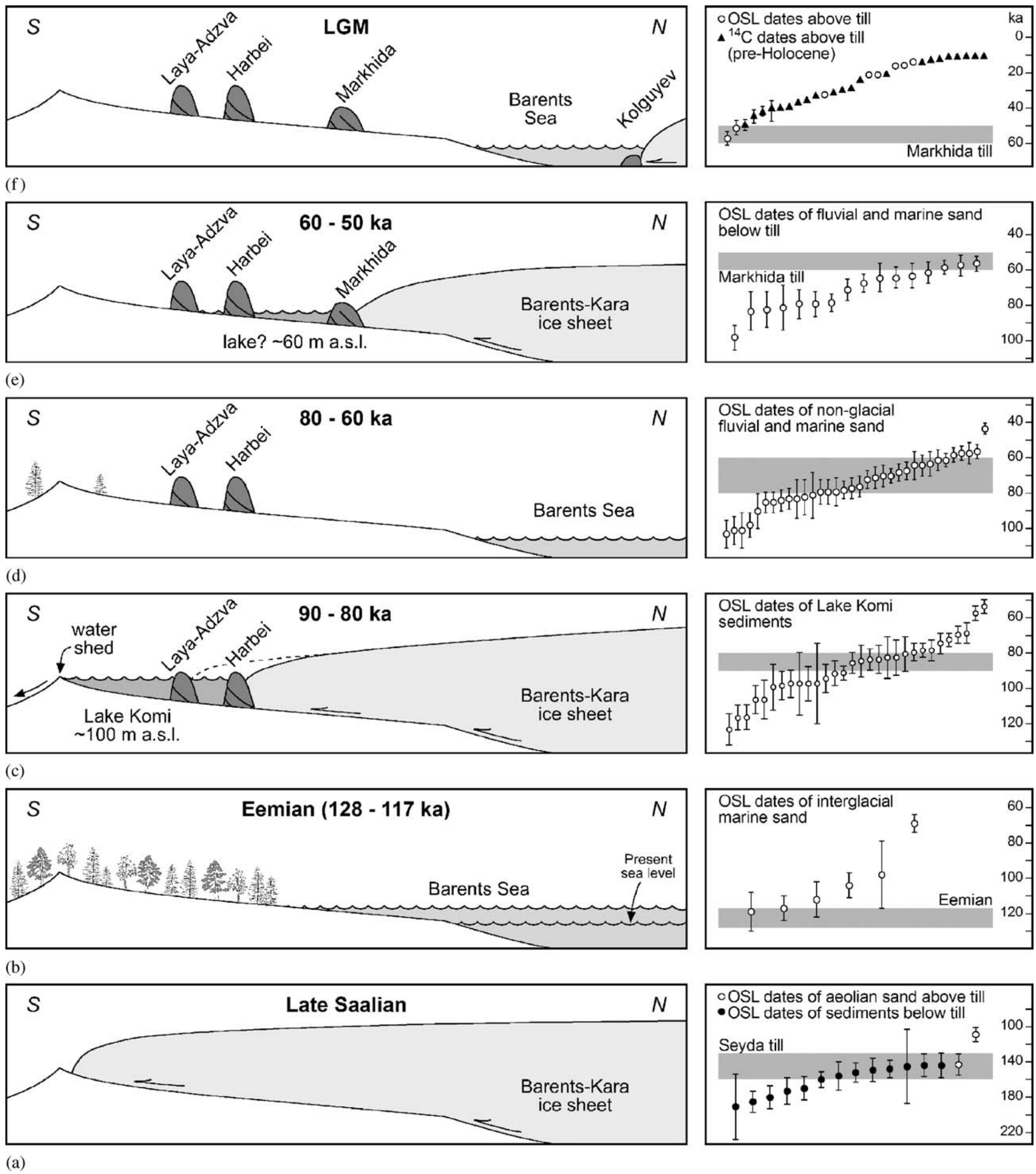

Fig. 8. Schematic north-south profiles across the Pechora Lowland showing: (a) the maximum extent of the Barents-Kara Ice Sheet during the Late Saalian (160–140 ka), (b) ice free forest environment with a high relative sea level during the Eemian, (c) Early Weichselian (90–80 ka) ice sheet maximum with a proglacial lake (Lake Komi), (d) ice free conditions during the early Middle Weichselian (80–60 ka), (e) the ice sheet maximum during the Middle Weichselian (60–50 ka) and (f) the ice front position during the Late Weichselian (LGM). Available ^{14}C- and OSL dates are plotted to the right.

southern boundary of the fresh hummock-and-lake glaciokarst landscape across the Pechora Lowland was collectively termed the Markhida Line and was originally considered to represent the same glaciation (Fig. 2). In the lowland area to the north of these moraines, Eemian marine sediments are glaciotectonically distorted and covered by tills (Lavrushin et al., 1989; Mangerud et al., 1999; Astakhov and Svendsen, 2002). Astakhov et al. (1999) subdivided this ice marginal zone into three types of glacial landscapes according the stage of postglacial modification: Markhida, Harbei and Halmer. The Halmer landscape on the western flank of the Polar Urals is the freshest, whereas the Markhida landscape in the west is more eroded. The west–east gradient in morphology is considered to be a result of the time-transgressive melting of stagnant glacier ice and permafrost and is not related to age differences of the moraines. At places, the Harbei landscape is still underlain by glacier ice (Astakhov and Svendsen, 2002). The pattern of ice-pushed morainic arcs and other directional features reflects a dominant ice flow from the Kara Sea shelf. The ice marginal features truncate the huge arcs of the Laya-Adzva and Rogovaya ice pushed ridges protruding to the south (Fig. 2). The latter moraines are also considered to delineate a Weichselian ice sheet advance, even though a Saalian age cannot be ruled out.

The Harbei-Halmer moraines are mapped around the northern tip of the Polar Urals and continue as the Sopkay moraines on the eastern side of the Urals (Fig. 2). According to our interpretation the ice sheet that deposited the Harbei and Halmer moraines blocked the northbound drainage and formed a huge ice dammed reservoir, named Lake Komi (Astakhov et al., 1999; Mangerud et al., 2001, 2004). The ice-dammed lake flooded the lowland areas in the Pechora Lowland up to a level of around 100 m a.s.l. (Fig. 7). Beach facies have yielded OSL dates (29), most of which are closely grouped in the range 100–80 ka. Excluding two outliers, the unweighted mean for the remaining 27 samples is 90 ± 1.6 ka, whereas the weighted mean is 82 ± 1.2 ka. The reason for the younger weighted mean is the larger standard deviation for the older samples than for the younger ones (Fig. 8) (Mangerud et al., 2001; 2004). OSL dates of sediments from the oldest generation of fluvial terraces (3rd terrace) that is incised into the floor of Lake Komi have yielded ages in the range 90–60 ka. The fact that normal fluvial drainage was established for a considerable period after the emptying of the ice-dammed lake indicates that the ice front withdrew far to the north.

The Markhida Moraine, at its type locality across the Pechora River valley, was deposited in front of the Barents-Kara Ice Sheet during the last shelf-centered glaciation that affected this part of the mainland. On the basis of several radiocarbon dates of wood extracted from diamictic sediments Grosswald (1993) ascribed this morainic ridge to an Early Holocene ice advance. However, Tveranger et al. (1995) demonstrated that the diamictic sediments with plant remains are Holocene solifluction deposits (flow till) and that the moraine itself is older. Tveranger et al. (1998) later obtained a series of finite radiocarbon dates of plant material with ages in the range 43–25 ka, from the youngest till and from underlying alluvial deposits in the well-studied section Vastianski Kon section along the Pechora River, suggesting that the last ice advance occurred during the Late Weichselian. In the reconstruction by Landvik et al. (1998) the Markhida Moraine was therefore considered to outline the LGM ice sheet margin in this part of Russia. However, a later redating of the Vastianski Kon strata yielded non-finite radiocarbon ages (Mangerud et al., 1999). We therefore conclude that the previously reported finite radiocarbon dates are providing too young ages and thus that the moraine was deposited during an older ice advance (Fig. 8). This assumption was also supported by the OSL chronology.

Based mainly on geomorphological considerations it was previously suggested that the ice sheet that deposited the Markhida Moraine across the Pechora River valley also dammed Lake Komi (Astakhov et al., 1999; Mangerud et al., 1999). However, a series of OSL dates on sediments below the till have yielded ages in the range 70–60 ka which are maximum ages for the ice advance (Henriksen et al., 2001) (Figs. 7 and 8). This indicates that the Markhida Moraine at the type locality is younger than Lake Komi (dated to 90–80 ka) and probably also younger than the Harbei-Halmer moraines further to the east that are believed to be contemporaneous with this ice-dammed lake (Mangerud et al., 2001). The eastern continuation of the Markhida Moraine is not clear, but recent geomorphological mapping suggests that it crosses the southern coastline of the Barents Sea a few km to the east of the Pechora River mouth (Nikolskaya et al., 2002). If correct, this implies that in the east the ice sheet margin was located on the sea floor off the present coastline. Minimum dates of the glaciation that deposited the Markhida Moraines are provided from sections in a wave-cut cliff on the Timan Beach at the Barents Sea coast (Mangerud et al., 1999). The lower part of the section consists of lacustrine sand that interfingers with solifluction deposits, which are covered by aeolian sand. Plant remains from the lacustrine sand yield non-finite radiocarbon ages and three OSL dates of the same unit produced ages in the range 57–32 ka (Fig. 8). A series of OSL dates from the overlying sand indicate that aeolian deposition prevailed during the period 21–14 ka. Based on the land based investigations we therefore conclude that the last ice advance that reached the Pechora Lowland culminated at the Markhida Moraine around 60–50 ka and that the ice front during the LGM did not reach the present day coastline.

3.8. Arkhangelsk region

According to the traditional view, the oldest Quaternary sediment exposed in river banks in this area is a Late Saalian till with Scandinavian erratics that was mapped across the Timan Ridge and into the Pechora basin where it corresponds with the Vychedga till

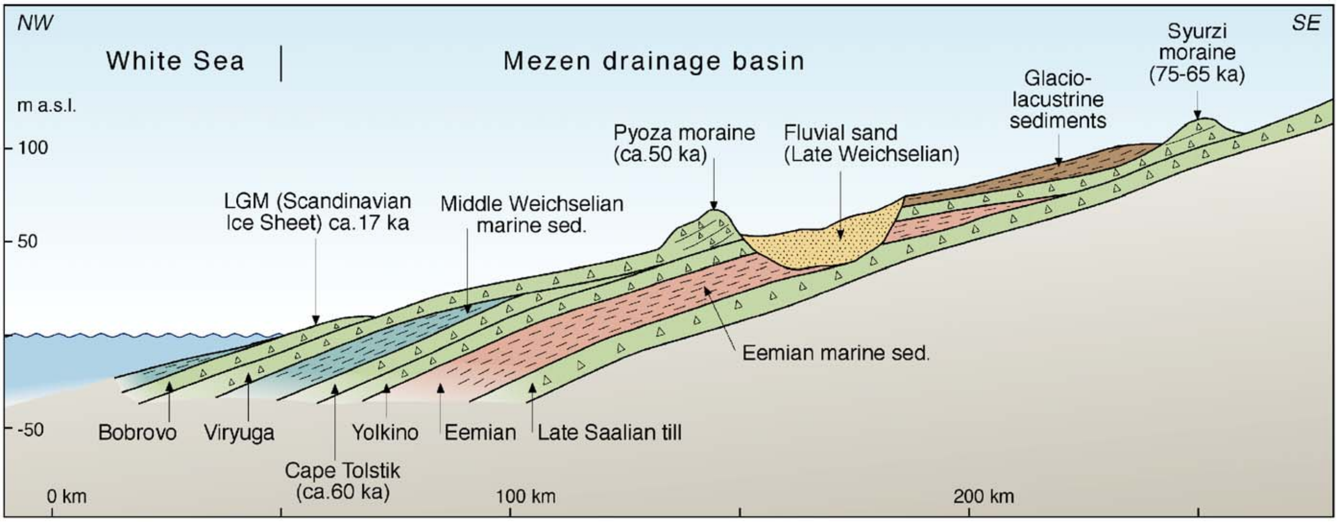

Fig. 9. Generalized stratigraphy from the Arkhangelsk Region (Mezen Basin) showing the inferred relations between tills, marine sediments and the mapped ice marginal features. Notice that there is a disagreement whether the Syurzi Moraine was deposited by a shelf-centered ice sheet (Chebotareva, 1977; Lavrov, 1991; Mangerud et al., 2004) or a terrestrial ice cap centered over the Timan Ridge (Demidov et al., 2004).

(Yakovlev, 1956; Andreicheva, 1992). Older deposits are found only in boreholes well below sea level.

During the last interglacial the lowland areas along the coast of the White Sea and the Barents Sea were affected by the Boreal Transgression (Fig. 9). In the western part of the Arkhangelsk region these marine sediments are sandwiched between two Scandinavian till sheets. The marine sediments have been correlated with the Central Russian terrestrial Mikulinian (Eemian) formation by means of pollen analysis (Devyatova, 1982; Molodkov, 1989; Funder et al., 2002).

The oldest dated signs of a Weichselian glaciation are found in sediment exposures along the upper reaches of the River Pyoza, a tributary to the Mezen River (Figs. 2, 9 and 10) (Houmark-Nielsen et al., 2001). In this area, a few (4) OSL dates from till covered proglacial sediments have yielded ages in the range 110–90 ka suggesting that the ice front was not far away (Fig. 10). However, the configuration of this glaciation is not clear. Normal northbound drainage is recorded in some fluvial sediments with similar OSL ages (Houmark-Nielsen et al., 2001) which may suggest that the area was not blocked by ice to the north at this time. The pollen composition in peat lenses embedded in overlying sediments reflects forest-tundra vegetation after the deglaciation, and permafrost conditions are inferred from ice-wedge casts.

Possibly, the maximum ice sheet extent to the west of the Timan Ridge is represented by the east–west trending belt of moraines, named Syurzi Moraines that are mapped between the upper reaches of the rivers Pyoza and Mezen (Figs. 2 and 9) (Chebotareva, 1977; Lavrov, 1991; Demidov et al., 2004). The ice margin that deposited these moraines blocked the northbound river drainage and terraces of proglacial ice-dammed lakes are found in the Mezen and Vashka river valleys at altitudes around 145 and 130 m a.s.l. (Lavrov, 1968, 1975). Sediment cores show that the related till covers marine sediments that accumulated during the Boreal (Eemian) Transgression, which implies that the moraines must be of Weichselian age (Devyatova and Loseva, 1964; Kalberg, 1968; Lavrov, 1991). The ice marginal features consist of a series of end moraine arcs opening towards the north and accordingly they were interpreted by previous Russian investigators as end moraines deposited by an ice sheet flowing southwards from the Barents Sea shelf (Chebotareva, 1977; Lavrov, 1991). This interpretation is supported by recent geomorphological mapping based on satellite images (Nikolskaya et al., 2002). However, Demidov et al. (2004) propose that the abovementioned moraines were deposited by a large terrestrial ice cap that covered much of the Mezen Basin (Kjær et al., 2001, 2003) (Fig. 2). This assumption is an implication of field investigations further to the north. Based on clast fabric measurements, glaciotectonic features and provenance studies of exposed till beds, Houmark-Nielsen et al. (2001) and Kjær et al. (2001, 2003) infer that the oldest Weichselian till (Yolkino till) in this region was deposited by a glacier that flowed towards N-NW from the Timan Ridge at around 75–65 ka and terminated off the present coast in the White Sea (Figs. 9 and 10). This interpretation implies that a large ice cap was centered over the Timan Ridge during the early Middle Weichselian (75–65 ka), after the drainage of the ice dammed Lake Komi (Mangerud et al., 2004). However, it is a problem that neither stratigraphic nor geomorphological evidence for the existence of an ice cap have

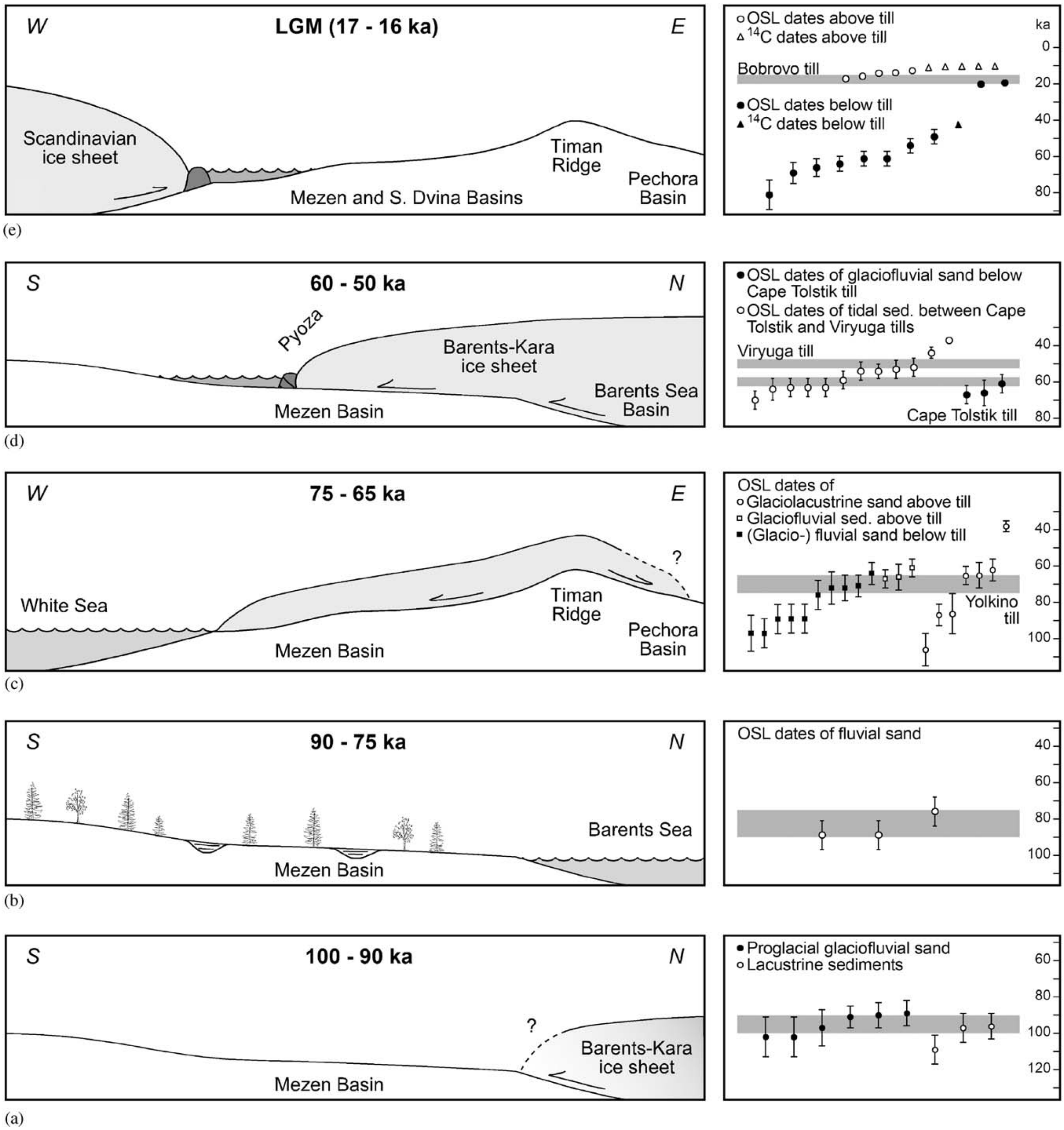

Fig. 10. Schematic profiles of the reconstructed ice sheets in the Mezen drainage basin. The figures illustrate: (a) the ice front during the Early Weichselian glacial maximum (c. 90 ka), (b) Early Weichselian interstadial, (c) east–west profile across the inferred ice cap over the Timan Ridge (75–65 ka), (d) an early Middle Weichselian readvance of the Barents-Kara Ice Sheet (60–50 ka) and the maximum extent of the Scandinavian Ice Sheet during the Late Weichselian (17–16 ka). Available OSL- and ^{14}C dates are plotted to the right.

been found along the eastern flank of the Timan Ridge and on the adjacent Pechora Lowland (Astakhov et al., 1999; Mangerud et al., 1999).

The next ice advance to affect the Arkhangelsk region is recognized from a till (Cape Tolstik till) that was clearly deposited from the Barents-Kara Ice Sheet (Fig. 9). In the Cape Tolstik section at the southern shore of the Mezen Bay, this till was deposited from due north, i.e. from the Barents Sea shelf (Kjær et al., 2003). Furthermore, tidal sediments that cover the Cape Tolstik till reveal a relatively high sea level (30–40 m a.s.l.) after the ice front had receded from its Middle

Weichselian maximum position reflecting a significant glacioisostatic depression. Ten OSL dates have provided a mean age of around 55 ka for this depositional event (Figs. 9 and 10). A second ice advance is represented by the Viryuga till that covers the abovementioned tidal sediments. The till was deposited by an ice sheet flowing from the NE towards SW, perhaps reflecting a shift of the major ice divide towards the east after the deglacial event recorded by the tidal sediments. We assume this ice sheet advance culminated soon after 55 ka and that the southern margin corresponds with pronounced ice-pushed moraines along the northern bank of the river Pyoza, named the Pyoza Moraine (Houmark-Nielsen et al., 2001).Towards the west these marginal moraines can be traced to the lower reaches of the Mezen River, where they have been overridden by a younger advance of the Scandinavian Ice Sheet (Fig. 2). Probably the ice front crossed the neck of the White Sea between the mouth of the Mezen River and the Kola Peninsula (Demidov et al., 2004), but this assumption is contradicted by some OSL dates of fluvial sediments suggesting that there was a northbound drainage here at this time (Fig. 10).

In the Severnaya Dvina catchment area there is an unconformity related to a low base level in the early Middle Weichselian record (Lyså et al., 2001). During the Middle Weichselian peat formation and a northbound fluvial drainage under permafrost conditions took place around 66–61 ka (Lyså et al., 2001). Only one till bed has been found above strata from the last interglacial in this area. This till bed truncates the Middle Weichselian fluvial succession. Ice-directional features, including clast fabrics in tills and glaciotectonic deformations in subtill sediments, show unequivocally that this till was deposited from the west; i.e. from the Scandinavian Ice Sheet (Fig. 10). This conclusion is also supported by provenance studies showing that the rock debris in the corresponding till originates from areas to the west. The maximum position of the ice sheet advance is recognized by well-preserved end moraines across the upper reaches of the Severnaya Dvina and Vaga river valleys (Devyatova, 1969; Atlasov et al., 1978; Arslanov et al., 1984; Larsen et al., 1999; Demidov et al., 2004). In the coastal areas along the White Sea to the northwest of the Mezen River the same till unit occurs stratigraphically above the early Middle Weichselian glacial deposits. Further to the north the eastern boundary of the Scandinavian Ice Sheet is not expressed. As was postulated already by Ramsay (1904) we assume that the ice front crossed the lower reaches of the Mezen River, or at least the southern part of the Mezen Bay, and that it ran along the western shore of the Kanin Peninsula. Probably this ice merged with the Barents-Kara Ice Sheet north of Cape Kanin. Based on OSL dates of fluvial and glaciolacustrine sediments below and above the till it is concluded that the maximum position was attained at around 17 ka and that deglaciation started close to 15 ka (Fig. 10) (Larsen et al., 1999).

3.9. Kola Peninsula

It is generally thought that the oldest till on the Kola Peninsula was deposited during the Moscow (Late Saalian) glaciation (cf. Lavrova, 1960; Grave et al., 1964; Armand et al., 1969). This till is in places overlain by intraglacial marine, mollusc-bearing silt and clay that is widely distributed in lowland areas of NW Russia (cf. Apukhtin and Krasnov, 1967; Gudina and Yevzerov, 1973; Ikonen and Ekman, 2001; Funder et al., 2002). These beds were deposited during the high sea-level stage of the Boreal Transgression, which most previous investigators ascribe to the Mikulino (Eemian) interglacial.

The Weichselian (Valdaian) glacial events on the Kola Peninsula are more controversial. Many Russian workers claim that there are two separate Weichselian till units, one that was deposited during the Late Weichselian and another that is older (cf. Grave et al., 1964; Nikonov, 1964; Evzerov and Koshechkin, 1991). However, only in the central part of the peninsula (Fig. 3), in the Khibyna-Lovozero and Kovdor areas, have two till beds been identified over Mikulinian (Eemian) deposits (Grave et al., 1964; Evzerov and Koshechin, 1991). During our investigations in the southern and southeastern part of the peninsula we found only one till unit, considered to be of Late Weichselian age.

In most of the sections studied on southern coastal Kola, a relatively thick glaciolacustrine unit, including waterlain diamicton lenses and IRD material, overlies the Eemian marine sediments. Four OSL dates from overlying fluvial sediments have yielded ages in the range 90–80 ka, suggesting that an ice dammed lake existed at this time or shortly before. The IRD material and lenses of waterlain diamicton within the glaciolacustrine facies indicate that an ice margin was located near the southern coast (Fig. 3). As there are no indications of any Early Weichselian glaciation on the Kola Peninsula north of the coastal sites we believe that the entrance to the White Sea Basin was blocked by the Barents-Kara Ice Sheet, even though the exact ice front position is not yet known (cf. Mangerud et al., 2004).

OSL dates of glaciofluvial deltaic sediments from the southern part of the peninsula have provided ages in the range 67–60 ka suggesting that a substantial glaciation occurred also at that time. The delta foresets indicate paleoflow towards the south, from an ice cap that covered the interior of the Kola Peninsula. Possibly, this glaciation corresponds with the first of the two Weichselian tills reported from that area (Grave et al., 1964; Nikonov, 1964; Evzerov and Koshechkin, 1991).

It is unclear whether the Kola Peninsula remained ice covered or not throughout the Middle Weichselian. From the interior of Kola (Monchegorsk), however, an OSL date of around 35 ka was obtained from glaciofluvial sediments covered by till, suggesting that a significant part of the peninsula was ice-free during a later stage of the Middle Weichselian.

The distribution and stratigraphic position of the youngest till show that the entire peninsula was ice covered during the LGM. Geomorphological and stratigraphical evidence suggests that the Scandinavian Ice Sheet covered the western parts of the peninsula, and the coastal areas along the White Sea. At this time an inactive ice dispersal centre, the Ponoy Ice Cap, was located over the eastern Kola Uplands. Field observations show that only a thin and patchy veneer of Quaternary sediments without any glacial landforms covers large areas in the central and eastern part of the Kola Peninsula. The landscape is characterized by weathered bedrock surfaces and tors (Lavrova, 1960; Lunkka et al., 2001a; Niemelä et al., 1993). Striated bedrock surfaces on the north-central coast reflect glacier flow from the inland areas towards the Barents Sea, indicating that the shelf-centered ice sheet had little influence on the ice flow on the Kola Peninsula.

There are two extensive belts of ice marginal ridges, the Keiva I and Keiva II moraines, on the southern and eastern parts of Kola (Lavrova, 1960; Ekman and Iljin, 1991; Niemelä et al., 1993). These end moraines reflect the interplay between the active White Sea Basin ice stream of the Scandinavian Ice Sheet in the south and the inactive Ponoy Ice Cap to the north between 16 and 12 ka (Fig. 3). Keiva I is a highly discontinuous ice marginal zone and is composed of numerous end-moraine ridges and outwash sand deposited along the margin of that part of the Scandinavian Ice Sheet that filled the White Sea basin (Lunkka et al., in preparation). Keiva II is the most prominent ridge system and can be traced parallel with the coastline for more then 200 km along the south-eastern part of the peninsula. Unlike Keiva I, this ridge system is a complex glaciofluvial formation that includes esker-type ridges, outwash deltas, and interlobate formations (Lunkka et al., 2001a). The final deposition of the central part of Keiva II took place at the margin of the Ponoy Ice Cap whereas, in the east, the Keiva II ridge represents an interlobate formation. In this part, sediments were derived from the Scandinavian Ice Sheet in the east and from the Ponoy Ice Cap to the west. Two OSL dates from glaciofluvial deltas associated with the Keiva II moraines yield ages of around 12 ka (Varzuga) and 13 ka (Strelna), suggesting that the Ponoy Ice Cap margin may have been at this position as late as during the Younger Dryas (Lunkka et al., 2001a).

3.10. North-western part of the Russian Plain

The extent of the Scandinavian Ice Sheet along its eastern flank is defined on the basis of geomorphological mapping and bore-hole data (e.g. Markov, 1961; Apukhtin and Krasnov, 1967; Malakhovsky and Markov, 1969; Krasnov, 1971; Aseev, 1974; Chebotareva, 1977; Atlasov et al., 1978; Ostanin et al., 1979; Gey and Malakhovsky, 1998; Gey et al., 2000; Lunkka et al., 2001b). The outermost ice sheet limit during the Weicheslian is marked by a system of pronounced ice marginal landforms that run across the NW Russian Plain from the Valdai Upland in the south to the Vaga Valley in the north (Krasnov, 1971). The surface till outside these ridges is considered to be deposited during the Moscow glaciation (Figs. 11 and 12), i.e. during the

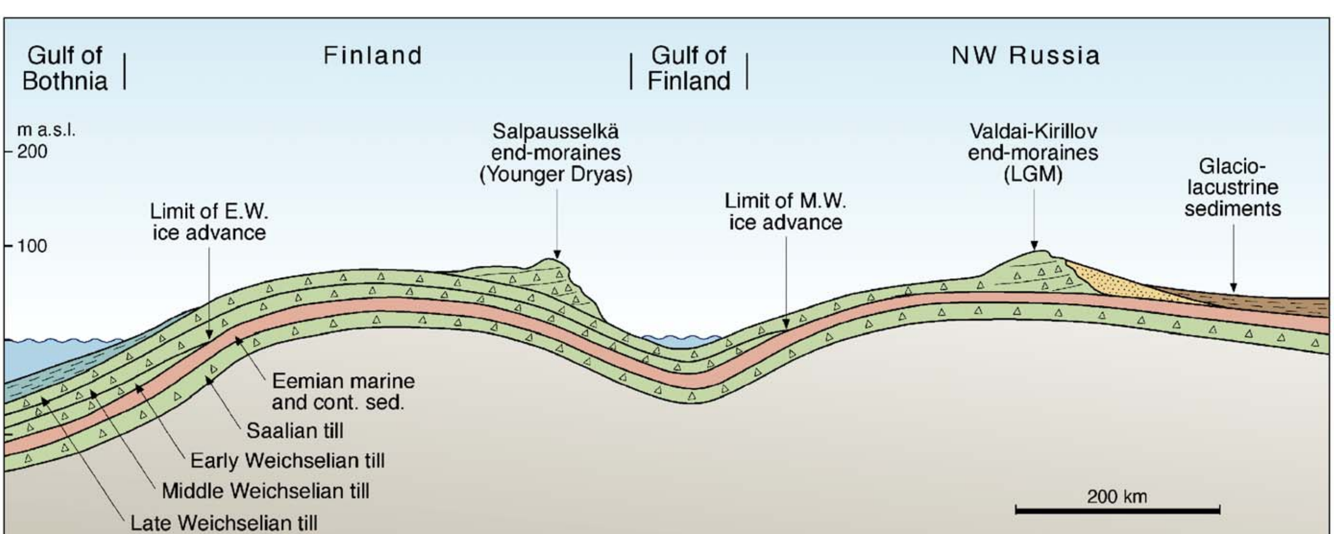

Fig. 11. Generalized profile from Finland to the NW Russian Plain showing the inferred relations between tills, marine sediments and the mapped ice marginal features.

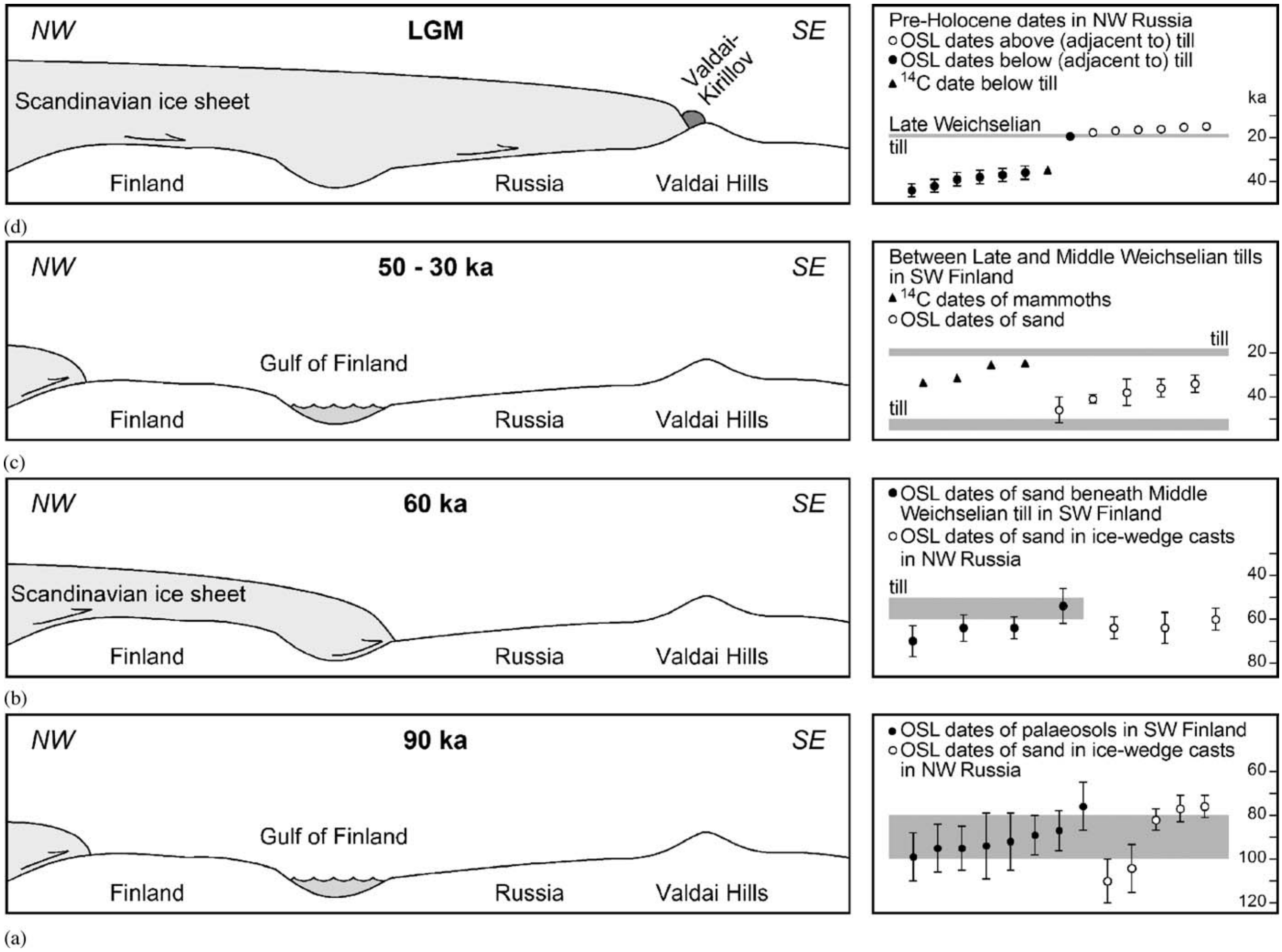

Fig. 12. Schematic southeast–northwest profiles across Finland and the NW Russian Plain showing: (a) the inferred maximum position of the Scandinavian Ice Sheets in Finland during the Early Weichselian (c. 90 ka), (b) the Middle Weichselian glaciation (c. 60 ka), (c) the maximum ice sheet extent during the late Middle Weichselian (60–50 ka) and (d) the maximum ice sheet extent during the Late Weichselian (20–18 ka). Avaialable OSL and ^{14}C dates are plotted to the right.

Late Saalian (e.g. Gey and Malakhovsky, 1998; Lunkka et al., 2001b; Demidov et al., 2004). This till bed is overlain by terrestrial Eemian sequences (cf. Grichuk, 1984).

Some investigators have suggested that the Scandinavian Ice Sheet reached the NW Russian Plain during the Early or Middle Weichselian (cf. Apukhtin and Krasnov, 1967; Krasnov, 1971; Arslanov et al., 1981; Zarrina et al., 1989). However, a more recent review of available data lends little support to the hypothesis that the NW Russian Plain was affected by two separate Weichselian glaciations (e.g. Faustova, 1995; Demidov et al., 2004). Our investigations west of the classical Valdai Moraines and east of Lake Onega suggest that the only till post-dating the Saalian till in this region is of Late Weichselian age (Fig. 3) (Lunkka et al., 2001b). Along a tectonic escarpment east and south of the Valdai moraines, we investigated some well-preserved glaciofluvial deltas and outwash plains that were previously interpreted as ice marginal deposits from the Late Weichselian glaciation (Krasnov, 1971). However, eight OSL dates from six glaciofluvial deposits along this ice marginal zone (Bugaly, Pikalevo, Kudrino, Chagolino, Nebolchi, Vyshny-Volochek) all have ages in the range 258–110 ka, suggesting that the outwash pre-dates the last interglacial (Figs. 11 and 12). The upper parts of these outwash deposits are often cryoturbated and include fossil ice-wedges capped with aeolian sediments. A series of nine OSL dates from the aeolian sand yielded ages in the range 82–37 ka (Fig. 12). Further to the east of the Valdai Uplands, in the Vologda and Nyandoma areas, OSL dates of cryoturbated sand covering pre-Eemian glacial sediments suggest that ice wedges were growing in a periglacial environment here around 64–60 ka (Lunkka et al., in preparation). Based on these observations and on well-dated multiple till sequences in western Finland (e.g. Hütt et al., 1993; Nenonen, 1995), combined with stratigraphical studies in southern

Finland and Estonia (e.g. Liivrand, 1991; Hirvas et al., 1995; Nenonen, 1995), it is concluded that the Scandinavian Ice Sheet did not reach southern Finland during the Early Weichselian (Figs. 11 and 12). However, the whole of Finland and parts of Estonia were covered by ice c. 60 ka, but the NW Russian Plain was not affected by the Early and Middle Weichselian glaciations.

Numerous ice sheet limits have been proposed for the LGM by various investigators over the past decades (cf. Gey and Malakhovsky, 1998), but when considered together across this large geographical area the differences between the various reconstructions are relatively small. According to our reconstruction the ice sheet limit during the LGM corresponds with relatively fresh-looking end moraines and hummocky landscapes previously mapped by Markov (1961), Apukhtin and Krasnov (1967), Malakhovsky and Markov (1969), Krasnov (1971), Gey and Malakhovsky (1998). These broad morainic ridges are, at places, conspicuous features in an otherwise flat terrain. Major ice lobes appear to have occupied the depressions of Lake Beloye Ozero (White Lake) and Kubenskoye-Vozhe-Lacha. In contrast to some previous reconstructions (Apukhtin and Krasnov, 1967; Krasnov, 1971), we conclude that the ice sheet did not reach the Rybinskoye Reservoir southeast of Lake Ladoga. In the Rybinskoye Reservoir area (Mologa basin) our LGM ice sheet limit differs from a number of previous estimates by c. 200 km (see Gey and Malakhovsky, 1998). As a whole, our limit depicts a slightly more restricted ice sheet extent than shown in earlier reconstructions (Krasnov, 1971; Velichko et al., 1997).

During the LGM and just after the ice sheet had retreated from the Kubenskoye basin, extensive lakes were formed in front of the ice (see Mangerud et al., 2004). The water level of these lakes, reconstructed from shorelines and deltas, was c. 130 m a.s.l. Wide straits linked these lakes and the melt water drainage was most probably southwards through the Sukhona river valley and eventually into the Volga catchment.

The age of the LGM in this region is constrained by a few radiocarbon dates of sub-till sediments near the ice margin. One date of 21.4 ka was obtained from a peat layer underneath the Late Weichselian till, in a section close to Lake Kubenskoye in the Vologda District (Arslanov et al., 1970). In Byelorussia further to the SW, a date of 18.7 ka was obtained from organic rich lacustrine silt covered by till (Arslanov et al., 1971; Faustova, 1984). In the Kirov-Vologda area the Late Weichselian ice sheet advance is now constrained by some OSL dates. A sandur delta deposited in front of the Late Weichselian ice margin was dated to around 19 ka, whereas samples of aeolian sand above glacial sediments have yielded consistent ages in the range 18–15 ka (Figs. 11 and 12) (Lunkka et al., 2001b). Based on these dates we now conclude that the maximum position of the ice sheet advance in the Vologda area was attained around 20–18 ka. Paleomagnetic, varve counting and radiocarbon dates from the eastern shore of Lake Onega indicate that this area was deglaciated between 14.4 and 12.9 ka (Saarnisto and Saarinen, 2001).

3.11. Southeastern Barents Sea shelf

Distal to the mouth of the Pechora River, Gataullin et al. (2001) recorded a 100–150 m thick wedge of prodeltaic marine sediments above the upper till unit (Figs. 2 and 7). A series of AMS dates of shells from cores in these marine sediments yielded consistent ages from about 40 ka and onwards (Polyak et al., 2000). From the occurrence of fine-grained marine sediments at presently shallow water depths, it is inferred that relative sea level remained at least as high as today during this period (Gataullin et al., 2001).

Above the prodeltaic sediment unit there is an erosional unconformity overlain by Holocene marine sediments (Fig. 7). Stratigraphically, the unconformity corresponds with buried beach ridges and shorelines that have been identified from seismic records down to present depths of 50–70 m. To the north these Middle Weichselian marine sediments abut a younger till sheet that can be traced into the central part of the Barents Sea Shelf. This erosional limit, termed the Kolguyev Line, is believed to outline the maximum extension of the Barents Ice Sheet during the Late Weichselian, i.e. the LGM limit (Fig. 2) (Gataullin et al., 2001). Some 50–100 km to the north of the inferred LGM limit a series of long ice-pushed bedrock and till ridges were mapped. This ice-marginal zone is termed the Kurentsevo Line and is correlated with the Murmansk Bank Moraines, a 400 km long chain of ice-pushed ridges north of the Kola Peninsula (Svendsen et al., 2004). Up to 100 m thick accumulations of glaciomarine sediments were mapped on the distal side of the ridges along the Kurentsovo Line whereas less than 10–20 m was found on the proximal side, indicating the ice front was stationary for a considerable time. We infer that the maximum ice sheet position was attained more or less simultaneously with the western margin of the Barents Ice Sheet about 20–15 ka (Landvik et al., 1998). Basal radiocarbon dates from sediment cores from the Central Deep, on the proximal side of these moraines yielded ages of 13–12.5 ka (Polyak et al., 1995).

Off the southwestern coast of Novaya Zemlya there is a pronounced thickening of glaciogenic sediments that circumscribe the coastline (Gataullin et al., 2001). This arched accumulation is considered to be the southern extension of a huge end-moraine complex that can be traced for hundreds of kilometers on the shelf to the west of Novaya Zemlya; the Admiralty Bank Moraines (Epstein and Gataullin, 1993; Gataullin and Polyak, 1997). The configuration of the ice sheet that deposited these moraines is not clear, but the orientation of the ridge system points towards an ice dispersal centre that was localized over the northernmost part of Novaya Zemlya and Franz Josef Land. Gataullin et al. (2001) and Svendsen et al. (2003) proposed that these moraines were formed during the Younger Dryas.

3.12. Kara Sea shelf and the western margin of the Laptev Sea

Morainic ridges show that the general glaciation limit was located along the western Laptev Sea continental margin (Fig. 2) (cf. Niessen et al., 1997). On the Kara Sea shelf the pre-Quaternary strata appear to be widely truncated by glacial erosion. At places several tills and/or thick sequences of pro-deltaic sediments cover this surface (Polyak et al., 2002; Stein et al., 2002). Evidently, the Kara Sea shelf has been repeatedly glaciated during the Quaternary.

Land based investigations in Siberia indicate that major ice domes were located over the Kara Sea shelf during the Late Saalian and during the Early- and Middle Weichselian, and most likely these ice sheets reached the Arctic Ocean. These glaciations are also seen from a high content of IRD in sediment cores from the continental slope. According to Knies et al. (2000) the youngest till on the sea floor to the east of Severnaya Zemlya dates from around 60 ka. The ice sheet that deposited the till had a grounding line at least 340 m below the present sea level along the shelf margin. This depositional event probably corresponds with stacked debris-flow deposits, interpreted as a glaciomarine fan, that extend from the shelf edge in the Vilkitsky Strait between Severnaya Zemlya and Taimyr Peninsula to the continental rise of the western Laptev Sea margin (Kleiber et al., 2001). Kleiber et al. (2001) infer that the ice-proximal facies are associated with the maximum extent of an ice sheet over the northern Kara Sea, which, according to their age model, occurred during Middle Weichselian time (MIS 4). The general absence of debris-flow lobes during MIS 3 suggests that there was a complete deglaciation of the eastern Kara Sea shelf following the early Middle Weichselian glaciation.

During the Late Weichselian the southern ice sheet limit was evidently located on the sea floor off the Siberan mainland. In the southern Kara Sea the LGM ice sheet most likely corresponded to a well-defined morainic ridge SE of the Novaya Zemlya Through (Fig. 2) (Svendsen et al., 1999; Polyak et al., 2000). Inside the through there is only a thin (4–5 m) veneer of marine sediments above the till, whereas a much thicker accumulation (up to 100 m) has been recorded closer to the morainic ridge. Further north, the ice limit was probably localized along the eastern margin of the Novaya Zemlya Through (Polyak et al., 2000, 2002). On the northern Kara Sea shelf the ice margin is recognized from a distinct moraine that overlies the aforementioned unconformity (Stein et al., 2002). The seafloor on the proximal side of the inferred ice sheet limit is characterized by an uneven, glacial morphology whereas to the east and south of the mapped boundary the erosional unconformity defines a flat surface only covered by Holocene marine sediments.

An erosional boundary, which probably formed during a period when the shallow part of the shelf was subaerially exposed, is widely recognized on top of prodeltaic marine sediments. A prominent feature to the south of the ice sheet limit is the presence of large (up to 50 m deep) channels that were probably eroded into the exposed shelf by river drainage. These channels have been traced across the shelf from the Ob and Yenissei estuaries down to present water depths of 140 m in the northeastern area (Stein et al., 2002). Polyak et al. (2002) noted at least two generations of channel fills and inferred that the youngest generation overlies the regional erosional unconformity on the shelf. In front of the channel mouths prodeltaic deposits up to 100 m thick have been recorded. These deposits may have accumulated in a freshwater reservoir on the shelf during the LGM, when the northbound drainage between Novaya Zemlya and Taimyr Peninsula was blocked by glacier ice. Alternatively, these accumulations could be normal prodeltaic marine sediments that accumulated during a period with a low sea level stand. A low relative sea level beyond the ice front at this time is consistent with some observations further to the east. At the western Laptev Sea shelf edge, Kleiber et al. (2001) identified a prograding submarine fan with a surface 100 m below the present sea level that was interpreted as a delta fed by fluvial input through a subaerially exposed Anabar-Khatanga paleovalley during the Late Weichselian.

4. Marine transgressions

4.1. The Boreal Transgression(s)

The last interglacial (Eemian/Mikulino/Kazantsevo) represents an important marker horizon that is used for long distance correlation and for constraining the extent of Weichselian ice sheets. According to the conventional view the northern rim of the Russian and Siberian mainland, from the White Sea to eastern Taimyr, was affected by a pronounced marine inundation at this time; the so-called Boreal Transgression (Biske and Devyatova, 1965; Ganeshin, 1973; Troitsky, 1975; Troitsky and Kulakov, 1976). Marine sediments that accumulated during this period have been traced up to

100 m a.s.l. on the Kola Peninsula, 70 m in the Arkhangelsk region, 60 m in the Pechora Lowland, 70 m in the Siberian plains and to over 100 m on central Taimyr (Figs. 4, 6, 7 and 10). The high relative sea level is explained by a significant glacioisostatic depression caused by the thick ice load during the preceding Late Saalian glaciation (MIS 6). Shallow-water boreal mollusks associated with the Atlantic Current and with restricted year-round ice-free areas characterize the marine formation. In some areas the fauna indicates that during wintertime (January) the sea water was as much as 4–8°C warmer than at present. A seaway through Karelia connected the Barents Sea with the Baltic and North Sea for a period of 2000–2500 years during an early stage of the interglacial, until isostatic uplift closed the passage at the watershed (Funder et al., 2002).

From the interglacial fauna, its stratigraphic position below till and the pollen successions, previous investigators ascribed the Boreal strata to the Eemian of Western Europe (Biske and Devyatova, 1965; Troitsky and Kulakov, 1976; Devyatova, 1982). This is now partly supported by ESR, OSL, U/Th and amino acid datings (Miller and Mangerud, 1985; Molodkov, 1989; Sukhorukova, 1998; Mangerud et al., 1999; Astakhov and Svendsen, 2002).

Even though several authors suggested that the Late Quaternary transgression with boreal fauna was unique in the lowlands of the Barents and Kara Sea region (Sachs, 1953; Troitsky, 1975), this marine formation is not readily distinguished from older (and possibly younger) marine events, which also produced similar assemblages. In this regard it should be mentioned that several sequences on the North Siberian Lowland conventionally labeled as sediments of the last (Kazantsevo) interglacial, contain the extinct species *Cyrtodaria jenisseae (angusta)*, *Astarte invocata* and *Astarte leffingwelli* (Kind and Leonov, 1982). Sachs (1953) contended that *Cyrtodaria jenisseae* survived until the Eemian time, although the present view finds this unlikely. Finds of boreal marine fauna are also known from Middle Pleistocene sequences of the Yenissei River valley (Zubakov, 1972). On the Pechora Lowland a marine formation with a boreal mollusk fauna that also includes *Cyrtodaria angusta* has been found in boreholes below sea level, beneath the Saalian (Vychegda) till, as well as in natural exposures 50–70 m a.s.l. (Zarkhidze, 1972). Two marine formations with boreal fauna deposited by the Boreal (s. stricto) and the Northern transgressions have been described in the Arkhangelsk region many times since the 1930s (Yakovlev, 1956; Biske and Devyatova, 1965). We therefore think it is very likely that the glaciated areas along the Kara Sea and Barents Sea were affected by several transgressions that are occasionally confused in stratigraphic interpretations.

4.2. Marine inundation of the Siberian mainland during the Early Weichselian

In the lowland of West Siberia and southern Taimyr there are some thick sequences of marine sediments that traditionally have been related to an Early–Middle Weichselian marine event called the "Karginsky transgression" (Andreyeva, 1980; Kind and Leonov, 1982). These strata contain a typical Boreal mollusc fauna, and the pollen composition suggests a forest environment when the sediments accumulated. It has now been demonstrated that the stratotype of the Karginsky formation in the Yenissei River valley is covered by till and that it most likely represents the Kazantsevo (Eemian) interglacial (Arkhipov, 1989; Astakhov, 2001). There is also reason to believe that some of the key sections of boreal marine sediments on western Taimyr that traditionally have been ascribed to the Karginsky interval belong to the Kazantsevo (Eemian) interglacial (Troitsky, 1975; Troitsky and Kulakov, 1976; Sukhorukova, 1999). Therefore we do not accept previous descriptions of the "Karginsky formation" as evidence of a Weichselian marine transgression.

However, our geological observations from the Taimyr Peninsula south of the Byrranga Mountains do indicate that the sea flooded this region shortly after the last (i.e. Early Weichselian) glaciation of this area. Deltaic marine sediments and beaches, not covered by till, show that central Taimyr was affected by a marine inundation up to a level of around 100 m a.s.l. (Figs. 4 and 5) (Möller et al., 1999). The mollusc fauna from these strata reflect a marine environment not much different from the present conditions along the Kara Sea coast and both ESR and OSL dates from these sections yield younger ages (96–70 ka) than "Boreal Transgression" sediments. We therefore conclude that the sea inundated the glacioisostatic depression produced by the preceding Early Weichselian ice sheet advance. This marine event may correspond with the *Portlandia* strata in the northern part of the West Siberian Lowland and on Yamal, that have been recorded up to around 30 m a.s.l. (Troitsky and Kulakov, 1976; Astakhov, 1992) (Fig. 6). It is unclear whether the sea also at that time covered the coastal areas along the Barents Sea coast.

4.3. Marine transgression in the Barents Sea region during the Middle Weichselian

Tidal sediments of early Middle Weichselian age have been described from sediment sections near the mouth of the Mezen River in the Arkhangelsk region (Kjær et al., 2003). The marine sediments, which are sandwiched between two till beds, have been OSL dated to around 60–50 ka and are found up to a level of 20–30 m a.s.l. (Figs. 9 and 10). Based on recent investigations we suspect that the sediments underlying the Markhida

Moraine in the Pechora Lowland is also of marine origin and not fluvial as was previously thought by Mangerud et al. (1999). A series of OSL dates from this sequence yield ages in the range 70–56 ka (Figs. 7 and 8). Possibly this unit should be correlated with the tidal sediments at Mezen that has been dated to around 55 ka (Kjær et al., 2003). Marine shorelines of this age have so far not been found on the Russian mainland to the east of the White Sea, although some authors suggested a Weichselian transgression (e.g. Lavrushin et al., 1989). Marine terraces of Middle Weichselian age were described from several of the Arctic islands in the Barents and Kara Sea region (Sachs, 1953; Bolshiyanov and Makeyev, 1995; Mangerud et al., 1998; Forman et al., 1999a, b; Zeeberg, 2001).

4.4. The Late Weichselian transgression—a marine event confined to the northern and western sector of the Barents Sea region

Raised shorelines of Late Weichselian age show that the sea inundated the lowland areas of Svalbard and Franz Josef Land immediately after deglaciation, defining a glacioisostatic uplift dome centered over the NW Barents Sea (Landvik et al., 1998; Forman et al., 2004). There are also raised shorelines along the Kola Peninsula, but they probably reflect the uplift dome of the Scandinavian Ice Sheet.

No raised strandlines from late glacial or early Holocene times are proven to exist on the northern margin of the continent east of the White Sea. From the occurrence of ice wedges, aeolian sediments and submerged peat deposits it appears that sea level must have been lower than at present during the whole the Late Weichselian and early Holocene. From the records in the Pechora Sea it is inferred that the relative sea level during this period fell to a present water depth of at least 50–70 m after the LGM, perhaps as late as the Early Holocene (Gataullin et al., 2001). On the Kara Sea shelf the sea level was also low at this time. Fluvial channels on the seafloor indicate that the rivers Ob and Yenissei were flowing hundreds of kilometres further to the north at a time when much of the shelf was subaerially exposed and underlain by permafrost (Polyak et al., 2002; Stein et al., 2002). The present water depths in the mouths of the submerged channels in the northeastern Kara Sea indicate that the contemporaneous sea level was more than hundred meters lower than today. Even though the postulated river valleys are not well dated, it seems likely that they formed either during the LGM or shortly after. During the Early Holocene the sea level was 30–50 m lower than today outside the Ob and Yenissei estuaries (Stein et al., 2002). This is not much different from the Laptev Sea shelf, where Bauch et al. (2001) estimated that the 50 m isobath was inundated a few hundred years after the Holocene transition at 11.5 cal. ka.

From the available sea level data we infer that there was no transgression above present sea level along the southern and eastern flanks of the Barents-Kara Ice Sheet in connection with the Late Weichselian glaciation. In the southeastern Pechora Sea there seems to have been modest glacioisostatic uplift following deglaciation, whereas much of the Kara Sea region may have subsided. As will be discussed below, this pattern reflects a more restricted ice sheet extent during the Late Weichselian, as compared to the preceding glaciations.

5. Synthesis of the ice sheet history

Judged from the geological records it appears that major glaciations affected the Eurasian Arctic at least four times during the last 160,000 years. Based on our investigations and on a review of previous work, we conclude that this happened during the Late Saalian (before 130 ka) and three times in the Weichselian; at 90–80 ka, 60–50 ka, and 20–15 ka. We have drawn tentative limits showing the maximum ice sheet extent for each of these glaciations (Figs. 13–16). However, the Scandinavian Ice Sheet limits outside Russia and the glacial limits in Great Britain and Ireland rely exclusively on published data from various sources. To a large extent we have utilized map reconstructions of glacial limits in different parts of Europe (e.g. Ehlers and Gibbard, 2004). The LGM limit and the Saalian maximum (Drenthe advance) are fairly well known in most areas of the European mainland. However, major uncertainties exist for the Weichselian glaciations that terminated inside the mapped LGM limit. Because of these uncertainties we have not drawn any limits of the ice sheet over Britain prior to LGM. It should also be noted that the maximum extent during the various glaciations was not necessary attained at the same time in various regions.

5.1. The Late Saalian glaciation (160–130 ka)

5.1.1. The ice sheet extent in northern Russia and Siberia

Astakhov (2004) discusses the Late Saalian glaciation of the Russian Arctic (Fig. 13). The only feasible explanation for the high Eemian sea levels along the northern margin of the continent is a strong glacioisostic depression. Thus, the Boreal Transgression substantiates the hypothesis that a huge coherent ice sheet reached far south on the continent shortly before the Eemian. It is noteworthy that the marine inundation during this interglacial affected an area that was much larger than during the younger transgressions, suggesting that the Late Saalian ice sheet complex was more extensive and perhaps longer lasting than those of the Weichselian.

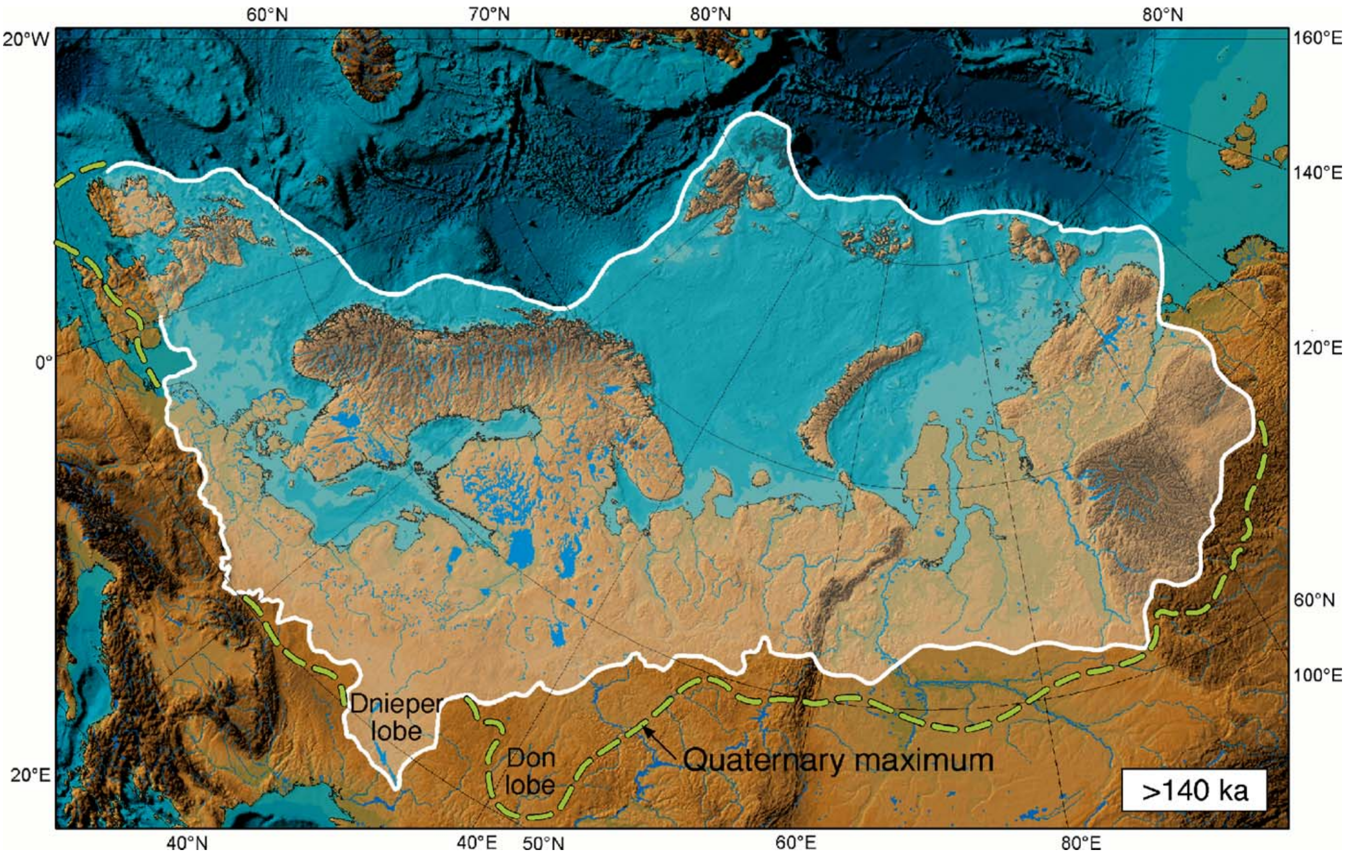

Fig. 13. A reconstruction of the maximum ice-sheet extent in Eurasia during the Late Saalian (c. 160–140 ka), based on review of published material. The ice sheet extent in Russia and Siberia during the Saalian is discussed further by Astakhov (2004). The corresponding ice limit on the European continent further west follows the Drenthe line (cf. Ehlers et al., 2004) and the boundary of the Dnieper lobe (cf. Velichko et al., 2004). The approximate maximum extent of the Quaternary glaciations (drift limit) is indicated by a dotted line. Notice that some other ice sheets and glaciers that existed at this time (Iceland, Greenland, Alps and other places) are not shown on this reconstruction.

The southernmost glaciation limit in West Siberia is located at 59°N, i.e.1400 km to the south of the Arctic coastline (Zarrina et al., 1961; Krasnov, 1971; Ganeshin, 1973). In Europe, the huge Dnieper and Don ice lobes that reached south of 50°N represent the maximum ice sheet extent. According to the traditional view the Dnieper lobe in Ukraine, the Don lobe in Central Russia, and the Samarovo glaciation in Siberia were all considered to be of Early Saalian age (Yakovlev, 1956; Arkhipov et al., 1986). However, new evidence suggests that the Don lobe belongs to a much older glaciation of Cromerian age (MIS 12 or 16) (Velichko et al., 2004). The main Saalian ice advance in Central Russia, that deposited the Moscow till, is now ascribed to MIS 6 (Shik, 1995). In Siberia this ice advance is thought to be represented by the Taz ice sheet, whose margin stood only 100–400 km north of the drift limit (Arkhipov et al., 1986; Arkhipov and Volkova, 1994).

In Europe outside Russia, the maximum Saalian glaciation was attained during the Drenthe advance that has been mapped across the continent (Ehlers et al., 2004). A slightly younger ice advance occurred during the Warthe stage when the ice front terminated 100–200 km further to the north. Much of the North Sea Basin seems to have been ice covered during the Late Saalian and in Britain the northern tip of East Anglia (Norfolk) seems to have been covered (Clark et al., 2004). However, the ice front position across the British Isles during the Saalian glaciation is not yet clear.

5.1.2. *Did a large ice shelf in the Arctic Ocean fringe the Late Saalian ice sheet?*

There is good evidence to suggest that the ice front reached the shelf break along the Norwegian Sea and the Arctic Ocean during the Late Saalian (Mangerud et al., 1998; Knies et al., 2001). Mapped areas on the mid Arctic Ocean Lomonosov Ridge crest show large-scale erosion to depths of 1000 m below present sea level (Jakobsson, 1999). That has been attributed to ice grounding (Polyak et al., 2001), or alternatively to ice berg grounding in combination with currents (Jakobsson et al., 2001). This raises the possibility of a grounded ice sheet fringed by a thick marine ice shelf that grew into the central Arctic Ocean (Fig. 13). Marine sedimentation above the erosional unconformity commenced during MIS 5e and thus places the timing for the ice grounding on the Lomonosov Ridge to MIS 6 (Jakobsson et al., 2001), the Late Saalian. The directions of the mapped glaciogenic erosional features on the Lomonosov Ridge and the redeposition of eroded material indicate an ice flow from the Barents-Kara Sea area (Polyak et al., 2001). However, these pieces of evidence do not necessarily imply a huge coherent Arctic Ocean floating ice shelf in analogy with the hypothesis by Mercer (1970) and Hughes et al. (1977). An alternative scenario may be that the Late Saalian Barents-Kara Ice Sheet produced huge deep keeled icebergs that drifted with the permanent Arctic sea ice and grounded on the Lomonosov Ridge crest. Evidence from deep icebergs in the Arctic Ocean has previously been found on the Yermak Plateau in the form of ploughmarks mapped down to more than 850 m below the present sea level (Vogt et al., 1994). However, the age(s) of those ploughmarks has yet to be determined.

5.2. *Early Weichselian glaciation (100–80 ka)*

5.2.1. *The maximum Weichselian ice sheet extent on mainland Russia*

In our reconstruction the outermost belt of topographically expressive moraines between southern Taimyr and the Pechora Lowland defines the maximum ice sheet extent after the last interglacial (Figs. 2 and 14). This ice sheet merged with a large ice cap covering the Putorana Plateau in Siberia. Probably highlands and islands fringing the Kara and Barents seas acted as ice sheet nucleation areas, growing ice caps that later on confluenced to form a coherent Barents-Kara Ice Sheet. Inside the proposed maximum limits on the Eurasian mainland there are many sites with reported Eemian interglacial marine sediments that are covered by till and, in many cases, by deposits with fossil glacier ice. South of these moraines the topography is far more subdued, and the youngest till is normally buried under non-glacial terrestrial and, in rare cases, by interglacial

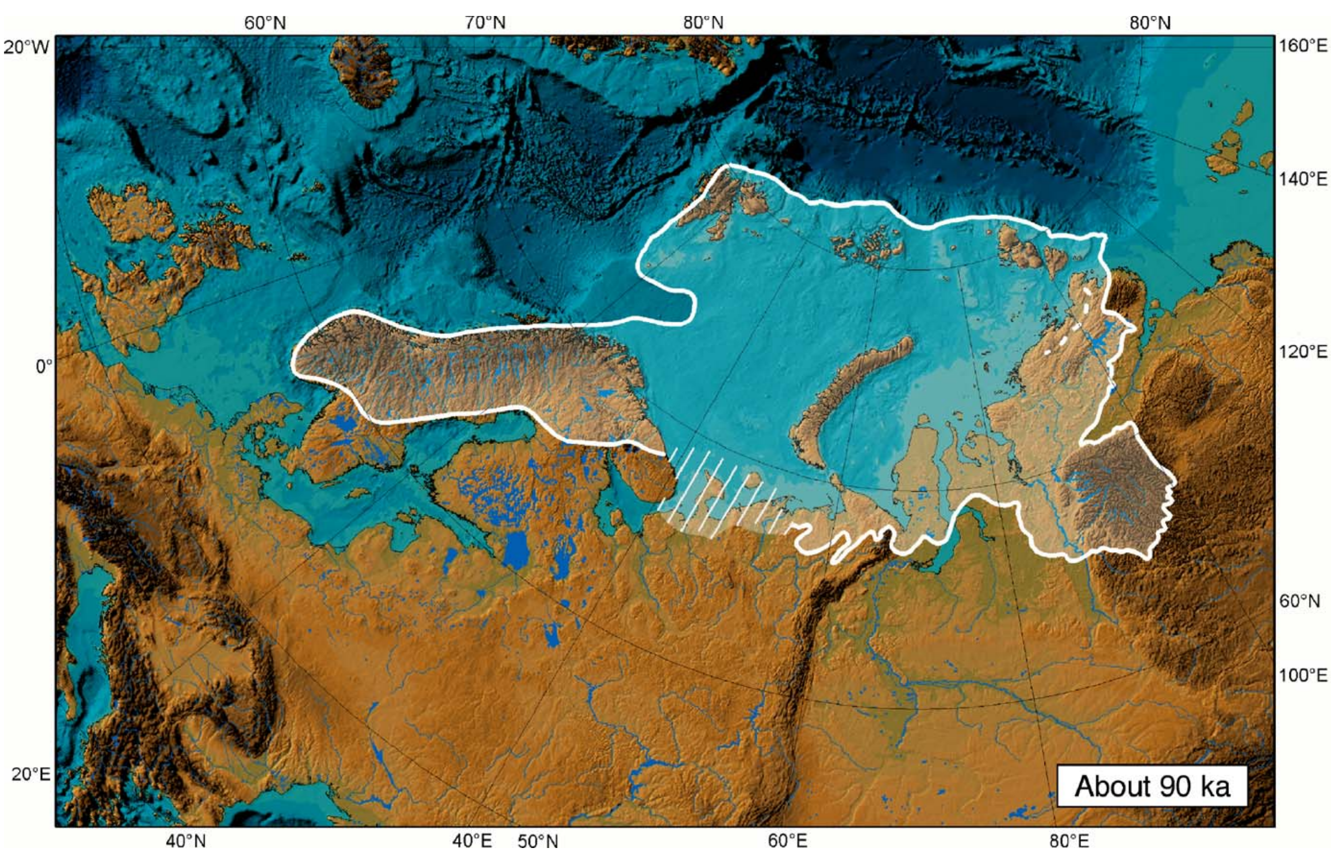

Fig. 14. A reconstruction of the Eurasian ice sheet extent during the Early Weichselian glacial maximum (90–80 ka). The reconstructed ice sheet limit in European Russia, Siberia and on the adjacent sea floor is to a large extent based on this study. The ice front position between the Pechora Lowland and the Kola Peninsula has not yet been defined and the uncertainties are indicated by the hatched field. The limit along the northern margin of the Barents Sea shelf is based on various sources (cf. Mangerud et al., 1998; Svendsen et al., 2004). The inferred ice extent around Scandinavia is modified from Andersen and Mangerud (1989), Lundqvist (1992, 2004) and Mangerud (2004). The suggested ice limit across Finnish Lapland is based on various sources (e.g. Hirvas, 1991; Helmens et al., 2000). The dashed line on northern Taimyr marks the retreat stage at the North Taymyr ice-marginal zone (NTZ) around 80 ka (cf. Fig. 5). The glacier distribution over the British Isles, Iceland, Greenland, Alps and some other mountain areas are not shown on this reconstruction. Notice that this reconstruction is only showing the ice limit and not the corresponding ice dammed lakes (cf. Mangerud et al., 2004).

marine deposits. The ice sheet expanded far south of the Byrranga Mountains, which implies that the ice was more than a thousand meters thick at the NW coast of Taimyr at the glacial maximum. Both flanks of the Polar Urals were bypassed from the north by flat lobes, and from the elevation of lateral moraines the ice surface at the northern tip of the Urals was around 600 m.a.s.l. The ice limit corresponding to this glaciation is mapped across the eastern part of Pechora Lowland but, as will be discussed below, the continuation further to the west is more uncertain.

The age of this glaciation is beyond the range of the radiocarbon method. Our OSL and ESR dating results substantiate the correlation of moraines between Siberian and European Russia. The dates obtained from the pro-glacial deltaic sediments in the Taimyr Lake basin indicate a minmum age of around 90–80 ka for the glacial maximum (Fig. 5). In the Pechora Lowland a large number (29) of OSL dates on beach sediments from the ice-dammed Lake Komi in front of the Barents-Kara Ice Sheet gave ages in the range 100–80 ka with a weighted mean of 82 ± 1.2 ka (Fig. 8) (Mangerud et al., 2001, 2004). Mainly from these lake dates we conclude that the ice sheet blocked the northbound drainage in that part of the continent for a short-lived period at about 90–80 ka (MIS 5b). Fluvial terraces incised into the floor of Lake Komi suggest that a normal fluvial drainage was resumed not later than around 80 ka, which is a minimum age for the deglaciation.

In the Arkhangelsk region the oldest dated signs of a Weichselian glaciation are reflected in till covered glaciofluvial and glaciolacustrine sediments along the river Pyoza in the Mezen drainage basin that accumulated around 100–90 ka (Fig. 10) (Houmark-Nielsen et al., 2001). These sediments may represent the same glacial event as discussed above, but the ice sheet configuration at this time remains uncertain. Mangerud et al. (2004) postulate that the ice front blocked the mouth of the White Sea during the glaciation, but this remains to be confirmed in the Arkhangelsk region.

5.2.2. The ice limit on the continental shelves

The ice sheet configuration on land implies that a major ice dispersal center existed over the Kara Sea. Most likely the Barents-Kara Ice Sheet terminated at or close to the northern margin of the continental shelf along the Arctic Ocean (Fig. 14). This configuration is supported by records of ice rafted debris (IRD) in sediment cores to the north of Severnaya Zemlya suggesting that a calving ice front existed close to this area around 90 ka (Knies et al., 2000). As was discussed above, data from the Pechora Lowland and the Kola Peninsula imply that the seafloor off the southern Barents Sea coast was glaciated, but the position of the ice limit is uncertain. It is also unclear if the southwestern Barents Sea was affected by this glaciation. So far only one till bed has been identified above the last interglacial in the outer part of the Bear Island Through (Sættem et al., 1992; Laberg and Vorren, 1995). Considering that there are hardly any data from the Barents Sea that can be used to define the western ice-sheet margin we have drawn the limit across the shelf between the Norwegian mainland and Svalbard as it was defined in the model simulation by Siegert et al. (2001).

Possibly, the Early Weichselian glacial maximum corresponds with the first post-Eemian ice advance that was recorded on Svalbard in the NW Barents Sea (Mangerud et al., 1998). Mangerud et al. (1998) suggested, however, that this ice advance occurred during MIS 5d (110 ka), whereas according to our chronology the maximum extent further to the east occurred during MIS 5b (90 ka). This age difference may be real, but it may also be an artifact of dating uncertainties. Considering that such a large glaciation affected the Kara Sea and the southeastern Barents Sea we find it most likely that also this ice advance affected the Svalbard region.

5.2.3. A restricted ice sheet over Scandinavia

There is a general consensus that the Scandinavian Ice Sheet was much smaller during the Early Weichselian compared with the Late Weichselian glacial maximum (Andersen and Mangerud, 1989; Lundqvist, 1992, 2004; Mangerud, 2004). At the peak of the first major ice advance the ice sheet covered the Norwegian mainland, but southern Sweden remained ice-free (Fig. 14). Mainly based on our review of published data we believe that also most of Finland remained ice free during the Early Weichselian (Hütt et al., 1993; Nenonen, 1995), but that Finnish Lapland and the northern parts of Russian Karelia were ice covered at around 90 ka (Hirvas, 1991; Helmens et al., 2000). The eastern ice margin was probably located near the western coast of Finland, trending northeastwards across Finnish Lapland.

Recent investigations on the southern part of the Kola Peninsula suggest that the Scandinavian Ice Sheet was located close to the northwestern bay of the White Sea Basin during the Early Weichselian glaciation (Fig. 14). There is no indication that the ice sheet advanced into the Dvina and Vaga river valleys on the eastern side of the White Sea, where only a Late Weichselian till have been found above Eemian strata (Devyatova, 1982; Larsen et al., 1999; Lyså et al., 2001; Lunkka et al., 2001b). The same conclusion was reached for the NW Russian Plain further to the south (Lunkka et al., 2001b).

5.3. Middle Weichselian glaciation (60–50 ka)

5.3.1. A readvance of the Barents-Kara Ice Sheet onto the mainland

A regrowth of the ice sheet occurred during MIS 4, leading to an ice advance that terminated on the Russian

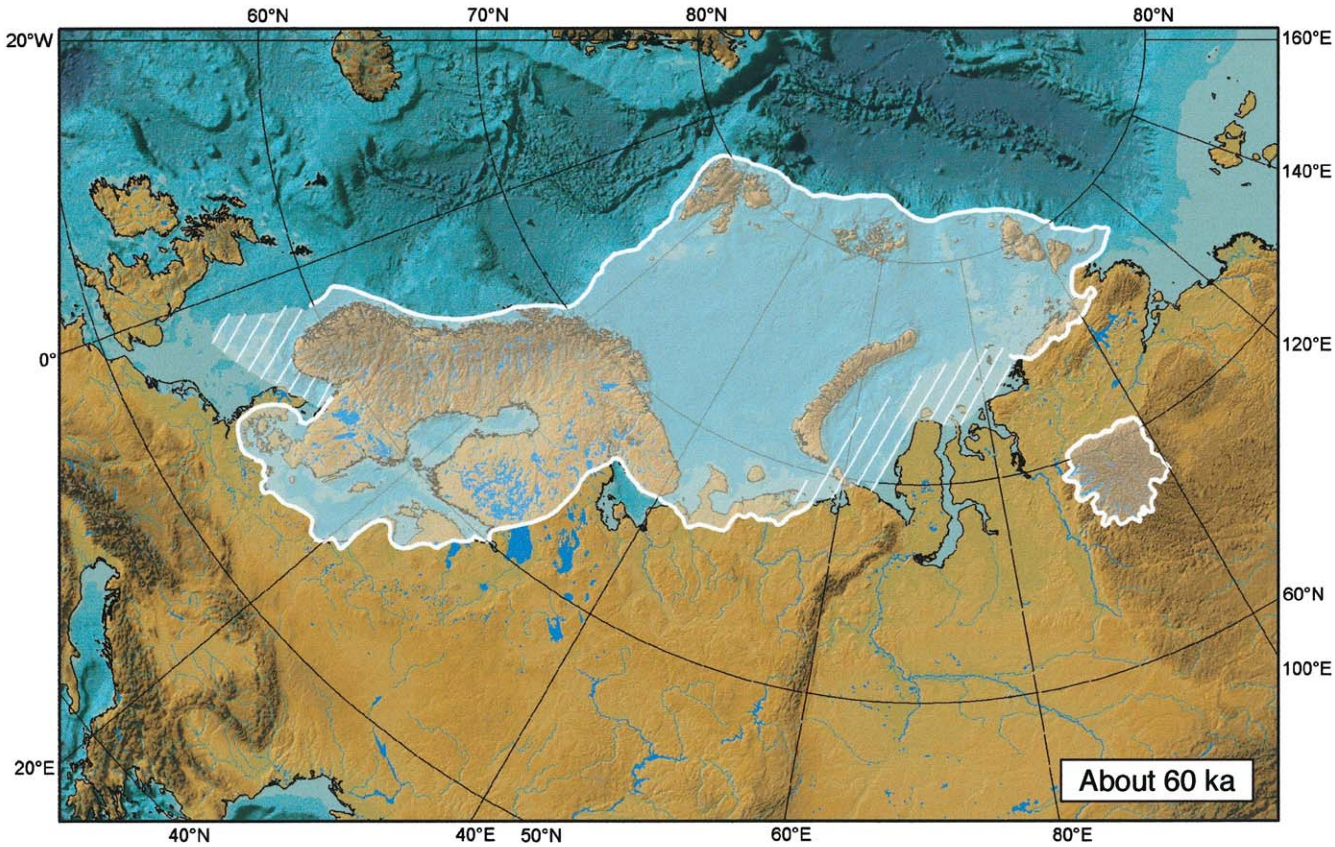

Fig. 15. A reconstruction of the Eurasian ice sheet extent during the Middle Weichselian glacial maximum (60–50 ka). The reconstructed ice sheet limit in European Russia, Siberia and on the adjacent sea floor is to a large extent based on this study. The ice margin across the southern Kara Sea shelf is tentative and the uncertainty is indicated by the hatched field. The ice limit on the Barents Sea shelf is based on various sources (cf. Mangerud et al., 1998). The inferred ice limits around Scandinavia is modified from Andersen and Mangerud (1989), Lundqvist (1992), Houmark-Nielsen (1999) and Mangerud (2004). Probably much of the shelf between the British Isles and southern Norway was glaciated at this time (Carr, 2004), but the ice sheet configuration is uncertain. The ice limit around the Putorana Mountains shows the Norilsk Stage (Kind, 1974; Isayeva, 1984) that was previously thought to be of Late Weichselian age. Notice that the glacier distribution over the British Isles, Iceland, Greenland, Alps and other mountain areas are not shown on this reconstruction. The inferred ice dammed lakes that correspond with the Barents-Kara Ice Sheet are shown in the paper by Mangerud et al. (2004).

mainland during an early stage of the Middle Weichselian (Fig. 15). In the east this glaciation affected a much smaller area of Siberia than during the Early Weichselian, whereas in the White Sea and the Arkhangelsk region this ice sheet had a larger extent.

Houmark-Nielsen et al. (2001) and Kjær et al. (2001, 2003) infer that the most extensive Weichselian till bed in the Mezen drainage basin (Figs. 9 and 10), the Yolkina till, was deposited around 75–65 ka by a large terrestrial ice cap centered over the Timan Ridge that terminated along the Syurzi Moraine (Demidov et al., 2004) (Fig. 2). However, the "QUEEN team" who has investigated the Pechora drainage area could not find any traces of the postulated ice cap on the Timan Ridge. From geomorphological considerations (Maslenikova, 2002; Nikolskaya et al., 2002) they infer that the glaciation which corresponds to the Syurzi Moraines was deposited by the Barents-Kara Ice Sheet and not by a terrestrial ice cap.

Regardless of the disagreement about the configuration of the abovementioned Syurzi/Yolkina glaciation (75–65 ka), it seems clear that the Barents-Kara Ice Sheet inundated the Mezen drainage basin two times during the period between 65 and 50 ka (Figs. 9 and 10). The first ice advance is reflected by the Cape Tolstik till that was deposited by a south-flowing ice sheet at around 60 ka. This till is overlain by tidal sediments that have been found up to 30–40 m a.s.l. reflecting a significant isostatic depression during ice recession. The overlying till (Viryuga till) is related to the Pyoza Moraine which is confidently correlated with the Markhida Moraine across the Pechora River. The OSL chronologies (Figs. 8 and 10) from both regions suggest that the Pyoza-Markhida endmoraine belt was deposited between 60 and 50 ka, perhaps close to 50 ka (Mangerud et al., 1999; Kjær et al., 2003). It is inferred that this ice margin east of the Pechora River continues northeastwards on the continental shelf, but its actual limit remains to be validated (Fig. 2).

In North Siberia a Middle Weichselian glaciation is associated with the North Taimyr ice-marginal zone (NTZ) (Figs. 2, 4 and 5). OSL dates from glaciolacustrine and glaciofluvial sediments that accumulated along and in front of these moraines have ages in the interval 70–54 ka (Alexanderson et al., 2001), roughly similar to the inferred age of the Middle Weichselian ice advance in the European Arctic. We therefore postulate that the NTZ also reflects a glacial event around 60 ka.

From the vast lowland areas between Taimyr and the Pechora River there are no convincing geological data to suggest any Middle Weichselian ice sheet advance (Figs. 2 and 6). As discussed below we therefore think that the ice margin was located somewhere on the floor of the Kara Sea (Fig. 15).

5.3.2. *The ice sheet configuration on the adjacent continental shelves*

Previous investigations have concluded that Svalbard and the NW Barents Sea shelf was affected by a major glaciation during the Middle Weichselian, culminating around 65–60 ka (MIS 4). The ice front at this time terminated near the western and northern shelf margins (Mangerud et al., 1998). At about this time also the northern Kara Sea shelf and Severnaya Zemlya was covered by a major ice sheet that extended to the shelf east thereof (Knies et al., 2000; Raab et al., 2003).

The location of the ice sheet margin further south is more problematic. We tentatively draw the southern limit on the shallow sea floor off the coastline in West Siberia and postulate that it crossed the coastline in the Pechora Lowland where it merged with the Markhida Moraine (Figs. 2 and 15). Probably the ice front crossed the entrance to the White Sea Basin (Demidov et al., 2004), which would imply that there was no ice-free corridor on the seafloor along the Kola Peninsula. It remains unknown if the Barents-Kara Ice Sheet merged with a local ice cap over the Kola Peninsula during this glaciation (Fig. 15).

In most areas the early Middle Weichselian ice sheet advance was followed by a comprehensive deglaciation that started around 50 ka. Raised marine sediments of Middle Weichselian ages have been found on Svalbard (Mangerud et al., 1998), Severnaya Zemlya (Bolshiyanov and Makeyev, 1995; Raab et al., 2003), Novaya Zemlya (Forman et al., 1999b) and Vaigatch Island (Zeeberg, 2001) reflecting strong isostatic rebound. Radiocarbon dates of shells in sediment cores from the seafloor off the Pechora Lowland indicate that the SE part of the Barents Sea shelf was ice free not much later than 40 ka (Polyak et al., 2000). Thick prodeltaic sediments of Middle Weichselian age have been mapped in front of the Pechora River (Gataullin et al., 2001).

5.3.3. *Did the Scandinavian Ice Sheet reach Russia?*

A regrowth of the Scandinavian Ice Sheet occurred during the Middle Weichselian, when a major ice lobe filled the Baltic Basin and advanced to its maximum position in southern Denmark (Houmark-Nielsen, 1989, 1999). At this time the ice sheet was more extensive than during the Early Weichselian, and seems to have covered most, if not all of Finland (Fig. 15). Our field investigations suggest, however, that the Middle Weichselian Scandinavian Ice Sheet did not reach as far east as the Late Weichselian one. We assume that the ice limit was located near the Finnish-Russian border. However, the Kola Peninsula was probably glaciated and the Scandinavian Ice Sheet probably reached into the northern White Sea basin.

5.4. *Late Weichselian glacial history (25–10 ka)*

5.4.1. *The Barents-Kara Ice Sheet—smaller than the preceding glaciations*

Previous investigations have demonstrated that a major ice dome formed over the north-western Barents Sea shelf and eventually expanded to the western and northern shelf margins during the Late Weichselian (Lubinski et al., 1996; Polyak et al., 1997; Landvik et al., 1998; Kleiber et al., 2000). From the occurrence of debris flow sediments and glaciomarine diamictons on the continental slope, Kleiber et al. (2000) infer that the ice sheet reached the northern shelf break as early as 23 ka. According to Landvik et al. (1998) the ice front was located along the western shelf break between 19 and 15 ka.

It has been a long-standing discussion whether the Barents-Kara Ice Sheet expanded onto mainland Russia and Siberia during the Late Weichselian. Many well-dated sedimentary sequences covering this interval are described from critical areas along the northern margin of the continent (e.g. Mahaney, 1998; Vasil'chuk and Vasil'chuk, 1998; Astakhov et al., 1999; Forman et al., 1999a; Mangerud et al., 1999; Alexanderson et al., 2002; Möller et al., 1999; Raab et al., 2003;). None of the sequences are covered by till, and yet all predate the LGM. The deposits consist mostly of aeolian or lacustrine, easily deformable soft silt and fine sand. We emphasise that these formations show no sign of having been overridden by any ice sheet (Mangerud et al., 2001). At several sites, deposition of aeolian sediments and formation of ice wedges took place during the LGM time span. These observations imply that the Barents-Kara Ice Sheet did not cover these land areas during the LGM, with the exception of the northern fringe of the Taimyr Peninsula (Fig. 16) (Alexanderson et al., 2001, 2002).

Based on marine geological and geophysical data the LGM ice sheet limit has been identified on the sea floor off the mainland (Svendsen et al., 1999, 2004; Polyak

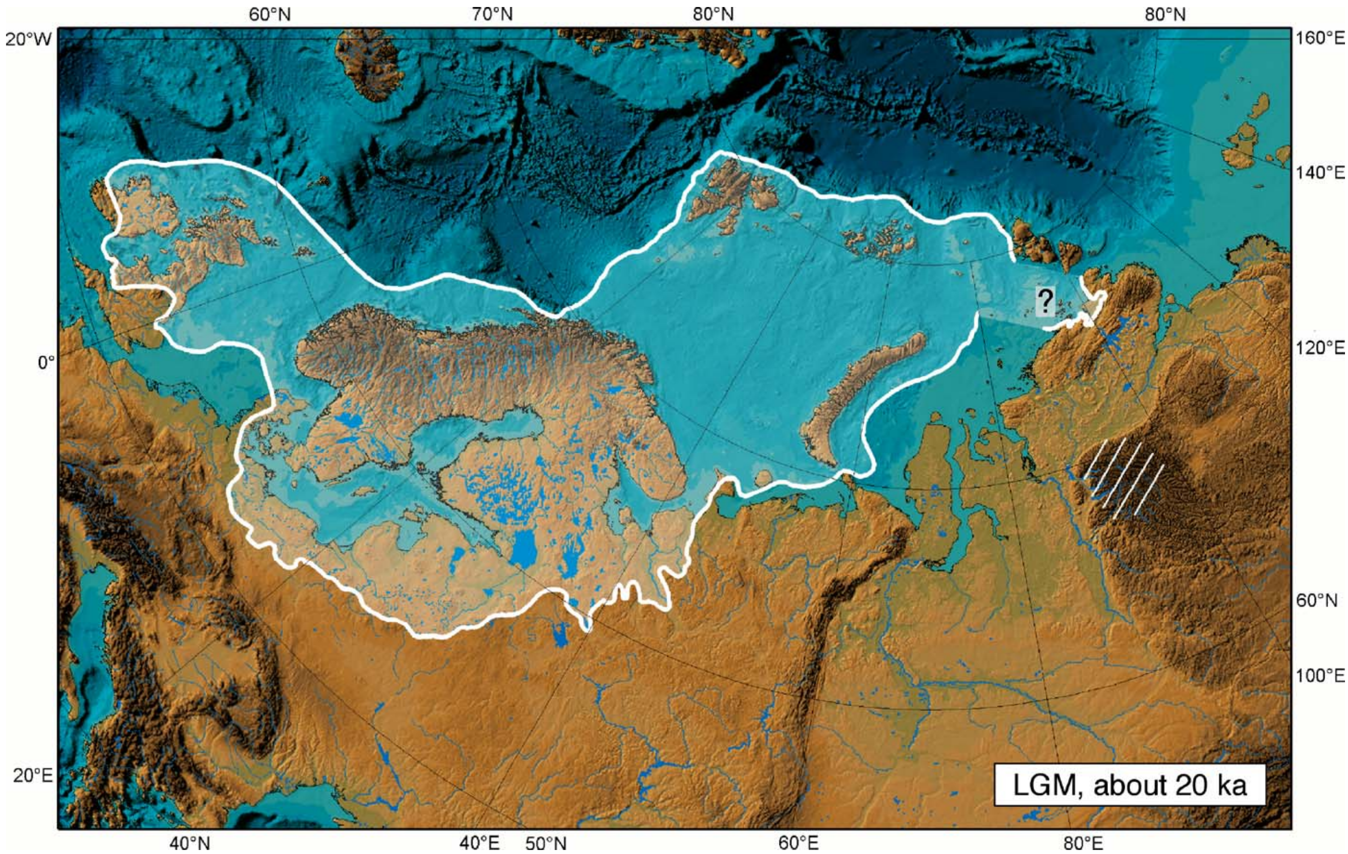

Fig. 16. A reconstruction of the Eurasian ice sheets at the Late Weichselian glacial maximum (LGM). The eastern limit of the Scandinavian Ice Sheet and the southern and eastern limit of the Barents-Kara Ice Sheet are to a large extent based on our own investigations. The northern and western ice sheet limit on the Barents Sea shelf is drawn according to the reconstruction by Landvik et al. (1998). The ice limits for the rest of Europe are taken from various sources (e.g. Ehlers and Gibbard, 2004). The presence of restricted valley glaciers on the Putorana Mountains is indicated by hatched lines. Notice that the glacier distribution over Iceland, Greenland, Alps and other mountain areas are not shown on this reconstruction.

et al., 2000, 2002; Gataullin et al., 2001; Stein et al., 2002). It is assumed that the southern flank of the ice sheet coalesced with the Scandianvian Ice Sheet near the northern tip of the Kanin Peninsula, but the exact boundary remains to be defined in the confluence zone (Fig. 16). In the Pechora Sea, further to the east, we believe the ice front reached the Kolguev Line, which depicts the southern extent of the Late Weichselian till on the Barents Sea shelf (Gataullin et al., 2001). In the southern Kara Sea the ice front was probably located along the southern and eastern margin of the Novaya Zemlya Through (Svendsen et al., 1999, 2004; Polyak et al., 2000). Further to the north the LGM limit has been mapped across the shallow shelf near the southern slopes of the St. Anna Through (Polyak et al., 2002; Stein et al., 2002). In general, the area on the proximal side of the inferred ice sheet limit is characterized by a rough morainic relief, whereas on the distal side the seafloor is graded and in places underlain by thick sequences of marine sediments not covered by till. Furthermore, incised river channels and the widespread occurrence of permafrost indicate that this area has been subaerially exposed at a time when the sea level was much lower than today.

Based on the record from Severnaya Zemlya it seems clear that the Barents-Kara Ice Sheet did not reach this archipelago and that local glaciers were probably even smaller than today (Makeyev et al., 1979; Bolshiyanov and Makeyev, 1995; Raab et al., 2003). Our investigations on the mainland suggest, however, that the NW coast of Taimyr was affected by a Late Weichselian ice advance directed from the continental shelf (Alexanderson et al., 2002). One possible interpretation is that the advancing ice formed part of the Barents-Kara Ice Sheet. In that case the ice sheet must have blocked the northbound drainage in West Siberia, as well as in the European part of the Russian mainland (Fig. 16). As discussed previously, however, aeolian sedimentation and growth of ice wedges during this time span exclude the possibiliy that a pro-glacial lake flooded the lowland areas along the Arctic coastline. Possibly the eroded channels on the Kara Sea shelf (Stein et al., 2002) contained rivers that flowed towards the Arctic Ocean during most of the LGM period. The ice advance that reached the NW-coast of Taimyr has been explained as a result of surging from the higher parts of the ice sheet at its Barents-Kara Sea interfluve north of Novaya Zemlya (Alexandersson et al., 2002). Accordingly, this event could have been very short-lived and the ice masses may have blocked the northward flow of water from the Yenissei and Ob rivers for only a brief interval. Traces of such a glacial surge from the west may actually correspond with some inferred ice marginal features on the shelf identified by Stein et al. (2002) and Polyak et al. (2002). Another, less likely possibility, is that the radiocarbon dates of the shells that were extracted from glacial ice on Taimyr are underestimating the real age of the mollusks and that the last ice advance that affected this area occurred during the foregoing Middle Weichselian glaciation. However, the earlier mentioned increase of sedimentation in the Taimyr Lake basin around 19 ka (Möller et al. 1999) suggest reverse drainage in the lower Taimyra and thus supports damming of the ice sheet in the north-west.

Apparently the Barents-Kara Ice Sheet started to recede from the northwestern shelf margin at around 15 ka (Landvik et al., 1998), when a distinct meltwater event is reflected in the oxygen isotope record (Landvik et al., 1998; Kleiber et al., 2000). The last remains of the Barents-Kara Ice Sheet were localized over the northern part of the Barents Sea region during the Younger Dryas, when isolated ice caps existed over Svalbard, Franz Josef Land and possibly Novaya Zemlya (Fig. 2) (Svendsen et al., 2004). The remaining ice caps melted away during the Early Holocene and during the Holocene climatic optimum the glacier coverage was probably significantly smaller than today (Svendsen and Mangerud, 1997).

5.4.2. *The Scandinavian Ice Sheet reached its maximum extent since the Late Saalian glaciation*

The investigations in the northwestern Russian Plain and in the Arkhangelsk Region reveal that the maximum extension of the Scandinavian Ice Sheet here since the Late Saalian glaciation occurred during the Late Weichselian (LGM) (Fig. 16). The inferred ice limit is recognized from a belt of fresh-looking moraines and hummocky landscapes with frequent lakes in the Vologda area east of Lake Onega (Gey and Malakhovsky, 1998; Lunkka et al., 2001b), and then stretch via the Nyandoma upland to the Vaga and Severnaya Dvina river valleys (Larsen et al., 1999; Demidov et al., 2004). In our opinion the ice sheet extent in the northern part of the Russian Plain was slightly more restricted than suggested in some previous reconstructions (Apukhtin and Krasnov, 1967; Krasnov, 1971). For example, according to our ice reconstruction the ice sheet did not reach the Rybinskoye Reservoir on the Upper Volga and Sukhona rivers. However, the ice limit defined by Lunkka et al. (2001b) broadly follows the ice marginal landforms mapped by the Russian Geological Survey (Krasnov, 1971) from the Valdai Hills to the Vaga valley in the north. To the north of the Dvina valley the eastern boundary of the Scandinavian Ice Sheet is not so well expressed, and we have not been able to trace the exact position of the maximum limit here. Probably it stretched along hummocky moraine belts on the Mezen and Kuloi water divide (Lavrov, 1991) into the Mezen Bay and then to the northwest shore of the Kanin Peninsula (Demidov et al., 2004). We conclude that Scandinavian ice filled the White Sea Basin and assume that the ice front reached the western coast of the Kanin Peninsula, where it coalesced with the Barents-Kara Ice Sheet on the continental shelf (Fig. 16). A separate ice dispersal center that was connected with the Scandinavian Ice Sheet, the Ponoy Ice Cap, was located on the eastern Kola Peninsula at this time.

During the LGM, large ice-dammed lakes flooded the river valleys in front of the ice margin. In the northwestern Russian Plain these interconnected lakes (Lake Sukhona, Lake Mologa Sheksna, and Lake Vaga) drained via the Volga River into the Caspian Sea. In the Arkhangelsk region meltwaters drained northwards along the ice margin, eastwards across the southern part of the Kanin Peninsula and further eastwards between the present landmass and the Barents-Kara Ice Sheet (Mangerud et al., 2004).

The timing of the LGM along the eastern flank of the Scandinavian Ice Sheet has previously been based on only two radiocarbon dates from organic sediments underneath the till, that provided ages of around 21.4 and 18.7 ka (Arslanov et al., 1970, 1971; Faustova, 1984). Our OSL dates of the ice marginal deposits yield ages of around 20–18 ka on the northwestern Russian Plain (Lunkka et al., 2001b) and around 17–15 ka in the Arkhangelsk area (Larsen et al., 1999). Even though OSL dates are not as precise as radiocarbon dates, the results obtained suggest that the maximum ice advance occurred a few thousand years later than along the western margin of the Scandinavian Ice Sheet where the ice advance culminated at around 22 ka (Sejrup et al., 1994; Larsen et al., 1999; Mangerud, 2004).

A series of radiocarbon dates from mammoth bones suggests that Finland was ice-free prior to the LGM, during the period 33–25 ka (Ukkonen et al., 1999). This would imply that the front of the Scandinavian Ice Sheet moved 1000 km southwards during only 7000–8000 years. Based on the dates from the ice marginal zone, Lunkka et al. (2001b) estimated that the ice sheet advanced more than 125 m per year during the Late Weichselian. The deglaciation seems to have started around 17–15 ka along the entire margin, and during the Younger Dryas the ice margin was located at the Saulpausselkä end moraines in Finland (Fig. 3).

5.5. Comparison between the Arctic Ocean record and the reconstructed ice sheet history

A compilation of the main sedimentological and isotopic results from a transect across the eastern and central Arctic Ocean (Spielhagen et al., 2004) is shown in Fig. 17. In the deep sea record two main depositional phases can be distinguished within the last 200 ka. The first phase was a long-lasting period between 185 and 135 ka (MIS 6) characterized by continuous high input of ice-rafted detritus (IRD). The second phase is the interval between 90 and 50 ka that include three separate IRD peaks. The clay mineral distribution in the layers with a high IRD content suggests a provenance from the Kara Sea or the western Laptev Sea (Spielhagen et al., 1997).

5.5.1. MIS 6 (180–130 ka)—the Late Saalian glaciation

The high IRD values during the MIS 6 correspond with the extensive Saalian glaciation when the Barents-Kara Ice Sheet grew far onto the Eurasian continent (Fig. 17). Because the IRD-rich strata rest directly on layers with a relatively high ^{10}Be content, identified as representing MIS 7, the enhanced IRD deposition is inferred to have started at the MIS 7/6 boundary (Spielhagen et al., 2004). We believe that most of the IRD were delivered by icebergs from the Siberian shelf margin suggesting that this glaciation lasted as long as 50,000 years, which to some extent may explain the large dimensions of the ice sheet complex. The termination of the high IRD input occurred at the transition to the Eemian interglacial (MIS 5e) at around 130 ka and corresponds with a strong meltwater signal, expressed by low oxygen and carbon isotope values of planktic foraminifers (Fig. 17). Considering the fact that the Barents-Kara Ice Sheet must have blocked the Ob and Yenissei Rivers (among others) during the Late Saalian we assume that the meltwater spike originated from the drainage of a large icedammed lake south of the ice sheet margin. As a matter of fact, there is evidence that such a lake extended over much of southern West Siberia during the Late Saalian (Arkhipov et al., 1995), but presently it is poorly dated.

5.5.2. MIS 5e–5c (130–95 ka)—limited ice rafting in the Arctic Ocean

During the Eemian (MIS 5e) and the first part of the Weichselian (115–90 ka) there was a low input of IRD, similar to Holocene values (Fig. 17). The sources may have been local ice caps on Arctic islands. Judged from the lithological composition some of the IRD may originate from the Canadian Arctic and/or North Greenland. From the high concentration of planktic foraminifers and the presence of coccoliths in the Lomonosov Ridge cores (Spielhagen et al., 2004), it is inferred that seasonally open waters existed in the eastern and central Arctic Ocean during MIS 5e and 5c.

5.5.3. MIS 5b (95–85 ka)—the first major ice advance during the Early Weichselian

The influx of IRD increased markedly between 90 and 80 ka (Fig. 17). This peak is not clearly visible in all sediment cores (e.g. PS51/038-4 from the Alpha Ridge and 96/12-1pc) (Jakobsson et al., 2001), but is very pronounced in higher-resolution cores from the Morris Jesup Rise (PS2200) and from the Lomonosov Ridge (PS2185) (Spielhagen et al., 1997). In the latter core this IRD peak occurs between two coccolith-bearing horizons that most likely correspond with MIS 5c and 5a, i.e. the IRD-peak dates from MIS 5b. The Early Weichselian ice sheet that terminated on the continent around 90–80 ka, may be the source for this IRD horizon. The planktic stable isotope records shows a pronounced freshwater peak at this interval, but significantly weaker than during the Late Saalian deglaciation (MIS6/5e). Possibly this event corresponds to the drainage of some of the ice-dammed lakes that existed to the south of the Early Weichselian ice sheet (Mangerud et al., 2001, 2004) and thus date the end of this glaciation. A weaker signal than during the preceding deglacation may theoretically be explained by a different routing of glacial meltwater, perhaps much of the water drained across the Barents Sea shelf and into the Norwegian Sea.

5.5.4. MIS 5a (85–72 ka)—another Early Weichselian ice advance?

The sediments above the IRD layer discussed above reflect a temporary return of planktonic foraminifera and coccoliths, suggesting an interval with seasonally open waters during MIS 5a (Jakobsson et al., 2001; Spielhagen et al., 2004). Following this period there is another phase with a high IRD input that has an age around 78–72 ka (Fig. 17). In three cores (PS2185, PS2200, and 96/12-1pc) where this IRD peak is clearly outstanding, it has a very characteristic shape. The IRD input started abruptly and decreased gradually from the peak level. The upper part of the IRD peak is associated with minor meltwater spikes in the planktic isotope records. A high smectite content indicates a provenance from the Kara Sea shelf or western Laptev Sea region. The timing of this signal may correspond to the final retreat of the Early Weichselian Barents-Kara Sea Ice Sheet from the NW coast of the Taimyr Peninsula and thus with emptying of the large ice-dammed lakes in the southern Kara Sea basin and in the West Siberian Lowland.

5.5.5. MIS 4–3 (72–25 ka)—the Middle Weichselian

Following the inferred deglaciation signal at around 78 ka the foraminifer abundances show an upward

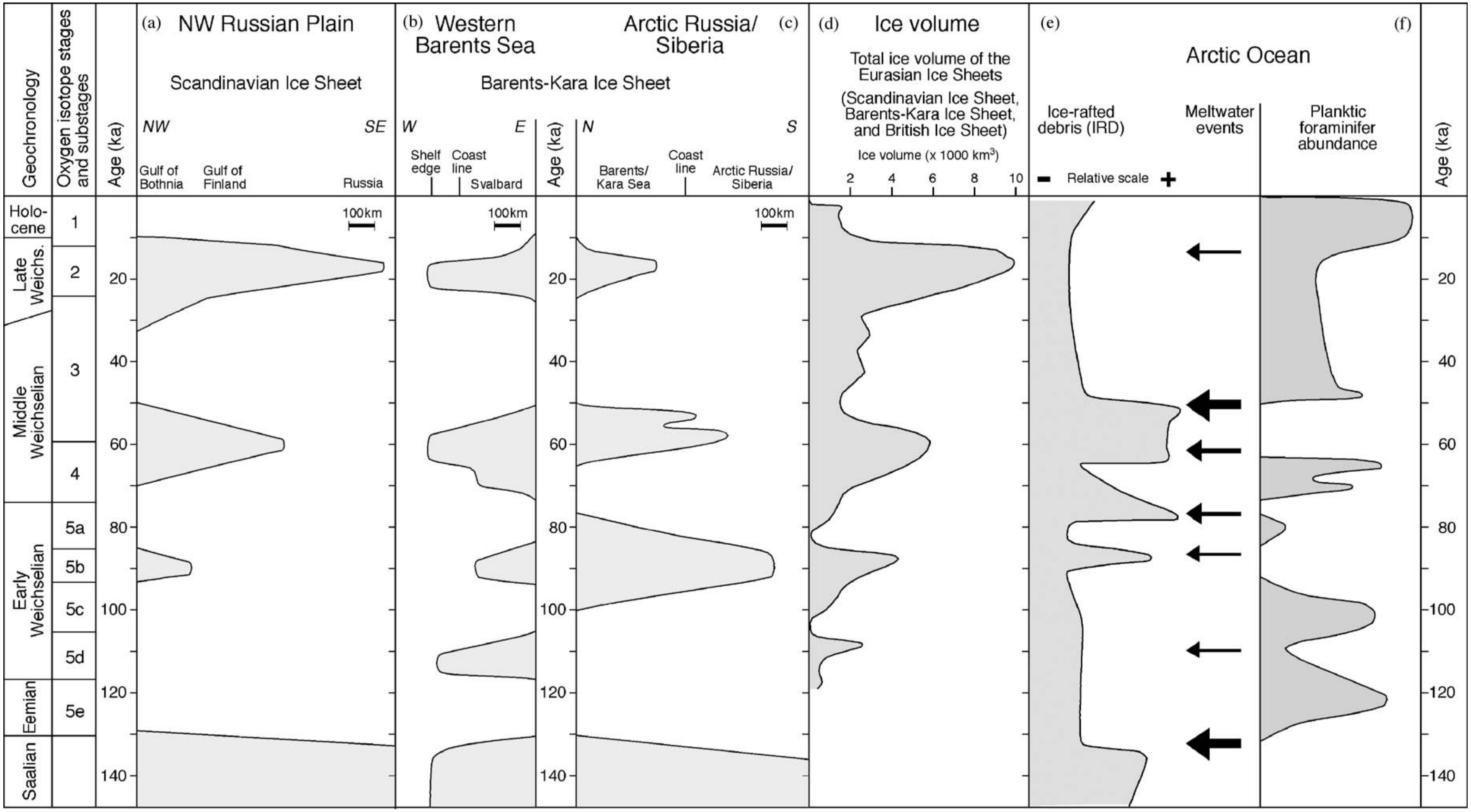

Fig. 17. Time-distance diagrams showing the growth and decay of the Eurasian ice sheets: (a) the Scandinavian Ice Sheets in Finland and Russia, (b) the Barents-Kara Ice Sheets on Svalbard in the western Barents Sea (Mangerud et al., 1998) and (c) the fluctuations of the Barents-Kara Ice Sheets in northern Russia/Siberia (this study). (d) Curve showing the modeled volumes of the Eurasian ice sheets (Siegert et al. 2001). Note that the model probably underestimates the volume of the Barents-Kara Ice Sheet during the Early- and Middle Weichselian glaciations. Curves showing the content of IRD and major meltwater events determined from the oxygen isotope records (e) and the planktic foraminifer abundance (f) in cores from the Arctic Ocean (Fig. 1). The presented core data are modified from Spielhagen et al. (2004).

increase whereas the IRD content is decreasing (Fig. 17). There are no foraminifers in core PS2185 because of carbonate dissolution, but a ^{10}Be peak in the sediments supports the existence of seasonally open waters and enhanced bioproduction between c. 73 and 65 ka (Spielhagen et al., 2004). Again we argue that the Arctic Ocean was seasonally open at this time, providing a moisture source that could promote the build-up of the Middle Weichselian ice sheet.

The uppermost, pronounced IRD layer in the Arctic Ocean records has an age of ca. 64–50 ka (Fig. 17). Most likely this layer, which started abruptly at all sites, corresponds to the Middle Weichselian ice sheet advance that has been OSL dated to around 60–50 ka. The thickness of the IRD layer is as much as 80–150 cm (40 cm in PS51/038-4), which gives a calculated average bulk sedimentation rate of 5–10 cm/ky (Spielhagen et al., 2004). This is by far the highest sedimentation rate recorded during the last 200 ka. The end of IRD input is associated with an outstanding meltwater spike in the planktic isotope record at c. 50 ka. We suggest it reflects the drainage of the postulated ice-dammed lakes that existed to the south of the Barents-Kara Ice Sheet during the Middle Weichselian (Mangerud et al., 2004). The IRD deposition decreased significantly after this deglaciation event and the sedimentation rates during the later stage of the Middle Weichselian remained very low. Probably most if not all of the ice sheet over the Barents-Kara sea shelves had melted away.

5.5.6. MIS 2 (25–10 ka)—the Late Weichselian

From the Late Weichselian there are no pronounced IRD peaks in the deep-sea records from the central and eastern part of the Arctic Ocean (Fig. 17). However, significant peaks of IRD deposition during the LGM interval are found in sediment cores from sites near the northern margin of the Barents Sea shelf (Nørgaard-Pedersen et al., 1998; Knies et al., 2001). These signals probably reflect that the regrowth of the Barents-Kara Ice Sheet during the LGM had a spreading center in the NW Barents Sea. In a recent reconstruction of the marine conditions during the LGM, Nørgaard-Pedersen et al. (2003) proposed that a relatively thick sea ice layer existed in the central Arctic Ocean, but relatively few icebergs. They interpret the pole ward decrease of LGM planktic oxygen isotope values as evidence for a decreased, but continuous river water supply to the Arctic Ocean. Because the meltwater events in the eastern and central Arctic Ocean during the last glacial termination (1) are much smaller than those at ca. 130 and 50 ka (cf. Stein et al., 1994; Nørgaard-Pedersen et al., 1998, 2003), we think the marine data support the terrestrial reconstruction, suggesting only a brief glacial surge across the northern Kara Sea during the LGM, with no large ice dammed lakes.

5.5.7. Conclusion

There is a good agreement between the signals recorded in the Arctic Ocean sediments and the ice sheet history as inferred from the continental records. This agreement supports the proposed ice sheet synthesis. It is noteworthy that the IRD peaks are punctuated by periods with seasonal open water in the Arctic Ocean. Possibly the Arctic Ocean during these periods provided the additional moisture source necessary for the build-up of the large ice sheets which formed over the Barents- and Kara Sea shelves.

6. Modeling results

6.1. Ice sheet reconstruction for the Late Weichselian

A numerical ice sheet model was used to reconstruct the Late Weichselian glaciation over Eurasia (Fig. 18c). Our initial results represent a "maximum-sized" reconstruction for the Late Weichselian, although even this is very much smaller than the huge Arctic ice sheet of Grosswald (1998). At 25 ka, we model the northern Barents Shelf as being covered by a relatively thin (<700 m) ice sheet. The basal ice-sheet topography manifests itself within the ice-surface morphology to form small ice domes over Severnaya Zemlya, Franz Josef Land and Novaya Zemlya, which feed ice outward in a pseudo-radial fashion from each archipelago. The ice thickness over Severnaya Zemlya and the northern Kara Sea was 100 m, and 200 m in the western Kara Sea.

After 22 ka, ice flowed northwards from Scandinavia into the Barents Sea causing the marine portion of the ice sheet to thicken. By 20 ka the ice flow was dominated by a major ice sheet divide over the central part of the Barents Sea shelf. The increase in ice thickness was moderated by the development of ice streams within the bathymetric throughs on the western and northern shelves, which acted to drain ice from the Barents Sea. Ice also flowed eastwards across Novaya Zemlya, resulting in a continuous ice sheet over the Barents and Kara seas. The ice thickness in the central Barents Sea was about 1000 m, whilst in the south-western Kara Sea it was 900 m. However, the ice thickness over Severnaya Zemlya and the northern Kara Sea had only increased to about 150 m.

At 15 ka the maximum ice thickness over Scandinavia was ~2700 m, whilst over the Barents Sea it was between 1500 and 1800 m. Maximum ice thickness across the Kara Sea varied from 1200 m close to Novaya Zemlya to a grounded ice margin along the eastern coast of the Kara Sea. Although the ice sheet over the central Barents Sea continued to grow between 20 and 15 ka, the ice thickness and surface elevation over Severnaya Zemlya and the northern Kara Sea remained largely unaffected during this period. Thus, at 15 ka, the ice

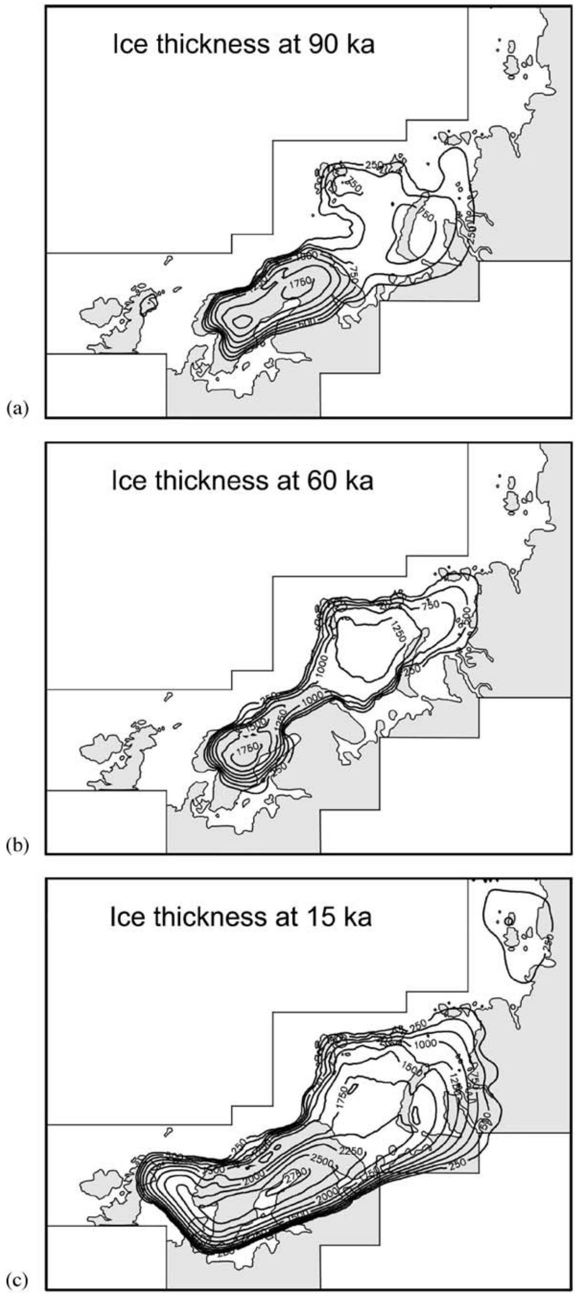

Fig. 18. Modeled ice-sheet thickness for the "maximum" model reconstruction at (a) 90 ka (Early Weichselian), (b) 60 ka (early Middle Weichselian), and (c) 15 ka (LGM). Contour interval 250 m. Note that the model reconstructions underestimate the thickness of the Barents-Kara Ice Sheet during the pre-LGM glaciations, as inferred from the geological observations (from Siegert et al., 2001).

thickness across Severnaya Zemlya was only 200 m in the south and zero in the north.

A full series of ice-sheet sensitivity analyses was performed on the ice sheet over the Eurasian High Arctic. Several experiments were undertaken to examine the sensitivity of the ice-sheet dimensions to changes in single environmental inputs used to force the model, where all other inputs were held at standard model values. Although the ice-sheet dimensions are most sensitive to alterations to imposed environmental conditions, the experiments indicate that relatively large ($\pm 10\%$) changes in the inputs of accumulation, iceberg calving and sea level do not adversely affect the main results and conclusions of this reconstruction. However, the experiments suggest that in case of extremely low precipitation rates on the eastern flank of the ice sheet, the modelled ice cover may appear too large in the Kara Sea region. In one experiment we adjusted the model's palaeoclimate to a situation where accumulation of ice was curtailed across the Kara Sea and Severnaya Zemlya. Low temperatures (–22°C mean annual) do not permit much surface melting and so ice is allowed to build up slowly via (a) sea-ice thickening over the Kara Sea and (b) ice flow from the Barents Sea. Under these extreme environmental conditions, a significantly smaller ice mass develops over the Kara Sea with a maximum thickness of 300 m at 15 ka. According to this "minimum-sized" scenario the northern Kara Sea shelf was covered by a very thin ice sheet with a grounding line at about 200 m below modern sea level and the St. Anna and Voronin throughs between Franz Josef Land and Severnaya Zemlya remained largely free of grounded ice. However, we note that instability in the ice margin along the northern Kara Sea could lead to rapid, short-lived glaciation of these through regions. A maximum ice thickness of only 50 m is modeled to the south of Severnaya Zemlya whilst in the north, similar to the "maximum reconstruction", ice-free conditions existed.

An inverse approach to ice sheet modeling was utilized, in which our ice sheet was forced to match the geological information of the ice sheet extent in the Eurasian Arctic by making adjustments to the paleoclimate forcing of the model. The existence of a thick ice dome over the Barents Sea shelf during the LGM, as predicted by the maximum size simulation, is substantiated by convincing geological data (Landvik et al., 1998). Thus, we think the model simulates fairly well the true dimensions of the Barents-Kara Ice Sheet during the Late Weichselian (Fig. 18). However, the minimum sized model fits better with the empirical observations from the areas further to the east. This mismatch can be accounted for by imposing a much stronger palaeoclimatic gradient across the ice sheet towards colder and drier conditions in the east.

6.2. Time dependent ice sheet modeling for the whole Weichselian period

We have also produced a time dependent model reconstruction of the repeated growth and decay of the Eurasian ice sheets over the whole of the Weichselian period back to the last (Eemian) interglacial (Figs. 17 and 18). This reconstruction is based on a simple forcing function using the predicted solar insolation at 60°N.

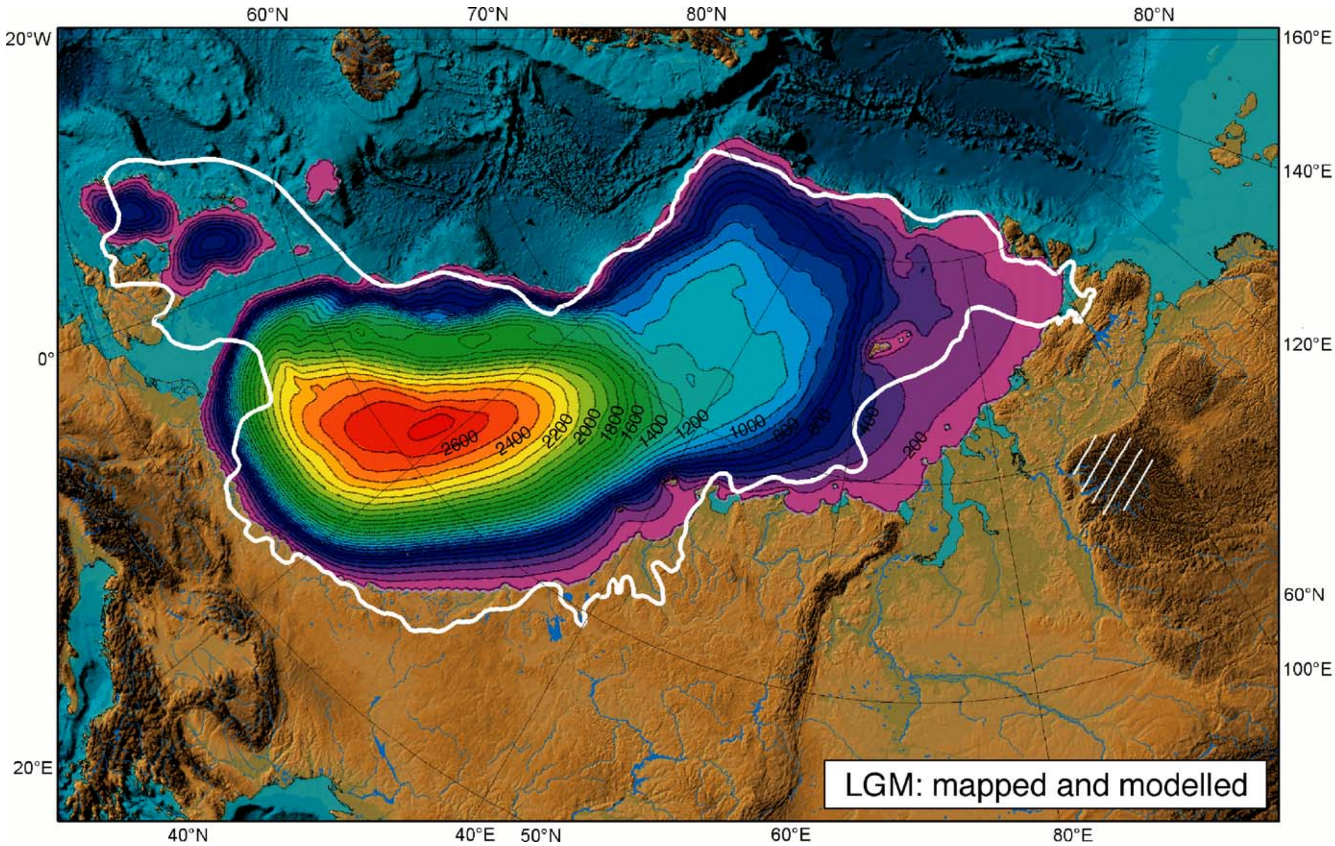

Fig. 19. The reconstructed LGM ice sheet limit (white line) from geological observations compared with a numerical model simulation (''maximum model'' of the Eurasian ice sheets (Siegert et al., 1999b). Notice that the numerical model slightly overestimate the ice sheet extent in the Kara Sea region.

Two reconstructions are developed as follows. A ''maximum'' reconstruction assumes that the modern-type temperature distribution across the Eurasian Arctic is reduced by 10°C at three stages during the Weichselian, which are related to minimum insolation level. Conversely a ''minimum'' model incorporates a reduction in temperature of only 5°C in Early and Middle Weichselian time. The growth and decay of the ice sheet is forced by the time-dependent variations in sea level and ELA. If mean air temperature is related linearly to insolation, the ''maximum'' model forced by the δ^{18}O sea-level function shows four distinct glacial episodes in the Weichselian, three of which result in major expansions of the ice sheet at around 90, 60 and 20 ka. The ''minimum'' model forced by the New Guinea sea-level function, air temperature being related linearly to this sea level, predicts very little ice prior to the Late Weichselian. The ''maximum'' model also differs from the ''minimum'' in that the latter reconstruction accounts for extra cold and dry conditions across the Kara Sea.

6.3. Comparison with the empirical reconstructions

In broad terms the geological evidence and the chronology of the reconstructed ice sheets compare fairly well with the ''maximum'' numerical model of the repeated growth and decay of the Eurasian ice sheets during the Weichselian (Fig. 19) (Siegert et al., 2001). That model creates three major glaciations in the Barents and Kara Sea region, culminating at around 90, 60 and at 20 ka (LGM). Moreover, in accordance with our geological findings in Russia and Siberia the model by Siegert et al. (2001) predicts that each ice sheet advance was followed by a nearly complete deglaciation of the shelves (Fig. 17). It is noteworthy that the modeled ice volume changes also roughly parallel the generalized glaciation curve for Svalbard and western Scandinavia (Mangerud et al., 1998; Mangerud, 2004).

In agreement with the empirical observations the time dependent model predicts that large ice sheets existed during the Early and Middle Weichselian, but the modeling underestimates the extension and thickness of the ice sheets in the Barents-Kara sea region. In contrast, during the Late Weichselian the maximum model predicts a Barents-Kara ice sheet that is notably larger than in our empirical reconstructions (Fig. 18), which then fit better with the ''minimum'' simulated ice sheet in this particular region. However, the ''minimum'' model reconstruction is hardly able to produce sizeable glaciations prior to the LGM, in any area. We therefore think that the ''maximum'' scenarios are more consistent with the geological evidence for the period prior to the Late Weichselian. A more realistic LGM scenario for the Barents-Kara Sea region is obtained by the maximum model if the accumulation of ice is somewhat curtailed over the Barents and Kara seas (i.e. as in the "minimum" reconstruction).

7. Conclusions

1. A huge ice sheet complex formed over northern Eurasia during the Late Saalian (160–130 ka), which was one of the most extensive Quaternary glaciations in this part of the world. A large ice shelf possibly fringed the Barents-Kara Ice Sheet at this time and may in fact have reached into the central Arctic Ocean.
2. We have reconstructed the limits of three major ice sheet advances following the last interglacial: (1) Early Weichselian (90–80 ka), (2) early Middle Weichselian (60–50 ka) and (3) Late Weichselian (20–15 ka) (Figs. 13–16). The results reveal that the ice sheet development in the more eastern part of the Eurasian Arctic followed a different pattern than over Fennoscandia and along the western margin of the Barents Sea shelf. The Barents-Kara Ice Sheets were getting progressively smaller during the successive glaciations, whereas the dimensions of the Scandinavian Ice Sheets increased through time (Fig. 17).
3. The maximum extent of the Barents-Kara Ice Sheet during the Early Weichselian (c. 90 ka) is defined by the southernmost belt of topographically expressed morainic ridges mapped throughout the Arctic mainland from southern Taimyr in Siberia to the Pechora Basin in the west. A major ice dome was located on the continental shelf in the northern Kara Sea during this glacial maximum. However, this time only a restricted ice sheet existed over Norway, Sweden and parts of Finnish Lapland.
4. The Early Weichselian glaciation was followed by a major deglaciation during a relatively warm interstadial around 85–75 ka (MIS 5a), when central Taimyr was affected by a marine inundation of the glacioisostatic depressed area.
5. A regrowth of the Barents-Kara Ice Sheet occurred during the early Middle Weichselian, leading to another ice advance well onto the northern margin of the Eurasian mainland at around 60–50 ka. This ice front was delineated by the North Taimyr ice marginal zone (NTZ) in North Siberia and possibly by the Markhida-Pyoza morainic belt between the Pechora and Mezen rivers in the European sector of the Russian mainland. During this glaciation the southern margin of the Scandinavian Ice Sheet reached Denmark and the eastern flank covered the whole of Finland, with an ice lobe reaching the White Sea Basin.
6. The glaciation around 60–50 ka was followed by a major Middle Weichselian deglaciation and most likely the entire Barents-Kara Sea shelves were ice free during the interval 50–30 ka.
7. During the Late Weichselian glacial maximum (20–15 ka) the southern and eastern flanks of the Barents-Kara Ice Sheet terminated on the seafloor in the south-eastern Barents Sea and on the western Kara Sea shelf, far inside its Early Weichselian maximum extent. On the northern Kara Sea shelf, however, the ice sheet may have advanced eastwards and temporarily inundated parts of northwesternmost Taimyr. Severnaya Zemlya was probably not affected by this glaciation. In contrast to the Barents-Kara Ice Sheet the Scandinavian Ice Sheet did not reach its maximum position until the Late Weichselian (LGM), when its eastern margin was located along a morphologically distinct ice marginal zone traceable from the north-western Russian Plain in the south to the Arkhangelsk region in the north.
8. A comparison between the reconstructed ice sheet history and the Arcric Ocean sediment records shows that the large ice sheet glaciations over the Kara Sea shelf, particularly their deglaciation phases, are seen as IRD layers in the deep sea cores. The deglaciations are also reflected as meltwater spikes. An interesting finding is that the Arctic Ocean was seasonally ice free between the major ice advances and may thus have been an important moisture source for the build up of the ice sheets.
9. A time dependent glaciological model forced by global sea level and solar changes generates expansions of Eurasian ice sheets at around 90, 60 and 20 ka, compatible with the geological record of ice growth. In broad outline the glaciations can thus be explained by the interaction of marine regressions and negative insolation changes.
10. When compared with the empirical geological reconstruction of the Late Weichselian ice sheets over the Eurasian High Arctic the model simulations indicate extremely low precipitation rates in the Kara Sea region, deterring ice growth in the more eastern areas of the Eurasian Arctic during the LGM. This is in contrast to earlier Weichselian and Saalian glaciations, where enhanced precipitation in the east would be required to build ice sheets compatible with the geological data.

Acknowledgements

This paper is a contribution to the European Science Foundation program "Quaternary Environment of the

Eurasian North'' (QUEEN). Many projects and a large number of investigators from 10 countries have contributed to this synthesis. This includes the multinational project ''Ice Sheets and Climate in the Eurasian Arctic at the Last Glacial Maximum'' (Eurasian Ice Sheets) that was financially supported by the European Union (Contract no. ENV4-CT97-0563) for the period 1998–2000. This project carried out field investigations in various areas of Russia and Siberia (Taimyr Peninsula, Pechora Lowland, Arkhangelsk Region, Kola and NW Russian Plain) as well as glaciological modelling. Several other projects, supported by national research councils, universities and other research institutes have contributed to this synthesis. The Russian–Norwegian project ''Paleo Environment and Climate History of the Russian Arctic'' (PECHORA), funded by the Research Council of Norway, has investigated the Pechora Lowland, Polar Urals and parts of West Siberia during a 10 years period between 1993 and 2003. The co-authors under this project partnership include J.I. Svendsen, V.I. Astakhov, J. Mangerud, O. Nikolskaya, M. Henriksen and A. Matioushkov. Much of the work carried out by this Russian–Norwegian team, including the logistics, was arranged and implemented by the Institute of Remote Sensing Methods for Geology (NIIKAM), St. Petersburg. In collaboration with V. Gataullin and L. Polyak, University of Ohio, the PECHORA project was also involved in the complilation and interpretation of geological and geophysical data from the SE Barents Sea. The Swedish work on Taimyr Peninsula, that include the contributions by C. Hjort, P. Möller and H. Alexandersson, have been financially supported by the Swedish Natural Science Research Council (Contract no. G-AA/GU09362-307), the Royal Swedish Academy of Sciences and the Swedish Board for Nature Conservancy. The logistics have to a large extent also been financed by the Swedish Polar Research Secretariat, through contracts with the INTAARI Company in St. Petersburg. Their main Russian scientific counterpart has been the Arctic and Antarctic Research Institute (AARI) in St.Petersburg, with D.Y. Bolshiyanov as project leader. Cooperation has also taken place with Danish scientists (project leader S. Funder, Geological Museum, Copenhagen). Two Russian–German projects, ''Late Quaternary environmental evolution of Central Siberia'' and ''System Laptev Sea 2000'', carried out field investigations on the Taimyr Peninsula, Severnaya Zemlya and the Laptev Sea Coast. This group of QUEEN investigators, that include the co-authors H.W. Hubberten and C. Siegert, was supported by the German Ministry of Education, Research and Technology (BMBF). With support from BMBF and the Russian Foundation of Basic Research, R. Stein and F. Niessen investigated the sea floor sediments in the Kara Sea. R.F. Spielhagen, who analyzed sediment cores from the Arctic Ocean, was funded by the BMBF and by the German Science Foundation through the project ''Paläoklimaprojekt'' (grant Th200/39-1). The work in the Barents and Kara seas by L.Polyak and V.Gataullin was part of the Russian–American Initiative on Shelf-Land Environments in the Arctic (RAISE) and was supported by the US NSF awards OPP-9818247 and OPP-0221468''. The work in the Arkhangelsk region, that include contributions by E. Larsen, I. Demidov, M. Houmark-Nielsen, K.H. Kjær and A. Lyså, were supported by the Barents Secretariat, the Danish and Norwegian research councils, the Swedish Polar Research Secretariat, the Crawford Foundation, the Geological Survey of Norway, and the De Beers company. The investigations on Yamal and Yugorski peninsulas in 1997, 1998 and 1999 were carried out by a Swedish–American–Russian team, including Ó. Ingólfsson, H. Lokrantz, V. Gataullin, M. Leibman, S. Forman and W. Manley, financed and supported in various ways by the Swedish Natural Sciences Research Council, the US National Science Foundation, the Swedish Polar Reasearch Secretariat, the Earth Cryosphere Institute in Moscow, University of Göteborg and the University of Illinois at Chicago. The glaciological modelling work, carried out by J. Dowdeswell and M. Siegert, was supported by the UK Natural Environment Research Council. The maps with the reconstructed ice sheet limits were compiled by M. Jakobsson who was supported by NOAA Grant NA97OG0241. E. Bjørseth, University of Bergen helped with the figures. The paper were reviewed by Jon Landvik and Horst Hagedorn. We sincerely thank all persons and institutes who have supported and otherwise contributed to this synthesis.

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