The eastern extent of the Barents–Kara ice sheet during the Last Glacial Maximum based on seismic-reflection data from the eastern Kara Sea

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Keywords
Eurasian Arctic margin; glacigenic sediments; Kara Sea; Last Glacial Maximum; Pleistocene glaciations; sub-bottom profiling.

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doi:10.1111/j.1751-8369.2008.00061.x

Abstract

We present sub-bottom profiling (sparker and Parasound) results from the eastern Kara Sea, on the Eurasian Arctic margin, which enable the identification of the Last Glacial Maximum (LGM) ice extent. The analysed profiles show that glacigenic diamicton is ubiquitous at the seafloor, east of about 95°E and 78°N. The eastern margin of this diamicton is expressed in a conspicuous morainic ridge at the entrance to the Vilkitsky Strait, and to the south the diamicton projection aligns with the LGM limit mapped at the north-western Taymyr. The bottom of the Voronin Trough further north is also covered with diamicton and has numerous erosional bedforms, indicating a streamlined flow of grounded ice along the trough. Accurate dating of the diamicton is not attainable, but the correlation of pre-diamict sediments to well-dated sections in the Laptev Sea, and available ^{14}C ages from sediments on top of the diamicton, indicate its LGM age. These results support the palaeogeographic reconstruction that assumes the extension of the LGM Barents–Kara ice sheet as far east as Taymyr. This configuration implies that LGM ice blocked the drainage of the Ob and Yenisey rivers on the Kara shelf. This inference is consistent with the presence of large (>100 km wide) lenses of basin infill adjacent to the southern margin of the diamicton. However, the limited distribution of the eastern Kara ice lobe, not extending on Severnaya Zemlya, suggests that the ice was fairly thin and short-lived: insufficient for the accumulation of the gigantic proglacial lakes that occurred during earlier glaciations.

Our knowledge of Quaternary glaciations in northern Eurasia, east of the Fennoscandian Ice Sheet, has significantly improved recently, largely thanks to the results of the Quaternary Environment of the Eurasian North (QUEEN) research programme (Fig. 1; Svendsen, Alexanderson et al. 2004; Mangerud et al. 2004; Larsen et al. 2006). This knowledge involves the distribution of ice masses on the continental shelf of the Barents and Kara seas and adjacent land, the damming and rerouting of voluminous, north-flowing rivers, and the related large-scale changes in the Eurasian climatic system. Paradoxically, in many aspects the bounds of the Barents–Kara ice sheet for the Last Glacial Maximum (LGM) are understood less than for older Weichselian glaciations, because the ice sheet covered land to a lesser extent, and the marine data coverage is insufficient for a comprehensive mapping of the ice limits. One of the least understood aspects is the eastward extent of the Late Weichselian ice sheet in the Kara Sea (Fig. 1). This gap in our knowledge considerably restricts the overall understanding of the LGM climatic ensemble, especially our ability to assess the contemporaneous discharge of Siberian rivers into the Arctic Ocean and to reconstruct Eurasian ice-sheet dynamics during and after the LGM. The up-to-date reconstructions (Svendsen, Alexanderson et al. 2004; Svendsen, Gatauliin et al. 2004) tentatively draw an ice-sheet margin along the western coasts of the Severnaya Zemlya archipelago, and connect it with the LGM

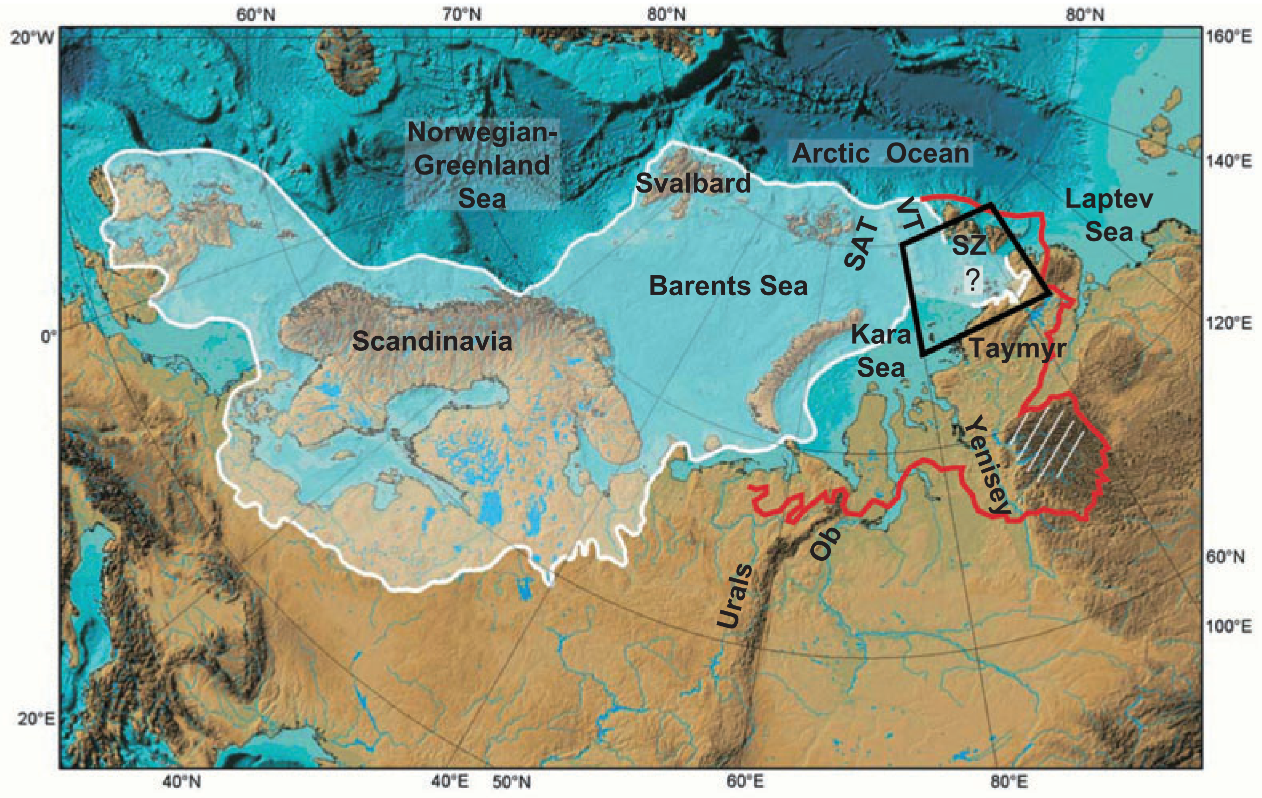

Fig. 1 Existing reconstruction of the Last Glacial Maximum in north-western Eurasia (modified from Svendsen, Alexanderson et al. 2004), illustrating the uncertainty of the eastern ice-sheet limit. The red line shows the maximal limit of the Barents–Kara ice sheet in the Late Pleistocene. The area of this study is boxed. Abbreviations: SAT, St. Anna Trough; SZ, Severnaya Zemlya; VT, Voronin Trough.

ice-marginal zone mapped on the northern Taymyr Peninsula (Alexanderson et al. 2001). This configuration featuring the unusual, elongated shape of the proposed ice-sheet extension towards Taymyr implies that the great west-Siberian rivers Ob and Yenisey were ice-dammed during the LGM, at least for some time. On the other hand, studies of sediment cores from the central Arctic Ocean indicate only a very minor influence of the LGM Eurasian ice sheets and deglacial discharge, in comparison with the earlier glaciations (Spielhagen et al. 2004). This implies that if ice-damming occurred in the Kara Sea during the LGM, it was not of a similar extent and/or duration compared with earlier glaciations. This paper aims to elucidate the problem of the eastern margin of the LGM ice sheet in the Kara Sea, based on marine geophysical/geological data.

Glacial-geological context in the Barents and Kara seas

Throughout most of the Barents Sea and the western part of the Kara Sea, seismic reflection records and sediment cores/boreholes that characterize the mostly thin (tens of metres) and patchy Quaternary sedimentary package show glacigenic diamicton at its base, unconformably truncating the easily deformable, largely Mesozoic bedrock strata (e.g., Elverhøi & Solheim 1983; Vorren & Kristoffersen 1986; Gataullin et al. 1993; Polyak et al. 1995; Polyak, Gataullin et al. 2000; Polyak, Levitan et al. 2000). Post-diamict sediments in these areas lack any evidence for a change from highstand to lowstand, and then back again to highstand, system tracts, as reported for example for the western Laptev Sea (Kleiber et al. 2001). Therefore, for most of the Barents Sea and the western part of the Kara Sea, the seismostratigraphic character of post-diamict sediments indicates that they were not controlled by falling and then rising sea levels, but were deposited only since the last (Late Weichselian) glaciation. This interpretation is corroborated by multiple radiocarbon ages from a number of localities, dating the oldest sediments above the diamicton to be slightly older than 13–14 Ky, and the transition from glaciomarine to fully marine environments near 9–10 Kya (Polyak et al. 1995; Vorren & Laberg 1996; Polyak, Gataullin et al.

2000; Svendsen, Gataullin et al. 2004, and references therein).

The above stratigraphy becomes more complicated in the shallow south-easternmost part of the Barents Sea (also known as the Pechora Sea), and further east, in the southern Kara Sea (Polyak, Gataullin et al. 2000; Polyak, Levitan et al. 2000; Gataullin et al. 2001; Gataullin et al. 2003; Dittmers et al. 2008). Glacigenic diamictons may occur here at the base of the Quaternary package, but the overlying deposits are generally thicker and have a more complex structure than in the Barents Sea. Thus, a large portion of this post-diamict section is composed of a complex seismo-/lithostratigraphic unit, interpreted to reflect an advance of nearshore/prodeltaic environments across the shelf with the falling sea levels, similar to the seismostratigraphy established in the western part of the Laptev Sea (Kleiber et al. 2001). Combined with ^{14}C ages from respective boreholes ranging to >30 Kya, this stratigraphy can be attributed to the time interval since the penultimate, not the last, glaciation of the Barents–Kara shelf. Accordingly, the geographic boundary between the two types of stratigraphy has been interpreted to reflect the south-eastern margin of the LGM Barents Sea ice sheet (Polyak, Gataullin et al. 2000; Gataullin et al. 2001), which is generally consistent with the up-to-date mapping of ice-sheet limits on adjacent land (Svendsen, Alexanderson et al. 2004). The extension of this boundary into the Kara Sea is not straightforward because of the generally high sediment thicknesses, the predominance of nonmarine or brackish-water facies lacking datable material, and the pervasive disruption of sedimentary records by permafrost and gas seepages (Gritsenko & Bondarev 1994).

The initial evidence has demonstrated that in general the LGM glacigenic diamicton extends eastwards across the northern Kara Sea, sparing its more southern areas (Polyak, Gataullin et al. 2002; Stein et al. 2002). However, the relationship of this glacigenic unit with the LGM morainic formation on the northern coast of Taymyr (Alexanderson et al. 2001) has remained unclear, especially as the lack of LGM glacial deposits on the major islands of Severnaya Zemlya became evident (Raab et al. 2003; Berger et al. 2004; Möller et al. 2006). Investigation of the southern Kara Sea by means of geoacoustic profiling (Dittmers et al. 2008) did not resolve this issue because of the weak penetration of echo soundings into sediments with high acoustic impedance, and a limited geographic coverage bounded by 78° N and 90° E. The exposure of the shallow southern Kara Sea shelf to extensive winnowing further complicates the interpretation of the history of sedimentary environments in this region.

We focus this paper on characterizing the distribution of glacigenic diamictons and the proglacial features in the eastern Kara Sea by using sub-bottom profiling data that indicate the overall geometry of diamict bodies, or at least clearly identify their top surface. To achieve this purpose, we utilize mostly unpublished marine data collected in the eastern Kara Sea on several expeditions by light seismic-reflection (sparker) or geoacoustic (Parasound) profiling (Fig. 2). As the data presented in this paper are compiled from several expeditions, the database does not form a systematic grid of lines over the large area of the eastern Kara Sea. However, the lines do cover several key areas for the identification of the distribution of glacigenic diamictons and related sedimentary facies, and for their placement into a stratigraphic framework. This compilation, therefore, enables a new level of understanding of the glacial impact on the sea floor in the eastern Kara Sea, and a much more definitive outlining of ice-sheet grounding limits than has been available from earlier studies.

Materials and methods

The parasound records under study (>1500 km in total) were obtained on RV *Polarstern* cruises ARK IX/4 and ARK XI/I (Damm et al. 1994; Stein et al. 1997) along the cruise tracks across the Kara Sea to and from the Laptev Sea, including the line along ca. 87° E in the Voronin Trough north of the area characterized by detailed bathymetry in Fig. 2. Technical characteristics of the equipment and data processing have been discussed elsewhere (Grant & Schreiber 1990; Kleiber et al. 2001). Sparker data (ca. 1300 km in total) were recorded in 2001 from HV *Gidrolog* (Polyak, Gataullin et al. 2002; Gainanov et al. 2005). The sparker system used 600 J of energy and maintained a central frequency of ca. 400 Hz, and had a signal length between 4 and 5 ms, which allowed a combination of a considerable (100+ m) sediment penetration with a fairly high resolution of at least 3–4 m. This configuration was especially beneficial for mapping glacigenic sediments that typically have high acoustic impedance, and are thus mostly impenetrable for higher resolution acoustic profilers. The signal was registered in the frequency band between 30 and 2000 Hz, but some records were later filtered at 60–1000 Hz to reduce noise and multiples. For a broader geographic coverage, we also used lower frequency sparker records collected in the 1980s (Vinogradov 1987). About 100 km of Parasound and 50 km of sparker profile sections are presented in Figs. 3–9 to exemplify key sites for understanding the distribution of glacigenic and related sea floor features in the eastern Kara Sea (see Fig. 2 for locations). To improve the sea floor morphological context for sub-bottom data, detailed hydrographic bathymetry charts from the eastern Kara Sea were

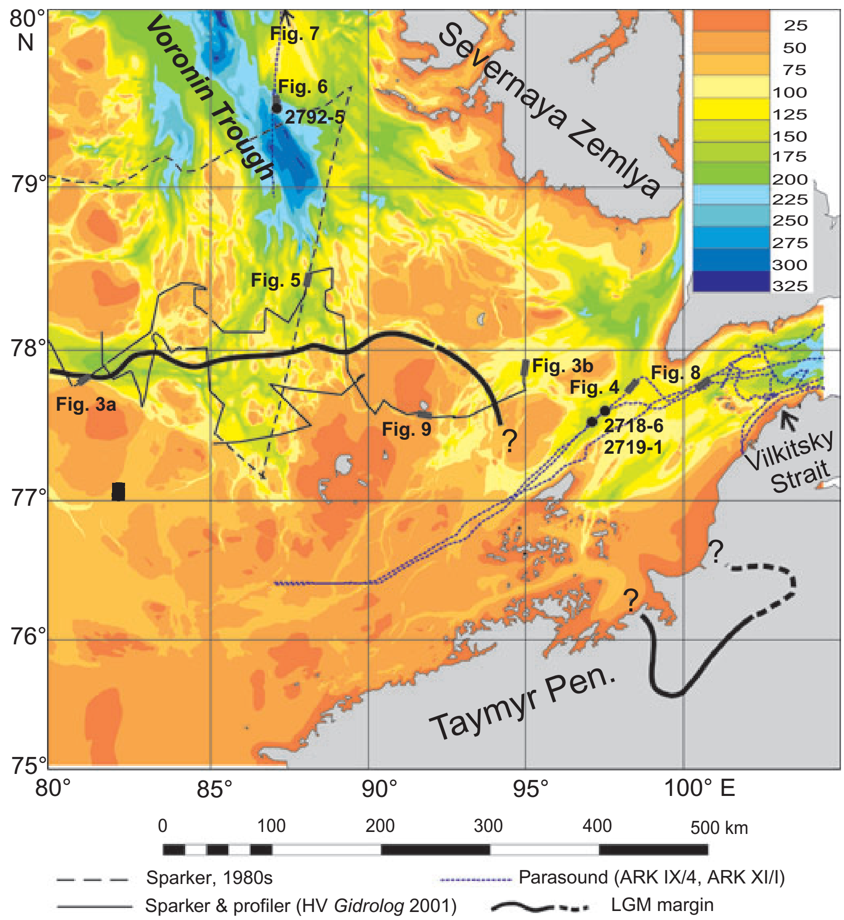

Fig. 2 Bathymetric chart of the eastern part of the Kara Sea, indicating the location of the sparker and Parasound lines, and sediment cores, discussed in the paper, as well as the earlier suggested position of the Last Glacial Maximum margin on the shelf (Polyak, Gataullin et al. 2002) and on north-western Taymyr (Alexanderson et al. 2001). Bathymetry was compiled from hydrographic charts with a scale of 1 : 200 000.

compiled with depth contour lines of 25 m (Fig. 2). Most of the charts have a scale of 1 : 200 000, and indicate sounding points spaced typically at 0.5–5 km apart. Depths were additionally verified along all available sub-bottom data lines.

Seismostratigraphic results

Diamicton distribution

Sparker records from the northern part of the study area (north of ca. 78° N) consistently show a characteristic sedimentary unit with irregular geometry, uneven, relief-forming top surface, sharp erosional bottom that truncates the underlying stratified deposit, and a chaotic to transparent acoustic signature lacking coherent internal reflectors (Fig. 3). These characteristics are indicative of glacigenic diamictons described widely from the more western areas of the Barents–Kara shelf (e.g., Elverhøi & Solheim 1983; Vorren & Kristoffersen 1986; Polyak et al. 1997; Polyak, Levitan et al. 2000; Gataullin et al. 2001), as well as elsewhere on glaciated continental margins of Eurasia, North America and Antarctica (Davies et al. 1997). The ubiquitous truncation of pre-diamict strata underlines the erosional character of contact typical for subglacial processes, similar to the Upper Regional Unconformity of the Barents Sea (e.g., Vorren & Kristoffersen 1986; Andreassen et al. 2008), whereas the uneven top surface of the diamicton may reflect a combination of sediment accumulation (ridging) and erosional processes during deglaciation. The truncated stratified deposit underneath the diamicton is consistently observed on seismic-reflection records in the study area, and further west, typically with an inclined bedding, including syn- or anticlyne structures, and a composite thickness of hundreds of metres. These strata have been identified in the northern Kara Sea as pre-Quaternary, mostly Mesozoic to Paleogene sedimentary bedrock (Vinogradov 1987; Okulitch et al. 1989; Shipilov & Matishov 2006). Another stratified, mostly horizontally bedded unit overlies the diamicton in topographic depressions, where this sediment may reach a few tens of metres, whereas, on topographic heights diamicton is commonly almost exposed (e.g., Figs. 3a, 4). The

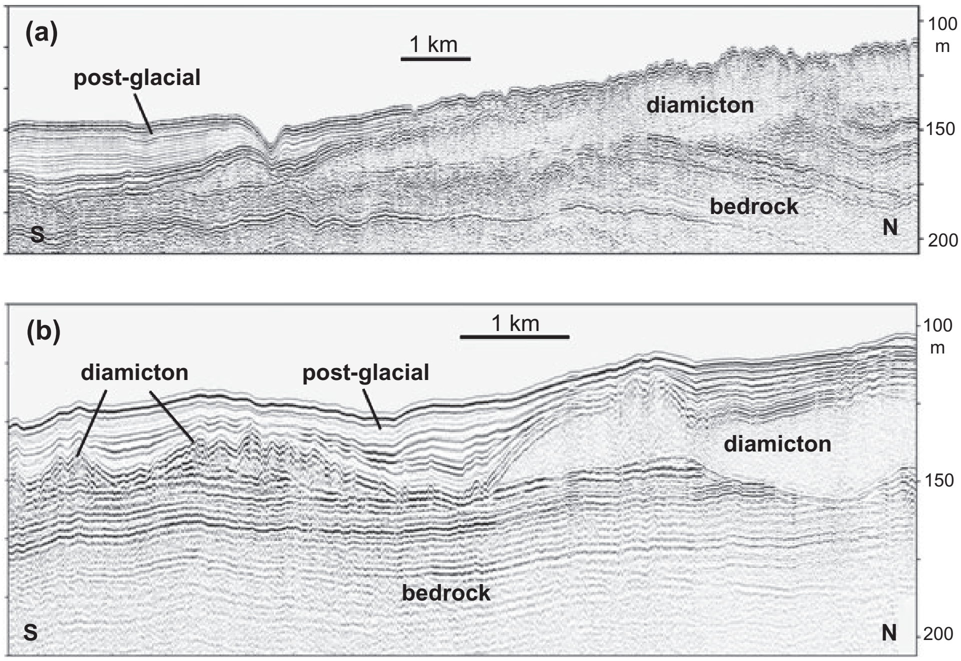

Fig. 3 Sparker lines from (a) the western part of the study area and (b) west of the Vilkitsky Strait, showing glacigenic diamicton wedges emplaced over the truncated bedrock, and overlain by stratified postglacial sediments; location shown in Fig. 2.

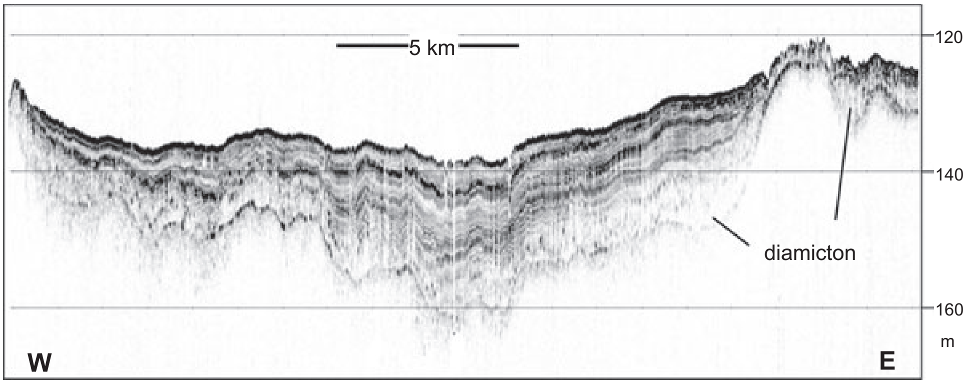

Fig. 4 1993 Parasound record west of the Vilkitsky Strait showing a lens of postglacial deposits infilling a sea floor depression with diamicton at the lens bottom; location shown in Fig. 2.

stratified infill may have been formed by a combination of deglacial inputs and then sediment redistribution during the postglacial sea-level rise. Although discontinuous (within the sparker record resolution), the diamict unit can be traced in the area west of the Vilkitski Strait to ca. 94° E, and does not occur further west. Parasound records collected in this area generally have a more limited penetration than sparker records, but typically allow an identification of at least the upper surface of the diamicton, and a characterization of stratified post-diamict sediments. At some portions, these records clearly show a widespread relief-forming, chaotic-signature unit, and the overlying stratified infill in the depressions (Fig. 4).

A principally similar stratigraphy characterizes both sparker and Parasound records from the Voronin Trough area further north. The character of sea floor erosion here is accentuated by large erosional forms, up to 4 km wide and 50 m high, carved in the bedrock and partially infilled with diamicton, with well-stratified post-diamict sediments crowning the stratigraphy (Figs. 5, 6). Detailed bathymetry charts indicate that these excavations have

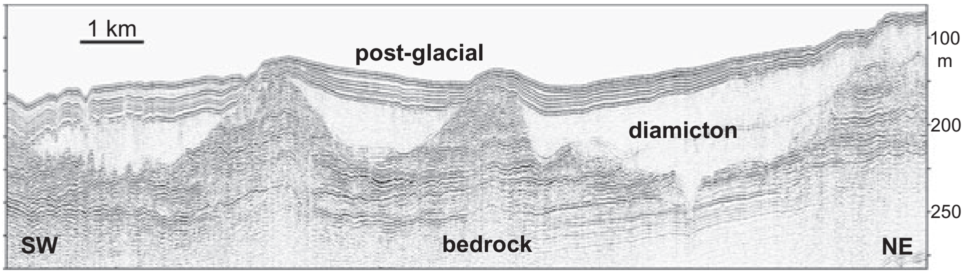

Fig. 5 Sparker line Gidr-01-15-2 from the southern end of the Voronin Trough. The record shows large erosional forms carved in the bedrock and partially infilled with diamicton, with stratified post-diamict sediments on top. A reflector within the diamicton separates either two generations or two different facies of glacial deposits; location shown in Fig. 2.

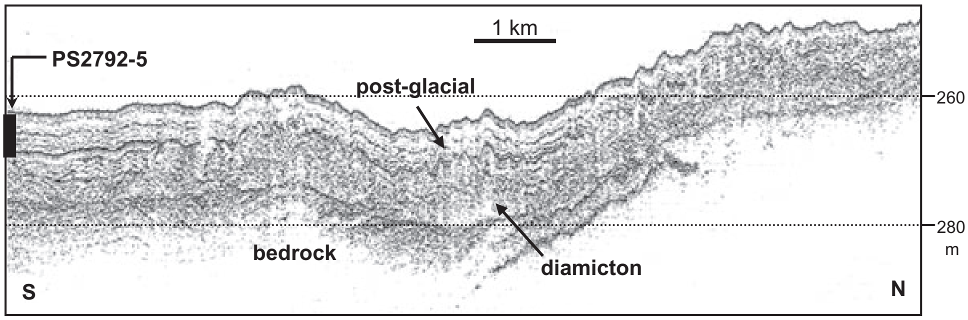

Fig. 6 1995 Parasound record from the Voronin Trough near the PS2792-5 core site. The core ends in the diamicton top; location shown in Fig. 2.

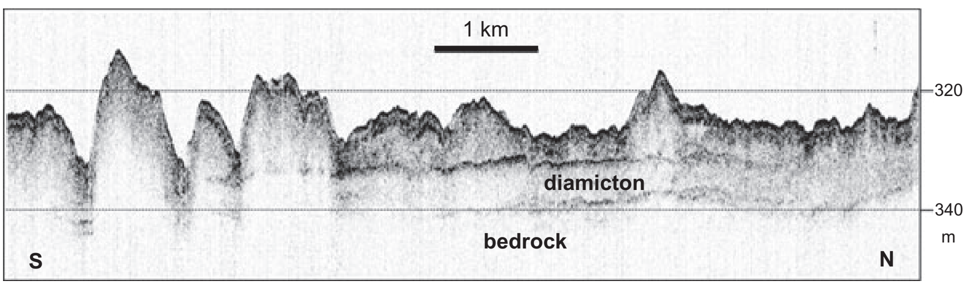

Fig. 7 1995 Parasound record from the Voronin Trough at ca. 81° N and 87° E (north of the margin of Fig. 2), showing morainic accumulations on top of eroded bedrock. A strong internal reflector in the diamicton possibly separates basal and ice-contact tills. See Fig. 5 for a better characterization of the bedrock.

elongated shapes and are generally aligned with the trough; however, the resolution of the bathymetric data is still insufficient to constrain the placement of the smaller scale morphological features, such as gouges and ridges/mounds, which occur at the top and, in some places, the bottom of the diamicton in this area. The Parasound record along 87° E further north (e.g., Fig. 7) shows that the diamicton is represented by a series of ridges that can be as large as 20 m high, and are complicated by smaller scale gouges, which can be attributed to iceberg scouring; in places the ridges are regularly spaced, similar to the fluted/drumlinized sea floor in the St. Anna Trough (Polyak et al. 1997).

To the east, the diamicton can be traced on Parasound records to the entrance of the Vilkitski Strait, at ca. 100°30′ E, where this unit forms a conspicuous, up to 20-m-thick and at least 10-km-across, accumulation (ridge) that wedges out eastwards (Fig. 8). This diamicton rests upon a stratified to transparent unit more than 50 m thick that infills depressions in the substratum topography, and can be correlated to the earlier investigated stratigraphy in the Vilkitski Strait and adjacent western Laptev Sea with ^{14}C ages extending to >35 Ky (Kleiber et al. 2001). East of this morainic ridge, a deposit that could be interpreted as diamicton in a similar stratigraphic position has not been encountered, except for a

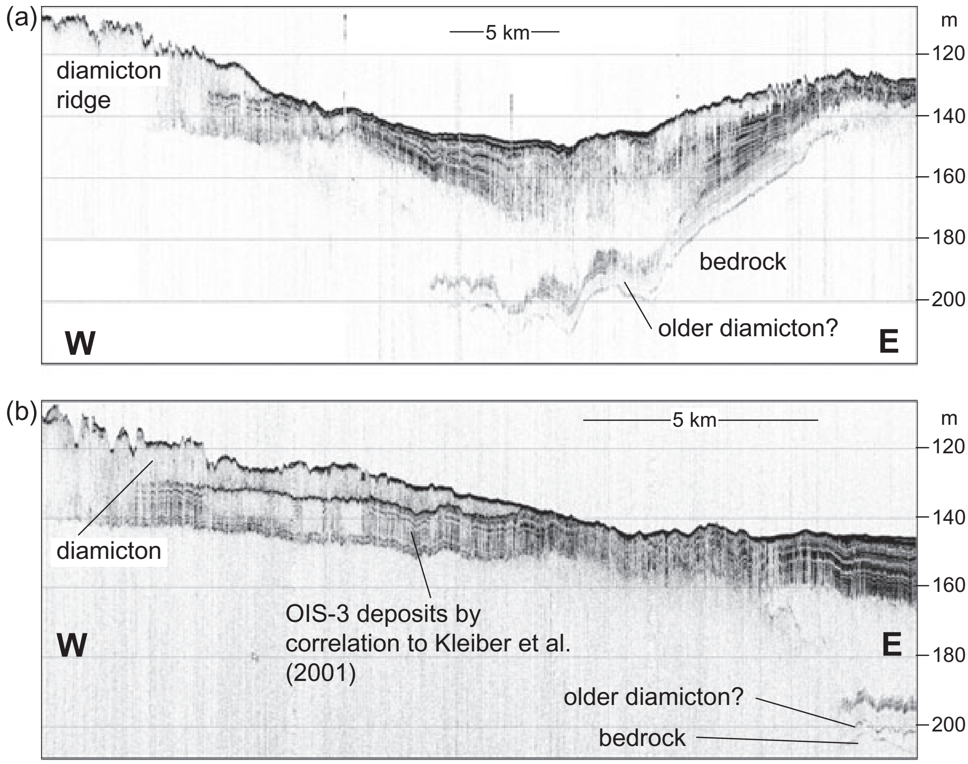

Fig. 8 (a) 1993 and (b) 1995 Parasound records from the western entrance to the Vilkitsky Strait showing a young morainic ridge on top of stratified sediments. The lower panel shows a more detailed picture of the ridge (note the larger horizontal scale); location shown in Fig. 2.

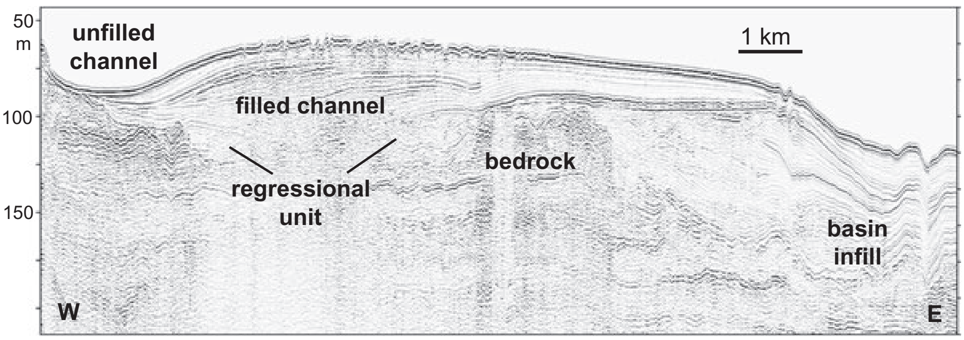

Fig. 9 Sparker line Gidr-01-17-6, south of the Voronin Trough, showing the progradational unit with the incised channel system and an infilled basin west of the Last Glacial Maximum diamicton limit; location shown in Fig. 2.

restricted area ca. 20 km across between 101 and 102° E. Instead, an older, relict generation of diamicton can be identified at several locations within the Vilkitski Strait, especially at local topographic heights (sills) (e.g., Damm et al. 1994: fig. 8.1–7).

Extra-diamict areas

In relatively deep areas of the Vilkitski Strait and adjacent western Laptev Sea, sediments on top of bedrock and/or a relict diamicton (where identified) are well stratified to transparent, and have a conspicuous basin-infill geometry. Based on seismic and sediment core stratigraphy, Kleiber et al. (2001) concluded that these sediments were deposited during the regressive–trangressive cycle encompassing the last interstadial (oxygen isotopic stage 3 [OIS 3]), the LGM and the Holocene. The shallow seafloor of the Laptev Sea further east is severely affected by permafrost and ice gouges, and is therefore unfavourable for seismostratigraphy.

In shallow areas of the southern Kara Sea outside the diamicton boundary, Quaternary deposits are largely characterized by a complex seismic reflection pattern, including common discontinuous, hummocky reflectors and prograding structures, as well as multiple channels up to 50 m deep and 5 km wide, both filled and unfilled with sediments (e.g., Fig. 9; Polyak, Gataullin et al. 2002; Stein et al. 2002; Gataullin et al. 2003). This unit, which is up to 100 m thick and is best characterized by sparker records, has been attributed to the propagation of nearshore/prodeltaic facies during the sea-level fall, similar to its stratigraphic counterpart in the Pechora Sea (Gataullin et al. 2001). Numerous distortions of seismic reflection may have resulted from the action of permafrost on the emergent sea floor, which is corroborated by the findings of frozen sediment in boreholes from the south-western Kara Sea (Gritsenko & Bondarev 1994). Areas fringing the progradational unit at water depths larger than about 70 m feature stratified sediment infill (e.g., Fig. 9; Polyak, Gataullin et al. 2002) similar to that found in the Vilkitski Strait (Kleiber et al. 2001). The largest basins, with up to 100-m-thick stratified deposits, are located at the mouths of major channels. To the east and/or north these basins are adjacent to the diamicton, with the upper part of the basin infill overlapping the diamicton to some extent (Fig. 3a). An erosional surface is widely recognized on top of the progradational unit, and can sometimes be traced in adjacent basin-fill deposits as a strong reflector. This surface constitutes an important regional stratigraphic marker that can be correlated as far west as the Pechora Sea, where it has been shown to represent the last sea-level lowstand (Polyak, Gataullin et al. 2000; Gataullin et al. 2001).

Age control

On sonar records running along the Vilkitski Strait, a package of well-stratified sediments overridden by the diamict ridge at the western entrance to the strait (Fig. 8) can be confidently correlated to marine deposits in the strait and adjacent western Laptev Sea (Khatanga Bay), which have been dated to OIS 3 and younger ages (Kleiber et al. 2001). This excludes the possibility that the ridge is part of widespread diamict deposits in and east of the Vilkitsky Strait, which are underlying OIS 3 sediments, and were probably formed during OIS 4 ("older diamicton" in Fig. 8) (Kleiber et al. 2001). Thus, the stratigraphic position indicates that the diamicton ridge in Fig. 8 was formed during the LGM. Consistently, only about 5–10% of sedimentary infill of the basin in front (east) of the ridge appears to be stratigraphically younger than the diamicton, which is similar to the proportion of Holocene sediments identified in basin infill deposits

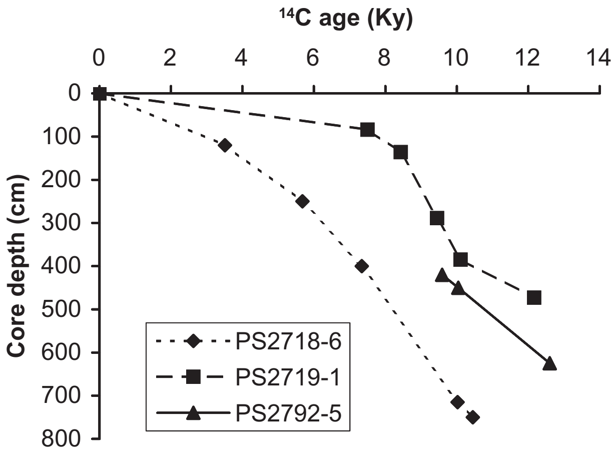

Fig. 10 Position of ^{14}C ages in sediment cores PS2718-6, PS-2719-1 and PS2792-5 (see Stein et al. 2001 and Levitan et al. 2000 for the age data). The diamicton surface is at ca. 680 cm in core PS2792-5 (see Fig. 6 for the accompanying sub-bottom record); location shown in Fig. 2.

further east (Kleiber et al. 2001). Westwards, well-stratified pre-diamict sediments are not preserved within the area of diamicton distribution, so that it rests directly on bedrock. Although thinning out and identified discontinuously, this younger (LGM) diamicton can be consistently found westwards to ca. 94°E on both Parasound and sparker records west of the Vilkitski Strait. This distribution, combined with a consistent character of diamicton emplacement and preservation, suggests that it was formed by the same glacial event.

^{14}C ages of two sediment cores from a lense of post-diamict stratified sediments west of the Vilkitski Strait, next to the one illustrated in Fig. 4, go back to ca. 10 and 12 Kya (Fig. 10; Stein et al. 2001; Levitan et al. 2000). Extrapolation of sedimentation rates of ca. 0.4 m Ky^{-1}, estimated between the two lowermost ages in PS9519-1, suggests that this stratified sediment might extend back in time beyond the LGM (Stein et al. 2001). However, the overall pattern of age–depth distribution indicates generally much higher rates of late glacial and early Holocene deposition of near 1 m Ky^{-1} (Fig. 10), which is consistent with data from similar stratigraphic settings in the south-western Kara Sea and Pechora Sea (Polyak, Gataullin et al. 2000; Polyak, Levitan et al. 2000; Polyak, Levitan et al. 2002), and cautions against simple linear extrapolation. It is likely that the generally massive sediment deposition during deglaciation and sea-level rise was interrupted by episodes with relatively low sedimentation rates, possibly related to climatic deteriorations (Polyak, Levitan et al. 2002; Stein et al. 2004). Overall higher deglacial sedimentation rates imply a younger age estimate for the surface of diamicton, consistent with the seismostratigraphy discussed above.

Several cores from the northern part of the Voronin Trough (Polyak, Levitan et al. 2002) have been shown to feature the diamicton and postglacial stratigraphy similar to that in the St. Anna Trough dated to the last deglaciation (Polyak et al. 1997; Hald et al. 1999). This interpretation is corroborated by the ^{14}C ages in core PS2792-5 (Stein et al. 2001), where the lower dating of ca. 12.5 ^{14}C Kya is located in laminated deglacial sediments just ca. 60-cm above the top surface of acoustically chaotic diamicton accumulation emplaced upon a truncated bedrock (Fig. 6). Thus, the diamicton in the Voronin Trough has the same LGM age as diamictons west of the Vilkitski Strait and the youngest morainic formation on the north-western coast of Taymyr, dated as younger than ca. 20 Ky (Alexanderson et al. 2001).

Interpretation and palaeoglaciologic implications

The characteristic pattern of seismic records associated with the diamicton in the study area (Figs. 3–8), including its uneven geometry, mostly unrelated to the underlying topography, and the conspicuous erosional bottom boundary extending to water depths of several hundred metres, indicate subglacial and/or ice-contact formation of the diamicton. These features contrast with sedimentary units that occur in extra-diamict areas as well as stratigraphically above the diamicton, and are apparently related to various subaqueous environments. The distribution of the diamicton, combined with seafloor morphology indicative of ice impact, can therefore be used for mapping the ice grounding limits, as has been done in the more western areas of the Barents–Kara shelf (e.g., Elverhøi & Solheim 1983; Vorren & Kristoffersen 1986; Polyak et al. 1995; Polyak et al. 1997; Gataullin et al. 2001), as well as on many other glaciated continental margins (Davies et al. 1997).

The distribution of predominant seismic stratigraphies on Parasound and high-resolution sparker records, with the postglacial sediment removed, is presented in Fig. 11. Low-resolution sparker lines, where interpretable, show compatible results. The diamicton, which is dated or correlated with the LGM, is ubiquitous north of about 78° N, and is also conspicuously present further south in the

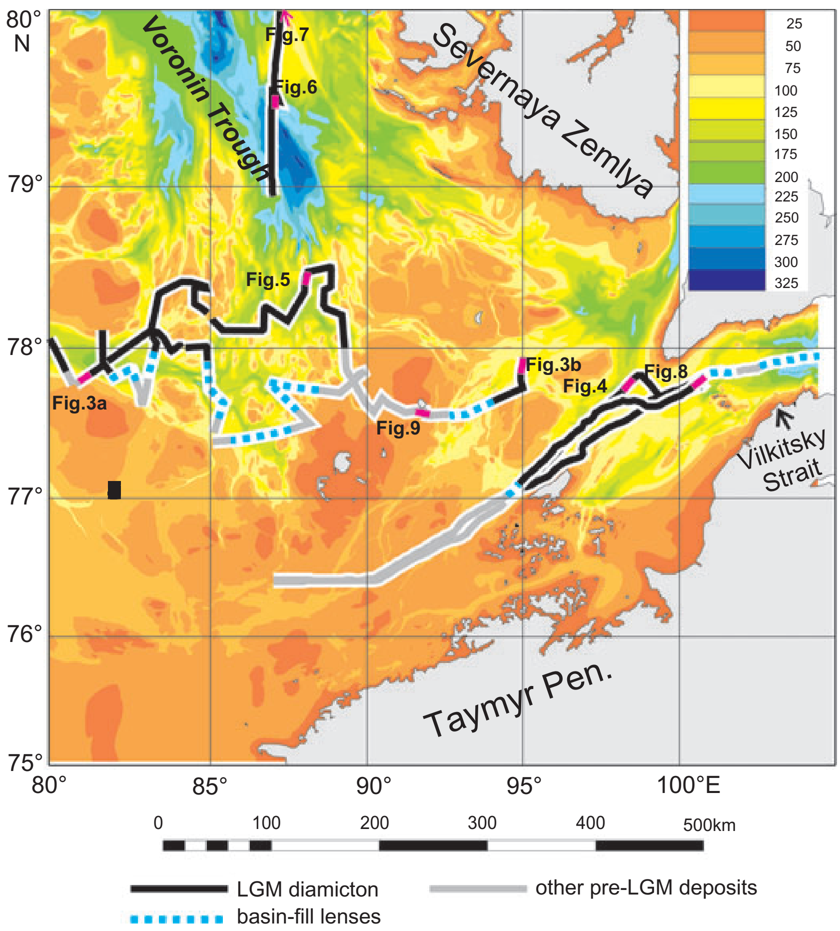

Fig. 11 Geographic distribution of the predominant seismostratigraphic features (with postglacial sediment removed) on Parasound and high-resolution sparker profiles. The sites of Figs. 3–9 are shown in magenta.

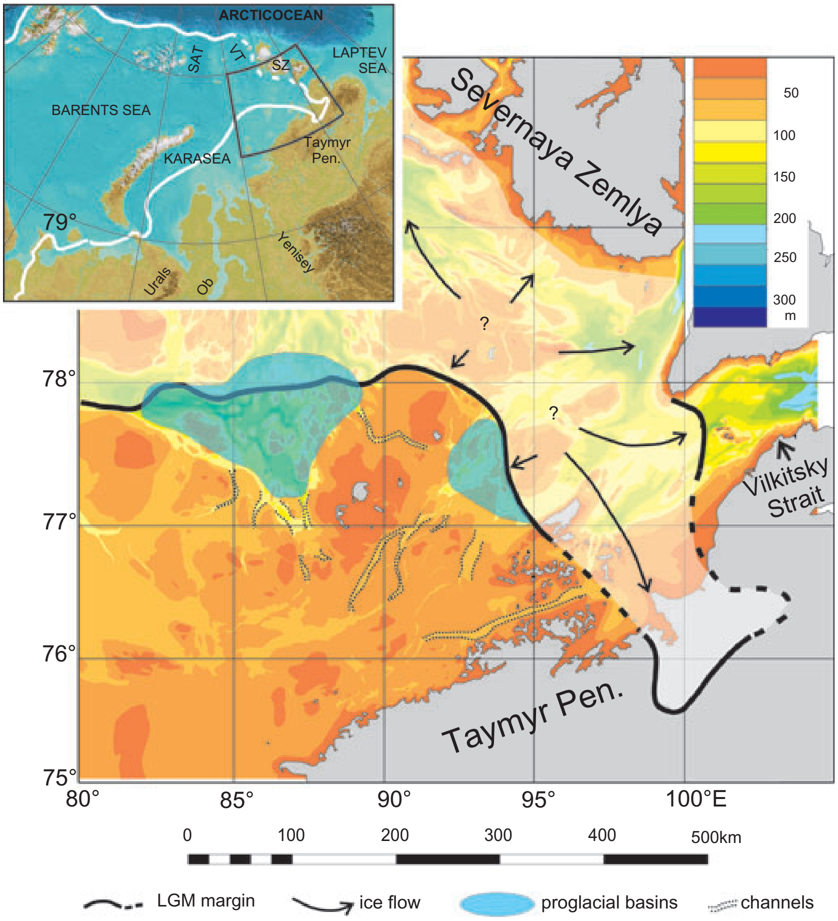

Fig. 12 Overview map of the eastern Kara Sea with the proposed Last Glacial Maximum (LGM) ice coverage (semitransparent white fill) and major proglacial basins (blue fill) based on the distribution of glacigenic diamictons and related sedimentary facies (Fig. 11). The extrapolated connections of the ice limits on the shelf and on Taymyr are indicated by the dashed lines; the problematic ice limit near Severnaya Zemlya is not outlined. Arrows show a tentative reconstruction of ice movement in the eastern Kara Sea ice lobe. Dotted lines show major exposed fluvial channels in extra-diamict area. The insert shows a broader overview of the LGM Barents–Kara Ice Sheet based on QUEEN reconstructions (Svendsen, Alexanderson et al. 2004) and confirmed by this study for the eastern Kara Sea.

area west of the Vilkitski Strait. Bathymetric lows adjacent to the diamicton margins feature thick basin-fill lenses that have been shown in the Vilkitski Strait to cover the time period extending to marine isotope stage 3 (MIS 3) (Kleiber et al. 2001). Other than these basins, the seafloor in the southern Kara Sea is mostly underlain with progradational pre-LGM deposits, intersected by multiple filled or unfilled channels. These deposits are best characterized on sparker records.

The consistent presence of the LGM glacigenic diamicton in the Voronin Trough and west of the Vilkitski Strait, as well as on the respective portion of the north-western Taymyr coast (Alexanderson et al. 2001) indicates that the eastern part of the Kara Sea has contained a sizeable grounded ice mass (Fig. 12). Although data coverage is insufficient to map the ice limit in detail, the good alignment of inferred ice margins favours the existence of a unified ice sheet (lobe), connected at the north-west to the main Barents–Kara ice sheet, rather than separate small ice caps. Although the south-western margin of this ice lobe is relatively well defined by the seismic evidence exemplified in this paper, its eastern limit has only been documented so far in the entrance to the Vilkitsky Strait (Fig. 8). The diamicton at this site is emplaced at the approaches to Severnaya Zemlya, but appears not to transgress the archipelago (Fig. 12), which is consistent with the lack of evidence for a unified LGM ice sheet on Severnaya Zemlya (Raab et al. 2003; Berger et al. 2004; Möller et al. 2006). Based on this pattern and the indications for the LGM glacial grounding in the Voronin Trough, we have mapped the north-eastern ice-sheet boundary close and more or less parallel to the Severnaya Zemlya coastline (Fig. 12), similar to a suggestion by Svendsen, Alexanderson et al. (2004). The dynamics and exact age of this ice mass is yet to be understood. The LGM till on the north-western Taymyr has been dated by radiocarbon dating to between ca. 20 and 12 ^{14}C Kya (Alexanderson et al. 2001), but the actual timing of its emplacement could be shorter than this interval. The marine sediment cores collected so far cannot provide a better age constraint, especially because of the pervasive absence of datable material in pro-glacial sediments. It is possible that the eastern Kara Sea ice tongue was built up when the main Barents–Kara ice sheet sagged, and opened way for moisture supply from the North Atlantic during deglaciation (Siegert & Dowdeswell 2004).

The bathymetry compilation performed provides some insight into the ice dynamics, especially in the Voronin Trough area, where medium-scale morphological features generally align with the orientation of the trough (Fig. 2), thus indicating a streamlined movement of ice along the trough. A higher resolution, swath bathymetry charting is needed to verify this pattern, and to map bedforms indicative of the direction of ice movement, such as has been performed for the Norwegian shelf and western Barents Sea (Ottesen et al. 2005; Andreassen et al. 2008). The diamicton distribution at shallower areas south of the Voronin Trough suggests that the ice tongue extending to the Taymyr was thin, as this ice was unable to override even small sea floor elevations at the approaches to Severnaya Zemlya and in the Vilkitsky Strait. The flow pattern of this ice is not clear. One possibility is that a local ice-spreading center existed on the shallow banks west of the southern part of Severnaya Zemlya, and coalesced with the main Kara ice dome located further west (Fig. 12). A detailed multibeam mapping of the sea floor in the study area may provide clues to the understanding of ice dynamics; further reconstruction of this ice lobe needs to employ palaeoglaciologic modelling.

The existence of large basins—exceeding 100 km wide—infilled with well-stratified sediments adjacent to the mapped ice margin from the south-west (Fig. 12), allows the interpretation that the flow of western Siberian rivers on the Kara Sea shelf was impinged upon by the LGM ice sheet for at least some time. Although these basins apparently started to form as estuarine accumulations during the low sea-level stand (Polyak, Gataullin et al. 2002; Dittmers et al. 2008), their consistent proximity to the LGM diamicton indicates the likelihood that at least part of the infill was deposited in ice-dammed conditions. The buried channels south of the basins might be related to this impingement, whereas unfilled channels could have been cut into pre-existing channel fill after the breaching of the ice dam, while the sea level was still relatively low. The accurate estimate of the extension of ice-dammed lakes on the shelf is not possible because soft sediments were eroded from shallow areas during the succeeding transgression. That said, we acknowledge that the overall area of these lakes was obviously much smaller than those formed during earlier glaciations (Mangerud et al. 2004). This implies that the LGM impingement of western Siberian rivers was likely to have occurred for a fairly short time, consistent with the above interpretation of the age constraints and ice dynamics of the mapped eastern Kara Sea ice tongue.

In summary, our data confirm that the LGM Barents–Kara ice sheet did impinge on the north-western coast of Taymyr, and filled the Voronin Trough at least for a short time, but did not have enough mass/height to transgress onto the Severnaya Zemlya archipelago. More studies, notably including swath sea floor mapping and palaeoglaciologic modelling, are needed to to fully understand the dynamics of this ice sheet.

Acknowledgements

Work on this paper was supported by the US National Science Foundation award OPP-0221468 to LP. We thank the crews and scientific parties of the RV *Polarstern* cruises ARK-IX74 and ARK-XI/1 and HV *Gidrolog* 2001. P. Rekant (All-Russia Research Institute of Geology and Mineral Resources of the World Ocean) assisted with mapping the seismic data. Comments from two anonymous reviewers helped to improve the manuscript.

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