Maximum extent of the Eurasian ice sheets in the Barents and Kara Sea region during the Weichselian

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Based on field investigations in northern Russia and interpretation of offshore seismic data, we have made a preliminary reconstruction of the maximum ice-sheet extent in the Barents and Kara Sea region during the Early/Middle Weichselian and the Late Weichselian. Our investigations indicate that the Barents and Kara ice sheets attained their maximum Weichselian positions in northern Russia prior to 50 000 yr BP, whereas the northeastern flank of the Scandinavian Ice Sheet advanced to a maximum position shortly after 17 000 calendar years ago. During the Late Weichselian (25 000–10 000 yr BP), much of the Russian Arctic remained ice-free. According to our reconstruction, the extent of the ice sheets in the Barents and Kara Sea region during the Late Weichselian glacial maximum was less than half that of the maximum model which, up to now, has been widely used as a boundary condition for testing and refining General Circulation Models (GCMs). Preliminary numerical-modelling experiments predict Late Weichselian ice sheets which are larger than the ice extent implied for the Kara Sea region from dated geological evidence, suggesting very low precipitation.

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In spite of their enormous size (millions of km^2), the former extent and chronology of the Eurasian ice sheets in the Barents and Kara Sea region are poorly documented, and for the Late Weichselian (isotope stage 2) they represent the largest uncertainty in the global distribution of glaciers (Fig. 1). Recently published reconstructions of the glacier coverage during the Late Weichselian glacial maximum, about 20 000 yr BP, range from a huge continuous ice sheet centred on the continental shelf in the Kara and Barents seas and extending eastwards to the Lena River (Grosswald 1993, 1998), to more localized ice caps over the Urals and the Arctic islands (Velichko *et al.* 1997).

In this paper, we summarize our current understanding of the last glaciations that affected the Russian Arctic and, based on the available evidence, we present a preliminary reconstruction of the maximum ice-sheet extent during the Early/Middle Weichselian (prior to 50 000 yr BP) and during the Late Weichselian (about 20 000–18 000 yr BP) (Fig. 1). These geological reconstructions will be tested and refined in our future field investigations. They are also being used together with numerical ice-sheet modelling to enhance our quantitative understanding of the palaeoclimatic conditions required for the growth and decay of the Weichselian ice sheets in the Eurasian North.

Our reconstructions of the ice-sheet extent are based on geomorphological mapping combined with stratigraphical work. In addition to satellite and aerial photographic interpretation, the mapping was carried out through land-based geological field investigations in several sectors of the Russian Arctic from the White Sea region to the Taimyr Peninsula (Fig. 1) (Astakhov *et al.* 1999; Hahne & Melles 1998; Larsen *et al.* 1999; Mangerud *et al.* 1999; Möller *et al.* 1999; Siegert *et al.* 1999; Tveranger *et al.* 1999). Exposed sections along rivers, lakes and coasts and sediment cores from lake basins have been investigated and dated. For the

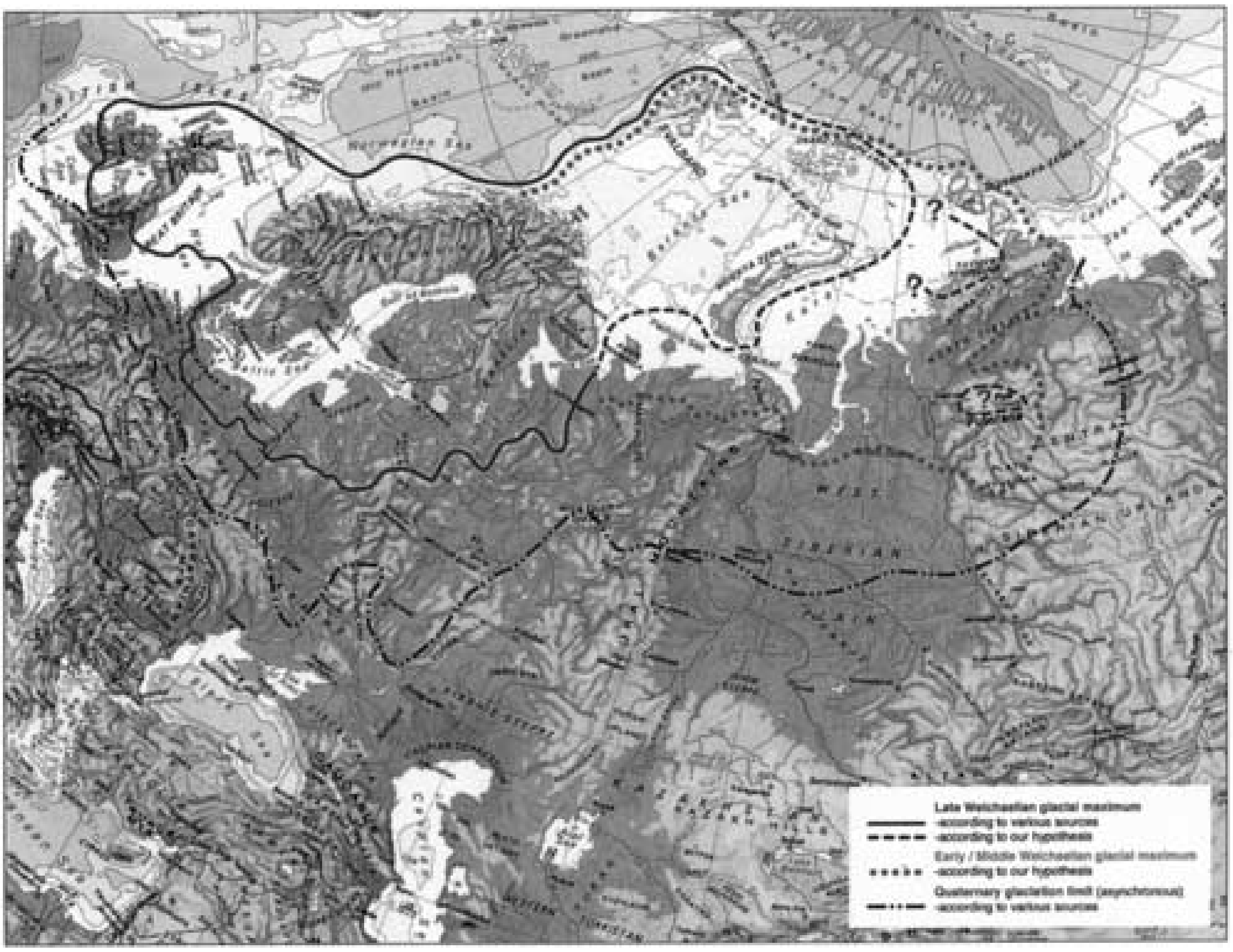

Fig. 1. Reconstructed ice-sheet extent for northern Eurasia during the Early/Middle Weichselian and the Late Weichselian glacial maximum, respectively. The Late Weichselian glacial maximum along the western margin of the Barents Sea is according to Landvik *et al.* (1998), whereas the Scandinavian Ice Sheet boundary is slightly modified from Andersen (1981) and Velichko & Faustova (1986). For the area between the Lake Onega and the White Sea this boundary has been modified by our investigations. The Quaternary glaciation limit is according to Arkhipov *et al.* (1986). The dotted and stippled lines are according to the present paper. The map is based on Lademanns Verdensatlas (Anon. 1984).

submarine area on the continental shelf, we have interpreted available seismic profiles and sediment cores.

We use the terms Eemian and Weichselian as stratigraphical nomenclature for the last interglacial (isotope stage 5e) and glacial (isotope stages 5d-2) periods, respectively. The Eemian and Weichselian are considered equivalent with the Mikulino and Valdai in European Russia and are correlated with the Kazantsevo interglacial and the Zyrianka (stadials)-Karginsky (interstadial) periods in Siberia. From correlation with the deep-sea stratigraphy we assume the ages of about 130 000–117 000 yr BP for the Eemian, 117 000–74 000 yr BP for the Early Weichselian (isotope stages 5d-5a), 74 000–25 000 yr BP for the Middle Weichselian (isotope stages 4–3), and 25 000–10 000 yr BP for the Late Weichselian (isotope stage 2) (Mangerud 1989).

The Weichselian maximum ice-sheet extent in northern Russia is partly identified, and strongly supported by stratigraphic evidence. On the proximal side of the youngest morainic ridges in the Arkhangelsk region (Larsen *et al.* 1999) and in the Pechora Basin (Tveranger *et al.* 1998; Mangerud *et al.* 1999) Eemian marine sediments are covered by till, whereas on the distal side of the moraines these sediments shows no sign of being overridden by glacial ice. Inside the proposed ice-sheet limit on the Siberian Lowland there are also many sites with marine sediments correlated with the Eemian that are covered by till (Arkhipov 1998; Astakhov 1992). Another observation that supports a Weichselian age for this glaciation is the frequent occurrence of buried glacier ice within areas affected by the Eemian transgression (Astakhov & Isayeva 1988). It seems unlikely that remnants of a former Saalian ice sheet could have survived the last interglacial in these areas.

Early/Middle Weichselian glacial maximum

Eastern and northern boundaries of the Scandinavian Ice Sheet

During the Early/Middle Weichselian, the maximum extent of the Scandinavian Ice Sheet was significantly more restricted than during the Late Weichselian (Andersen & Mangerud 1989). Recent investigations in the Arkhangelsk region indicate that the Scandinavian Ice Sheet did not inundate the Dvina River basin at this time (Larsen *et al*. 1999). As an implication of the ice sheet reconstruction described below, we assume that the Scandinavian Ice Sheet coalesced with the Barents Ice Sheet, but we have no observations yet to substantiate this assumption and this needs to be tested in the field.

Southern and eastern margins of the Barents and Kara ice sheets

To the east of the White Sea is an east–west trending belt of hummocky morainic landscapes that can be traced across the mainland from the Arkhangelsk region to beyond the Urals (Astakhov *et al.* 1999) (Fig. 1). The southern boundary of these landscapes, called the Markhida Line, is considered to be a nearly synchronous southern limit of the last Barents and Kara ice sheets. In the western part of the Pechora Basin, the Markhida moraines demarcate the maximum extent of all Weichselian glaciations. Farther to the east, in the Pechora Basin, the Laya–Adzva and Rogovaya morainic lobes, which protrude a 100 km to the south of the Markhida Line, are also considered to postdate the Eemian.

The pattern of ice-pushed ridges, flutes and other directional features indicates that the Russian mainland from the Taimyr Peninsula to the Pechora River was affected by ice flow from the Kara Sea, whereas the Barents Ice Sheet affected only a narrow zone between the White Sea and the Pechora Basin. In the Polar Urals the ice flow, which deposited horseshoe-shaped end moraines up to 560 m a.s.l., was directed up-valley. This indicates the absence of a contemporaneous ice dome in the mountains (Astakhov *et al.* 1999). Beyond the margin of the Kara Ice Sheet in the Urals traces of only small alpine glaciers have been found.

To the south of the Markhida moraine, we have mapped the shorelines of a large ice-dammed lake reaching up to around 100 m a.s.l., called Lake Komi. These shorelines can be traced from the Urals across the Pechora Lowland and into the Mezen Basin in the west (Astakhov *et al*. 1999). Lake Komi was formed in front of the last ice advance of the Barents and Kara ice sheets onto mainland Russia. A reconstruction of the surface form of this ice sheet in the European part of the Russian Arctic is presented by Tveranger *et al.* (1999). In the Pechora Basin, luminescence dating of beach sediments that were deposited in the pro-glacial lake have yielded ages in the range 93 000–76 000 yr BP (Mangerud *et al*. 1999). A number of radiocarbon-dated sediment sequences, including three sections with Palaeolithic artifacts, indicate that a normal northward drainage towards the Arctic Ocean was restored prior to 40 000 yr BP (Mangerud *et al*. 1999). Thus, from the available evidence, we conclude that the last glaciation reaching the Markhida Line occurred during the Early/Middle Weichselian.

The maximum ice-sheet limit in the European part of the Russian Arctic is correlated with similar ice-pushed morainic ridges in the Ob and Yenissei river valleys on the West-Siberian Lowland (Arkhipov 1998; Astakhov 1998). Based on the character of ice-marginal forms, it is suggested that during the glacial maximum the Kara Ice Sheet was merging with a separate ice cap centred on the Putorana Plateau (Makkaveyev *et al.* 1982). On the Taimyr Peninsula, the southern limit of the contemporaneous Kara Ice Sheet is probably outlined by a distinct northeast trending system of moraine ridges (the Dzhangoda–Syntabul–North Kokora Ridge) that can be traced without break across the entire peninsula south of the Byrranga Mountains (Andreyeva 1978; Makkaveyev *et al*. 1982; Kind & Leonov 1982; Astakhov 1998).

As in the Pechora Basin, the last glacial maximum that affected the West Siberian Lowland seems to have occurred early in the Weichselian (Astakhov 1992, 1998). This conclusion is based on many radiocarbon-dated sediment sequences covering the youngest post-Eemian till, indicating that the last ice sheet covering these areas disintegrated and became stagnant more than 40 000 yr BP.

Bedrock surfaces in the Byrranga Mountains on the Taimyr Peninsula, which lie inside the Weichselian Ice Sheet limit, are often deeply weathered with the frequent occurrence of tors (Möller *et al*. 1999). In addition, the landscape is characterized by slope and fluvial processes rather than glacial activity. Möller *et al*. (1999) conclude that a substantial amount of time has passed since the area became ice-free, and they suggest that the last deglaciation took place during the Early Weichselian but that a Late Saalian age could not be excluded. However, considering that the Kara Ice Sheet advanced more than 800 km to the south of the Yenissei River mouth after the last interglacial (Astakhov 1998), it probably also inundated the central part of the Taimyr Peninsula (Fig. 1).

Unlike the European part of the Russian mainland, there is evidence to suggest that the northern part of the West Siberian Lowland and the central Taimyr Peninsula were inundated by a marine transgression following the last deglaciation (Arkhipov 1998; Möller *et al.* 1999). From the Taimyr Peninsula, Möller *et al*. (1999) describe marine deltaic sediments not covered by till at an altitude of around 100 m a.s.l., reflecting a strong glacioisostatic depression caused by the former ice load. On the basis of radiocarbon and Electron Spin Resonance (ESR) dates, they suggest an Early Weichselian age for this transgression, which is also a minimum age for the last glaciation that affected the area.

On Severnaya Zemlya there are shorelines uplifted to about 120 m a.s.l. A series of radiocarbon dates on shells, driftwood, whales and walrus bones have yielded ages ranging between more than 50 000 yr BP to about 21 000 yr BP (Bolshiyanov & Makeyev 1995). We consider these to be minimum dates and most likely these shorelines were formed soon after an Early/Middle Weichselian deglaciation, although an interglacial (Eemian) age cannot be ruled out. An extensive glaciation that terminated at the shelf edge is indicated by investigations of marine sediment cores from the continental slope to the northeast of Severnaya Zemlya. They show a pronounced peak in the content of ice-rafted debris (IRD) around 60 000 yr BP and a smaller peak around 90 000 yr BP (Knies 1998; Knies *et al*. 1998).

Late Weichselian glacial maximum

Eastern boundary of the Scandinavian Ice Sheet

In the Arkhangelsk region, the maximum position of the Scandinavian Ice Sheet is recognized by fresh-looking end moraines and a hummocky landscape across the Dvina River valley (Larsen *et al*. 1999). These broad morainic ridges are conspicuous features in an otherwise flat terrain and are correlated with large end moraines 100 km east of Lake Onega, which again are mapped as more or less continuous with the classical Valdai end moraines in Russia (Yakovlev 1956).

A Late Weichselian age for these moraines is inferred by correlating to areas farther south where the glacial maximum occurred after 21 000 yr BP (Arslanov *et al.* 1970; Velichko & Faustova 1986). In the Arkhangelsk region, luminescence dates suggest that the maximum position was attained after 17 000 calendar yrs ago, and that deglaciation started about 16 000 calendar yrs ago (Larsen *et al.* 1999). The region east of Lake Onega was deglaciated between 14 400 and 12 900 calendar yrs ago (Saarnisto *et al.* 1998).

Southern and eastern margins of the Barents Ice Sheet

In contrast to the moraines that were deposited in front of the Scandinavian Ice Sheet, we concluded above that the youngest ice-marginal formations across the Pechora Basin are of Early/Middle Weichselian age. Minimum dates of deglaciation on the proximal side of the moraine indicate that the last ice sheet that covered this coastal area melted away before 40 000 yr BP (Mangerud *et al*. 1999). Furthermore, there are no indications that the Pechora River basin was inundated by a younger ice-dammed lake in front of an advancing ice sheet. On the contrary, a normal drainage northward towards the ocean seems to have prevailed during the Middle and Late Weichselian.

On the Yamal Peninsula in West Siberia, the youngest till deposited by the Kara Ice Sheet is overlain by continental sediments from which a series of radiocarbon dates have given ages in the range 33 000–12 000 yr BP (Gataullin & Forman 1997; Gataullin *et al*. 1998; Mahaney 1998; Mahaney *et al*. 1995). This indicates that the coastal area was outside the maximum Late Weichselian ice-sheet limit.

Several investigations of lake sediments and other deposits demonstrate that the southern and central parts of the Taimyr Peninsula have been ice-free the last 40 000–50 000 yr (Isayeva 1984; Melles *et al*. 1996; Hahne & Melles 1997, 1998; Siegert *et al*. 1998; Möller *et al*. 1999). However, preliminary results of recent investigations suggest that the northwestern coast of the Taimyr Peninsula was inundated by a younger ice-sheet advance from the Kara Sea that terminated along a distinct ice-marginal boundary 50–75 km inside the present coastline, originally described by Isayeva (1984). The morainic landscape to the north of this line is fresh and underlain by thick buried glacier ice. A radiocarbon date on a marine mollusc from the till yielded an age of around 20 000 yr BP and plant material deposited in connection with deglaciation has given radiocarbon ages of around 9500 yr BP (Hjort *et al*. unpublished). This boundary most likely represents the maximum position of a Late Weichselian glacier advance from the continental shelf.

From Severnaya Zemlya, a series of radiocarbon dates on several different materials, including mammoth tusks, have yielded ages in the range 25 000–19 000 yr BP. This implies that when the dated animals were living the local glaciers on these islands were no larger than they are today (Makeyev *et al*. 1979; Bolshiyanov & Makeyev 1995). In fact, some bones were found so close to the present-day glaciers that it suggests the glaciers may have been smaller than today. This conclusion is also supported by investigations of sediment cores from the continental slope to the northeast of Severnaya Zemlya (Knies, 1998; Knies *et al*. 1998). In contrast to the Early/Middle Weichselian glacial maximum, the Late Weichselian marine sediments here are characterized by a very low content of ice-rafted debris (IRD), indicating that no calving glaciers existed on these islands at this time.

The conclusion that the southern limit of the Barents and Kara sea ice sheets was located offshore of the Russian mainland, from the White Sea to the Taimyr Peninsula, is supported by some marine geological data. From a sediment core taken to the northeast of the Pechora delta, two radiocarbon dates on foraminifera above the till have yielded ages of more than 35 000 yr BP (Polyak 1996). This indicates that the southernmost part of the Barents Sea was also beyond the Late Weichselin ice limit. In the Pechora Sea, to the northeast of this core site, there are accumulations of silt and clay that are more than 100 m thick, found in depressions on the till surface. We interpret these accumulations as glaciomarine sediments that were deposited close to, but outside, the Late Weichselian ice-sheet margin. There are no well-defined morainic ridges that demarcate the maximum ice-sheet extent in the southeastern part of the Barents Sea and we have tentatively drawn the Late Weichselian ice-sheet limit along the northwestern rim of the basin containing thick sediments in the Pechora Sea. Sediment cores taken half way between southern Novaya Zemlya and Northern Norway, just inside the proposed ice-sheet limit, indicate that this part of the shelf was covered by the Barents Ice Sheet shortly before 12 700 yr BP (Polyak *et al*. 1995).

Based on available seismic profiles from the eastern Barents Sea and western Kara Sea, we assume that Novaya Zemlya was ice-covered during the Late Weichselian and that the maximum ice-sheet boundary corresponds with a well-defined morainic ridge around the southern part of the eastern Novaya Zemlya Trough in the Kara Sea (Gataullin 1995). On the floor of this trough there is only a thin (4–5 m) veneer of marine sediments above the till, whereas a thick accumulation (up to 100 m) has been recorded in the Yugorsky Depression to the southeast of the morainic ridge.

From the existing marine geological data, we infer that the Barents Ice Sheet was merging with or inundated a local ice dome over Novaya Zemlya during the Late Weichselian.

Putorana Ice Cap

The Putorana Plateau is encircled by a system of morainic ridges well inside the proposed Early Weichselian moraines. Based on radiocarbon dates from under the corresponding till, it has been proposed that these inner moraines mark the Late Weichselian glacial maximum (Isayeva *et al*. 1976). However, this conclusion should be tested by further investigations. Sediment coring of a lake basin situated on the proximal side of the proposed Late Weichselian moraines may suggest that the glacier coverage on the Putorana Ice Cap was more restricted than hitherto assumed (Hahne & Melles 1997). This is supported by geomorphological studies in the same area (Bolshiyanov *et al.* 1998; Sharev 1998).

Discussion

Early/Middle Weichselian glaciation

Morphological indicators of ice flow and the pattern of end moraines indicate that, during the Early/Middle Weichselian, major ice domes were localized both on the Kara Sea and Barents Sea continental shelves, forming a huge continuous ice sheet that advanced far onto the Russian mainland. We infer that the western and northern rims of this ice sheet terminated along the shelf edge. Investigations on Svalbard indicated that these islands were inundated by the Barents Ice Sheet twice during the Early/Middle Weichselian, about 110 000 and 60 000 yr BP (Mangerud *et al*. 1998). However, Mangerud *et al.* (1998) assumed that the southwestern part of the Barents Sea was probably not ice-covered at that time. Our present hypothesis challenges the latter assumption, because a shelf-centred ice sheet that extended well onto Northern Russia in the Mezen and Pechora river basins must have had a considerable extension in the Barents Sea. The fact that Lake Komi flooded the pro-glacial river valleys up to 100 m a.s.l. implies that the northbound drainage was blocked by glacier ice, and that there was no ice-free corridor on the shelf along the Kola Peninsula and northern Norway (Astakhov *et al*. 1999).

We are not yet able to constrain the age of the Early/Middle Weichselian glacial maximum on the Russian mainland. The dates from the European part of the Russian Arctic suggest that a major shelf-centred glaciation affected the mainland during isotope stage 4 (75 000–55 000 yr ago), but the Weichselian maximum may have occurred at an earlier stage (Mangerud *et al*. 1999).

The Late Weichselian glacial maximum

Most of the Barents Sea was evidently glaciated during the Late Weichselian. Most investigators believe that this shelf-centred ice sheet coalesced with the Scandinavian Ice Sheet in the southwestern part of the Barents Sea (Landvik *et al*. 1998). From sediment cores taken in the Saint Anna Trough, between Franz Joseph Land and Severnaya Zemlya, Polyak *et al*. (1995, 1997) obtained minimum dates of around 13 300 yr BP for the last deglaciation, indicating that glacier ice from the Barents Ice Sheet filled this trough during the last glacial maximum. They also inferred that a smaller ice cap was located on the northern Kara Plateau on the eastern side of this trough.

In contrast to the Barents Sea, the Late Weichselian ice-sheet extent in the Kara Sea region was much more restricted than at the Early/Middle Weichselian glacial

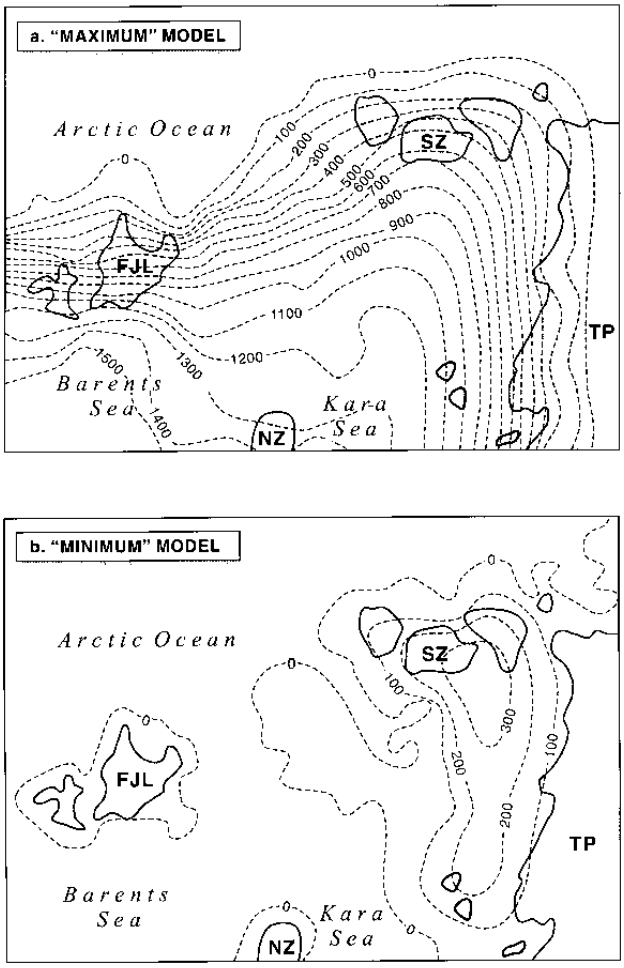

Fig. 2. Numerical ice-sheet model reconstructions for the Late Weichselian in the Russian High Arctic. (a) 'Maximum' reconstruction. (b) 'Minimum' reconstruction. FJL is Franz Joseph Land, NZ is Novaya Zemlya, SZ is Severnaya Zemlya and TP is Taimyr Peninsula.

maximum and we conclude that the Russian mainland was not glaciated at this time. Based on the many radiocarbon dates of mammoth remains on Severnaya Zemlya, we also believe that this archipelago was probably situated outside the Late Weichselian ice-sheet limit. Although from a glaciological point of view it is difficult to conceive a glacier advance that inundated the northwestern coast of the Taimyr Peninsula without affecting Severnaya Zemlya (Fig. 1), the new radiocarbon dates mentioned above (Hjort *et al*, unpublished) seem to indicate that the western Taimyr Peninsula alone was inundated by a restricted ice cap centred on the shallow shelf areas to the northeast of Novaya Zemlya.

The pattern of shoreline displacement also provides some constraints on the dimensions of the former ice sheets. The pattern of postglacial emergence indicates that a thick ice dome existed in the northern Barents Sea during the Late Weichselian (Forman *et al*. 1995; Landvik *et al*. 1998). Lambeck (1995, 1996) predicted shoreline elevations based on forward glacioisostatic modelling from reconstructed ice sheets and compared them with observed and dated shorelines to provide constraints on the size of grounded ice sheets in the Barents and Kara Sea region. In conformity with our reconstruction, he infers that no substantial ice was located over the Kara Sea or West Siberia during the Late Weichselian. It is noteworthy that uplifted Late Weichselian and Holocene shorelines occur only in areas inside our proposed ice-sheet limit. The high sea-level events that are recorded in the Pechora Basin, West Siberian Lowland, Taimyr and on Severnaya Zemlya are older and reflect the more extensive Early/Middle Weichselian and/or Saalian glaciations.

The main argument for postulating that the Barents Ice Sheet coalesced with or inundated glaciers on Novaya Zemlya during the last glacial maximum is the fact that there are no ice-marginal formations that demarcate an eastern limit for the Barents Ice Sheet and there are no indications that the till surface in the eastern Barents Sea is covered by pre-Late Weichselian sediments. Prominent arc-shaped morainic ridges, the so-called Admiralty Bank Moraines, are found on the continental shelf to the west of Novaya Zemlya (Ephstein & Gataullin 1993; Gataullin & Polyak 1997). These ridges, which are considered to be of Late Weichselian age, reflect ice dispersal from Novaya Zemlya. One implication of our reconstruction is that these moraines were deposited by an ice cap centred over Novaya Zemlya after the Late Weichselian glacial maximum. A few radiocarbon dates on peat material from Novaya Zemlya have yielded ages of around 15 000 yrs BP (Serebryanni & Malyasova 1998), which provide a minimum age for the recessional moraines, assuming that the dated material was not contaminated with old carbon (coal, limestone).

Numerical ice-sheet modelling

A numerical ice-sheet model was also used to reconstruct the Late Weichselian glaciation of the Russian High Arctic (Siegert *et al.* 1999). The modelling assumed ice growth from interstadial conditions 30 000 years ago, through the Late Weichselian glacial maximum, followed by deglaciation. Several model experiments were undertaken, and 'maximum' and 'minimum' ice-sheet reconstructions were produced (Fig. 2). These initial model runs allowed the Eurasian Ice Sheet to grow and decay in a manner largely unconstrained by the geological data on the extent of the ice margin at the Late Weichselian glacial maximum (Fig. 1), with the exception of the eastern margin of the ice sheet which was not allowed to spread onto the Taimyr Peninsula (Möller *et al.* 1999).

At the Late Weichselian, our model predicted a 'maximum' ice sheet, which was over 1300 m thick west of Novaya Zemlya and 400–600 m thick over Severnaya Zemlya and Franz Joseph Land (Fig. 2a). Ice flow at the glacial maximum was dominated by a large (1500 m thick) ice dome located over the central Barents Sea and Novaya Zemlya. Subsequent to grounded-ice expansion to the shelf break along the northern margin of the Barents Sea, ice streams were activated within several bathymetric troughs, draining ice from the central Barents Sea to the Arctic Ocean (Dowdeswell & Siegert 1999). The largest of these ice streams was located within the St. Anna Trough (cf. Polyak *et al*. 1997), draining approximately 15 km^3 per year of ice from the ice sheet (Siegert *et al*. 1999). This reconstruction is compatible with geological data indicating ice loading of the Barents Sea region (Lambeck 1995, 1996), but produced an ice cover which was much thicker and more extensive than that reconstructed for the Kara Sea area based on geological data (Fig. 1).

In contrast, a 'minimum' model of the Late Weichselian glaciation predicted a non-glaciated western Kara Sea, and ice growth initiated from, and limited to the shores of, the Russian High Arctic archipelagos (Fig. 2b). In this model experiment, iceberg calving was allowed to occur at all places where the grounded ice margin was located below sea level, giving a significantly higher mass loss than in our 'maximum' reconstruction, where iceberg calving was curtailed everywhere but at the continental shelf break. The 'minimum' model was run for a shorter period than the 'maximum' model, from ice-free conditions at 22 000 model years ago to 17 000 model years ago. The resulting ice distribution at the last glacial maximum showed a much more limited glaciation than in the 'maximum' model (Fig. 2). Ice extent in the Kara Sea was limited to the shallow shelf bordering the Taimyr Peninsula. An ice thickness of up to 350 m was modelled to the south of Severnaya Zemlya. However, even our 'minimum' numerical reconstruction of the Late Weichselian ice cover over Severnaya Zemlya appears too large relative to geological data. This suggests that, in this model experiment, the imposed climate still delivers an excess of precipitation to this extremely cold and dry climatic region.

Further modelling work will adopt a full inverse approach to ice-sheet reconstruction, utilizing the chronologically controlled geological evidence on Late Weichselian ice-sheet extent shown in Fig. 1. In these experiments, the entire margin of the ice sheet will be forced to be compatible with the mapped margins. By varying the temperature and precipitation inputs to the model, and constraining the position of the ice margin, we will then be able to extract the likely palaeoclimate under which the Eurasian ice sheets developed.

Conclusions

We conclude that a huge ice sheet with major ice domes centred in the Barents and Kara seas advanced far onto the Russian continent between the White Sea and the Taimyr Peninsula during the Early/Middle Weichselian and impounded the northbound drainage into the Arctic Ocean. In contrast to the glaciations in Scandinavia, Great Britain and North America, the Early/Middle Weichselian ice sheets were much larger than those of the Late Weichselian glacial maximum. We now consider it proven beyond any doubt that the reconstruction of the Late Weichselian glacial maximum for the Russian Arctic proposed by Grosswald (1993, 1998), which is widely referred to in textbooks and used as a boundary condition in General Circulation Models, is incorrect and depicts ice sheets that are much too large. According to our reconstruction, the ice-sheet extent in the Eurasian Arctic during the Late Weichselian was less than half the size of Grosswald's (1993, 1998) reconstruction. With the possible exception of the northwestern coast of the Taymyr Peninsula, we conclude that the entire Russian mainland to the east of the White Sea was not inundated by the Barents or the Kara Ice Sheet during the Late Weichselian. Preliminary numerical-modelling experiments predict Late Weichselian ice sheets which are larger than the ice extent implied for the Kara Sea region from dated geological evidence (Figs. 1 & 2). This suggests that the palaeo-climate at the eastern margin of the Eurasian Ice Sheet is even drier than that used in our models.

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