Late Quaternary paleoclimatic reconstructions along the Eurasian continental margin

Spätquartäre paläoklimatische Rekonstruktionen entlang des Eurasischen Kontinentalhanges

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dedicated to my parents

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Die vorliegende Arbeit ist die inhaltlich unveränderte Fassung einer Dissertation, die 1999 im Fachbereich Geowissenschaften der Universität Bremen angefertigt wurde.

Contents

Summary

Reconstructions of Weichselian glaciations along the Eurasian shelf range from isolated small ice caps over the Eurasian archipelagos to a large ice-sheets covering the entire Siberian shelf and extending far into continental Eurasia. The most recently published map of the maximum Weichselian ice sheet extents, reveals that the western Laptev Sea continental margin and the Franz Victoria Trough (FVT) are located at the ice sheet limits. Therefore, high resolution seismic profiles (PARASOUND, 4 kHz) recorded by the German R/V "Polarstern" and selected sediment cores of these two key areas were investigated to constrain timing and extent of the Weichselian glaciations and to test published reconstructions.

On the western Laptev Sea continental margin and the adjacent Vilkitsky Strait, four correlatable seismic units, named I (youngest) to IV, were identified in the upper Quaternary sedimentary succession.

Seismic unit I is a thin drape, mostly deposited during the post-glacial sea-level rise and dated to the Holocene.

Seismic unit II is characterized by wedge-shaped deposits along the western Laptev Sea shelf edge. These wedges are interpreted as river deltas and based on their present water depth formed during marine isotope stage (MIS) 2. The deltas indicate that the river runoff continued during the Weichselian sea-level lowstand during MIS 2. The exposure of the Laptev Sea shelf and the presence of active rivers are confirmed by permafrost and filled paleoriver channels identified in the PARASOUND profiles, respectively. In general, the filled paleoriver channels are located in the major submarine valleys of the Laptev Sea shelf and thus relict features of the present rivers Anabar, Khatanga, Olenek, Lena, and Yana. The paleoriver north of the Taymyr Peninsula and the New Siberian Islands, however, represent likely smaller drainage systems. The uppermost sediments of the Anabar-Khatanga sea-level lowstand deltas are characterized by an enhanced magnetic susceptibility. The increased input of magnetic grains is radiocarbon dated to approximately 13 - 10 ka and derives from the exposed magnetite schists and volcanic rocks of the Anabar shield and Putoran Plateau in the Anabar and Khatanga river catchments. Because the high magnetic sediment show comparable linear sedimentation rates (LSR) as the Holocene sediments of the Laptev Sea continental margin, the Putoran Plateau and Anabar shield must have released considerably higher quantity of eroded material. This increased input is most likely related to a deglaciation of the Putoran Plateau and/or Anabar shield and thus a strong indication for the local glaciations as suggested by other authors.

Seismic unit III is of draping character and the layered internal reflection pattern suggest undisturbed, hemipelagic conditions. An increasing thickness from the continental rise towards the shelf edge implies a sediment input from the Laptev Sea. However, the absence of submarine fan built-up along the shelf edge during the deposition of unit III indicates a lack of point sources. This implies a higher sea level compared to unit II. We suggest that the riverine outflow was closer to the shelf edge compared to today but further landward than during MIS 2. Consequently, the sediment input to the upper

continental slope was enhanced but less restricted to local depocenters compared to unit II.

Seismic unit IV is characterized by stacked transparent lenses, interpreted as debris flow deposits. The distribution of the debris flow deposits indicates that the debris were released at the shelf edge of the eastern Vilkitsky Strait and moved gravitationally through the Vilkitsky-Khatanga Channel down onto the continental rise. In high latitudes, submarine fans dominated by debris flows imply a periodic or continuous high sediment input by a fast-flowing glacier/ice sheet directly to the upper continental slope. Therefore, they are used as indication of an extensive glaciation on the continental shelf. We suggest that the high sediment input to the upper continental slope in the eastern Vilkitsky Strait derives from advances of the Kara Sea ice sheet and the ice covering Severnaya Zemlya. The absence of morainal ridges in the Vilkitsky Strait probably indicates that the grounding line reached the shelf edge during times of maximum extent of the ice sheet into the fjord-like Vilkitsky Strait. The lack of continuous debris flow deposits towards the Laptev Sea shelf edge clearly indicates that the ice sheet did not extend east of the Taymyr Peninsula onto the Laptev Sea shelf. In summary, our results are consistent with the recently published map of the maximum Middle Weichselian glaciations in area of the western Laptev Sea.

Stacked debris flow deposits were also identified in the PARASOUND profiles from the continental slope in front of the FVT. A grounding-line advance to the shelf break, which is approximated to 23 ^{14}C ka, is supported by the identification of diamicton, interpreted as basal till, near the shelf break. The distribution of the gravity flow deposits suggests that the FVT acted as conduit probably leading to an enhanced flow of the northern Svalbard/Barents Sea ice sheet (SBIS). An enhanced flow associated with an earlier glaciation, as suggested for the eastern Svalbard Islands, could help to explain the early advance of the northern SBIS to the shelf edge of FVT compared to western Svalbard. After several ice sheet instabilities marked by significant input of ice rafted detritus to the continental margin, the disintegration of the northern SBIS (Termination Ia) is indicated by an isotopically defined meltwater signal dated to 15.4 ^{14}C ka in association with a distinct pulse of ice rafted detritus. This initial disintegration may reflect a climatic influence through a reduction of precipitation in association with the cooling cycle predating the Heinrich event H1, the decoupling of the glacier bed due to an eustatically or isostatically induced rise in sea level and/or a response to increased summer insolation. The drastic change in sedimentary pattern on the upper continental slope, dated to about 13.4 ^{14}C ka, is interpreted as grounding-line retreat from the shelf edge. The further stepwise retreat of the northern SBIS is indicated by two distinct pulses of ice rafted detritus which appear to be contemporaneous with the onset of distinct ice rafting events and pulses of glacimarine sedimentation in adjacent areas between 13 and 9.4 ^{14}C ka. Bioturbation, which generally occurs throughout the entire core sections covering the debris flow deposits, suggesting seasonally open water conditions prevailed along the northern Barents Sea at least as far east as the FVT during the last glacial/interglacial cycle.

Kurzfassung

Die Modelle zur Rekonstruktion der Weichsel Eisschilde entlang des Eurasischen Schelfes reichen von isolierten kleinen Eiskappen auf den Eurasischen Inselgruppen bis hin zu einem zusammenhängenden Eisschild, welches den gesamten Eurasischen Schelf bedeckte und sich bis weit auf den Eurasischen Kontinent hinaus erstreckte. Kürzlich erschienene Rekonstruktionsmodelle der maximalen Ausdehnungen der Weichsel Eisschilde deuten an, daß der westliche Laptev See Kontinentalabhang und der Franz Victoria Trog an den jeweiligen Eisgrenzen lagen. In der vorliegenden Arbeit wurden hochauflösende seismische Profile (PARASOUND, 4 kHz) und ausgewählte Sedimentkerne dieser Schlüsselregionen auf geologische Hinweise mit dem Ziel untersucht, Zeitpunkt und maximale Ausdehnung der Weichsel Vereisungen zu belegen und bereits veröffentlichte Rekonstruktionsmodelle zu prüfen.

Auf dem westlichen Laptev See Kontinentalabhang und in der angrenzenden Vilkitsky Straße wurden im oberen Teil der quartären Ablagerungen vier korrelierbare seismische Einheiten, I (jüngste) bis IV, ausgeschieden.

Einheit I ist eine dünne Deckschicht holozänen Alters, welche während des post-glazialen Meeresspiegelanstieges abgelagert wurde.

Einheit II bildet entlang der westlichen Laptev See Schelfkante charakteristische keilförmige Ablagerungen. Diese Keile werden als Flußdeltas interpretiert und aufgrund ihrer heutigen Wassertiefe dem marinen Isotopenstadium (MIS) 2 zugeordnet. Die Flußdeltas deuten darauf hin, daß der Oberflächenabfluß während des Weichsel Meeresspiegeltiefstandes anhielt. Das Freiliegen des Laptev See Schelfes und das Vorhandensein aktiver Flüsse können durch die Permafrost Obergrenze bzw. die gefüllten Paläoflußrinnen in den PARASOUND Profilen belegt werden. Die Paläoflußrinnen liegen überwiegend in den großen submarinen Tälern des Laptev See Schelfes und können somit den Flüssen Anabar-Khatanga, Olenek, Lena und Yana zugeordnet werden. Die Paläoflußrinnen nördlich der Taymyr Halbinsel und der Neu Sibirischen Inseln deuten wir als Relikte lokaler Entwässerungssysteme. Die obersten Sedimentschichten des Anabar-Khatanga Meeresspiegeltiefstandsdeltas weisen stark erhöhte magnetische Suszeptibilitätswerte auf. Der erhöhte Eintrag von magnetischem Material, welcher von den aufgeschlossenen Magnetitschiefern und den vulkanischen Gesteinen des Anabar Schildes bzw. des Putoran Plateau stammt, ist auf 13 - 10 ka datiert. Weil die höher magnetischen Ablagerungen und die holozänen Sedimente des Laptev See Kontinentalsaumes vergleichbare lineare Sedimentationsraten aufweisen, muß auf dem Anabar Schild und dem Putoran Plateau erheblich mehr Material erodiert worden sein als in heutiger Zeit. Der erhöhte Eintrag und dessen Zeitpunkt deuten wir als Abschmelzsignal und somit als starkes Indiz für die von anderen Autoren vorgeschlagene Vergletscherung des Anabar Schildes und des Putoran Plateau.

Einheit III zeigt vorwiegend ein parallel geschichtetes Reflektionsmuster, welches auf ungestörte, hemipelagische Ablagerungsbedingungen schließen läßt. Eine zunehmende Mächtigkeit vom unteren Kontinentalhang zur Schelfkante, deuten auf einen Sedimenteintrag von der Laptev See hin. Das

Nichtvorhandensein von Flußdeltas in Einheit III lassen darauf schließen, daß keine punktförmigen Sedimentquellen an der Schelfkante existierten und somit der Meeresspiegel höher war als während der Ablagerung der seismischen Einheit II. Die Mächtigkeitszunahme zur Schelfkante hin deutet an, daß die Flußmündungen näher an der Schelfkante lagen als heute.

Einheit IV wird in den PARASOUND Profilen von gestapelten transparenten Linsen dominiert, welche als Schlammstromanlagerungen interpretiert werden. Die räumliche Anordnung der Schlammstromablagerungen impliziert, daß Schlammströme auf dem obersten Kontinentalhang in der östlichen Vilkitsky Straße losbrachen und durch die Vilkitsky-Khatanga Rinne bis an den unteren Kontinentalhang hinabflossen. In hohen Breiten weisen schlammstrom-dominierte, submarine Schuttfächer auf einen periodischen oder kontinuierlichen hohen Sedimenteintrag von einem bis an die Schelfkante vorstoßenden Gletscher/Eisschild hin und somit auf eine großflächige Vereisung des kontinentalen Schelfes. In Falle der östlichen Vilkitsky Straße stammt der hohe Sedimenteintrag höchstwahrscheinlich von Vorstößen des Kara See Eisschildes und der Vereisung von Severnaya Zemlya. Das Fehlen von Moränen in der Vilkitsky Straße deutet darauf hin, daß während der maximalen Ausdehnungen das aufliegende Eis die Schelfkante überfahren hat. Andererseits ist das Fehlen von kontinuierlichen Schlammstromablagerungen zur Schelfkante der Laptev See hin ein deutliches Anzeichen dafür, daß die Eisschilde sich nicht über die Taymyr Halbinsel hinaus auf die Laptev See ausdehnten. Zusammenfassend kann gesagt werden, daß die hier präsentierten Resultate die neuesten Rekonstruktionen der Weichsel Vereisungen im Bereich der westlichen Laptev See bestätigen.

Nördlich des Franz Viktoria Troges (FVT) am Kontinentalhang konnten ebenfalls sich überlagernde Schlammstromablagerungen aus PARASOUND Profilen identifiziert werden. Ein Vorstoßen des nördlichen Svalbard/Barents See Eisschildes bis an die Schelfkante des FVT, datiert auf ca. 23 ^{14}C ka, wird durch Diamikt, interpretiert als Grundmoräne, nahe der Schelfkante belegt. Die räumliche Anordnung der Schlammstrom-ablagerungen lassen vermuten, daß der FVT zu einer Kanalisation und dem damit verbundenen beschleunigten Fließen des nördlichen Barents See Eisschildes geführt hat. Ein beschleunigtes Fließen und eine frühere Vereisung, wie bereits für Ost-Svalbard vermutet wird, könnten das frühe Vorstoßen des nördlichen Barents See Eisschildes zur Schelfkante (verglichen mit West-Svalbard) erklären. Fluktuationen des Eisschildes werden durch einen deutlich steigenden Anteil eisbergtransportierten Materials (IRD) in den Sedimenten des Kontinentalhanges dokumentiert. Der einsetzende Rückzug des nördlichen Barents See Eisschildes, welcher sich als deutliches Schmelzwassersignal in der Sauerstoff Isotopenkurve und in einer IRD-reichen Lage widerspiegelt, konnte auf 15.4 ^{14}C ka datiert werden. Die Ursachen für den Rückzug sind vermutlich in einer Verringerung des Niederschlages während der Abkühlung vor dem Heinrich-Ereignis H1, dem Aufschwimmen des Eisschildes im Zusammenhang mit einem eustatisch oder isostatisch induzierten Meeresspiegelanstieg und/oder als Folge einer erhöhten Sonneneinstrahlung zu sehen. Die drastische Änderung im Reflektionsmuster der Sedimente des oberen Kontinentalabhanges um ca. 13.4 ^{14}C ka wird als Folge des Rückzuges des Eisschildes von der Schelfkante interpretiert. Der darauffolgende, sich schrittweise vollziehende Rückzug des nördlichen

Barents See Eisschildes wird durch zwei IRD-reiche Lagen, welche in angrenzenden Gebieten zwischen 13 und 9.4 ^{14}C ka auftreten, dokumentiert. Bioturbation, die generell in den Sedimenten oberhalb der Schlammstromablagerungen vorherrscht, läßt auf eine östliche Ausdehnung von saisonal offenen Wasserbedingungen entlang der nördlichen Barents See bis mindestens zum Franz Viktoria Trog hin schließen.

1. Introduction

The Arctic Ocean and its marginal seas exert major influences on the global climate and its change through time (e.g. NAD science committee 1992 and references therein; Wadhams, Dowdeswell & Schonfield 1996 and references therein; Aagaard & Carmack 1994). High northern latitude oceans directly influence the global environment through the formation of permanent and seasonal ice covers, transfer of sensible and latent heat to the atmosphere, and fresh water export, regulating the intensity of the global thermohaline circulation (Aagaard & Carmack 1994; Thiede & Myhre 1996). Variations in snow and ice cover result in distinct changes of the surface albedo, and with it, the atmospheric radiation balance, the temperature and salinity of the upper water masses, and the bioproductivity (e.g. Stein 1998, and references therein). The sea-ice formation on the Arctic shelves is strongly controlled by the fresh-water input, approximately half of it contributed by river input (Stein 1998 and references therein). Also, this fresh-water input plays an important role by maintaining the low-salinity surface layer and by the formation of the intermediate/bottom water formation of the Arctic Ocean. A decrease in fresh water supply would cause a weakening of the low-salinity surface layer of the Eurasian Basin, perhaps to the threshold of allowing local convection to the underlying warmer Atlantic layer, with an attendant increase in the northward heat transport and a decrease in the ice cover (Aagaard & Carmack 1994). Freshwater export of the Arctic Ocean regulates the intensity of the convection in the high northern latitudes of the Atlantic, which drives much of the global thermohaline circulation (Aagaard & Carmack 1989). Each stable modes of the thermohaline circulation, which is intimately involved in the redistribution of heat over the globe (Broecker et al. 1985), is associated with a very different global climate (Manabe & Stouffer 1988). Aagaard and Carmack (1994) hypothesize that at some level of increased export of fresh water from the Arctic Ocean, convection would cease; the northward transport of Atlantic water would decrease; and the climatological ice cover would spread southward.

During the Late Quaternary, the variations in sea-ice cover circumpolar ice sheets extent, and the fresh water formation steering the northward heat transport by the Atlantic´s thermohaline circulation are also regarded as main mechanism for the evolution of the global climate system (Broecker et al. 1990, 1992, 1994a; Clark 1990; Berger & Jansen 1994; Thiede & Myhre 1996). The primary objective of this study is therefore to render a contribution to the necessary reconstructions of the chronology and extent of the Arctic ice covers, which are still in debate (Thiede 1996; Svendsen et al. 1999), and to document indications of continuous river runoff as a major input of fresh water to the Arctic Ocean during the Late Quaternary.

During the last two decades, it has been recognized that the evolution of high latitude, submarine fans situated on passive margins in front of fjords or large cross-shelf troughs differs from low latitude, river-fed fans (Damuth and Kumar 1975; Damuth & Embley 1981; Damuth et al. 1983, 1988; Flood et al. 1991; Laberg, 1994; Dowdeswell et al. 1996). The seismic architecture of high latitude fans is dominated by series of elongated "sediment lenses", interpreted as debris flows, whereas low latitude fans are characterized by downlap sequences and turbidites, building up typical large channel-levee complex (Damuth & Flood 1985). Submarine fans on high latitude margins are fed by glaciers or ice sheets, which supply most of the sediments. Debris flows are generated from sediments temporary redeposited by glacier or ice sheet grounding lines at the shelf break during peak glacials (e.g. Dowdeswell et al. 1998; Vorren et al. 1998). Therefore, their growth pattern is controlled by the oscillations of the glacier or ice sheets. Hence, high latitude fans have the potential to document ice proximal conditions and thus are indicative of long term climatic variations (Laberg & Vorren 1995; Vorren et al. 1989).

1.1 Objectives of this study

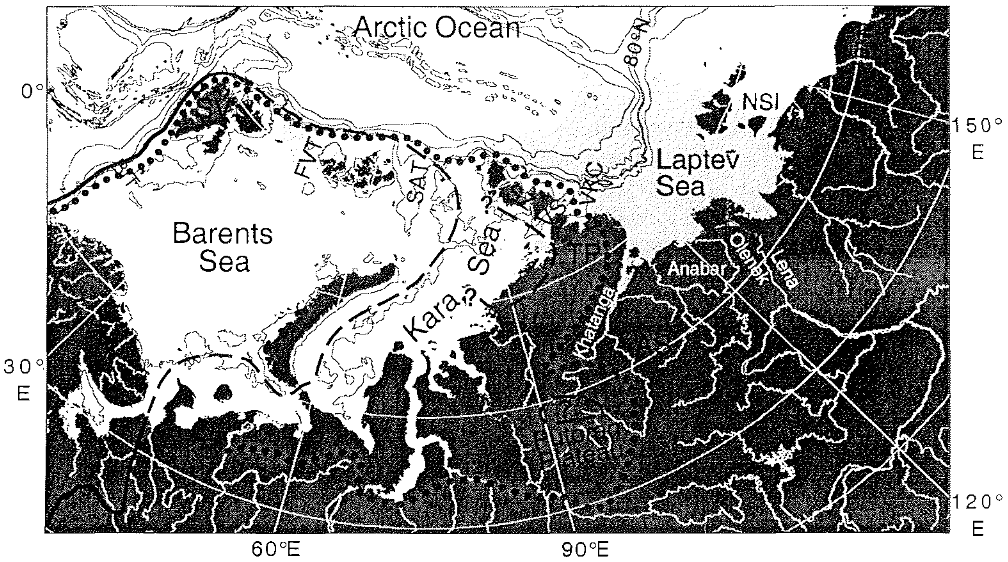
In this study we have focused on the Laptev Sea continental margin and the Franz Victoria Trough, including the adjacent continental slope (Fig. 1.1). On the recently published map of the maximum extent of the Eurasian ice sheets during the Weichselian (Fig 1.1, Svendsen et al. 1999) the western Laptev Sea and the northern Franz Victoria Trough are situated at the proposed maximum ice-sheet limits. Therefore, the adjacent continental margins bear the potential for the formation of debris flow dominated submarine fan deposited during glacial phases, as already suggested by Vorren & Laberg (1997) for the Franz Victoria Trough based on bathymetric features. Furthermore, is todays river discharge into the Laptev Sea a key source for the Arctic freshwater budget.

Therefore, the main objectives of this study are:

- to identify, correlate and map seismic units in high resolution seismic records (PARASOUND, 4 kHz) from the continental margin of the western Laptev Sea and in front of the Franz Victoria Trough.
- to provide age estimates by linking the seismic units to dated gravity cores and to interpret the seismic units in terms of sequence stratigraphy.
- to identify the sedimentary processes leading to the formation of the seismic units and to gain information from core data in order to outline the Late Quaternary environmental evolution of the above two areas; in particular, to find geological evidence for ice proximal conditions and thus to test former ice-sheet reconstructions.
- to document geological indications of an exposure of the Laptev Sea shelf and to confirm a continuous river runoff during the Weichselian sea-level low stand, using high resolution seismic profiles and core logging data.

1.2 Outline of this study

This study includes four chapters (2 to 5) presenting previous published or submitted articles. Chapter 2 (Late Pleistocene paleoriver channels on the Laptev Sea shelf - implications from sub-bottom profiling. Kleiber, H.P. & Niessen, F. 1999) presents sub-bottom reflection patterns of filled paleoriver channels and the permafrost surface in the uppermost sediments of the Laptev Sea shelf. It describes their distribution and present water depth. On basis of the global sea-level curve, the timing of formation and filling of the



— — Late Weichselian glacial maximum according to Svendsen et al. (1999)
—— Early/Middle Weichselian glacial maximum according to Svendsen et al. (1999)
Area under investigation of this study

BIT = Bear Island Trough, SV = Svalbard, FVT = Franz Victoria Trough, SAT = Saint Anna Trough, SZ = Severnaya Zemlya, VS = Vilkitsky Strait, VKC = Vilkitsky-Khatanga Channel, TP = Taymar Peninsula, AS = Anabar Shield, NSI = New Siberian Islands

Figure 1.1: Regional setting of the two study areas along the Eurasian continental margin.

channels, and the permafrost surface are evaluated. The article discusses the link to todays large central Siberian rivers, the relevance of the paleorivers and permafrost with regard to the exposure of the shelf, and the existence of a major or local ice sheets in the Laptev Sea areas.

Chapter 3 (The Late Quaternary evolution of the western Laptev Sea continental margin, Arctic Siberia - implications from sub-bottom profiling. Kleiber, H.P., Niessen, F. & Weiel, D. submitted to Boreas) addresses to the uppermost, four seismic units, which were identified in the sedimentary succession of the western Laptev Sea and adjacent Vilkitsky Strait and mapped. Based on geometry and internal reflection pattern of the four seismic units, which ages are determined by radiocarbon dated cores and sequence stratigraphy, the paleoenvironmental conditions during the Late Quaternary in the area are reconstructed. Furthermore, the recently proposed maximum ice-sheet extent of the Kara Sea ice sheet (Svendsen et al. 1999) can be confirmed.

Chapter 4 (Variations of continental discharge pattern in space and time - implications from the Laptev Sea continental margin, Arctic Siberia. Kleiber, H.P. & Niessen, F. submitted to International Journal of Earth Science) documents in more detail the variable sediment input and distribution to the Laptev Sea continental margin during late marine isotope stage (MIS) 2 and the Holocene. Evidence is identified based on radiocarbon dated magnetic susceptibility logs and sediment thickness in high resolution seismic profiles.

Reconstructed sediment source areas and pathways are discussed and changes in sediment composition are linked to local glaciations in the catchment area during the Late Weichselian.

Chapter 5 (The Late Weichselian glaciation of the Franz Victoria Trough, northern Barents Sea: Ice sheet extent and timing. Kleiber, H.P., Knies, J. & Niessen, F. submitted to Marine Geology) outlines the advance of the northern Svalbard/Barents Sea ice sheet to the shelf edge of the Franz Victoria Trough based on indications from high resolution seismic profiles and three AMS ^{14}C dated sediment cores. Instabilities and the stepwise retreat of the ice sheet is discussed using evidence such as distinct radiocarbon dated pulses of ice rafted detritus, oxygen isotope measurements and geo-chemical data.

2. Late Pleistocene paleoriver channels on the Laptev Sea shelf - implications from sub-bottom profiling

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2.1 Abstract

Bottom and sub-bottom reflection patterns received by the PARASOUND system (4 kHz) document 24 filled paleoriver channels in the uppermost sediments (1-13m) of the Laptev Sea shelf. The surfaces of the paleochannel fillings range from 32 to 97 m below the present sea level. The rivers are supposed to have been active during Weichselian time when the sea level was up to 120 m below that of today. They were probably filled during Termination 1 until the transgression reached the present-day 30 m-isobath. The observed paleoriver channels are most likely related to the Olenek, Lena and Yana rivers and to local drainage systems on the Taymyr Peninsula and the New Siberian Islands. In the depth range of 2 to 20 m sub-bottom, a strong post-sedimentary reflector is commonly found, interpreted as the surface of submarine permafrost. The formation of paleoriver channels and permafrost is associated with subaerial exposure and suggest that most of the Laptev Sea shelf area was not covered by a large ice sheet during the last glacial maximum.

2.2 Introduction

Presently, central Siberian rivers (e.g. Lena) drain large amounts of freshwater loaded with sediments into the Laptev Sea which is one of three epicontinental seas located along the northern coast of central Asiatic Russia (Holmes and Creager 1974) (Fig. 2.1). Therefore, the Laptev Sea is a key location for understanding sediment transport processes and rates into the Arctic Ocean and their variability under different climatic conditions. Knowledge about existence and location of paleochannels on the shelf is fundamental because channels indicate major trajectories of sediment transport in Pre-Holocene time. Then channels control past sediment input and distribution on the upper continental slope of the Laptev Sea and thus local sediment budgets of the Arctic Ocean. Also, evidence for river drainage across the shelf would provide a valuable argument against the presence of a large ice sheet on the Laptev Sea shelf (Grosswald 1990) and support the formation of permafrost on the exposed shelf during the period of late Pleistocene glacial-eustatic regression described by Hubberten and Romanovskii (in press).
High resolution sub-bottom profiling surveys were carried out during two expeditions (ARK-IX/4 and ARK-XI/1) by the RV "Polarstern" (Fütterer 1994; Rachor 1997) (Fig. 2.1). The profiles show evidences for the existence of numerous filled paleochannels on the Laptev Sea shelf. Examples of preliminary results are published in Fütterer (1994), Nürnberg et al. (1995) and Rachor (1997). In this study a complete investigation of occurrence of paleochannels in the Laptev Sea profiles of the ARK-IX/4 and ARK-XI/1 expeditions is presented. Different to earlier investigations (Holmes and

Creager 1974; Treshnikov 1985), which suggested paleoriver channels based on bathymetry, we used sub-bottom structures for channel identification. The advantage is that the erosive incision and the different sedimentary structures of the channel fillings and the surrounding strata can be observed. Also, limited information about the depths and widths of the paleochannels can be obtained.

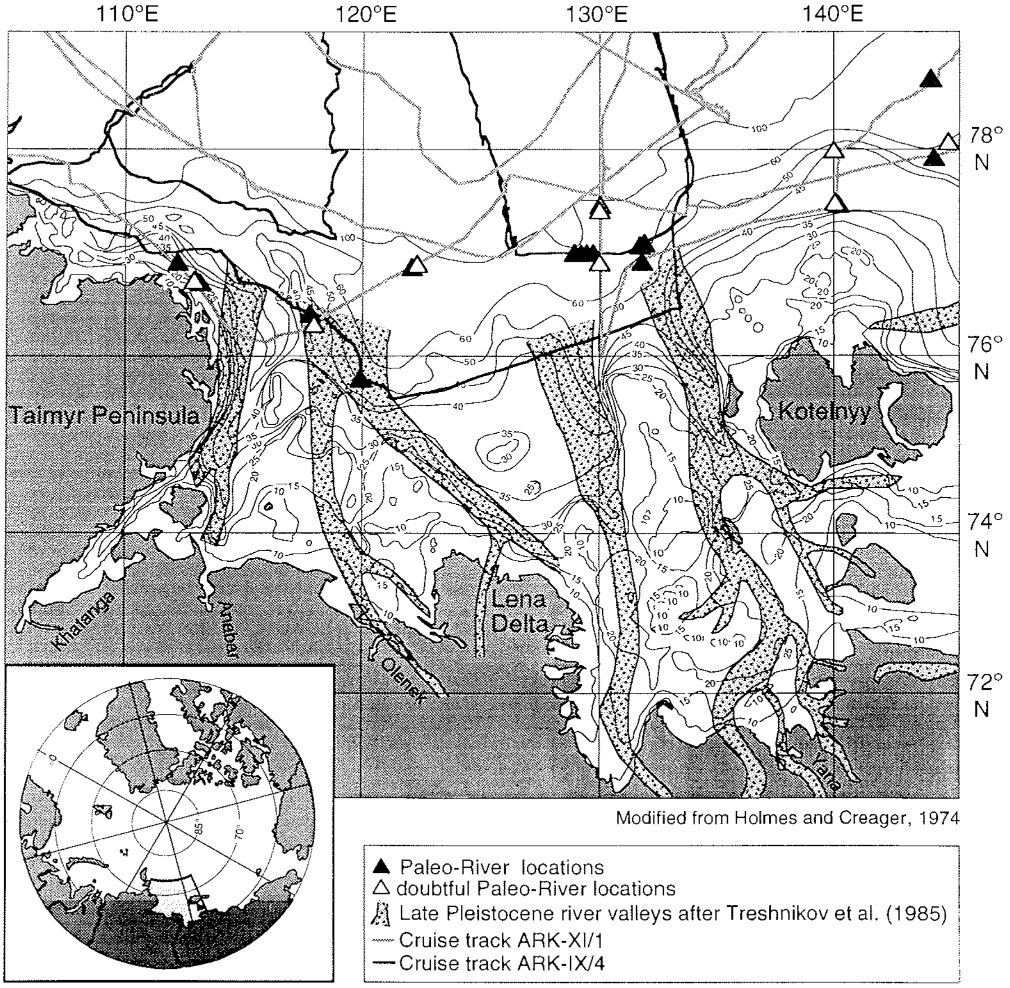

Fig. 2.1: Bathymetry of the Laptev Sea modified from Holmes and Creager (1974), cruise tracks of the two RV "Polarstern" expeditions ARK-IX/4 and ARK-XI/1, and distribution of paleoriver channels identified in PARASOUND profiles.

2.3 Methods

High resolution sub-bottom profiling

The hull-mounted PARASOUND echosounder designed by STN Atlas Electronik GmbH (Bremen, Germany) radiates simultaneously two primary sonic frequencies. A constant frequency of 18 kHz and a second frequency, which can be selected by the operator between 20.5 and 23.5 kHz. As a result of the superimposition of the two primary frequencies in the water column, known as the parametric principle, a secondary frequency is created. The latter is equal to the difference between the two primary frequencies ranging between 2.5 and 5.5 kHz, respectively (Grant and Schreiber 1990). The secondary frequency is suitable for continuos sub-bottom profiling of the uppermost normal consolidated sediment layers (Spiess 1993). Because the secondary frequency is only generated in the central part of the beam, where the highest energy levels occur, the angle of the sounding cone is about 4° (Grant and Schreiber 1990). The narrow beam angle results in a small acoustic footprint diameter on the sea floor, which allows high vertical as well as a lateral spatial resolution. The sub-bottom penetration is up to 100 m with a vertical resolution of 5 to 30 cm (Grant and Schreiber 1990; Rostek,1991). In this study the secondary frequency was set to 4 kHz.

Incising Pleistocene channels were identified using the following diagnostic criteria: (i), an erosive, u-shaped sub-bottom morphology and (ii), an undeformed fill geometry. Channel locations were mapped as doubtful when one of the criteria above was not clearly fulfilled.

The width of the paleochannels were calculated from the GPS-coordinates. Morphometric measurements, such as paleowidth and paleodepth, were carried out as defined in figure 2.2.

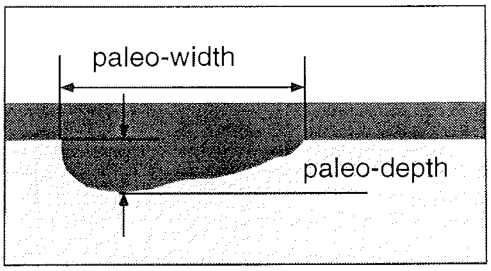

Fig. 2.2: Definitions of morphometric paleochannel features.

2.4 Results

In the outer shelf region of the Laptev Sea a total of 24 filled paleochannel cross-sections are recorded, 9 of which are classified as doubtful (Fig. 2.1). Geographically, four groups can be distinguished: (i), three paleochannels northeast of the Taymyr Peninsula, (ii), five paleochannels in the central Laptev Sea, (iii), ten paleochannels northwest of the New Siberian Islands and (iv), six paleochannels north of the New Siberian Islands (Fig. 2.1). The positions as well as the internal reflection patterns of the individual cross-section suggest, that several images could originate from the same paleorivers. Sedimentological or morphological features of individual paleochannels cannot be assigned as typical to one of the four locations.

The surfaces of the paleochannel fillings are located between 32 to 97 m below the present sea level. The recorded channel widths range from 86 to 5331 m, the recorded channel-depths from 3.5 to 13 m. The channel fillings consist of stratified sediments (23 paleochannels). If the channels are cut into inclined stratified sediments, the filling of the channels do not show similar inclination but are parallel to the present sea floor (Fig. 2.3). In addition, six sites are characterized by lateral accretional filling pattern (Figs 2.3, 2.4). Only one channel shows an acoustically transparent filling (Fig. 2.5).

The filled paleochannels as well as the slightly deformed or "folded", stratified

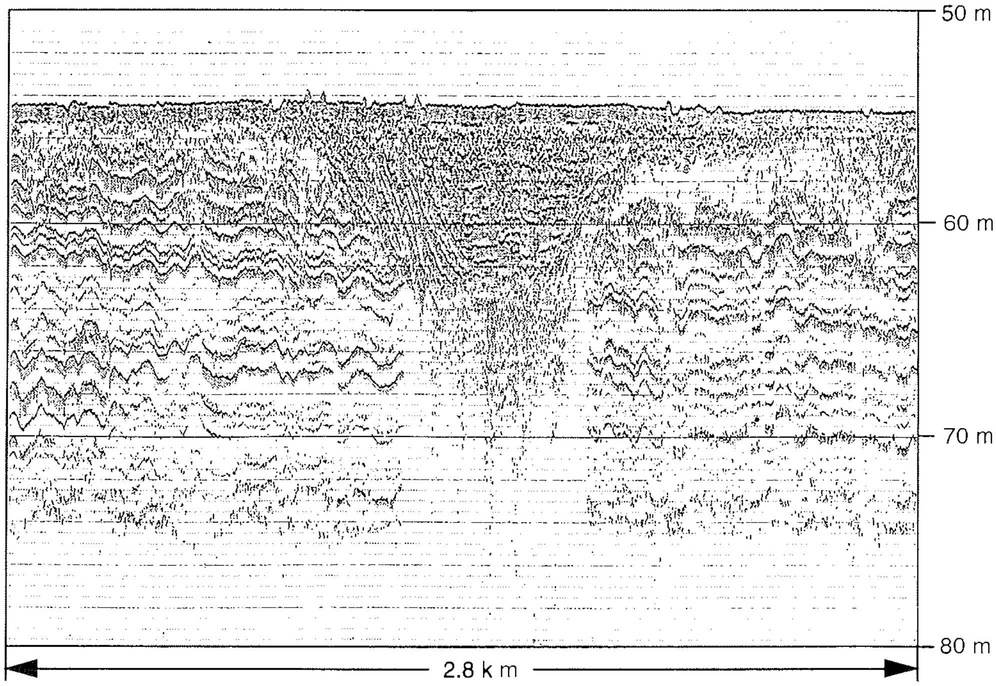

Fig. 2.3: PARASOUND profile north of the New Siberian Islands between 77° 57.0'N / 143° 57.5'E and 77° 57.3'N / 144° 05.3'E, showing a filled paleochannel cutting into well stratified, inclined sediments. Note the accretional reflection pattern on the left hand side of the channel fill.

shelf sediments are overlain by a horizontal bed (Figs 2.3, 2.4, 2.5). This bed is mostly characterized by a continuous basal reflector which cuts unconformably the reflectors below. This top layer measures 0.5 to 2 m in thickness.

In the depth range of 2 to 20 m sub-bottom, a strong reflector is commonly observed, which causes an acoustic impedance high enough, to prevent further sound penetration. This reflector appears conformably as well as unconformably to the bedding with a flat or hummocky top (Fig. 2.6). Below the paleochannels this reflector either diverges downward or cannot be observed because high acoustic impedance of the fillings prevent recording of reflectors from the underlying stratified sediments. In areas, where this reflector cannot be identified, the penetration reaches up to 65 m sub-bottom.

2.5 Discussion

Most likely the observed paleoriver channels are related to the Olenek, Lena and Yana rivers. It is interesting to note that for these rivers our channel locations match the reconstruction of major paleovalleys under the Laptev Sea (Treshnikov et al. 1985) (Fig. 2.1). The paleovalley of the Anabar-Khatanga rivers assumed by Treshnikov et al. (1985) can neither be confirmed nor an other paleodrainage can be suggested based on our profiles. The existence of paleoriver channels implies that the Central Siberian freshwater drainage into the Arctic Ocean continued during the

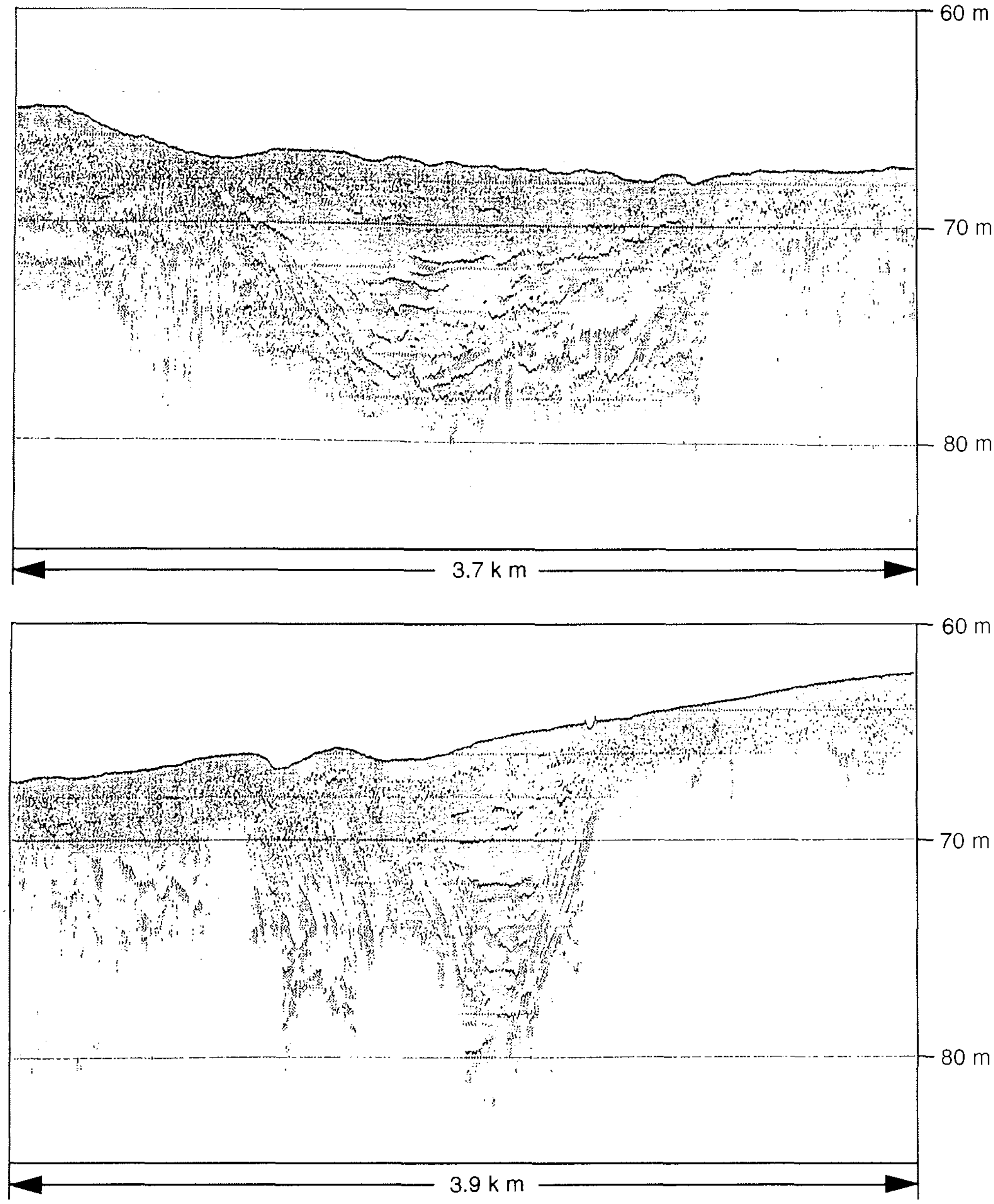

Fig. 2.4: Two PARASOUND profiles northwest of the New Siberian Islands between 77° 03.0'N / 131° 05.3'E and 77° 02.0'N / 130° 57.5'E (a) resp. 77° 02.0'N / 130° 57.5'E and 77° 02.0'N / 130° 48.1'E (b). Due to the angular unconformity the fillings of the paleochannels can clearly be distinguished from the truncated stratified sediments below and from the thin homogeneous cover. The distance between the two paleochannel sites is only 3.7 km, thus they most likely represent two cross-sections of the same meandering river.

Weichselian glacial period. The mouths of these channels along the low-stand coast formed several point-sources of sediment input to the Arctic Ocean. Ongoing studies will show whether submarine fans are developed on the continental slope and rise which are related to the observed channels.

Channel systems directly north of the Taymyr Peninsula and the New Siberian Islands can hardly be linked to the drainage pattern of the major Siberian rivers. Nevertheless, the geometry of these channels imply drainage comparable to that of the larger river systems. Strong local drainage and channel formation could be the result of rivers formed at the termination of Weichselian glaciations caused by melting of local ice sheets and/or glaciers. Based on seismic and coring results from lakes on the Taymyr Peninsula, Niessen et al. (1999) suggest that the last major glaciation in the area occurred during marine isotope stage 4. Thus, the channels north of the Taymyr Peninsula maybe related to drainage from such an ice sheet. On the New Siberian Islands, Flint (1971) reconstructed an ice sheet of about 200 m in thickness and 250 km in diameter of which the southern margin reached the mainland coast. The age of this glaciation is unknown. However, if the ice sheet existed and melted during some period of this last sea level lowstand, drainage channels north of the New Siberian Islands like those observed in this study would be eroded into the exposed shelf. Since the glaciation history of the Laptev Sea area is still discussed controversially (e.g. Dunayev and Pavlidis 1990; Grosswald 1990; Romanovskii 1996) further investigations are necessary to test these hypotheses.
Taken into account that the intersection angles of the cruise track and the paleochannels are unknown, the width/depth ratios and the relief on basal scour surface can hardly be used for separating the meandering from the braided river system (Füchtbauer 1988; Schumm 1977). The paleoriver cross-sections show erosive, single channels deeper than 3m, all characterisic features of a meandering river (Miall 1977). The accretional reflection pattern of the stratified fillings, is interpreted as epsilon cross-bedded units caused by

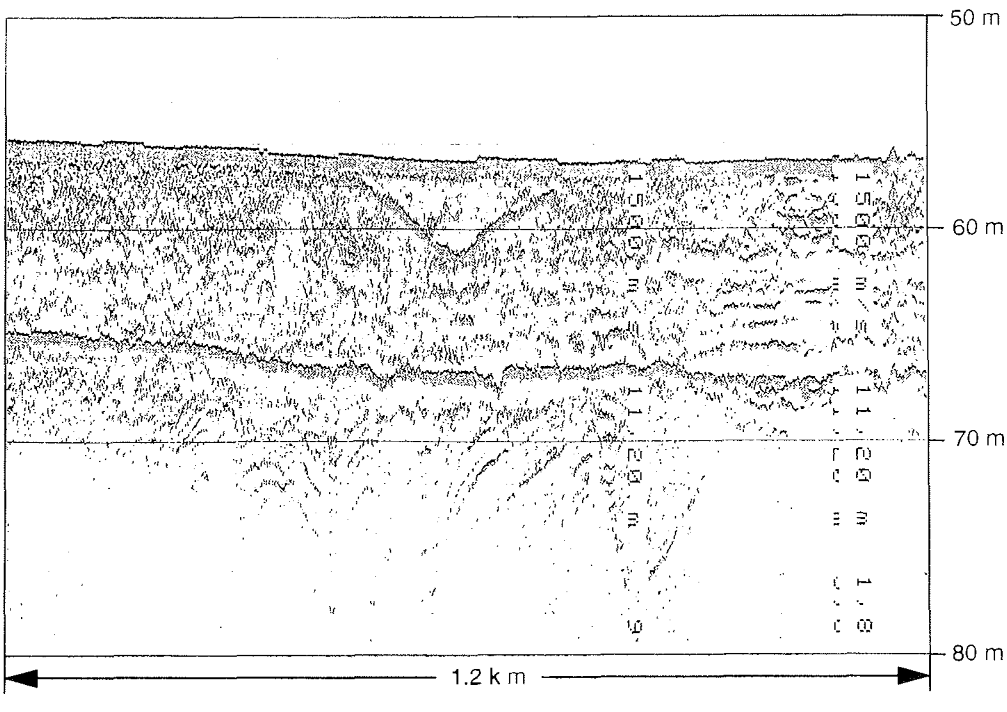

Fig. 2.5: PARASOUND profile northwest of the New Siberian Islands between 76° 57.2´N / 131° 33.7´E and 76° 56.7´N / 131° 31.6´E, showing a filled paleochannel.

lateral accretion on an inclined surface. These sediment bodies are typical for point bars of a meandering channel, but can also be observed locally in a more braided river system (e.g. Allen 1983). Crossbedded structures indicating longitudinal bars, common in a braided river system (Miall 1977) have not been observed. Although most of the observations point to meandering rivers, a clear statement concerning the river type is hardly possible from this study because further important river variables like drainage pattern across the entire shelf, sinuosity or mode of sediment transport remain undetermined.

Sub-horizontal filling of channels cut into inclined sub-bottom layers of probably older Pleistocene age (Fig. 2.3) clearly indicate that the channels were filled during morphological condition similar to that of today. This shows that the channels are relatively young and can be related to erosion during the last sea-level low-stand. The recorded depth of the paleochannel filling surfaces below the present sea level indicates that the rivers must have been active during Weichselian time when the sea level was at least 100 m lower than today (e.g. Chappell and Shackleton 1986; Fairbanks 1989). They were probably filled during Termination 1 (onset ca. 18 ka) until the transgression reached the present-day 30 m-isobath approximately 10,000 years B.P. (Blanchon and Shaw 1995). The uppermost bed which covers the filled paleorivers and the stratified sediments of probably Pleistocene age equally, is interpreted as Holocene deposits.

The unconformable character of the strong second sub-bottom reflector is indicative for a post sedimentary origin which is interpreted as the surface of submarine permafrost (e.g. Rogers and Morak 1983). The formation of thick permafrost is only possible if subaerial exposure of the Laptev Sea shelf area occurred during times of the Weichselian sea-level low stand (Hubberten and Romanovskii, in press). The permafrost situation under the paleochannels remains unclear because we cannot distinguish whether the reflector is not present or not seen because of strong backscatter from the channel base and fill.

The coexistence of paleorivers and permafrost is a strong argument against a glaciation of the Laptev Sea shelf during the Weichselian as suggested by

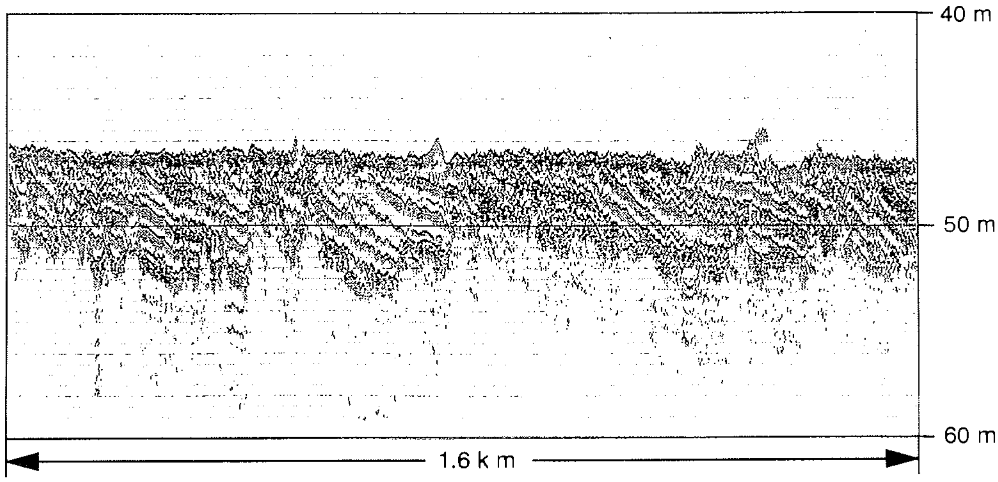

Fig. 2.6: PARASOUND profile northwest of the Taymyr Peninsula between 76° 18.1'N / 117° 30.2'E and 76° 18.5'N / 117° 33.2'E, showing strong reflectors cutting the stratified sediments between 4 to 7 m sediment depth, thus indicating their post-sedimentary origin.

Grosswald (1990). This is consistent with observed PARASOUND penetration into pre-Holocene Laptev Sea shelf deposits down to tens of meters which indicates lack of ice load during the Last Glacial. Generally, the surface of ice-consolidated sediments are excellent sound reflectors and little or no sound penetrates through such sediment interfaces (Damuth 1978).

2.6 Conclusions

Laptev Sea paleochannels identified in this study match the location of paleovalleys reconstructed from other investigations. The rivers are supposed to have been active during the Weichselian sea-level low stand. This implies that they drained freshwater and sediment into the Arctic Ocean during marine isotope stage 2, 3 and 4. Epsilon cross-bedded units favor meandering Pleistocene river systems on the Laptev Sea shelf. Our study suggests that deltas were formed along the low-stand paleoshore line which functioned as point-sources of sediment input onto the upper continental slope of the Arctic Ocean. On the shelf, the river channels were probably filled between Termination 1a and the early Holocene, when the transgression reached the present-day 30m-isobath. The filled channels were then covered by sediments of which the reflection geometry suggests that they are of Holocene age.

Some paleochannels north of the Taymyr Peninsula and north of the New Siberian Islands can geographically hardly be related to the large Siberian rivers. This suggests further investigations in order to test whether local glaciation and subsequent drainage from deglaciation can explain the observed pattern.

Nearly throughout the entire investigated area, the existence of a post-sedimentary reflector about 2 to 20m sub-bottom suggests that submarine permafrost is common on the Laptev Sea shelf. It is not evident from this study whether the permafrost continuous under the paleochannels or not.

There are three observations which indicate that most of the Laptev Sea shelf area was not covered by an extended ice sheet during the last glacial maximum: (i), the acoustic penetration into the Pleistocene sediments indicates no overconsolidation by an ice sheet, (ii), the existence of paleochannels are indicative for continuation of Eurasian river-drainage during the Weichselian and (iii), a strong post-sedimentary reflector indicates the existence of relict submarine permafrost.

3. The Late Quaternary evolution of the western Laptev Sea continental margin, Arctic Siberia - implications from sub-bottom profiling

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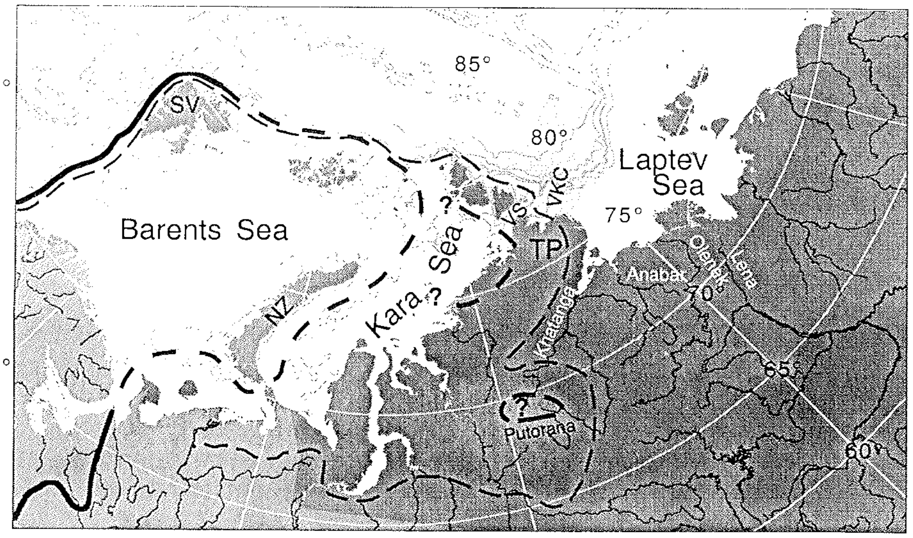
3.1 Abstract

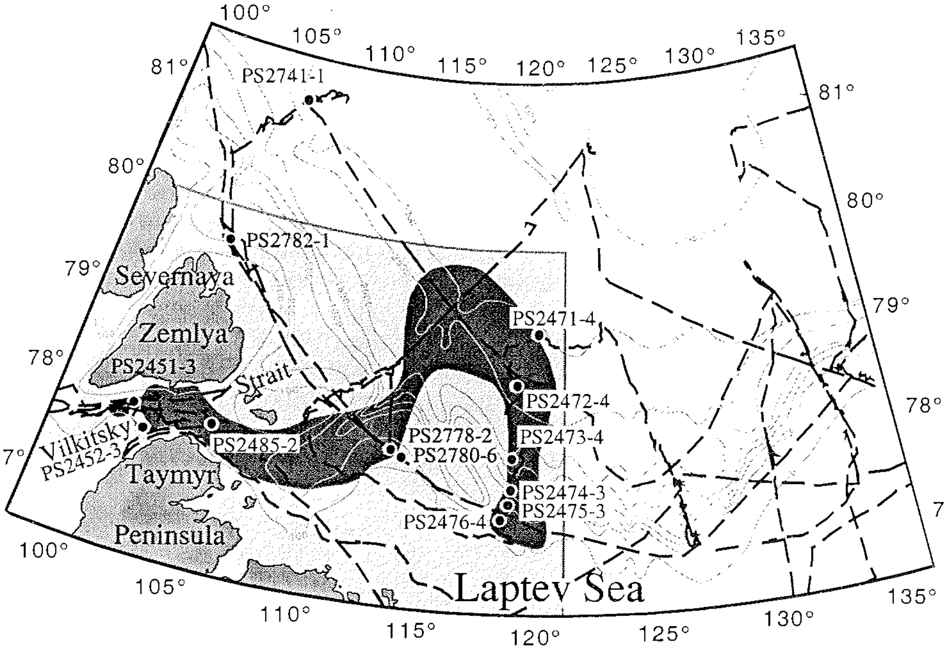
High resolution seismic profiles (PARASOUND, 4 kHz) of the western Laptev Sea continental margin and adjacent Vilkitsky Strait were studied in order to gain new evidence about the Weichselian glaciations in Central Siberia and to test reconstructions of maximum ice-sheet extents. Four regionally correlatable seismic units, named I (youngest) to IV, were identified in the upper Quaternary sedimentary succession: (I) a thin drape, (II) prograding wedge shaped deposits along the shelf edge, (III) layered sediments of draping and infilling character with increasing thickness towards the western Laptev Sea shelf edge and the Vilkitsky Strait, (IV), stacked debris flow deposits. The thin drape of unit I is radiocarbon dated to Holocene age and mainly deposited during the transgression of the Laptev Sea. The wedge shaped deposits of unit II are interpreted as river deltas, referring to point sources along the shelf edge during the Late-Weichselian sea-level lowstand, indicating that the river input across the Laptev Sea shelf was continuous during marine isotope stage (MIS) 2. The layered sediments of unit III indicate hemipelagic conditions, referring to a sea level highstand. The pronounced thickening of unit III towards the shelf edge of the western Laptev Sea reflects the lowering of the global sea level during MIS 3 and the related, increased riverine input due to the northward shift of the Siberian coast line. The stacked debris flow deposits of unit IV extend continuously from the shelf edge in the Vilkitsky Strait to the continental rise of the western Laptev Sea continental margin. They indicate that large quantities of sediments were directly deposited on the upper continental slope during advances of the Kara Sea ice sheet to the shelf break. These ice-proximal conditions are presumably linked to the Middle Weichselian glaciation (MIS 4). Our evidence confirm earlier reconstructions, suggesting that in Central Siberia the Middle Weichselian glaciation (MIS 4) was of larger extent than the Late Weichselian glaciation (MIS 2).

3.2 Introduction

Reconstructions of the Weichselian glaciations along the Eurasian shelf range from isolated small ice caps over the Eurasian archipelagos to a large ice-sheet covering the entire Siberian shelf and extending far into continental Eurasia e.g. Hughes et al. 1977; Grosswald 1980, 1990, 1998; Dunayev 1988; Astakhov 1992, 1998; Elverhøi et al. 1993). The recently published map of the maximum Eurasian ice sheets extent during the Weichselian (Fig. 3.1) (Svendsen et al. 1999), based on field investigations and interpretation of offshore seismic data, reveals that the Kara Sea ice sheet reached the east coasts of Severnaya Zemlya and Taymyr Peninsula only during the Early/Middle Weichselian. The Late Weichselian ice sheet extent on the Kara Sea was much more restricted to the western part of the Kara Sea and



— - Late Weichselian glacial maximum according to Svendsen et al. (1999)
— — Early/Middle Weichselian glacial maximum according to Svendsen et al. (1999)
Area under investigation of this study



transparent lenses

area where seismic units I-VI could be identified and mapped

Fig. 3.1: Regional setting of the study area at the Laptev Sea continental margin. The cruise tracks of the RV "Polarstern" are shown by stippled lines, the dotted area represents the mapped area.
SV = Svalbard, NZ = Novaya Zemlya, VS = Vilkitsky Strait, TP = Taymyr Peninsula, VKC = Vilkitsky-Khatanga channel.

the Barents Sea. Furthermore, Svendsen et al. (1999) suggest that the Russian mainland was situated outside the Late Weichselian ice sheet limits, possibly except the northern coast of Taymyr Peninsula. Radiocarbon dated remains of mammoth reveal that Severnaya Zemlya was not glaciated during the Late Weichselian (Svendsen et al. 1999). Numerical ice sheet modeling was carried out to reconstruct the Late Weichselian glaciation in the Russian High Arctic (Siegert et al. in press). In the "maximum-sized" model, largely unconstrained by geological data, the eastern Kara Sea ice sheet covers partly Severnaya Zemlya and reaches the western Vilkitsky Strait. In the "minimum-sized" reconstruction, which was forced to be compatible with geological information, Severnaya Zemlya is ice free and the eastern Kara Sea ice sheet restricted to the easternmost Kara Sea.

In the Early/Middle Weichselian ice sheet reconstruction, the Vilkitsky Strait, located between Severnaya Zemlya and the Taymyr Peninsula, and the adjacent western Laptev Sea continental margin are situated at the eastern boundary of the Kara Sea ice sheet. Therefore the geological record of this key area offers an excellent opportunity to test ice sheet reconstructions. By now, only little information on the marine record of this area has been published (Fütterer 1994; Niessen 1995; Niessen et al. 1996; Rachor 1997; Weiel 1997).

Terrigenous sediment supply to high latitude continental margins is mainly controlled by the input from glaciers/ice sheets, iceberg and sea-ice transport, river discharge, cold dense shelf water and aeolian supply (e.g. Darby et al. 1989; Stein & Korolev 1994). Submarine fans on high latitude margins fed by large glaciers or ice sheets are dominated by stacked debris flow deposits (Damuth & Flood 1985). Sets of debris lobes are generated during peak glacials when the grounding line of a fast-flowing glacier or ice sheet reaches the shelf break (e.g. Dowdeswell et al. 1998; Vorren et al. 1998). Hence, growth pattern of high latitude submarine fans are controlled by the oscillations of glacier or ice sheet margins and have thus the potential to document long term climatic signals (Laberg & Vorren 1995; Vorren et al. 1988, 1989). In contrast, river fed fans are characterized by downlap sequences on the continental slope and turbidites building up typical channel-levee system (Damuth & Flood 1985). Incised channels on the exposed shelf of the Arctic Ocean during glacial times (e.g. Kleiber & Niessen 1999) are indicative of continuous river runoff and non-existence of ice sheets in such areas.

In high resolution sediment echosounding profiles different sedimentary facies such as sets of debris flow lobes, channel-levee systems and layered pelagic sediments can clearly be distinguished (e.g. Damuth 1975, 1980; Embley 1976; Kuhn & Weber 1993; Pratson & Laine 1989). In this paper we are using high resolution seismic profiles and data from sediment cores from the Vilkitsky Strait and adjacent western Laptev Sea continental margin to identify geological evidence for past ice-proximal environments on the western Laptev Sea continental margin in order to test the suggested Weichselian reconstructions of the Kara Sea ice sheet. However, one of the main problems in the Arctic Ocean is the chronology of Quaternary deposits. Radiocarbon datings are sparse and a high-resolution stratigraphic framework is not yet established, mainly because the occurrence of microfossils is limited and often discontinuous (e.g. Spielhagen et al. 1997). For the first time, we present an age model for the Arctic Ocean based on seismic sequence stratigraphy. Elsewhere, the concept of sequence stratigraphy has been successfully applied to Late Quaternary marine depositional sequences (Boyd et al. 1989;

Trincardi et al. 1994). On passive and non-glaciated continental margins the primary control on seismic sequences is the eustatic sea level which can be linked to age using the global oxygen isotope records (e.g. Chappell & Shackleton 1986). In addition, a multiparameter chronology based on radiocarbon datings, biostratigraphy, magnetostratigraphy and clay mineral assemblages is compiled and compared with the sequence stratigraphic age model suggested in this paper. This can only be achieved if the core data can be linked to the seismic record on a larger, regional scale. For this purpose, magnetic susceptibility records from earlier publications (Fütterer 1994; Nürnberg et al. 1995; Stein et al. 1999) are used to establish a spatial core correlation pattern in which chronological information can be linked to the seismic units.

3.3 Methods

The hull-mounted PARASOUND echosounder designed by STN Atlas Electronik GmbH (Bremen, Germany) combines a narrow beam survey (NBS) system for the accurate determination of the water depth, with a sediment echosounder system (Sub-bottom Profiler) for sedimentological and echostratigraphic survey (Rostek et al. 1991). In addition to a constant primary sonic frequency of 18 kHz (NBS) a second primary sonic frequency, which can be selected by the operator between 20.5 and 23.5 kHz is simultaneously radiated. As a result of the superimposition of the two primary frequencies in the water column, known as the parametric principle, a secondary frequency is created. The latter is equal to the difference between the two primary frequencies ranging between 2.5 and 5.5 kHz, respectively (Grant & Schreiber 1990). The secondary frequency, which was set to 4 kHz in this study, is suitable for continuous sub-bottom profiling of the uppermost normal consolidated sediment layers (Spiess 1993). Because the secondary frequency is only generated in the central part of the beam, where the highest energy levels occur, the angle of the sounding cone is about 4° (Grant & Schreiber 1990). Due to this small beam angle, the acoustic footprint diameter is only 7% of the water depth. Thus, a high vertical and a lateral spatial resolution in the sub-bottom profiles is achieved. The main disadvantage of the narrow beam angle is that signals from a seafloor with a inclination >2° are reflected to the side of the vessel and only weak scattered sound can be recorded (Spiess 1993). A seismic velocity of 1500 m/s was used to estimate sediment thickness.
Approximately 18,000 km of PARASOUND profiles over an area of approximately 332,000 km^2 (Fig. 3.1) constitute the data base of this study. The seismic data were recorded during the RV "Polarstern" cruises ARK IX/4 (Fütterer 1994) and ARK XI/1 (Rachor 1997) and is of variable quality. Secondary noise from ice breaking, recording failures due to ice and air bubbles under transmitter/receiver units as well as geometric effects resulting from ice ramming of the vessel caused some sections of poor quality. Because these sections are of minor lateral extent, key seismic reflectors can generally be correlated. The different seismic facies are classified after the schemes of Damuth (1975, 1980) and Pratson & Laine (1989).
Sediments were collected with a gravity corer (12 cm core diameter) and a Kastenlot (rectangular cross section of 30 * 30 cm) built at the Hydrowerkstätten Kiel, Germany. Magnetic susceptibility measurements of the entire core sections were performed in 1-2 cm intervals using a Bartington MS-

2 loop sensor. The measured values (10^{-5} SI) were corrected by a sensor-specific correction factor according to the manufacturer's correction instructions for the Bartington MS2B sensor system (For specifications see table 3.1). Magnetic susceptibility is defined as the dimension-less proportional factor of an applied magnetic field in relation to the magnetization in the sample (expressed in SI units). Magnetic susceptibility is normally controlled by be variation in the content of ferrimagnetic minerals (magnetite, titanomagnetite or maghemite), which, in marine sediments of high latitude, generally derives from terrigenous input (Thompson & Oldfield 1986).

	ARK-IX/4 (1993)	ARK-XI/1 (1995)
Loop sensor type	MS-2B (Bartington Ltd.)	
Loop sensor diameter	14 cm	
coil diameter (D_C)	15.3 cm	14.8 cm
core diameter (d) SL	12 cm	
core diameter (d) KAL	9.36 cm	
Alternating field frequency	approx. 80 A/m RMS	
Magnetic field intensity	0.565 kHz	
Loop sensor correction coefficient	$-0.0401777814 + 2.58316811*(d/D_C)$^2.26972891	

Tab. 3.1: Magnetic susceptibility specifications used during the different cruises.

3.4 Results

Seismic stratigraphy of the western Laptev Sea continental margin
Four seismic units, I (youngest) to IV were identified in the Vilkitsky Strait and the adjacent western Laptev Sea continental margin. Because the penetration of the PARASOUND system is limited, and tnus not the entire sedimentary succession could be recorded, the seismic units were numbered top down to permit a continuous numbering in view of further seismic investigations.
The upper three units (I-III) are bounded at the base by relatively high amplitude, key-seismic reflectors, which are laterally continuous (Figs 3.2, 3.3). Using these key-seismic reflectors, the distribution and the thickness of these seismic units were mapped (Fig. 3.4). The basal key-seismic reflector of unit IV could only be recorded in very limited profile sections. Therefore, the mapped thickness represents a minimum estimate.
Based on internal reflection pattern, continuity, geometry and erosive behavior, three main seismic facies were identified within the four seismic units: layered, prolonged and transparent (Fig. 3.5). In addition, the transparent facies was subdivided into three subfacies: transparent lenses, transparent sectors and transparent layers. The characteristic features of the seismic facies are listed in table 3.2.

Unit I
Unit I drapes concordantly the variable topography of the underlying seismic units (Fig. 3.2) almost continuously within the mapped area (Fig. 3.4). Only on steeper slope sections in the Vilkitsky Strait, Vilkitsky-Khatanga channel and on the uppermost continental slope adjacent to the shelf break unit I is generally missing. In the eastern Vilkitsky Strait, unit I shows often an increased thickness on eastern sides of topographic elevations. On the continental shelf and slope the thickness varies mainly between 1 - 2.5 m (locally up to 5 m) and thins on the continental rise to 0.5 - 2 m. In general,

seismic facies	penetration thickness	internal reflection pattern	lateral extent	geometry	basal reflector
layered (Fig. 3a)	< 50 m	parallel to subparallel occ. divergent	>70 km	drape occ. wedge	mainly concordant
prolonged (Fig. 3b)	< 10 m	prolonged to strong surface reflector	not mapped in this study	not recordable	subbottom reflectors are absent
transparent lenses (Fig. 3c)	1 - 22 m	none	0.3 - 10 km	lenticular to sigmoidal	even to slightly wavy/ locally truncating
transparent sectors (Fig. 3d)	4 - 30 m	none	2.5 - 20 km	irregular	not defined by reflectors diffuse
transparent layer (Fig. 3e)	< 50 m	none	< 25 km	drape/ infilling character/ ridge	smooth to rounded

Tab. 3.2: Characteristic features of the three seismic facies recorded in the mapped area.

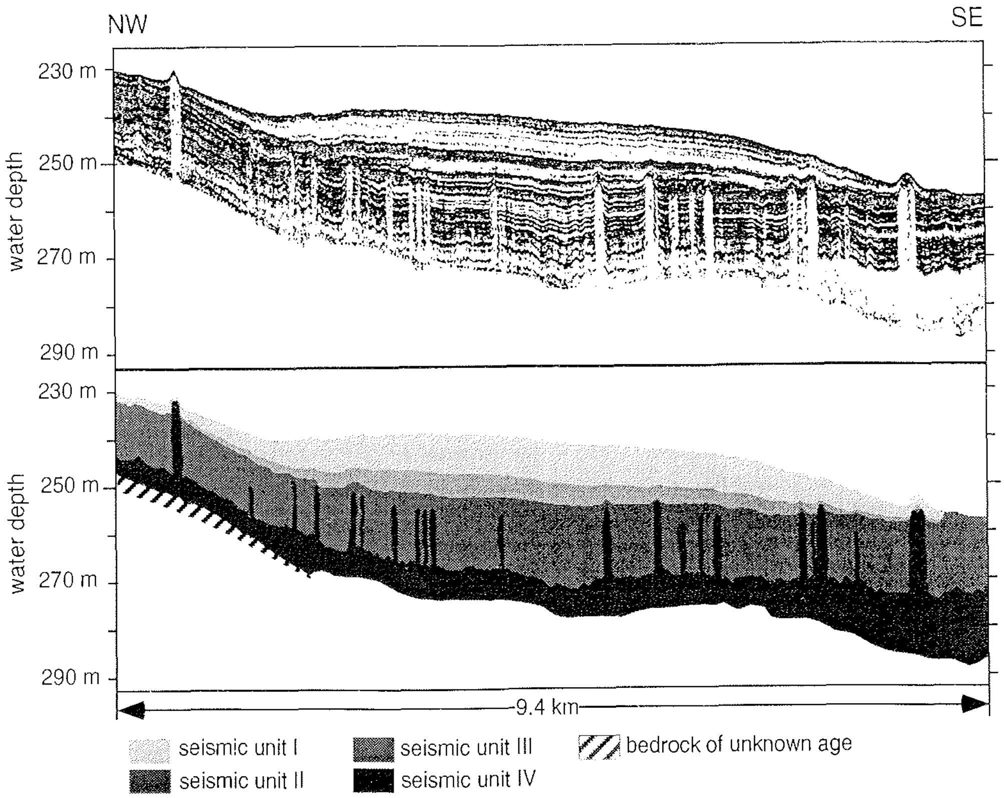


Fig. 3.2: PARASOUND profile of the central Vilkitsky Strait between 77° 57´ N / 103° 57´ E and 77° 57´ N / 104° 27´ E, showing the diapires of unit IV.

unit I is acoustically transparent, only in profile sections, where unit I is >2.5 m thick, a layered facies is developed (Fig. 3.2).
In local high-accumulation depocenters of unit I, north of Taymyr Peninsula, along the southern slope of the upper Vilkitsky-Khatanga channel and on eastern sides of topographic elevations in the eastern Vilkitsky Strait (Fig. 3.2), unit I is of lenticular to sigmoidal shape and up to 18 m thick (77° 44.7´N / 104° 38.1´E). In high accumulation areas, unit I is acoustically dominated by the layered facies which shows downlaps and internal convergence.

Unit II
Unit II forms several thick, wedge shaped high-accumulation depocenters along the shelf edge of the western Laptev Sea, locally reaching up to almost 100 m in thickness (Figs 3.3, 3.4). These main depocenters are thinning over several kilometers to a 3 - 0.5 m thick, concordant and discordant drape (Fig. 3.3) which can be identified almost continuously in the mapped area (Fig. 3.4). In the Vilkitsky Strait, unit II forms a 2 - 5 m thin drape, generally pinching out on steeper slope sections (Fig. 3.2), leading to a patchy distribution (Fig. 3.4).
Unit II is acoustically dominated by the layered facies. In the main depocenters downlaps, internal convergence and reflection terminations at the upper boundary are observed (Fig. 3.3). Transparent lenses are generally missing in unit II with the exception of a small local occurrence in wedge shaped depocenters northeast of the Taymyr Peninsula (Fig. 3.6). The discordant lower boundaries of the transparent lenses indicate truncation during emplacement. Single lenses range between 1 - 6 m in thickness and 1.1 - 5.0 km in width.

Unit III
Unit III generally drapes the topography of the underlying units (Figs 3.2, 3.3) and is acoustically dominated by the layered facies (Fig. 3.4, 3.6). In 86 % of the mapped area where unit III was identified, unit III exhibits a layered internal reflection pattern. The remaining 14 % are characterized by the three subunits of the transparent facies. Unit III varies in thickness from 35 m at the shelf edge to < 2 m on the lower continental rise (Fig. 3.4). Different from unit II, unit III forms no distinct wedge shaped high-accumulation depocenters, but thins more gradually with increasing water depth. Downlaps, internal convergence and discordant upper boundaries are only observed close to the shelf break.
Single and stacked transparent lenses were identified between the central Vilkitsky Strait and the upper Vilkitsky-Khatanga channel and on the eastern continental margin of the mapped area (Fig. 3.6). The stacked transparent lenses are separated by single distinct reflection bands or by sequences of layered facies up to several meters in thickness. Because the PARASOUND penetration is generally insufficient to locate the base of unit III underneath the stacked transparent lenses, the mapped thicknesses (Fig. 3.6) are minimum thicknesses.
Transparent sectors occur only along the Laptev Sea shelf edge east of 115°E, in the uppermost part of the Vilkitsky-Khatanga channel and in the eastern Vilkitsky Strait (Fig. 3.6). They vary from 4 - 30 m in thickness, are 2.4 to > 20 km wide, and replace the entire layered facies of unit III in places.
Transparent layers were identified in the central Vilkitsky Strait where they extend continuously over several kilometers (Fig. 3.6). North of the Taymyr Peninsula, the transparent layers infill the hummocky relief of the underlying units and reach up to 50 m thickness (Fig. 3.5e). Southwest of Severnaya Zemlya Archipelago they mainly drape the smooth to flat relief of the

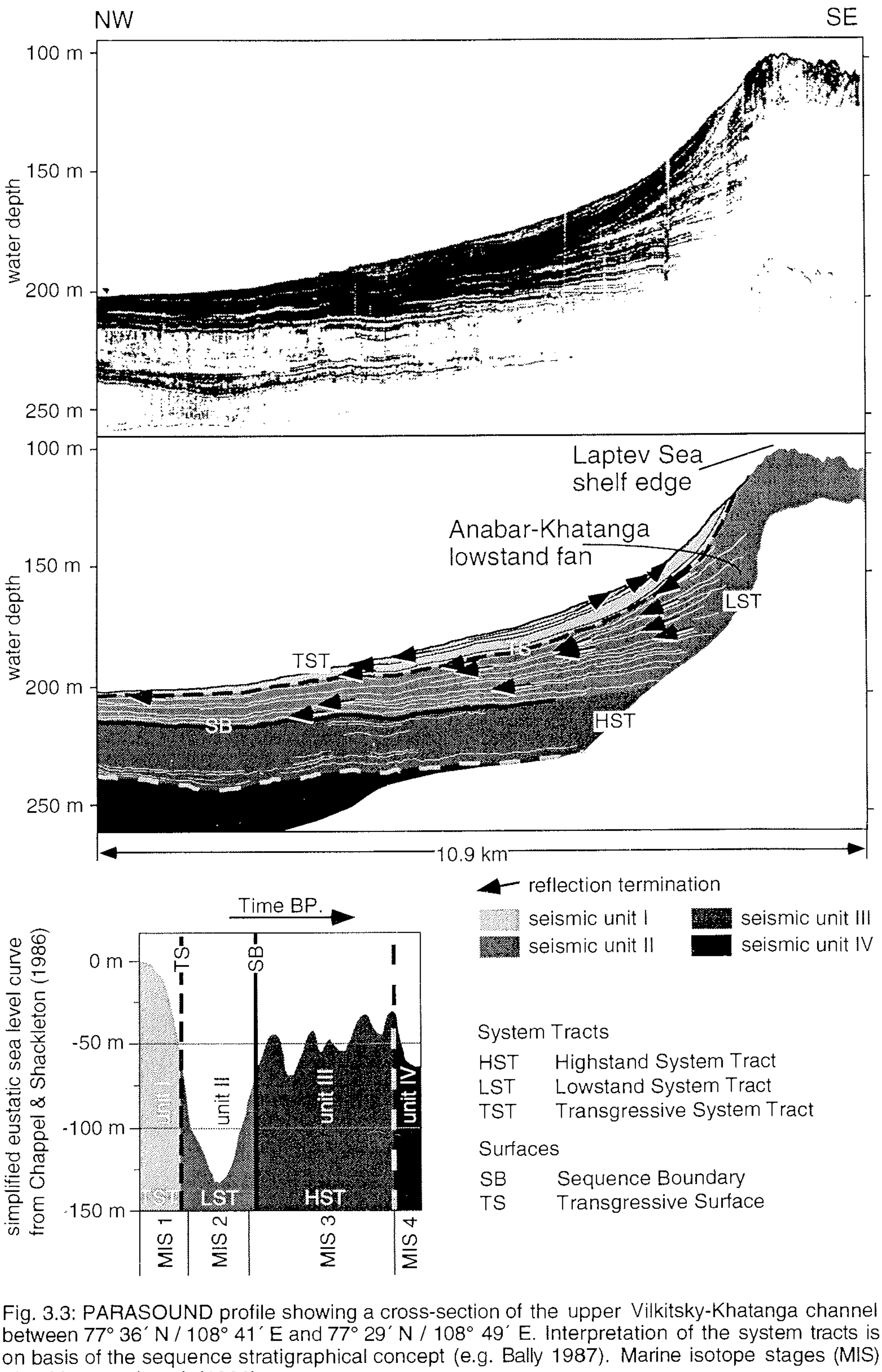


Fig. 3.3: PARASOUND profile showing a cross-section of the upper Vilkitsky-Khatanga channel between 77° 36´ N / 108° 41´ E and 77° 29´ N / 108° 49´ E. Interpretation of the system tracts is on basis of the sequence stratigraphical concept (e.g. Bally 1987). Marine isotope stages (MIS) after Mangerud et al. (1996).

underlying units, reaching several meters in thickness. Because the seismic signal is often too weak to locate the basal reflector of the transparent layers it cannot be determined whether the base is erosive or not.

Unit IV

Unit IV is acoustically dominated by transparent lenses (Figs 3.4, 3.6). In 75% of the area, where unit IV was identified, facies is characterized by transparent lenses. They extend continuously from the eastern Vilkitsky Strait down to the continental rise (3200 m water depth), where a large debris flow dominated submarine fan of approximately 28000 km^2 is developed. The absence of debris flow deposits and slump scars on the central Laptev Sea continental margin indicates that the Laptev Sea is not the source area of these fan deposits. In the Vilkitsky Strait and on the continental rise, the penetrated thickness of the transparent lenses varies from 5 - 10 m. On the upper continental slope, the penetrated thickness increases to 45 - 55 m (Fig. 3.6). Single lenses reach 2.5 - 22 m in thickness, 0.4 - >10 km in width and are separated by distinct reflectors or layered sequences up to 4 m thick (Fig. 3.5c). The lenses show a convex surface, whereas their bases truncate the underlying sediments in places.

In the eastern Vilkitsky Strait and the lower Vilkitsky-Khatanga channel, numerous diapires generated from unit IV sediments migrate into the overlying strata. The diapires are characterized by acoustic voids and deform the overlying layered sedimentary sequence.

In the southwestern Vilkitsky Strait, unit IV consists of a single transparent layer, which drapes the topography represented in limited profile sections by a distinct basal reflector. The thickness of this transparent layer is generally below 10 m and the lateral extent several kilometers. Based on their draping character the transparent layers were separated from the transparent lenses. No seismic reflectors were recorded from below the basal reflectors of the transparent layers.

On the continental slope and upper continental rise east of the Vilkitsky-Khatanga channel, unit IV consists predominantly of layered facies. Mainly in steeper slope sections, the layered facies shows internal convergence and a discordant surface boundary.

3.5 Discussion

3.5.1 Paleoenvironmental implications

Unit I

The continuous distribution in association with the rather uniform thickness and draping character in the entire study area indicate hemipelagic conditions for the deposition of unit I. The absence of local high-accumulation depocenters and the partly developed layered facies support an undisturbed sedimentation and thus a relatively high sea level. The slightly increasing thickness of unit I from the continental rise to the western Laptev Sea shelf edge suggests that most of the particulate material derives from the shelf. Particle input is predominantly from the large rivers draining into the Laptev Sea (e.g. Gordeev et al. 1996; Rachold et al. 1996). The absence of unit I at the shelf edge and on the uppermost slopes of the Vilkitsky-Khatanga channel is likely related to bottom currents, driven by down-slope cascading of cold and saline shelf waters. These dense bottom currents are generated during intensive saisonal sea-ice formation in the southwestern Laptev Sea, in

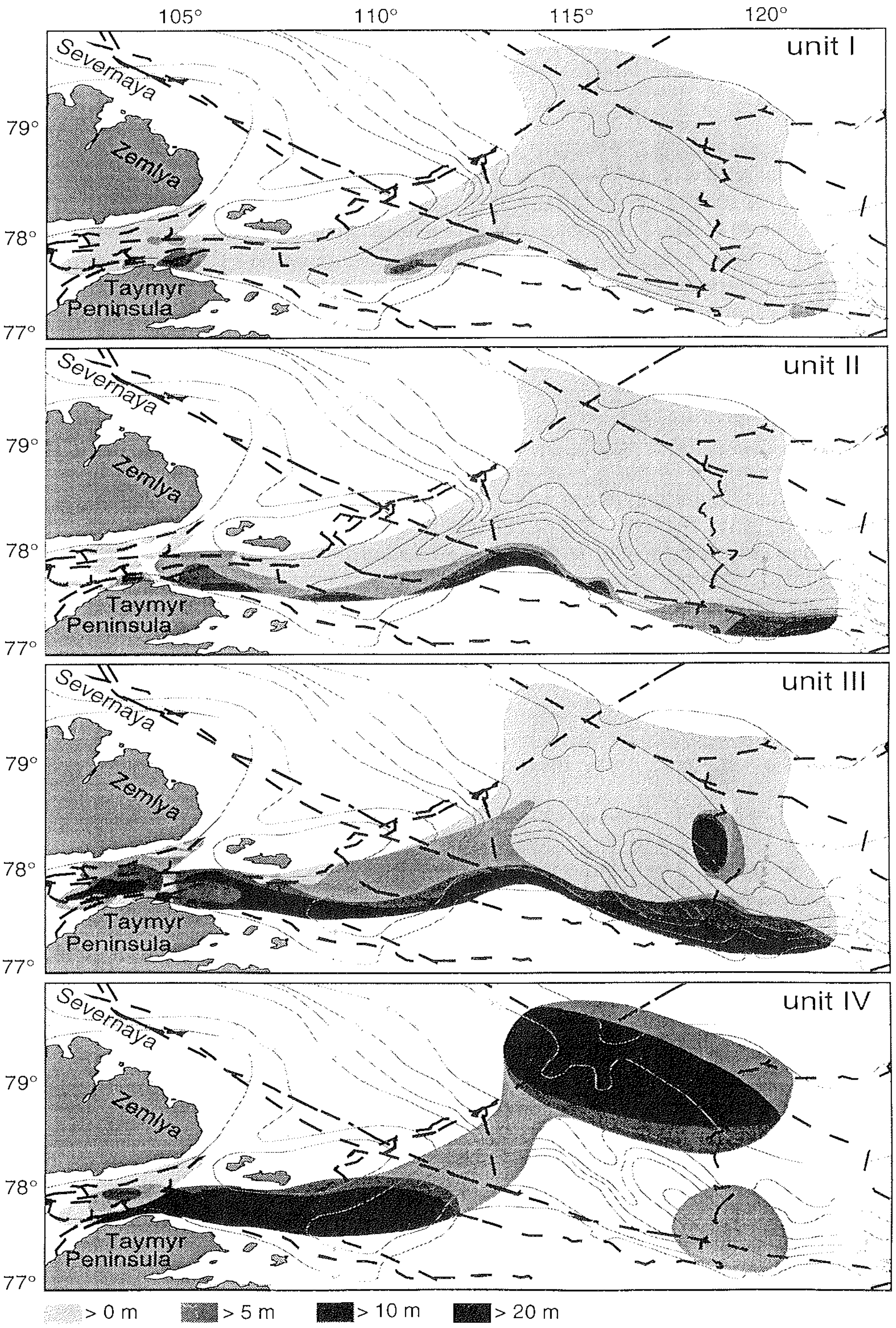


Fig. 3.4: Bathymetric maps (contours) showing the distribution and the related thicknesses of the four seismic units. The cruise tracks of the RV "Polarstern" are shown by grey, stippled lines. The profile sections represented by black, solid lines were used for mapping.

association with the reduction of river run-off. Transport across the shelf is probably through the major submarine valleys (Holmes & Creager 1974; Churun & Timokhov 1995). High saline bottom may also be responsible for the sigmoidal deposits of unit I in the Vilkitsky Strait. The occurrence of asymmetric sigmoidal deposits on eastern slopes implies a drainage direction from west to east which suggests the eastern Kara Sea as possible source area. The existence of strong bottom currents in the Vilkitsky Strait is also pointed out by a channel-levee system recorded in high resolution echosounding profiles (Fütterer 1994).

Unit II

The distribution of several isolated sediment wedges of unit II refers to sediment point sources along the western Laptev Sea shelf edge. These point sources can be linked to the submarine valleys on the Laptev Sea shelf as indicated by Holmes & Creager (1974) and may be related to sediment transport in paleorivers across the shelf (Kleiber & Niessen 1999). Therefore, we suggest that the wedge-shaped deposits represent former submarine fans of the Anabar-Khatanga and Olenek rivers and possibly some smaller rivers on Taymyr Peninsula, draining during the Late Weichselian sea-level lowstand across a non-glaciated, aerially exposed shelf directly onto the submerged uppermost continental slope. The observed internal convergence and downlap structures, interpreted as shingled turbidites, are characteristic for lowstand wedges (Emery & Myers 1996). The entire absence of stacked debris flow lobes in the deposits of unit II indicates that glacimarine fan deposits typical for ice sheet boundary conditions are missing. Therefore, we suggest that no glacier/ice sheet extended to the shelf edge in the study area during the deposition of unit II.

The draping character and the generally layered facies of unit II on the continental margin point to hemipelagic depositional conditions, implying rather low sedimentation rates oceanward of the locally inferred paleoriver fans.

Unit III

The draping character and layered internal reflection pattern suggest undisturbed, hemipelagic depositional conditions. This is supported by the generally low amplitude reflections occasionally intercalated with high amplitude reflections, interpreted as thinly bedded marine mud intercalated by beds of coarser material (e.g. Emery & Myers 1996). An increasing thickness towards the shelf edge in the entire mapped area is indicative of sediment input from the Laptev Sea. However, the fact that no single wedges are formed during the deposition of unit III points to a lack of point sources and the related submarine fan built-up along the shelf edge. This can be explained by a higher sea level compared to the situation of the overlying unit II. The paleocoast line might have been located in the mid to outer shelf area. Consequently, the riverine outflow was closer to the shelf edge compared to today and the sediment input to the upper continental slope and Vilkitsky Strait was enhanced but less restricted to local depocenters compared to unit II. As inferred from figure 3.3, the onset of wedge formation is gradual rather than abrupt. Therefore we suggest a general lowering of the sea level during and/or at the end of the time unit III was deposited.

The general absence of debris flow lobes in the deposits of unit III on the western Laptev Sea continental margin indicates that there was no ice sheet in the eastern Kara Sea. Sediment instabilities on the upper continental slope

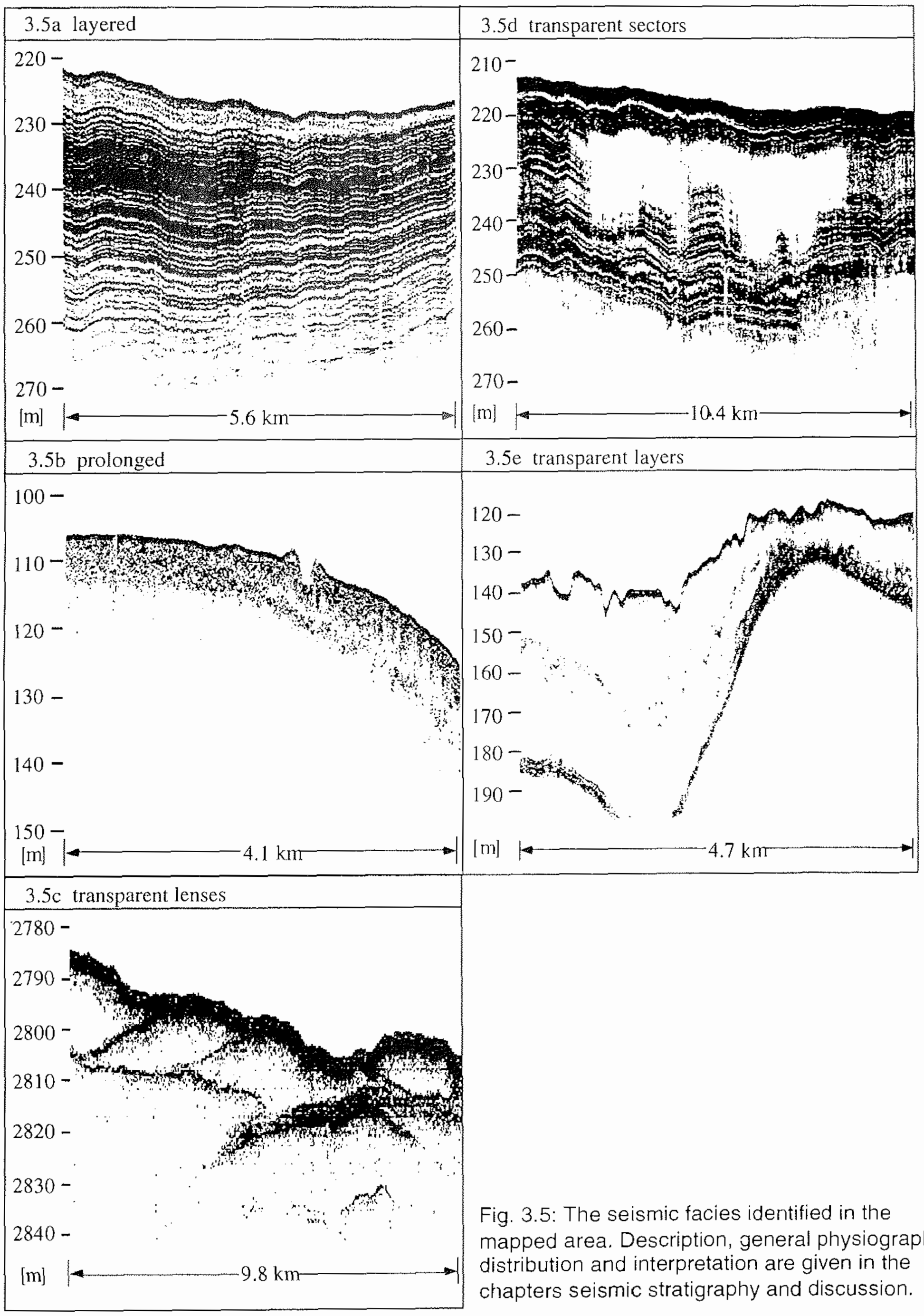


Fig. 3.5: The seismic facies identified in the mapped area. Description, general physiographic distribution and interpretation are given in the chapters seismic stratigraphy and discussion.

in relation with increased sedimentation rates may explain the local occurrence of stacked debris flow lobes and turbidites in the deposits of unit III on the continental margin in the eastern part of the mapped area (Fig. 3.6).
High sedimentation rates of unit III accumulation depocenters in the Vilkitsky Strait are explained by smaller size of local basins because of the lower sea

level during time of deposition compared to today. High sedimentation rates are supported by the transparent facies of unit III. The transparent layers, which seem to lack an original layering, can be caused in water-lain muds by very steady and possibly rather rapid depositional processes (Collinson & Thompson 1982). The transparent sectors are interpreted as post-depositional phenomenon. The loss of the original layering is likely caused by a temporary liquefaction. For example, sea level changes or earthquakes can change the sedimentary structure of a loosely packed sediment by increasing the pore-fluid pressure (Collinson & Thompson 1982). Loosely packed sediments are generated during rapid deposition when the low permeability of fine-grained sediments prevents pore-fluid escape and sediment compaction at a rate that balances the increased overburden, and thus producing excess pore-fluid pressure (Collinson & Thompson 1982).

Unit IV

Transparent lenses, first interpreted by Damuth (1978) in 3.5 kHz records from the Bear Island and North Sea trough mouth fans as debris flow deposits, are the dominant reflection pattern of seismic unit IV (Fig. 3.6). In high latitudes, debris flow dominated submarine fans imply a periodic or continuous high sediment input by a fast-flowing glacier/ice sheet directly to the continental slope and upper rise (Damuth 1978). Therefore, debris flow dominated submarine fans are used as indication of an extensive glaciation on the continental shelf as described by e.g. Damuth (1978), Vogt et al. (1993), Laberg & Vorren (1996), Vorren et al. (1989) for the Bear Island Trough or by Solheim et al. (1992) for the Isfjorden Fan on the Svalbard continental margin.
The distribution and lack of debris flow deposits along the western Laptev Sea shelf edge indicates that the debris were released at high rates in the eastern Vilkitsky Strait and moved gravitationally through the Vilkitsky-Khatanga channel onto the continental rise down to 3200 m below present sea level. We suggest that the occurrence of debris flow deposits in the Vilkitsky-Khatanga channel is indicated by the presence of numerous mud-diapires. Debris flows have likely a high water content and thus a lower density than the overlying sedimentary sequence, causing density inversion in the sedimentary sequence (Fig. 3.2) (Fütterer 1994; Rachor 1997). The distribution of the debris flow deposits suggests that the high sediment input to the upper continental slope in the eastern Vilkitsky Strait derives from advances of the eastern Kara Sea ice sheet to the shelf edge off Severnaya Zemlya and Taymyr Peninsula. Similar to the Bear Island trough (Laberg & Vorren 1996), the absence of morainal ridges in the PARASOUND profile of the eastern Vilkitsky Strait probably indicates that the grounding line reached the shelf edge. This also implies that the top debris flow deposits and the transparent layers of unit IV found in the Vilkitsky Strait were deposited during times of retreat and/or deglaciation of the Kara Sea ice sheet into the fjord-like Vilkitsky Strait. The acoustic transparency of the layers in PARASOUND profiles of the southwestern Vilkitsky Strait indicates normal consolidated muds which point to pro rather than subglacial deposition. According to Collinson & Thompson (1982), the acoustic transparency of deposits suggests a very steady and possibly rather rapid deposition of very fine grained sediments which is typical for ice-proximal glacial-marine environments (e.g. Osterman & Andrews 1983) commonly associated with deglaciation (e.g. Niessen & Whittington 1997). However, the absence of morainal ridges and the non-identification of consolidated diamicton in the PARASOUND profiles of the Vilkitsky Strait do not allow mapping or verification of the exact boundary of the maximum ice

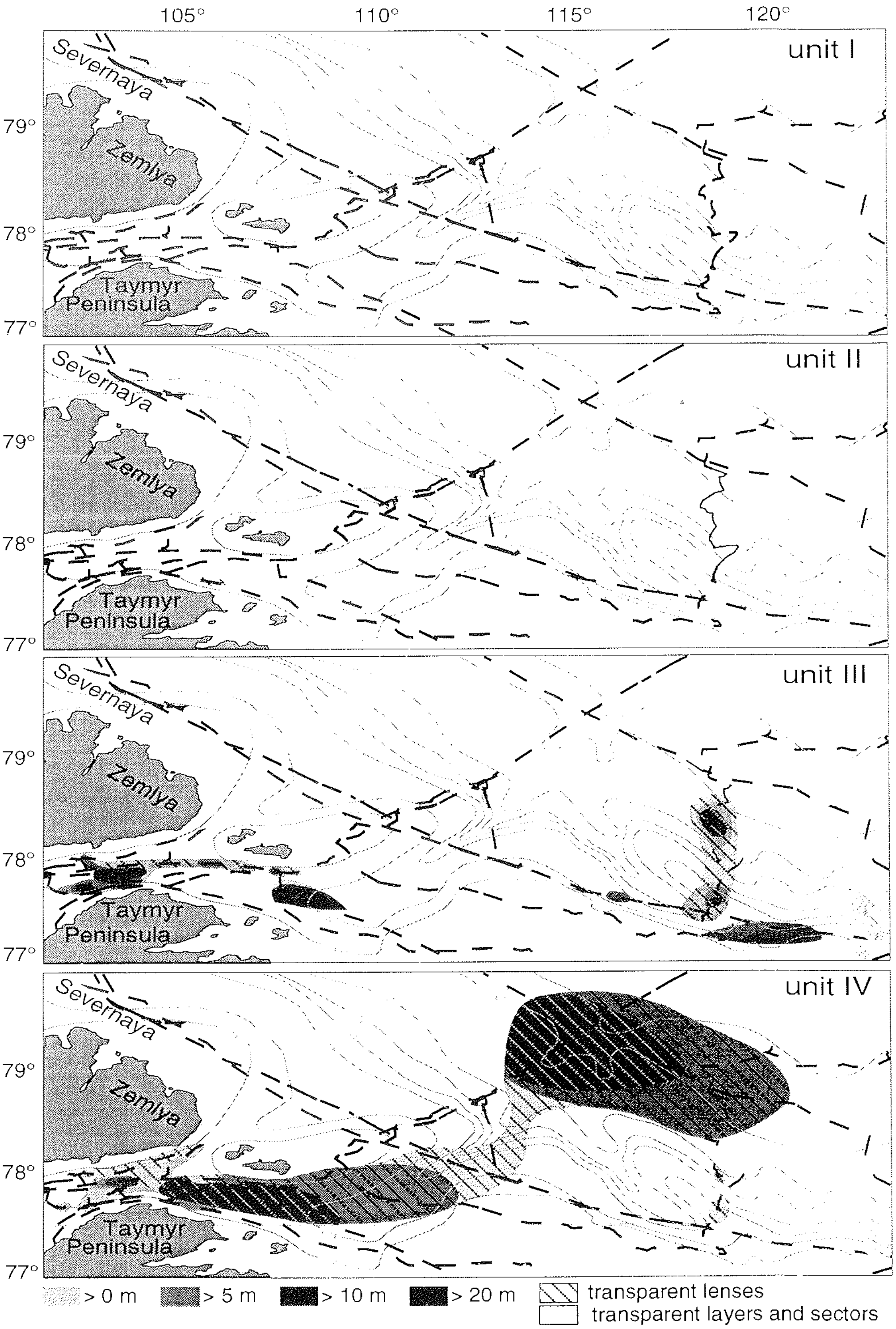


Fig. 3.6: Bathymetric maps (contours) showing the distribution and the related thicknesses of the transparent facies of the four seismic units. The cruise tracks of the RV "Polarstern" are shown by grey, stippled lines. The profile sections represented by black, solid lines were used for mapping.

sheet extent as suggested by Svendsen et al. (1999). Nevertheless, the lack of continuous debris flow deposits towards the Laptev Sea shelf edge clearly indicates that the ice sheet did not extend east of the Taymyr Peninsula onto the Laptev Sea shelf. The latter is consistent with maximum ice sheet map of Svendsen et al. (1999).

The layered sequences intercalated with the debris flow lobes on the continental rise are interpreted to represent intervals of hemipelagic sedimentation implying ice-distal environments during times of smaller ice extent in the Kara Sea.

The presence of the Kara Sea ice sheet on Severnaya Zemlya and the Taymyr Peninsula and its subsequent deglaciation makes it impossible to reconstruct a sea level for the time of unit IV deposition. Stacked debris flow deposits are caused by gravitationally-forced redeposition and cannot be interpreted in terms of sequence stratigraphical system tracts. Moreover, most of the western area, where ice-proximal debris flow deposits (unit IV) were mapped, are likely affected by isostatic depression and subsequent rebound which cannot be quantified from our data. Marine deltaic sediments and shorelines uplifted to 100 m on Taymyr Peninsula and to 120 m a.s.l. on Severnaya Zemlya Archipelago were reconstructed by Möller et al. (1999) and Bolshiyanov & Makeyev (1995), respectively. Consequently, isostatic rebound must have influenced at least the lowermost part of the overlying unit III. This implies a higher sea level at the onset of unit III, related to the isostatic depression caused by the maximum Kara Sea ice sheet extent, followed by a sea level lowering related to isostatic rebound.

3.5.2 Age and depositional history

During the Weichselian, continental margins were affected by a stepwise fall in eustatic sea level that culminated during the last glacial maximum (LGM) of marine isotope stage (MIS) 2, followed by the much faster rise in sea level that occurred after 17 ka (Chappell & Shackleton 1986; Fairbanks 1989). The magnitude of this sea-level fluctuation was ca. 120 m (e.g. Fairbanks 1989). Sedimentary deposits on continental margins affected by sea level changes can be subdivided into a number of distinct, contemporaneous depositional packages, defined by their internal geometry, the nature of their boundaries and the stacking pattern. These depositional packages are called system tracts and refer to distinct phases of the sea-level fluctuation (Loutit et al. 1988; Posamentier & Vail 1988; Boyd et al, 1989; Thorne & Swift 1991). The correlation of system tracts with the eustatic sea-level curve provide a regional stratigraphic framework, which has to be confirmed by core data. (e.g. Emery & Myers 1996; Trincardi et al. 1996; Rodero et al. 1999). In this study, the sequence stratigraphic concept has only be applied to system tracts, not characterized by ice-proximal facies (units I-III) and thus primarily controlled by sea-level fluctuations and the paleocoast line on the very flat Laptev Sea.

In the PARASOUND profiles of the study area, two discontinuities are identified (solid lines in figure 3.3), based on basal reflection terminations (downlaps). These two discontinuities subdivide the Late Quaternary stratigraphic record into a transgressive (TST), lowstand (LST) and highstand system tracts (HST).

Seismic unit I is recorded on the entire Laptev Sea continental margin, indicating a rise in relative sea level compared to the underlying seismic unit II, which is only identified in the PARASOUND profiles from the western Laptev Sea slope and rise. Figure 3.7 reveals that the thickness of seismic unit I

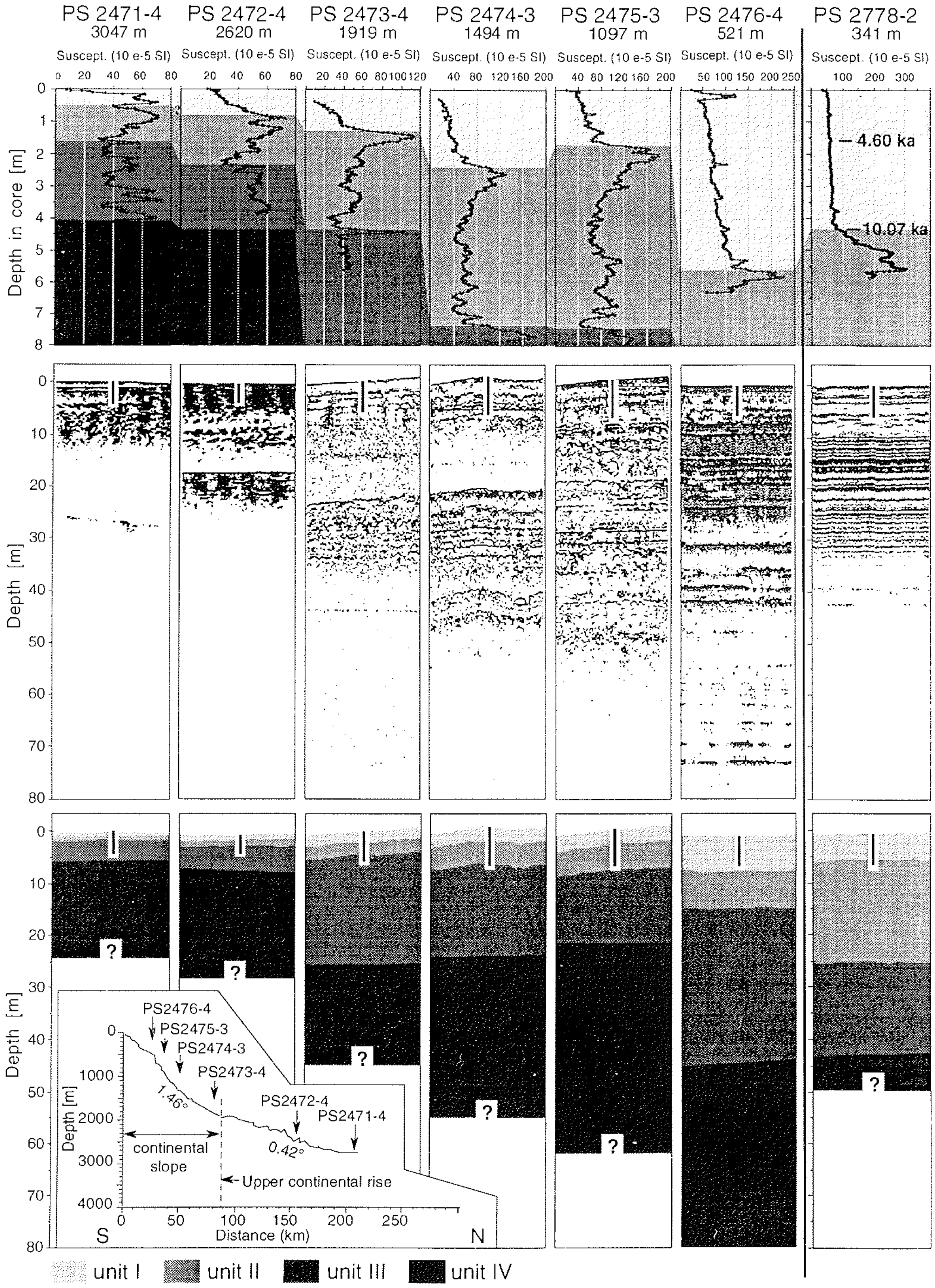


Fig. 3.7: Magnetic susceptibility logs (modified after Fütterer 1994) and PARASOUND records of the cores PS2471-4 - PS2476-4. The radiocarbon dated core PS2778-2 (corrected by a reservoir effect of 440 years; Weiel 1997) is added (for location see figure 1).

corresponds to the thickness of the upper part of the magnetic susceptibility logs of cores PS2471-4 to 2778-2 (Fig. 3.7), which base is radiocarbon dated to 10.07 ka (Tab. 3.3; Weiel 1997). Taking into account that erosional processes reach the bottom of the central Laptev Sea in a present water depth of around 30 m, as suggested by Stein & Korolev (1994), the undisturbed deposition of the uppermost seismic unit may have started when the water depth at the shelf edge rose to around 30 m. In the site of the Anabar-Khatanga lowstand fan, the shelf edge is in a present water depth of 100 m. Therefore the deposition of seismic unit I probably started when the eustatic sea level reached the level of 70 m around 11 ka. ago (e.g. Chappel & Shackleton 1986; Fairbanks 1989; Blanchon & Shaw 1995). Therefore, we suggest that seismic unit I represents mostly Holocene deposits. Moreover, Bauch et al. (1999) show that most of the Holocene sediments in the Laptev Sea are deposited before ~6 ka, because the interval after 6 ka is characterized by very slow sedimentation rates. The decrease of sedimentation rates are explained by a further southward retreat of the fluvial depocenters during the Laptev Sea transgression (Bauch et al. 1999). This implies that the Holocene sediments deposited as unit I on the outer shelf and slope represent largely a transgressive system tract, probably overlain by a thin HST which is not resolved in the PARASOUND profiles. A Holocene age of seismic unit I is confirmed by the correlation of the magnetic susceptibility records of the cores from the western Laptev Sea continental margin (PS2471-4 to PS2476-4) with the radiocarbon dated magnetic susceptibility record of the nearby core PS2778-2 (Fig. 3.7), by the maxima abundance of coccolithes in the upper 25 cm (Fütterer 1994; Nürnberg et al. 1995; Andruleit unpub. data) and by "warm" dinoflagellate cysts in the upper 50 cm of core PS2471-4 (Fig. 3.8) (Müller subm.) indicating interglacial conditions (Holocene).

Sample number	Core	Depth	Carbon source [cmbsf]	^{14}C-Age [uncorr.]	^{14}C-Age [corr. 440yrs]	References
KIA112	PS2485-2	180	bivalves	8900 ± 60	8460	Weiel 1997
KIA113	PS2485-2	435	bivalves	10320 ± 80	9880	Weiel 1997
KIA119	PS2778-2	153	bivalves	5040 ± 60	4600	
KIA120	PS2778-2	434	bivalves	10510 ± 60	10070	Knies 1999
KIA2746	PS2782-1	338	mixed forams	>44140		

Tab. 3.3: AMS ^{14}C-datings performed on bivalves and mixed foraminifers from cores PS2485-2, PS2778-2 and PS2782-1 at the "Leibniz-Labor für Altersbestimmungen" University of Kiel, Germany.

The underlying seismic unit II, which occurs only below the shelf edge on the continental margin and is characterized by downlaps and prograding aggradational layers, is interpreted as LST. The onset of unit II is marked by a typical sequence boundary (Fig. 3.7) (Bally 1987). We suggest that the formation of the LST occurred in a present water depth between 70 and 120 m (Fig. 3.3). During the Late Weichselian regression, the sea level reached -70 m close to the MIS 3/2 boundary at around 27 ka (Chappel & Shackleton 1986). According to global sea-level reconstructions (e.g. Fairbanks 1989) the sea level fell to -120 m at ~18 ka and rose back to - 70 m at ~11.5 ka. Thus, the LST represents mostly deposits of MIS 2. During the entire period riverine input to the Arctic Ocean continued as suggested by low planktic $\delta^{18}O$ values in the sediments of the central Arctic Ocean (Nørgaard-Pedersen 1996).

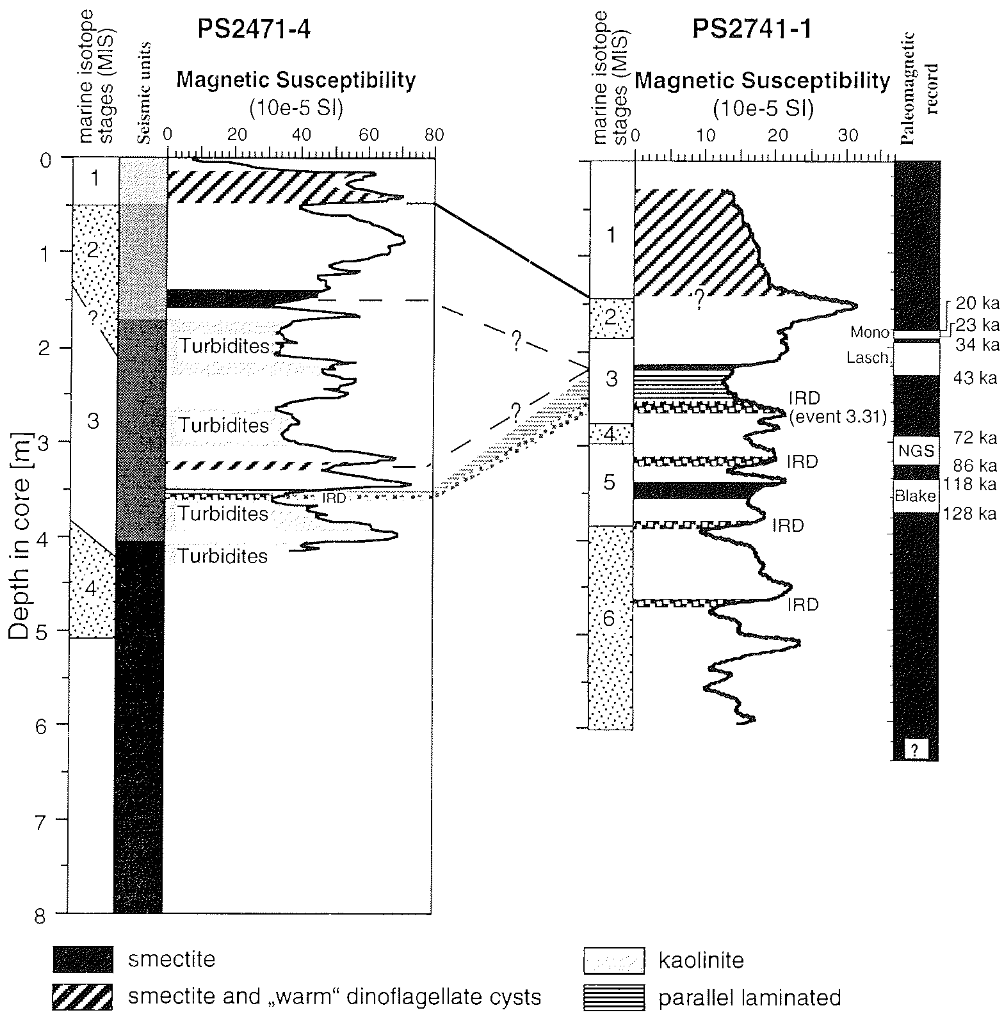


Fig. 3.8: Correlation of core PS2471-4 and PS2741-1 (for location see figure 1) based on clay mineral assemblages, dinoflagellate cysts and sedimentary structures (Knies 1999; Müller subm.). The correlation reveals that the IRD pulse between 357 - 358 cm in core PS2471-4 correlates with IRD event 3.31 of core PS2741-1 (Knies 1999). Modified after Müller (subm.).

The third system tract, which corresponds with seismic unit III, is characterized by low amplitude reflections and parallel layering. Downlaps and progradational aggradation are missing. This pattern is typical for a highstand system tract, deposited under hemipelagic conditions and a relatively high sea level. The increasing thickness of unit III towards the shelf edge implies a higher input of particulate matter deriving from the edge of the Laptev Sea shelf. An increased export of particulate matter to the upper Laptev Sea continental margin can be expected during MIS 3, when the global sea level was generally 30 - 55 m lower than the present sea level and the rivers drained closer to the shelf edge than today. A MIS 3 age for seismic unit III is supported by Stein et al. (1999), who interpreted the sediments containing the significant abundance of *Gephyrocapsa* spp. between 2 - 3 m in core PS2471-4 (Fig. 3.8) as MIS 3 deposits. Furthermore, a MIS 3 age is confirmed by the

correlation of core PS2471-4 with core PS2741-1 northeast of Severnaya Zemlya Archipelago based on IRD content, clay mineral assemblages, dinoflagellate cysts and sedimentary structures (Knies 1999; Müller subm.) (Fig. 3.8). The correlation suggests that the only IRD pulse in core PS2741-1, between 3.57 and 3.58 m, correlates with the youngest IRD event in core PS2741-1 which occurred during MIS 3.31 (Fig. 3.8) according to the paleomagnetic record (Knies 1999).
The stacked debris flow deposits of seismic unit IV cannot be interpreted in terms of sequence stratigraphy and eustatic sea level because ice-marginal conditions imply relative sea level changes influenced by isostatic downpressing and subsequent rebound. However, our interpretation suggests, that the stacked debris flow deposits are older than MIS 3. Therefore, we suggest that the ice-proximal facies is associated with the last maximum extent of an ice sheet on the Kara Sea, Severnaya Zemlya and Taymyr Peninsula that occurred during Middle Weichselian time (MIS 4) as suggested by Svendsen et al. (1999). This is consistent with evidence from terrestrial and marine records of the region. For example, permafrost sequences (Siegert et al. 1999), sediment cores and high-resolution seismic profiles of lake sediments (Niessen et al. 1999) on the Taymyr Peninsula, indicate that the last glaciation of the area occurred during the Middle Weichselian (MIS 4). Moreover, a radiocarbon dating reveals that the youngest marine diamicton in core PS2782-1 east of Severnaya Zemlya Archipelago (Table 3.3; Fig. 3.1), showing push moraine structures down to a water depth of 390 m (Niessen et al. 1996), is related to the last seaward ice sheet advance during Middle Weichselian time (Knies 1999). Therefore, together with other evidences our results support the recently published map of the Middle Weichselian glaciation in Siberia published by Svendsen et al. (1999) (Fig. 3.1).

3.6 Summary and conclusions

Four seismic units, I (youngest) to IV were identified in the Late Quaternary sedimentary succession of the Vilkitsky Strait and the adjacent western Laptev Sea continental margin, Arctic Siberia. The uppermost three units (I to III) lack evidence of ice proximal facies and thus indicate that no large ice sheet was present in the eastern Kara Sea, Taymyr Peninsula and Severnaya Zemlya during times of deposition. In contrast, unit IV represents a glacimarine fan on the continental slope of the western Laptev Sea, typically formed during ice sheet advances to the shelf break.
The uppermost seismic unit I is identified as transgressive drape, radiocarbon dated to Holocene age. The absence of Holocene deposits at the shelf edge and on the uppermost slopes of the Vilkitsky-Khatanga channel in association with sigmoidal Holocene deposits in the Vilkitsky Strait are likely related to cold and saline bottom currents formed during intensive ice formation in the southwestern Laptev Sea and eastern Kara Sea.
The second seismic unit is interpreted as lowstand system tract and thus implying a MIS 2 age. At the western Laptev Sea shelf edge, seismic unit II consists of a wedge-shaped, prograding submarine fan with a surface 100 m below the present sea level. The fan was fed by fluvial input through a subaerially exposed Anabar-Khatanga paleovalley.
Seismic unit III is a typical highstand system tract, based on the draping character of the layered sediments observed over large distances in the study

area. The increasing thickness towards the Laptev Sea shelf implies a higher input of particulate matter deriving from the Laptev Sea shelf and thus a coast line more to the north than present. We suggest that this corresponds to the sea level situation during MIS 3, with river estuaries close to the shelf edge of the Laptev Sea. A MIS 3 age of seismic unit III is supported by linking the seismic record with sediment cores for which chronologies were suggested by a recently published work. This includes a significant abundance of *Gephyrocapsa spp.* between 2 - 3 m in core PS2471-4 (Fütterer 1994; Nürnberg et al. 1995) and an IRD peak of MIS 3.31 in core PS2741-1 (Knies 1999).
In summary, our age model of unit I to III based on sequence stratigraphy and global sea level interpretation is in good agreement with the sparse chronological information from sediment cores. We conclude that the seismic profiles can provide useful chronological information for continental margins in the Arctic Ocean if ice-proximal depositions can be excluded from facies analysis.
The lowermost seismic unit IV indicates an ice sheet grounding line near the shelf break, which we associate with a maximum Weichselian ice sheet extent during MIS 4. This conclusion is consistent with results from other work on permafrost sequences, sediment cores and high-resolution seismic profiles of lake sediments on the Taymyr Peninsula, and push moraine structures off Severnaya Zemlya Archipelago. All evidences suggest that the last glaciation in the study area occurred during the Middle Weichselian (MIS 4) rather than during MIS 2, originally interpreted as the Last Glacial Maximum. Therefore, our study confirms the recently published map of maximum ice sheet extent on the Siberian shelf for Middle (MIS 4) and Late (MIS 2) Weichselian glaciation by Svendsen et al. (1999).

4. Variations of continental discharge pattern in space and time - Implications from the Laptev Sea continental margin, Arctic Siberia

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4.1 Abstract

Variations in sediment input and distribution to the Laptev Sea continental margin during the Holocene and Termination I could be identified based on radiocarbon dated magnetic susceptibility logs and sediment thickness in high resolution seismic profiles. Magnetic susceptibility of surface samples reveals an increased input of magnetic grains to the Laptev Sea deriving from the Anabar and Khatanga river catchments. Exposed magnetite schists and volcanic rocks of the Anabar shield and Putoran Plateau, respectively, function as major source of magnetic material. The distribution of magnetic susceptibility in association with the thickness of the Holocene sediments indicates bottom-current induced sediment transport guided by major submarine valleys on the Laptev Sea shelf. The sites of filled paleoriver channels identified in the seismic profiles suggest that during the Late Weichselian sea-level lowstand, river runoff continued through four of the major valleys on the exposed Laptev Sea shelf. The sediments at the top of the lowstand deposits in front of the Anabar-Khatanga valley, represented in the seismic profiles by prograding deltas, are characterized by outstandingly high magnetic susceptibility values. Radiocarbon datings approximate the deposition of these high magnetic sediments between 10 and approximately 13.4 ka. It is suggested that this increased input of magnetic material is related to the deglaciation of the Anabar shield and the Putoran Plateau and thus support their glaciation during marine isotope stage (MIS) 2.

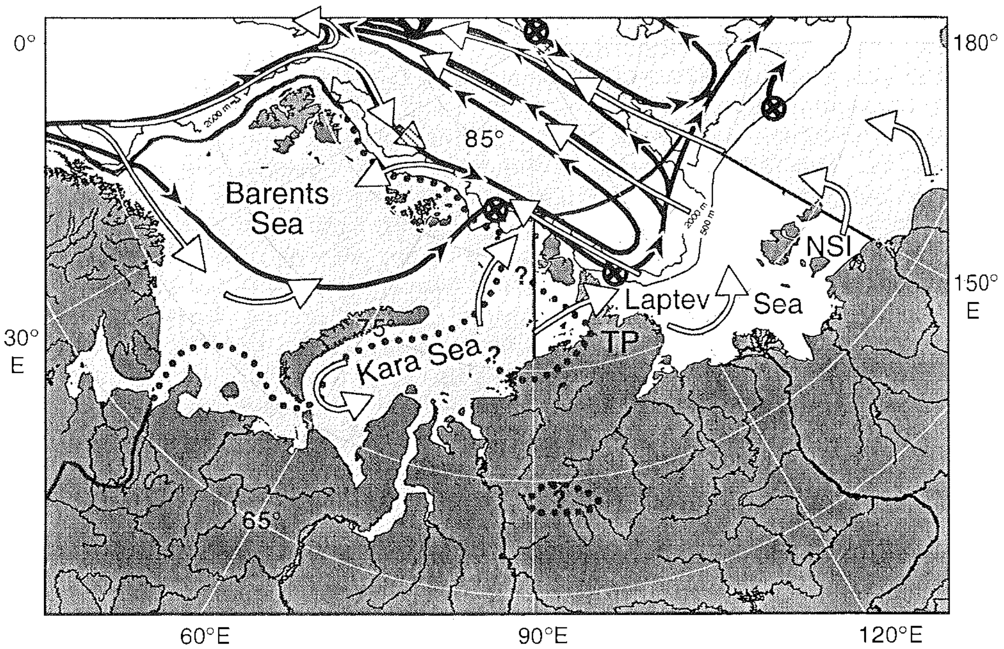
4.2 Introduction

Sedimentation in the Eurasian part of the Arctic Ocean is characterized by a high input of terrigenous material derived from the surrounding land masses, supplied by major river systems and coastal erosion (Are 1994; Rachold et al. 1997). Because of the permanent ice cover, biological productivity is relatively low compared to other oceans. Therefore, the sediments of the Arctic Ocean are dominated by a terrigenous composition, whereas biological particles occur only in minor amounts (Stein 1996). Thus, distribution pattern of mineralogical parameters in space and time can be used to study the imprint of processes on the sedimentary record and document past changes in the depositional environment (e.g. Wahsner et al. 1999 and references therein).
In marine sediments, magnetic susceptibility is routinely measured on whole cores and often used for high resolution lateral core correlation (e.g. Nürnberg et al. 1995; Stein et al. 1999). Magnetic susceptibility is defined as the dimension-less proportional factor of an applied magnetic field in relation to the magnetization in the sample (expressed in SI units). On basis of frequency dependent magnetic susceptibility measurements a significant insitu formation of ultrafine (<0.03mm) superparamagnetic, ferrimagnetic minerals produced

by bacteria and chemical processes (e.g. Chang & Kirschvink 1989; Thompson & Oldfield 1986; Dearing 1994) and aeolian input can be excluded in the sediments of the Eurasian part of the Arctic Ocean (Niessen & Weiel 1996). Therefore, variations in magnetic susceptibility in the sediments of the Eurasian part of the Arctic Ocean exhibit changes of input of ferrimagnetic grains magnetite, titanomagnetite or maghemite; Thompson & Oldfield 1986) deriving from terrestrial bedrock erosion. Volcanic rocks can contain significantly higher amounts of ferrimagnetic minerals compared to other rock types. Consequently, using magnetic susceptibility, different source areas of terrigenous sediments in Ocean sediments can be distinguished and pathways can be identified (Thompson & Oldfield 1986).
Based on high resolution seismic profiles (PARASOUND, 4 kHz), radiocarbon dated sediments and the sequence stratigraphic concept, Kleiber and Niessen (subm.) suggest that during the Late Weichselian sea-level lowstand continuos river run-off across the exposed Laptev Sea shelf led to the formation of river deltas along the western Laptev Sea shelf edge. The deltas are covered by a thin drape of Holocene age, mainly deposited during the early Holocene transgression of the Laptev Sea area, which was not covered by an ice sheet from MIS 3 to MIS 1.
In this study, we present maps of the magnetic susceptibility distribution of surface samples and the top layer of the Late Weichselian sea-level lowstand deltas and maps of the sediment thickness of the Holocene deposits and the sea-level lowstand deltas. Aim is, to identify source areas, to document variations in the depositional environment, and to reconstruct the sediment pathways to the continental margin of the Laptev Sea (Fig. 4.1) during these two time intervals.

4.3 Materials and methods

Sediment cores presented in this study were collected during the RV "Polarstern" cruises ARK-IX/4 (Fütterer 1994), ARK-XI/1 (Rachor 1997) and ARK-XIV 1-B (Kassens in prep.), using a gravity (12 cm core diameter) and Kastenlot corer (rectangular cross section of 30 * 30 cm) built at the Hydrowerkstätten Kiel, Germany.
Volume magnetic susceptibility is routinely determined on board in 1-2 cm intervals on entire core sections, using a Bartington MS-2 loop sensor. Measurements (10^{-5} SI) are corrected, according to the manual of the Bartington MS2B sensor system, by a sensor-specific correction factor (For specifications see table 4.1). In the distribution map of the magnetic surface susceptibility (Fig. 4.3) samples collected during the cruise TRANSDRIFT I (RV "Ivan Kireyev"; Kassens & Karpiy, 1994) are included. The volume magnetic susceptibility of these freeze-dried surface samples (13.6 cm^{3}) were measured by Niessen and Weiel (1996) at high (4.6 kHz, hf) and low (0.46 kHz, lf) frequencies in SI units (10^{-5}) using a MS2B Bartington Ltd (UK) susceptibility control unit. The volume magnetic susceptibility of defined sample volumes (13.6 cm^{3}) measured by the MS2B Bartington Ltd (UK) susceptibility control unit can directly be compared with the corrected loop sensor measurements (pers. comm. M. Pirrung).
High resolution sub-bottom profiles were recorded by the hull-mounted PARASOUND echosounder (STN Atlas Electronik GmbH Bremen, Germany). The PARASOUND system combines a narrow beam survey (NBS) system



surface water circulation pattern (after Gordienko & Laktionov, 1969)
submerging Atlantic surface water (after Gordienko & Laktionov, 1969)
intermediate and bottom water circulation pattern (Rudels et al., 1994; Jones et al., 1995)
Arctic bottom water formation (Jones et al., 1995)
Late Weichselian glacial maximum (Svendsen et al., 1999)

Fig. 4.1: Regional setting of the study area (brighter area) at the Central Siberia continental margin. The bathymetry is signified by the 500 and 2000 m contours. The surface water circulation is represented by white arrows (after Gordienko & Laktionov 1969); the intermediate and bottom circulation pattern are represented by black arrows (after Rudels et al. 1994; Jones et al. 1995). The dotted line shows the maximum extend of the Late Weichselian glaciation according to the hypothesis of Svendsen et al. (1999). TP = Taymyr Peninsula, NSI = New Siberian Islands.

	ARK-IX/4	ARK-XI/1 and ARK XIV 1-B
Loop sensor type	MS-2B (Bartington Ltd.)	
Loop sensor diameter	14 cm	
coil diameter (D_C)	15.3 cm	14.8 cm
core diameter (d) SL	12 cm	
core diameter (d) KAL	9.36 cm	
Alternating field frequency	approx. 80 A/m RMS	
Magnetic field intensity	0.565 kHz	
Loop sensor correction coefficient	-0.0401777814 + 2.58316811*(d/D_C)^2.26972891	
measurement interval	2 cm	1 cm
measuring time	10 sec	

Table 4.1: Bartington MS-2 loop sensor specifications used during the different cruises.

(18 kHz) for accurate determination of the water depth, with a sediment echosounder system (20.5-23.5 kHz, selected by the operator) for sedimentological and echostratigraphic survey (Rostek et al. 1991). As a result of the superimposition of the two simultaneously radiated primary frequencies in the water column, known as the parametric principle, a secondary frequency is created. The latter is equal to the difference between the two primary frequencies (Grant & Schreiber 1990) and was set to 4 kHz in this study. The secondary frequency is suitable for continuous sub-bottom profiling of the uppermost normal consolidated sediment layers (Spiess 1993). Because the secondary frequency is only generated in the central part of the beam, where the highest energy levels occur, the angle of the sounding cone is about 4° (Grant & Schreiber 1990). Due to the small beam angle, the acoustic footprint diameter is only 7% of the water depth. The small footprint diameter allows a high vertical as well as a lateral spatial resolution. The main disadvantage of the narrow beam angle is that signals reflected from a seafloor with an inclination >2° travel beyond the detectors (Spiess 1993). In this case only weak backscatter can be recorded. A seismic velocity of 1500 m/s was used to estimate sediment thickness.
The evaluated seismic data recorded during RV "Polarstern" cruises ARK-IX/4 (Fütterer 1994), ARK-XI/1 (Rachor 1997) and ARK-XIV 1-B (Kassens in prep.) are used to determine the thickness of the uppermost two seismic units. The different echo-characters are classified after the schemes of Damuth (1975, 1980) and Pratson and Laine (1989).

4.4 Results

The magnetic susceptibility logs of the cores from the study area can be subdivided into three characteristic units, named A (youngest) to C (Fig. 4.2). Unit A shows low, uniform magnetic susceptibility values, varying between 10 and 60 $*10^{-5}$ SI (Fig. 4.2). The base of these uniform uppermost core intervals is approximated by radiocarbon datings to 10 ka (Fig. 4.2; Table 4.2), implying that the interval is of Holocene age. This is confirmed by six radiocarbon dates determined in different cores and depth levels of unit A (Fig. 4.2). The transition to the underlying unit B is marked by a distinct increase in magnetic susceptibility (Fig. 4.2). Unit B is characterized by magnetic susceptibility peak values, which function as marker for lateral core correlation (Fig. 4.2). Peak values range from 35 $*10^{-5}$ SI northeast of Severnaya Zemlya up to 200 $*10^{-5}$ SI in core site PS2778, situated at the shelf edge of the western Laptev Sea (Figs 4.2, 4.4). Based on the estimated Holocene boundary at the base of unit A and radiocarbon datings in cores 2719-1, PS2741-1 and PS2742-5 (Fig. 4.2), mean linear sedimentation rates (LSR) of unit B are roughly estimated to 35.8, 21.6 and 17.0 cm/ky, respectively. These LSR are comparable to mean Holocene LSR along the Laptev Sea continental margin (e.g. Bauch et al. 1996; Spielhagen et al. 1996; Weiel 1997; Stein et al. 1999). On basis of the estimated Holocene boundary and the LSR, the initial deposition of unit B was extrapolated in cores PS2719-1, PS2741-1 and PS2742-5 to 13.4, 12.5 and 12.8 ka, respectively. The transition to unit C is represented by a distinct decrease in magnetic susceptibility. The magnetic susceptibility values of unit C range from 10 $*10^{-5}$ SI in core PS2741-1 northeast off Severnaya Zemlya up to 90 $*10^{-5}$ SI in core PS2475-3 on the western Laptev Sea continental margin (Figs 4.2, 4.4). Compared to unit A the magnetic susceptibility values of

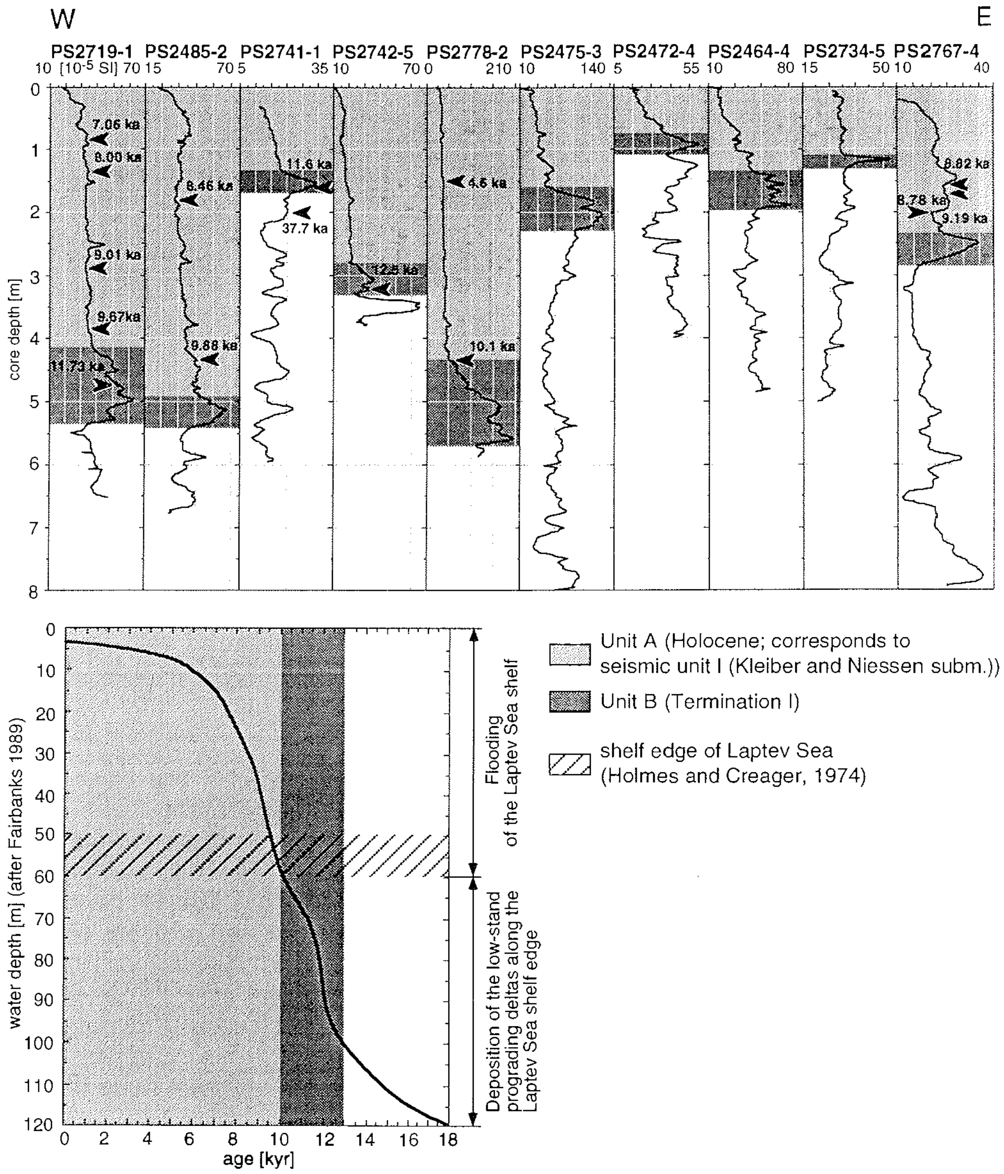


Fig. 4.2: Magnetic susceptibility logs of cores from the Laptev Sea continental margin and eastern Kara Sea (for locations see figure 4.4). The estimated uniform Holocene deposits are light grey shaded whereas the distinct peak, representing Termination I deposits, are dark grey shaded. The lower sketch shows the deposition of the two units in relation to the global sea-level curve of Fairbanks (1989) and the water depth of Laptev Sea shelf edge after Holmes and Creager (1974).

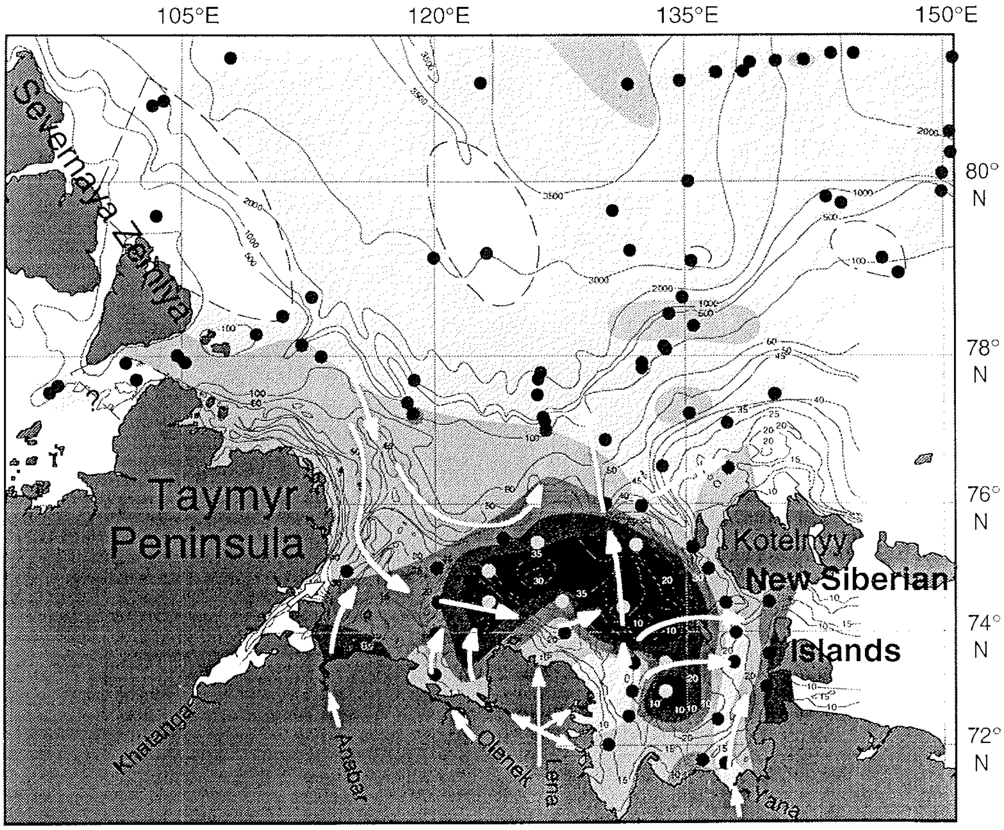
unit C are more variable (Fig. 4.2).
The lateral distribution of the magnetic susceptibility of the surface samples and the peak values of unit B are mapped (Figs 4.3, 4.4). The distribution pattern of the surface samples (Fig. 4.3) reveals that the highest values are determined in the central Laptev Sea. Increased values are measured towards the estuary of the Anabar river and south of Kotelnyy. The lowest magnetic

Core	Sample number	Depth [cmbsf]	Carbon source	^{14}C-Age [BP]	reservoir effect [BP]	^{14}C-Age (corr.) [BP]	Reference
PS2485-2	KIA112	180	bivalves	8900	- 440	8460 ± 60	Weiel (1997)
PS2485-2	KIA113	435	bivalves	10320	- 440	9880 ± 80	
PS2719-1	KIA8212	84	bivalves	7500	- 440	7060 ± 35	Stein (subm.)
PS2719-1	KIA8213	136	bivalves	8435	-440	7995 ± 40	
PS2719-1	KIA8214	289	bivalves	9450	-440	9010 ± 55	
PS2719-1	KIA8215	385	bivalves	10105	-440	9665 +50/-45	
PS2719-1	KIA8216	473	bivalves	12165	-440	11725 ± 60	
PS2741-1	KIA4764	160	mixed forams	12040	- 440	11600 ± 70	Knies et al. (1999)
PS2741-1	KIA110	200	N. pachy sin.	38160	- 440	37720 ± 3500	
PS2742-5	KIA2737	324	mixed forams	12910	- 440	12470 ± 80	Knies (unpubl. data)
PS2767-4	KIA1471	152 - 154	bivalves	9260 ± 40	- 440	8820 ± 40	Spielhagen (unpubl. data)
PS2767-4	KIA1472	172 - 174	bivalves	9220 ± 40	- 440	8780 ± 40	
PS2767-4	KIA1473	420	bivalves	9630 ± 40	- 440	9190 ± 40	
PS2778-2	KIA119	153	bivalves	5040	- 440	4600 ± 60	Weiel (1997)
PS2778-2	KIA120	434	bivalves	10510	- 440	10070 ± 60	

Table 4.2: Results of Accelerator Mass Spectrometry (AMS) ^{14}C performed on bivalves, *N. Pachy* sin. and mixed foraminifers at the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research, University of Kiel, Germany.

susceptibility values are recorded in front of the estuaries of the Lena and Yana rivers. North of the Yanariver estuary, following the Yana submarine valley (Holmes & Creager 1974), the surface sediments show rather low magnetic susceptibility values (Fig. 4.3). From the Laptev Sea continental slope down to the abyssal plain, the magnetic susceptibility values generally range between 10 - 20 $*10^{-5}$ SI, with patches of slightly higher or lower values (Fig. 4.3). Using the peak values of unit B, the lateral distribution of the magnetic susceptibility in this marker horizon shows an almost concentric decrease north of core PS2778 (Fig. 4.4). Strong gradients occur towards the northern and northwestern Laptev Sea continental rise, whereas the decrease of magnetic susceptibility towards the Vilkitsky Strait and northeastern Laptev Sea continental margin is more gradually (Fig. 4.4).

In the PARASOUND profiles of the upper sedimentary succession of the western Laptev Sea continental slope and rise, four seismic units, I (youngest) to IV, were identified (Kleiber & Niessen subm.). Based on the medium to high amplitude basal key seismic reflector, seismic unit I was identified in PARASOUND profiles from almost the entire Laptev Sea continental margin and thus the mapping could be expanded in this study (Fig. 4.5). In the entire study area, unit I is mainly of draping character and acoustically transparent (Fig. 4.6). In general, the thickness of the Holocene deposits varies in PARASOUND profiles between 1 and <5 m (Fig. 4.5), resulting in LSR between 10 - 50 cm/ky. Only in few profile sections, the thickness of seismic unit I reach up to 10 m and show a layered internal reflection pattern (Fig. 4.7). These high accumulation depocenters are situated in the western Vilkitsky Strait, north of Taymyr Peninsula, at the shelf edge north of the Anabar-Khatanga submarine valley, in the southern part of the eastern Lena submarine valley, and in the northern section and on the shelf north of the Yana submarine valley (Fig. 4.5). On the Laptev Sea shelf, seismic unit I is



Bathymetry modified from Holmes and Creager, 1974

- Cores investigated in this study

Magnetic susceptibility > $50*10^{-5}$ SI
Magnetic susceptibility 40 - 50 $*10^{-5}$ SI
Magnetic susceptibility 30 - $40*10^{-5}$ SI
Magnetic susceptibility 20 - 30^{-5} SI
Magnetic susceptibility 10 -20^{-5} SI
Magnetic susceptibility 0 -10^{-5} SI

Fig. 4.3: The magnetic susceptibility distribution of the surface samples on the Laptev Sea continental margin. The white arrows reveal the general surface circulation pattern and river input (modified after Suslov 1961).

often bounded by a continuous, distinct to to prolonged basal reflector. The acoustic penetration is limited to < 10m, and no reflectors are recorded from below the prolonged basal reflector. The thickness of seismic unit I corresponds with the thicknesses of the uniform upper core sections (Fig. 4.7). Therefore, we support the suggestion by Kleiber et al. (subm.) that seismic unit I represents mainly Holocene deposits.

In addition to the 24 filled paleoriver channels identified by Kleiber and Niessen (1999) based on their erosive, u-shaped sub-bottom morphology and undeformed fill geometry, further eight channels were found and mapped (Fig. 4.4). The filled paleoriver channels are up to 11 m deep, covered by the uppermost seismic unit and situated in the eastern Lena and Yana submarine valleys (Fig. 4.4).

PARASOUND profiles from the Laptev Sea continental slope and rise reveal

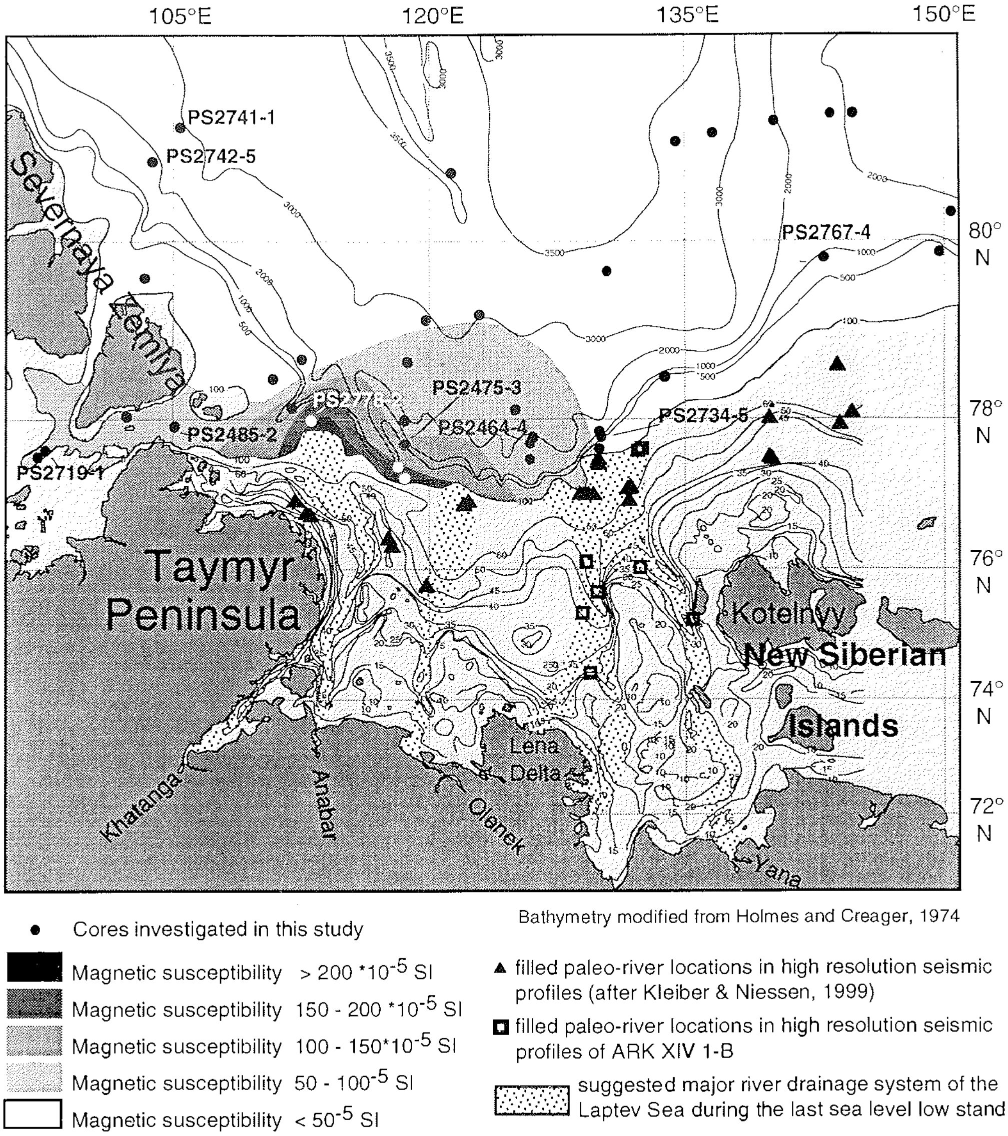
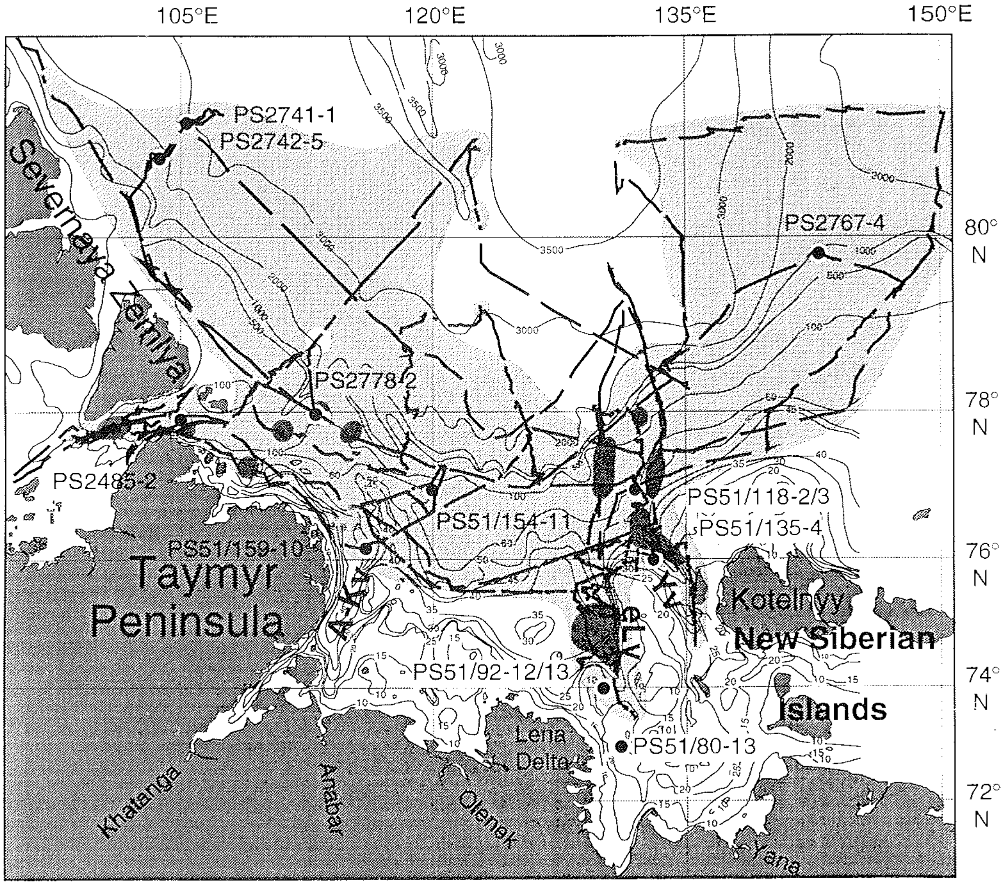


Fig. 4.4: The magnetic susceptibility distribution of the distinct peak representing the top of seismic unit II. Light grey shading represents the exposed shelf area (-100 m) during the Late Weichselian sea-level lowstand. The dotted areas on the exposed Laptev Sea shelf, represent the courses of the major rivers draining directly to the shelf edge.

that the high magnetic core sections represent the top of seismic unit II (Fig. 4.7). Along the western Laptev Sea shelf edge, this second seismic unit is characterized by up to 100 m thick, prograding wedges (Fig. 4.8). Based on the sequence stratigraphic concept, Kleiber et al. (subm.) interpret these prograding wedges as lowstand deltas, deposited during the Late Weichselian sea-level lowstand (marine isotope stage (MIS) 2). On the Laptev Sea shelf, the second seismic unit is not present.



Bathymetry modified from Holmes and Creager, 1974

A-Kv Anabar-Khatanga valley
eLv eastern Lena valley
Yv Yana valley

Holocene sediment thickness 5 - 10 m
Holocene sediment thickness < 5 m
— — PARASOUND profiles analysed in this study
● Core locations of radiocarbon dated Holocene (see tab. 2; H.Bauch, unpubl. data)

Fig. 4.5: The thickness of the Holocene deposits, estimated according to the thickness of the uppermost seismic unit in the PARASOUND profiles, shown as dotted, black lines. In the shown core sites, the thickness of the Holocene sediments could be verify based on radiocarbon datings (see table 4.2 and H. Bauch unpubl. data).

4.5 Discussion

The distribution of the magnetic susceptibility in the surface sediments of the Laptev Sea suggests that the magnetic material is imported by the Anabar and probably Khatanga rivers (Fig. 4.3). In the catchment area of the Anabar river, the magnetic material derives from the magnetite schists exposed in the Anabar shield (Vinogradov et al. 1973) (Fig. 4.9). This source region is also

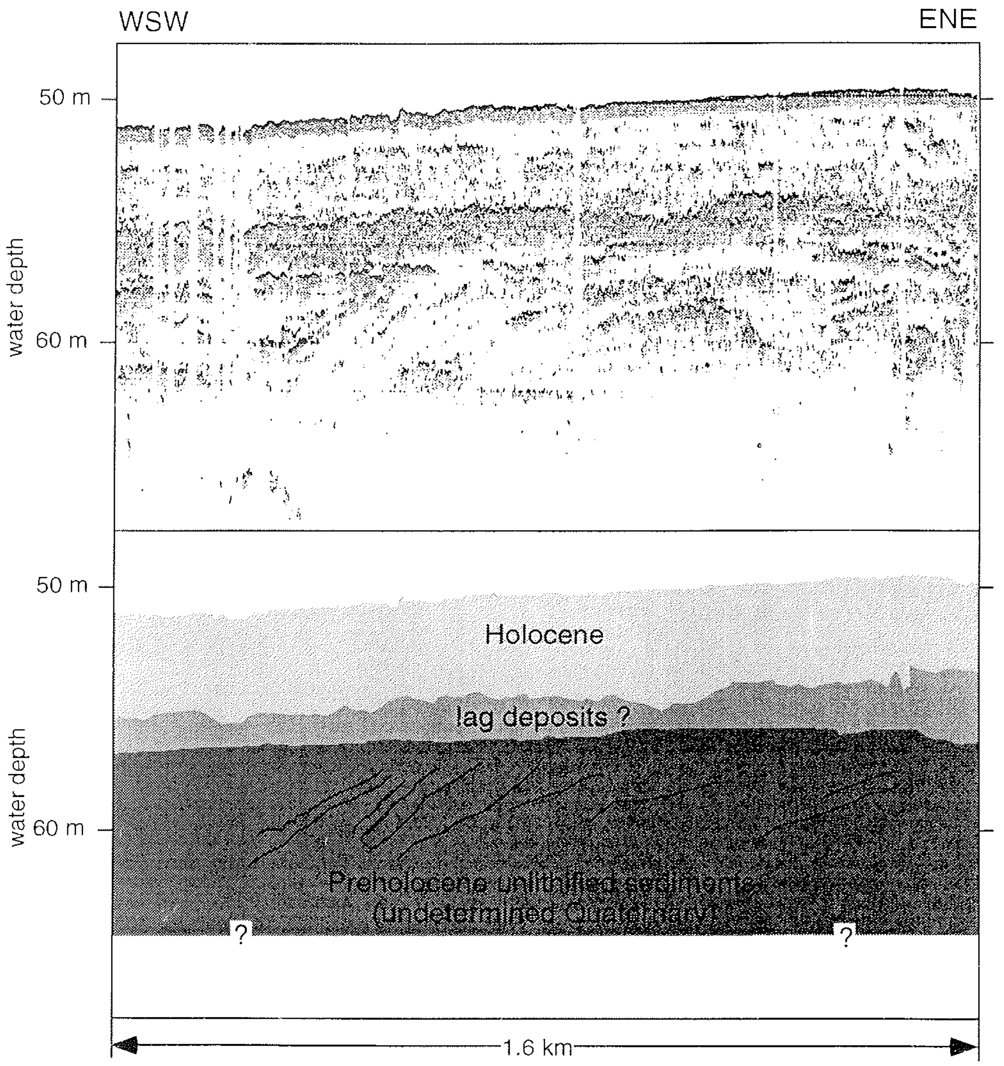


Fig. 4.6: PARASOUND profile of the northern, eastern Lena valley (eLv, see figure 4.5) between 75° 45´ N / 130° 24´ E and 77° 46´ N / 130° 27´ E, showing the transparent upper seismic unit I, interpreted as Holocene deposit.

indicated in surface sediments of the western Laptev Sea by increased contents of pyroxene (Stein & Korolev 1994; Behrends 1999; Peregovich et al. 1999), which is derived from the pyroxene-plagioclase gneiss of the Anabar shield (Vinogradov et al. 1973). The Khatanga river drains a large area of Triassic volcanic rocks of the Putoran Plateau, including trap-basalts (Duzhikov & Strunin 1992) (Fig. 4.9), which function as source of magnetite and titanomagnetite. In the surface sediments of the western Laptev Sea this source area is also indicated by the increased content of smectite (Wahsner et al. 1999). In contrast, the Paleozoic to Mesozoic sedimentary rocks in the catchment area of the Lena and Yana rivers do not contain large quantities of magnetic minerals. Therefore, the magnetic susceptibility of the surface sediments in the eastern Laptev Sea is rather low. The low magnetic surface

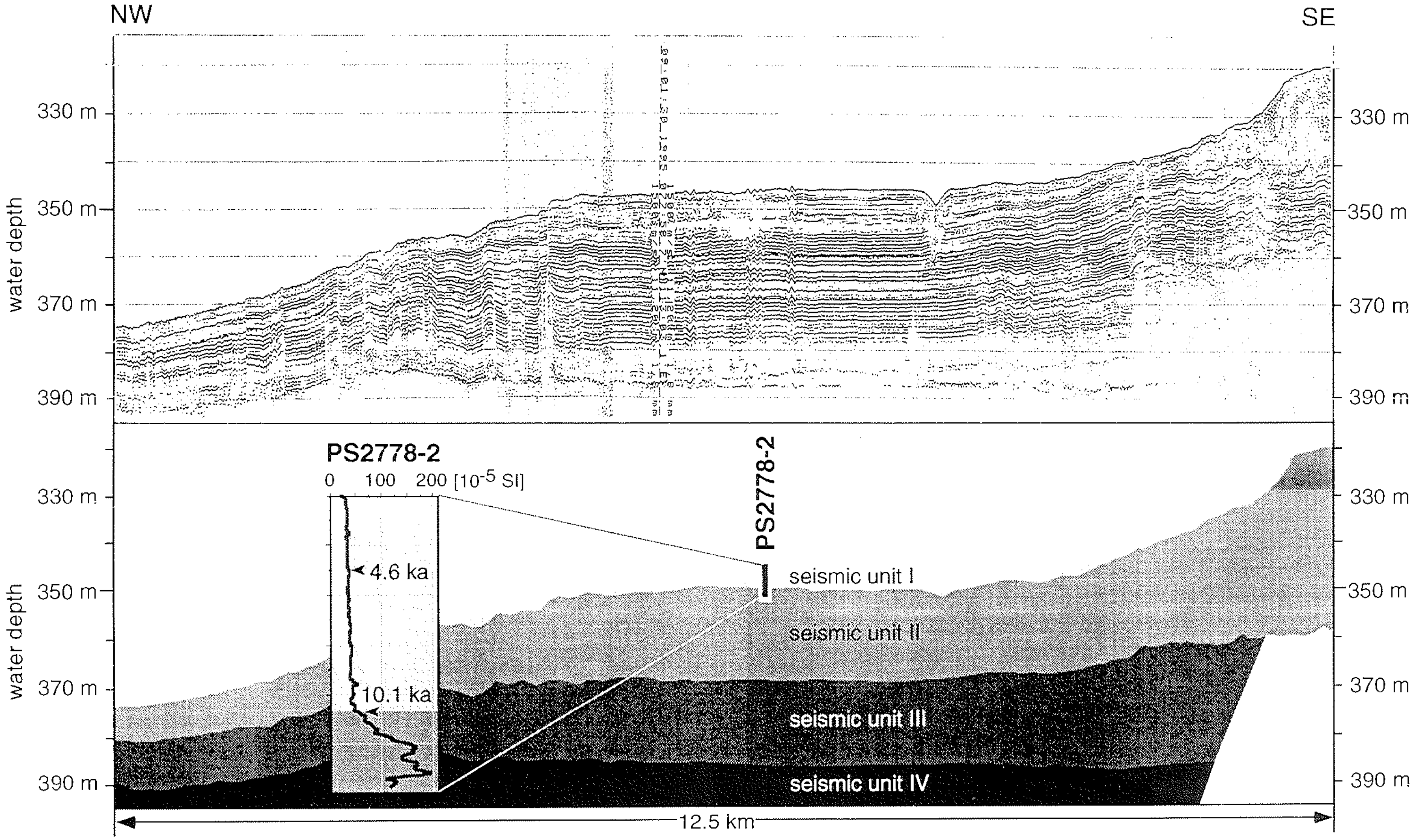


Figure 4.7: PARASOUND profile showing a cross-section of the wedge shaped deposits of seismic unit II in the site of core PS2778 at the western Laptev Sea continental shelf edge between 78°03´N/ 113°01´E and 77°57´N/ 113°16´E (for location see figure 4). Seismic units after Kleiber & Niessen, subm.

susceptibility from the estuary of the Yana river following the Yana submarine valley to the north, suggests that the drainage of the Laptev Sea is strongly controlled by the bathymetry. This is supported by the distribution of the main Holocene depocenters and the grain-size distribution of the surface sediments. Because the main Holocene depocenters are located in the eastern Lena submarine valley, in and north of the Yana submarine valley, and at the shelf edge north of the Anabar-Khatanga submarine valley (Fig. 4.5). The grain-size distribution implies that the deposition of silty clay sediments, characterizing the fluviatile input (Holmes & Creager 1974), are dominant in the Anabar-Khatanga, eastern Lena and Yana channels (Benthien 1994).

The increased magnetic susceptibility of the surface sediments south of Kotelnyy and in the central Laptev Sea, which are significantly higher than the surface samples in front of the estuary of the Anabar river, indicate that other processes than pure riverrine input has to be considered to explain the distribution pattern in these areas. The increased values south of Kotelnyy may be related to the erosion of Paleozoic and Tertiary basalts and volcanic rocks exposed on the New Siberian Islands (Fujita & Cook 1990). In addition, Stein and Korolev (1994) suggest that the high amount of magnetite in the surface sediments south of Kotelnyy and in the central part of the Laptev Sea may due to erosional processes in the very shallow-water environments. Erosion, reworking and redeposition of Pre-Holocene sediments in the Laptev Sea are caused by wave-induced bottom currents (Are 1994) and ploughing of icebergs and sea-ice press ridges (Fig. 4.10). Latter are identified in the PARASOUND profiles northeast of the Taymyr Peninsula, of the central Laptev Sea and northwest of Kotelnyy (e.g. Rachor 1997; Kassens in prep.).

On the Laptev Sea continental margin and in the eastern Kara Sea, radiocarbon datings reveal that the deposition of the high magnetic material, indicated by characteristic peaks in the magnetic susceptibility logs, occurred approximately between 13.4 ka and the beginning of the Holocene (10 ka) (Fig. 4.2). In PARASOUND profiles from the western Laptev Sea continental margin, the magnetic susceptibility peak deposits represent the top of lowstand deltas along the shelf edge, fed by point sources during MIS 2 (Kleiber et al. subm.). During MIS 2, when the sea level was >100 m lower than at present (e.g. Blanchon & Shaw 1995; Fairbanks 1989; Shackleton 1987), the entire Laptev Sea shelf was exposed. On basis of filled paleoriver channels in the PARASOUND profiles (Fig. 4.4) and the bathymetry (Holmes & Creager 1974) we suggest that the rivers remained active during MIS 2 and drained through four major valleys across the exposed Laptev Sea shelf (Fig. 4.4). A continuos river runoff during the last sea-level lowstand is also indicated by low planktic δ^{18} O values in the central Arctic Ocean (Nürnberg et al. 1995; Nørgaard-Pedersen 1996).

Based on the proposed paleodrainage pattern (Fig. 4.4), we suggest that the two major prograding lowstand wedges at the western Laptev Sea shelf edge represent former deltas of the Anabar-Khatanga and Olenek rivers. Thesmaller deltas between 105° and 110°E (Fig. 4.7) are likely related to local drainage systems on the Taymyr Peninsula, which were according to the maximum extent of the Late Weichselian glaciation (Svendsen et al. 1999) not related to a local glaciation and subsequent drainage as proposed by Kleiber and Niessen (1999). The Anabar-Khatanga lowstand delta coincide spatially with the distribution of the highest magnetic susceptibility values in sediments deposited between about 13.4 and 10 ka on the western Laptev Sea

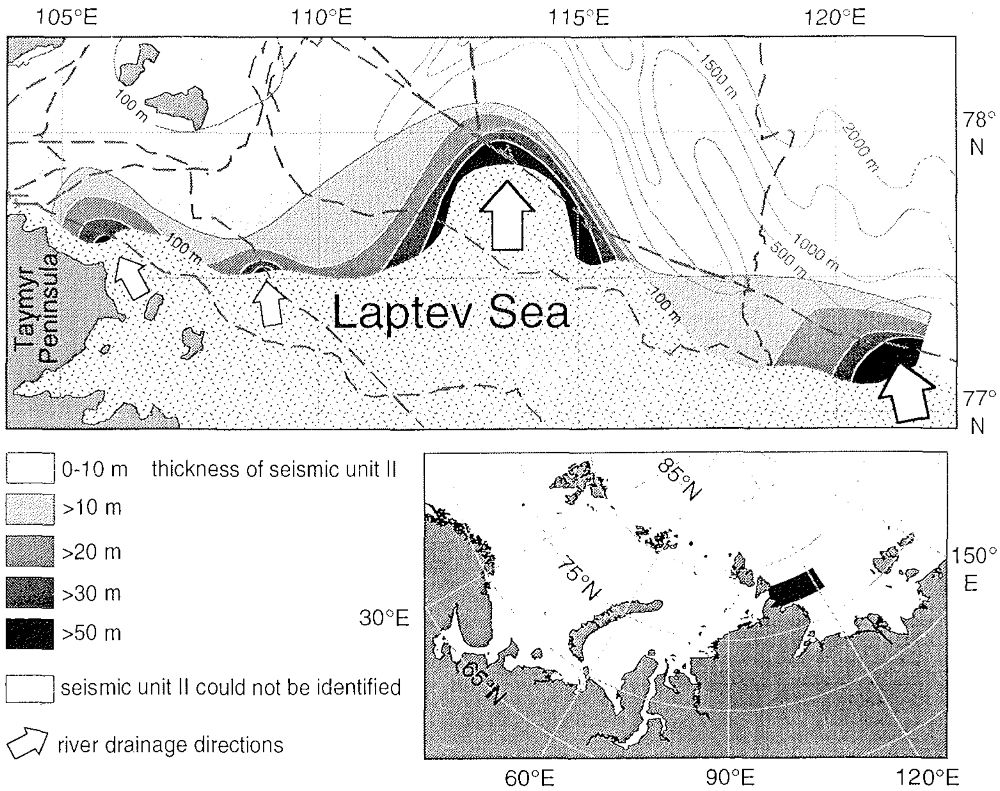


Fig. 4.8: The thickness of the prograding sea-level lowstand deltas along the western Laptev Sea shelf edge based on PARASOUND profiles.

continental margin (Fig. 4.4). Thus, during Termination I, the Anabar-Khatanga paleoriver mouth acted as point-source of high amounts of magnetic minerals. Likely, the distribution of the magnetic susceptibility along the Laptev Sea continental margin (Fig. 4.4) is a reflection of the Arctic Ocean circulation pattern during Termination I, suggesting a west-east oriented current parallel to the paleocoast. This implies that the circulation pattern during Termination I was comparable to the present intermediate and bottom water circulation pattern (Fig. 4.1) (Rudels et al. 1994; Jones et al. 1995). For this reason, the increased magnetic susceptibilityvalues in the core PS2719 -1 of the eastern Kara Sea (Figs 4.2, 4.4) point to an increased input of magnetic material. This increased input likely derives from the Jenessej river, draining the volcanic rocks of the Putoran Plateau. The sediments in the top of the Anabar-Khatanga lowstand delta show comparable LSR as Holocene sediments. Therefore, the remarkably higher magnetic susceptibility of the upper sediments of the Anabar-Khatanga lowstand delta (200 $*10^{-5}$ SI) compared to surface values in the estuary of the Anabar river (45 $*10^{-5}$ SI) indicate that the volcanic terrain of the Putoran Plateau and/or magnetite schists of the Anabar shield must have released considerably higher quantity of eroded material.
We suggest that this increased input may indicate the deglaciation of the Putoran Plateau and/or Anabar shield, which started according to the peaks in the susceptibility logs around 13.4 ka and lasted until about 10 ka

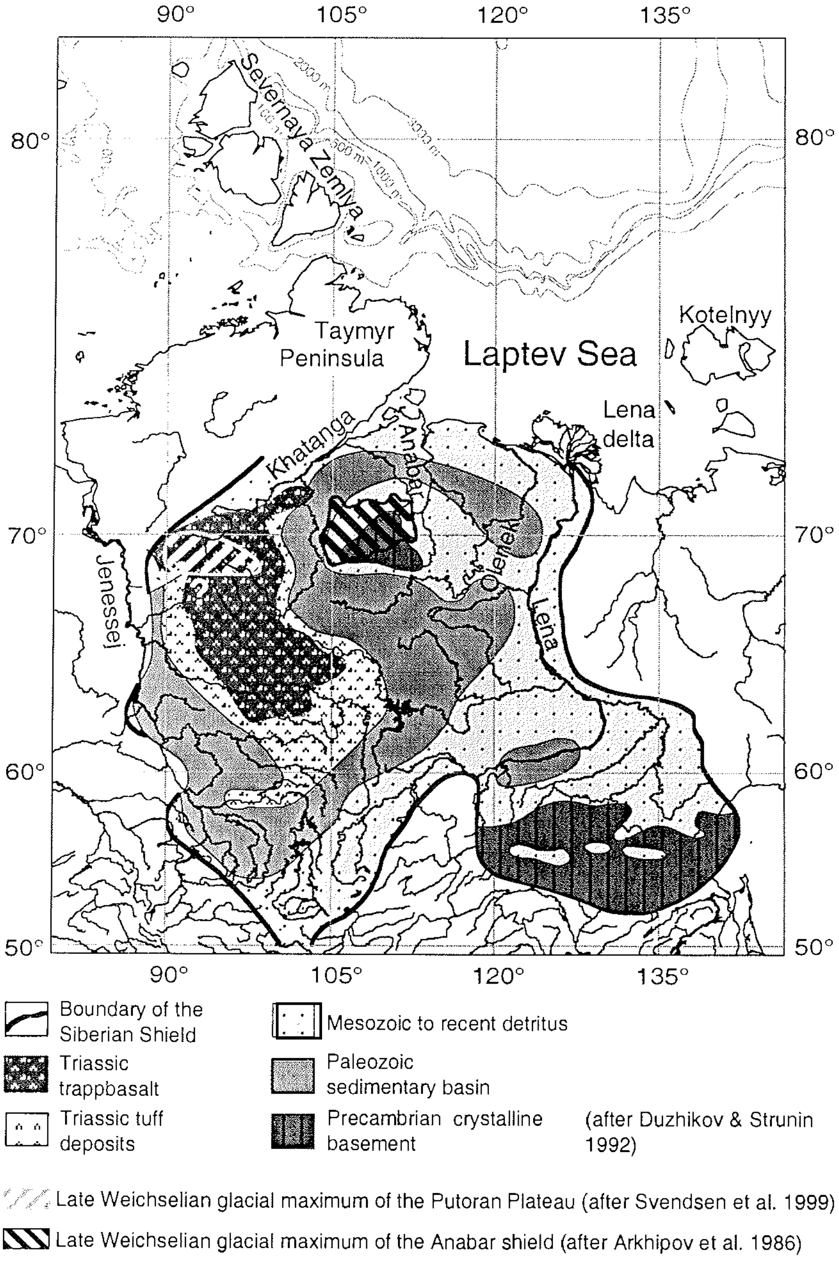


Fig. 4.9: Geological overview of the Noril'sk region (after Duzhikov & Strunin 1992).

(Termination I). Therefore, the higher magnetic susceptibility values may function as indicator for the mountain glaciation of the Putoran Plateau as suggested by e.g. Velichko (1979), Melles et al. (1996) and the Anabar shield (Arkhipov 1995; Velichko et al. 1997).

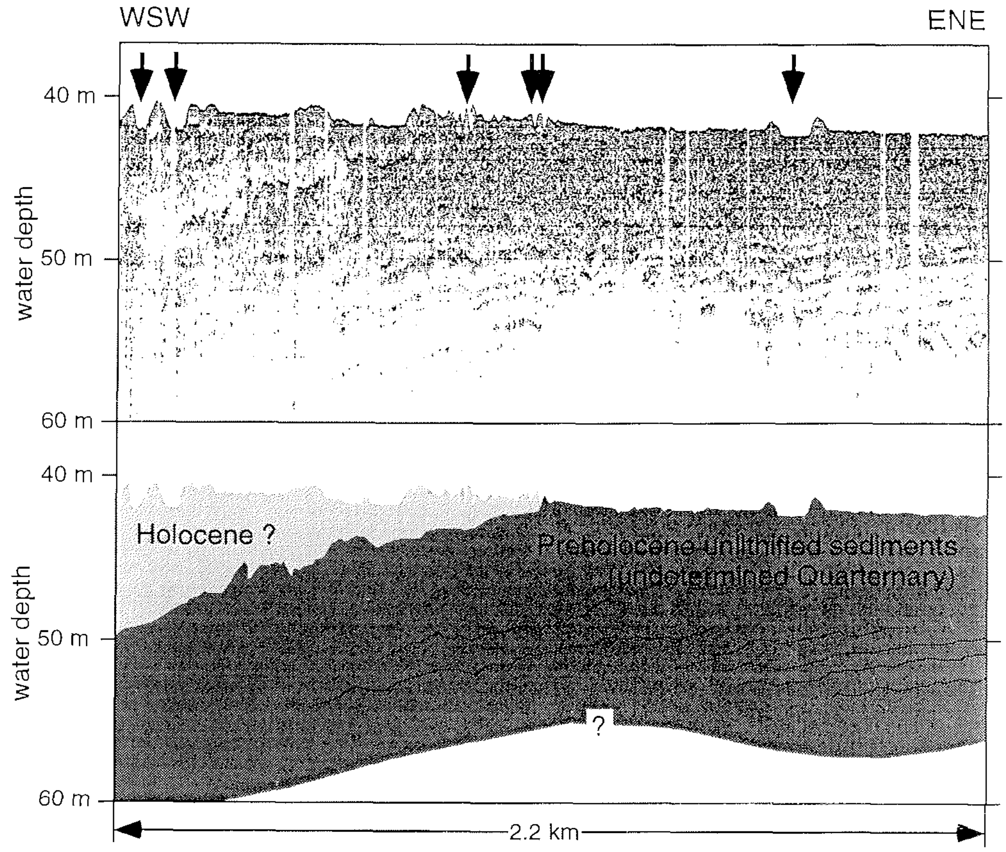


Fig. 4.10: PARASOUND profile of the northeastern Laptev Sea between 76° 25′ N / 133° 32′ E and 76° 25′ N / 133° 28′ E, showing exposed Pre-Holocene sediments eroded by iceberg and sea-ice press ridges indicted by black arrows.

4.6 Summary and conclusions

The surface distribution of magnetic susceptibility in the Laptev Sea indicates that the major import of magnetic material derives from the Anabar and Khatanga rivers. Magnetite schists exposed in the Anabar shield and extensive Triassic volcanic rocks, including trap-basalts are suggested as main source areas. Low magnetic susceptibility values from the Yana estuary along the Yana submarine valley to the north and the distribution of the Holocene high accumulation depocenters in or in front of the submarine valleys of the Laptev Sea shelf indicate that the bottom circulation and related sediment transport is controlled by bathymetry.
The magnetic susceptibility logs from the cores of the western Laptev Sea continental slope and rise show a distinct peak in sediments deposited between approximately 13.4 and 10 ka. The distribution map of magnetic susceptibility peak values reveals that the highest accumulation of magnetic minerals occurred in a sea-level lowstand delta in front of the Anabar-Khatanga submarine valley. Filled paleoriver channels, identified in the PARASOUND profiles, suggest that the river runoff was continuous through four of the major valleys of the exposed Laptev Sea shelf during MIS 2. Similar LSR during the deposition of sediments characterized by the magnetic

susceptibility peak and Holocene deposits imply an increased input of magnetic material during approximately 13.4 - 10 ka. This increased input is interpreted as reflection of the deglaciation of the Anabar shield and the Putoran Plateau and subsequent release of fine-grained glacigenic debris enriched in ferrimagnetic minerals into the Khatanga and Anabar rivers.

5. The Late Weichselian glaciation of the Franz Victoria Trough, northern Barents Sea: Ice sheet extent and timing

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5.1 Abstract

High resolution seismic profiles (PARASOUND, 4 kHz) and three sediment cores from the Franz Victoria Trough and adjacent continental slope were studied in order to constrain the timing and extent of the northern Svalbard/Barents Sea ice sheet during the Late Weichselian glaciation. Stacked debris flow lobes and layers of glacimarine diamicton on the lower continental slope indicate that large quantities of glacially derived sediments were deposited by the northern Svalbard/Barents Sea ice sheet directly onto the upper continental slope at approximately 23 ^{14}C ka. A grounding-line advance to the shelf break is supported by the identification of diamicton, interpreted as till, in the seismic profile near the shelf break. After several ice sheet instabilities marked by significant input of ice rafted detritus to the continental margin, the disintegration of the northern Svalbard/Barents Sea ice sheet (Termination Ia) is indicated by an isotopically defined meltwater signal dated to 15.4 ^{14}C ka and a distinct pulse of ice rafted detritus. The drastic change in sedimentary pattern on the upper continental slope, dated to about 13.4 ^{14}C ka, is interpreted as grounding-line retreat from the shelf edge. A further stepwise retreat of the northern Svalbard/Barents Sea ice sheet is indicated by pulses of ice rafted detritus which appear to be contemporaneous with the onset of distinct ice rafting events in adjacent areas and pulses of glacimarine sedimentation in the southwestern Barents Sea.

5.2 Introduction

In earlier studies, reconstructions of Late Pleistocene ice sheets along the Eurasian continental margin were discussed controversially, even for the Last Glacial Maximum (LGM) (e. g. Vogt et al., 1994). Postulated scenarios ranged from isolated small ice caps over the Eurasian archipelagos to a large ice sheet covering the entire Siberian shelf and extending far into continental Eurasia (e. g. Hughes et al., 1977; Grosswald, 1980, 1990, 1998; Dunayev and Pavlidis, 1990; Astakhov, 1992, 1998; Elverhøi et al., 1993). For the Barents Sea, the distribution of glacial diamicton and morainal banks leaves little doubt that even the deepest basins were covered by grounded ice during the Late Weichselian (Elverhøi et al., 1990; Solheim et al., 1990; Gataullin et al., 1993; Polyak et al., 1995).
Due to severe sea ice conditions, the Franz Victoria Trough (FVT) (Fig. 5.1) is one of the least accessible and poorly understood areas with respect to the glacial and deglacial history (e. g. Polyak and Solheim, 1994; Forman et al., 1995; Solheim and Forsberg, 1996; Lubinski et al., 1996; Landvik et al., 1998). Despite lack of direct evidence, most reconstructions including the recent summary paper by Svendsen et al. (1999, and references therein) suggest that during the Late Weichselian the grounding line of the northern Svalbard/Barents Sea ice sheet (SBIS) reached the outermost, northern

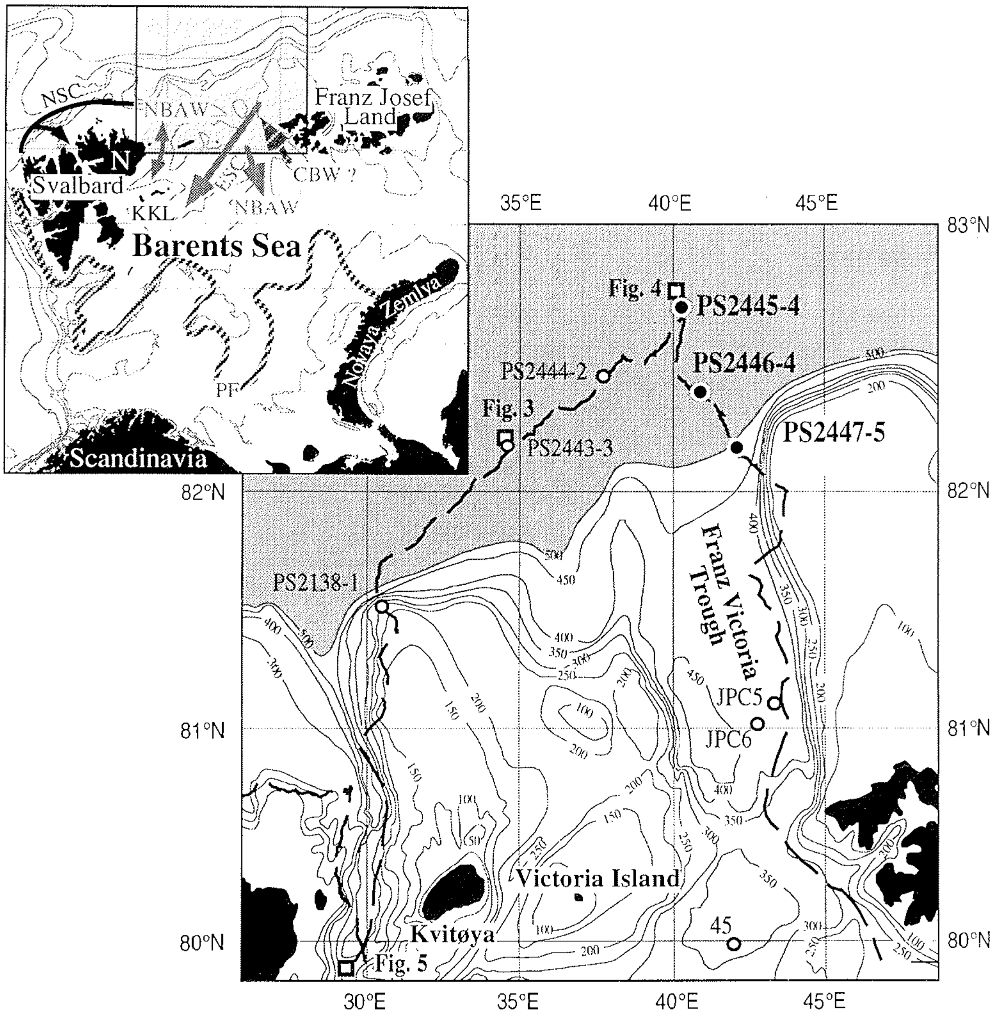

Fig. 5.1. Regional setting and bathymetry of the study area at the northern Barents Sea continental margin (50 m contours above 500 m). Light grey shading represents water depth greater than 300 m; dark grey shading represents water depth greater than 500 m. The circulation of the main warm surface water currents (Atlantic water: dark arrows), the cold surface currents (Arctic water: light arrows) (modified after Pfirman et al., 1994 and references therein) and the location of the oceanic polar front (PF, striped line) (after Vinje, 1985 and Loeng, 1991) are shown. The PF divides colder and fresher Arctic water in the north from relatively warm and saline water of Atlantic origin in the south.
N = Nordaustlandet, KKL = Kong Karls Land, NSC = North Spitsbergen Current, ESC = East Spitsbergen Current, NBAW = Northern Barents Atlantic derived Water, CBW = Cold Bottom Water. 45, JPC 5/6 and PS2138 are sites of sediment cores presented by Polyak and Solheim (1994), Lubinski et al. (1996) and Knies and Stein (1998). The investigated ship tracks are shown as black, dotted lines.

margin of the FVT and an initial retreat at ~15 ^{14}C ka. This assumption is based on inferences from the southwestern Barents Sea, the regional uplift pattern, correlations with regional meltwater events, bathymetric features and models of ice sheet dynamics (e. g. Elverhøi et al., 1990, 1993; Siegert and Dowdeswell, 1995; Lambeck, 1995, 1996; Vorren and Laberg, 1997). Recent studies of a 3.5 kHz seismic profile and sediment cores in the southern and the central FVT reveal that the three recorded seismic units represent a typical deglaciation succession of glacial diamicton, interpreted as basal till, overlain by laminated glacimarine and bioturbated postglacial sediments (Polyak and Solheim, 1994; Lubinski et al., 1996). Radiocarbon datings of the laminated glacimarine mud postulate an ice retreat prior to 12.9 and 13.2 ^{14}C ka and suggest that normal marine conditions were established close to 10 ^{14}C ka (Polyak and Solheim, 1994; Lubinski et al., 1996). The 3.5 kHz seismic profile shows that the till bed extends continuously across the central FVT. This implies that the SBIS was grounded down to a modern water depth of at least 470 m (Lubinski et al., 1996). Seismic studies in the northern parts of the trough as far north as 81.5°N also suggest that the sea floor is covered by the same till bed (Landvik et al., 1998). However, direct evidence for maximum ice sheet extension and deglaciation pattern from the outer shelf edge do not exist.

Therefore, the main objective of this study is to outline a more detailed history of the SBIS in the FVT during the Late Weichselian and provide a more comprehensive fundament for future ice sheet modeling along the northern Eurasian continental margin (cf. Landvik et al., 1998). For this reason, we have studied seismic profiles (PARASOUND, 4 kHz) and three sediment cores from the FVT and adjacent continental slope to constrain waxing and waning of the SBIS along the northern Barents Sea margin. The data document spatial and temporal variations in sedimentary environment during the Late Weichselian and provide evidence for the extent of basal till in the FVT.

5.3 Data acquisition and methods

High resolution sub-bottom profiles were recorded by the hull-mounted PARASOUND echosounder (4 kHz) (cf. Grant and Schreiber, 1990, for technical details). A seismic velocity of 1500 m/s was used to estimate sediment thickness. The evaluated seismic profiles were recorded during RV "Polarstern" cruises ARK-IX/4 (Fütterer, 1994) and ARK-XIII/2 (Niessen and Kleiber, 1997) and are of variable quality. Secondary noise from ice breaking, recording failures due to ice and air bubbles under transmitter/receiver units as well as geometric effects resulting from ice ramming of the vessel caused some sections of poor quality. However, successions of high quality profile sections, mainly recorded during station time when the vessel drifted with the ice, are sufficient to estimate the extent of the seismic signatures and thus the distribution of the seismic units over the entire continental slope. The different seismic facies are classified after the schemes of Damuth (1975, 1980) and Pratson and Laine (1989).

The investigated sediment cores (PS2445-4, PS2446-4, PS2447-5) were recovered during the RV "Polarstern" cruises ARK IX/4 (Fütterer, 1994) from the continental margin north of the FVT (Fig. 5.1), using a gravity (12 cm core diameter) and Kastenlot corer (rectangular cross section of 30 * 30 cm) built at the Hydrowerkstätten Kiel, Germany. The sediment cores were routinely sampled at 5 to 10 cm intervals; additional samples were taken in intervals of changing lithology and/or color. X-ray radiographs were taken continuously downcore from sediment slabs of ca. 1 cm thickness in order to determine clast contents, sedimentological structures, and bioturbation.

Total carbon (TC), total organic carbon (TOC) and nitrogen were determined using a Heraeus CHN-O-RAPID analyzer. Total organic carbon/total nitrogen

(C/N) weight ratios characterizing the composition of the organic matter, were calculated as total organic carbon/total nitrogen ratios. In general, terrigenous organic matter (TOM) shows C/N-ratios >15, marine organic matter (MOM) C/N-ratios <10 (Scheffer and Schachtschabel, 1984). Compositional variations of organic matter (OM) were additionally inferred from the hydrogen index HI [mgHydroCarbon/gTOC] obtained from Rock-Eval pyrolysis (cf. Espitalié et al., 1984). In immature TOC-rich sediments, HI-values of <100 mgHC/gTOC are typical of TOM, whereas HI-values of 200-400 mgHC/gTOC are characteristic of organic matter with a significant amount of MOM (Tissot and Welte, 1984).
The carbonate content was calculated as CaCO3 (%) = (TC-TOC) * 8.333 (for detailed method description see Stein, 1991). The dolomite content was measured by means of a Philips PW3020 diffractometer and determined using the Qualit software package described in detail by Emmermann and Lauterjung (1990) and Vogt (1997).
Stable oxygen and carbon isotope measurements on the planktic foraminifera *Neogloboquadrina pachyderma* sin. from the >63 µm fraction were performed by means of a Finnigan MAT 251 mass spectrometer (AWI, Bremerhaven). Results are expressed in the d-notation (permille versus Vienna Pee Dee Belemnite (PDB)). Chosen samples for accelerator mass spectrometer (AMS) radiocarbon (^{14}C) datings were measured at the Leibniz Laboratory for Radiometric Dating and Stable Isotopic Research, University of Kiel, Germany (Table 1). The ^{14}C ages are $\delta^{13}C$-normalized and corrected for oceanic-reservoir effects by subtracting of 440 years (Mangerud and Gulliksen, 1975).
In order to estimate the amount of ice rafted debris (IRD), which is used to represent rates of iceberg calving (Elverhøi et al., 1995a) the coarse-grained detritus (>2 mm) was counted on X-ray radiographs in 1 cm intervals downcore (Grobe, 1987).

Core	Sample number	Depth [cmbsf]	Carbon source	^{14}C-Age [uncorr.]	Error	^{14}C-Age [corr. 440 yrs]
PS2445-4	KIA4767	131	mixed forams	14880	±130	14440
PS2445-4	KIA366	191	N. pachy [sin.]	19720	±350	19280
PS2446-4	KIA4760	6	N. pachy [sin.]	1100	±60	660
PS2446-4	KIA1286	150	N. pachy [sin.]	12860	±90	12420
PS2446-4	KIA4761	180	mixed forams	15870	±90	15430
PS2446-4	KIA4762	357	mixed forams	19730	±60	19290
PS2446-4	KIA1285	420	mixed forams	21550	±250	21110
PS2446-4	KIA4763	520	mixed forams	23580	±60	23140
PS2447-4	KIA4768	174	mixed forams	13830	±80	13390

Table 5.1: Results of Accelerator Mass Spectrometry (AMS) ^{14}C performed at the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research, University of Kiel, Germany.

5.4 Physiographic settings

The FVT, located between Svalbard and Franz Josef Land, forms the deepest and widest conduit from the northern Barents Sea into the Arctic Ocean (Fig. 5.1). In the presented PARASOUND profiles, the trough intersects the

continental slope at 410 m water depth and reaches a central depth of 512 m (81° 01.4´N, 43°43.0´E). The continental slope north of the FVT shows in the PARASOUND profile an uneven to partly smooth relief and varies in slope gradient between 1.3° and 3.6°.
Today, the entire study area is located north of the oceanic polar front (Fig. 5.1) and hence strongly influenced by advecting water masses. The fresh surface water layer (<4-5°C, 31.0-34.2 ‰ salinity) is 5-30 m thick and caused by melting of the sea-ice cover (Loeng, 1991; Loeng and Vinje 1979), which varies substantially on seasonal and inter-annual time-scales (cf. Vinje, 1976). A <5-15 m thick, stable transition layer (Gerdes and Schauer, 1997) separates the fresh surface water layer from the underlying Arctic water layer. The Arctic water originates from convection during sea-ice formation in fall and winter and is advected out of the Arctic Ocean into the Barents Sea by the ill-defined East Spitsbergen current (Fig. 5.1) (Mosby, 1938; Midttum and Loeng, 1987; Pfirman et al., 1994). The Arctic water layer is typically found between 20-200 m and overlies the temperature and salinity maximum (<2.9°C, <35.0 ‰) of the northern Barents Atlantic-derived water masses (Fig. 5.1) between 200 and 500 m water (Mosby, 1938; Midttum and Loeng, 1987; Pfirman et al., 1994; Gerdes and Schauer, 1997). Below this Atlantic layer down to several hundred meters water depth lies a colder and less saline bottom water mass (Deep Arctic Ocean water, <0°C, >34.8‰) originating from the Norwegian-Greenland Sea and dense brine rejection during sea ice formation along the northern Barents Sea (Midttum, 1985; Rudels, 1986; Polyak and Solheim, 1994; Lubinsky, et al., 1996; Schauer et al., 1997).

5.5 Results

5.5.1 Seismostratigraphy

In the PARASOUND profiles (4 kHz) three seismic units were identified based on their internal reflection pattern, geometries and basal key seismic reflectors of mainly medium to high amplitude. Because the seismic signal is generally too weak to conclusively locate the Mesozoic sedimentary bedrock surface (Upper Regional Unconformity (URU) in the southern and western Barents Sea; Solheim and Kristoffersen, 1984), the mapped thicknesses of the Quaternary sediments represent only estimates of the minimum thickness (Fig. 5.2).
The uppermost seismic unit is acoustically transparent and drapes the variable topography of the underlying units (Figs 5.3, 5.4). The thickness of the upper unit varies between 0.5 and 2 m (Figs 5.3, 5.4).
The second seismic unit is on the continental shelf and west of core location PS2444 (Fig. 5.1) dominated by a continuous, prolonged to semi-prolonged reflector, limiting the acoustic penetration to 5-20 m. North of the FVT and in restricted PARASOUND profile sections west of Franz Josef Land (south of 81°31.1´N/43°10.7´E) and close to the shelf edge the acoustic penetration increases to 30 m (Fig. 5.2). In these PARASOUND profiles, the second seismic unit is of draping to infilling character, shows a subparallel layering or is acoustically transparent and varies in thickness between 1 and 5 m (Figs 5.3, 5.4). Northeast of Nordaustlandet, as far north as 80°53.6´N, 29°48.3´E (195 m water depth) (Fig. 5.2) the second seismic unit forms numerous morainal ridges (Fig. 5.5). They are identified on the basis of their characteristic asymmetric shape and reveals a distinct to prolonged reflector.

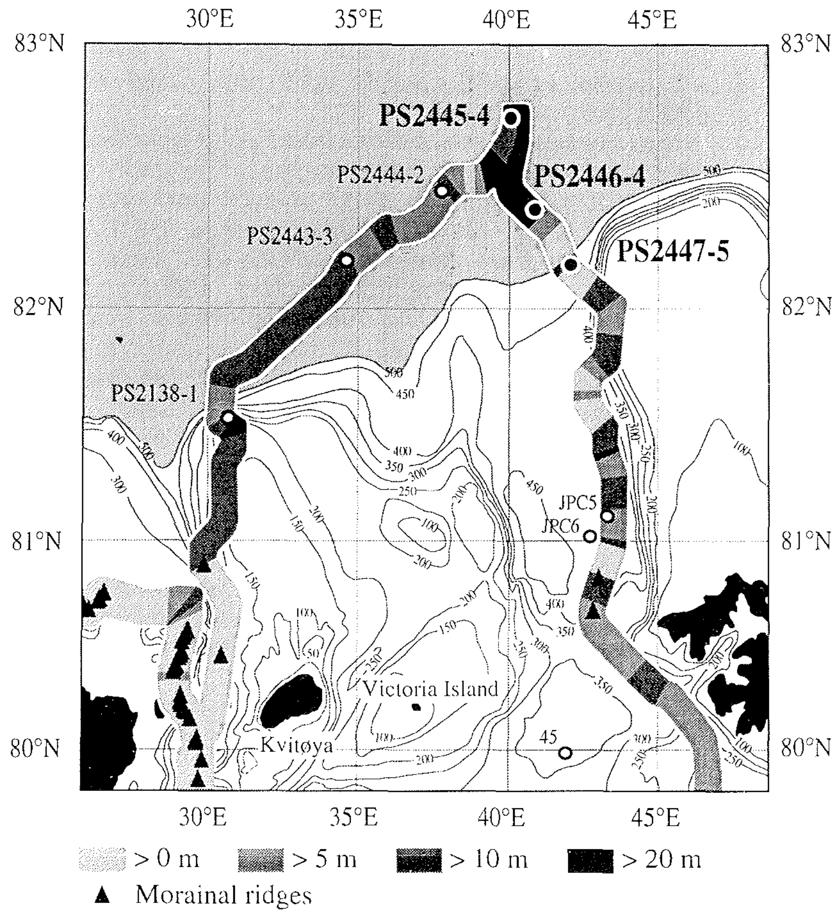

Fig. 5.2. Bathymetric map of the study area showing the minimum thickness of the Quaternary sediments, indicated by the maximum penetration of the PARASOUND system along the ship tracks (dotted lines).

The morainal ridges reach up to several km in width and a maximum height of 50 m. They are either exposed on the sea floor or conformably draped by the uppermost acoustic unit.

The third seismic unit was only identified in PARASOUND profiles from the continental slope east of core site PS2443 and from the FVT. On the continental slope north of the FVT, the third seismic unit is acoustically characterized by stacked, transparent lenses and layers (Figs 5.3, 5.4, 5.6). The penetrated thickness of the third seismic unit varies generally around 20 m. Single layers and lenses reach up to 10 m in thickness, several kilometers in width and are separated by distinct to discontinuous reflectors or occasionally by layered sequences up to several meters thick. The lenses show irregular to convex shapes, wedge out and truncate the underlying sediments (Fig. 5.3). The layers are characterized by rather undisturbed, continuous thicknesses and mainly even to slightly wavy bases (Fig. 5.4). In places, the uppermost meters of the third seismic unit show either a intermitted layering, including core locations PS2446 and PS2447, or a prolonged surface echo, limiting the acoustic penetration <10 m.

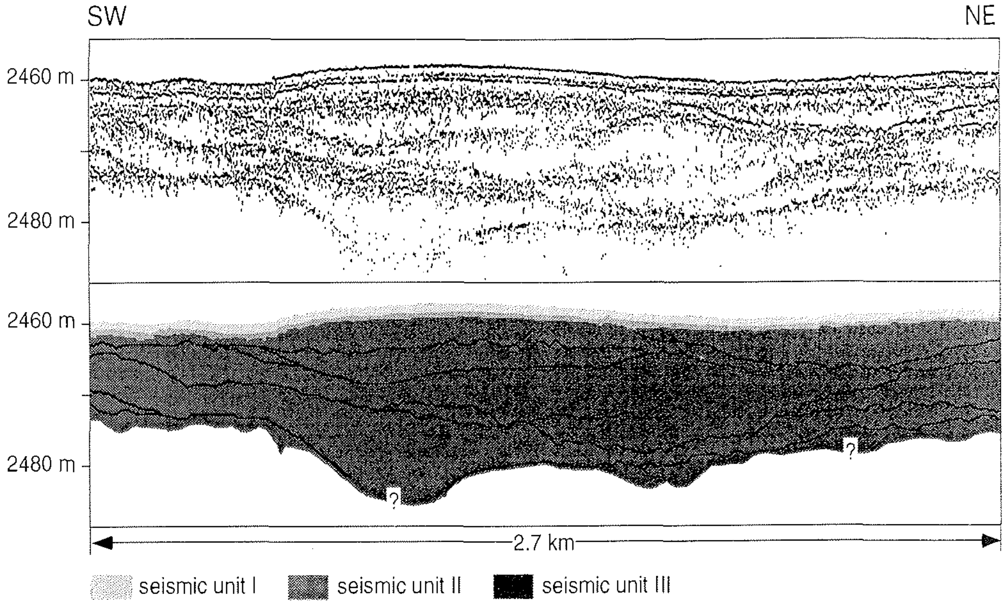

Fig. 5.3. PARASOUND profile showing truncating, stacked transparent lenses (for location see figure 5.1). The profile section was recorded while the ship remained on station during coring operation.

In the FVT, the third seismic unit is dominated by the transparent facies. The basal reflector of the third seismic unit was only detected in limited profile sections south of 81°35'N. No internal reflectors were recorded from below this basal reflector, therefore the underlying seismic unit was described by Lubinski et al. (1996) as acoustic basement of unknown age. West of Franz Josef Land, as far north as 80°51.2'N, 43°11.0'E (460 m water depth), morainal ridges were recorded. Because they are conformably draped by the uppermost transparent seismic unit and the subparallel layered second unit these moraines are assigned to the third seismic unit, unlike those northeast of Nordaustlandet.

5.5.2 Lithostratigraphy

The sedimentary record of the three studied sediment cores (PS2445-4, PS2446-4, PS2447-5) can be divided into five lithostratigraphic units on the basis of lithology, IRD content, sedimentary structures and geochemical features (Figs 5.7, 5.8).

Lithostratigraphic unit 1 represents in all cores the basal unit, consisting of a very dark olive grey, massive diamicton. The diamicton is matrix supported, poorly sorted and includes a high content of gravel, cm-sized stones and scattered mud clasts. The matrix is a sandy clayey silt. In core PS2447-5 the uppermost meters of the diamicton reveal a diffuse stratification. The TOC content ranges from 1.0-1.8 wt. %. C/N ratios vary between 20-30 and HI values are generally about 75 mgHC/gTOC . The upper massive diamicton in core PS2446-4 is lithologically and geochemically comparable to the basal diamictons, but shows an imbricated clast fabric and slightly normal grading.

Lithostratigraphic unit 2 consists of a dark to olive grey, laminated silty clays, which are intercalated by gravel lenses and show a very low IRD proportion.

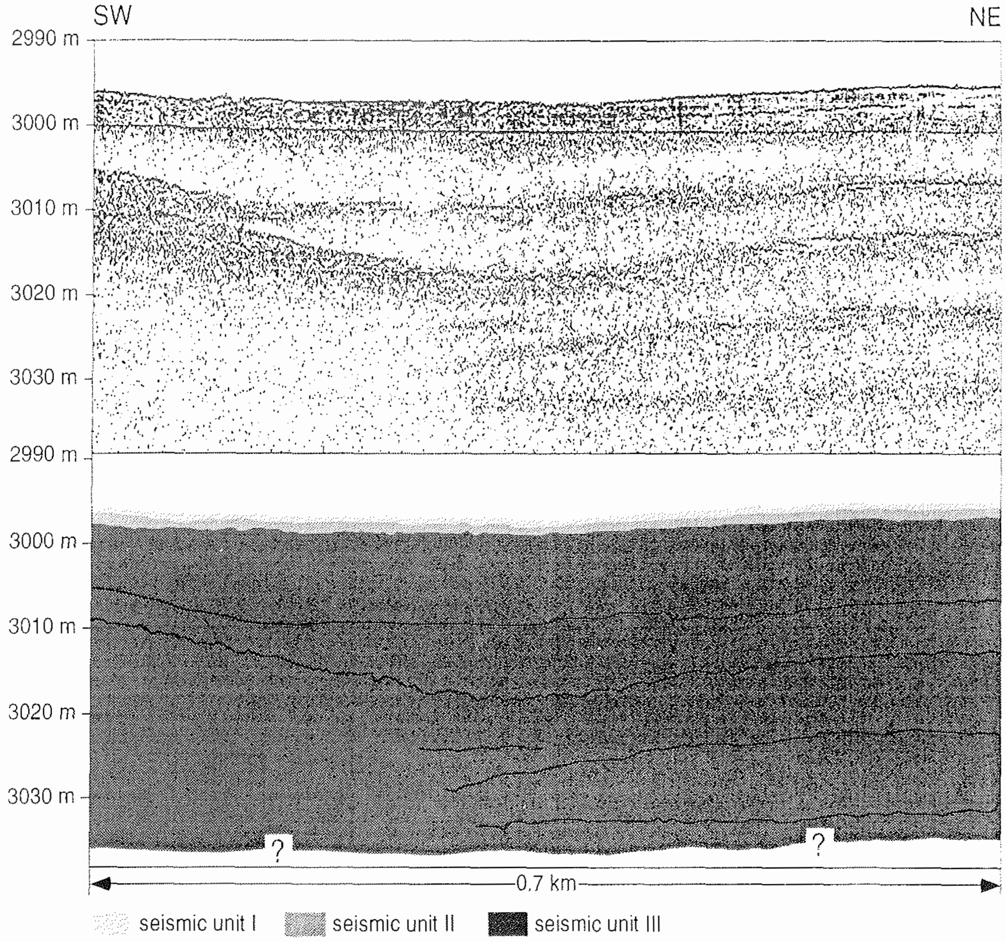

Fig. 5.4. PARASOUND profile showing transparent layers intercalated by transparent lenses (for location see figure 5.1). The profile section was recorded while the ship remained on station during coring operation.

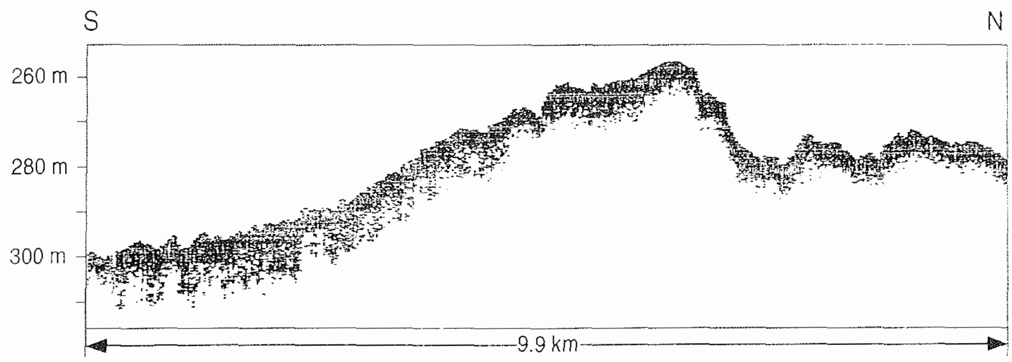

Fig. 5.5. PARASOUND profile recorded east of Nordaustlandet (for location see figure 5.1), showing a characteristic asymmetric cross section interpreted as morainal ridge. The ridge reveals a prolonged to semi-prolonged reflector and is exposed on the sea floor

Individual laminated silty clay layers show truncating, graded sandy bases. The laminated silty clays show a variable TOC content generally between 0.7-1.7 wt. %. C/N ratios range from 17-25 and the HI values from 50-75 mgHC/gTOC. The CaCO3 content varies between 2 and 12 wt. %.
Lithostratigraphic unit 3 consists of a dark to olive grey or greyish brown, bioturbated silty clays. Only sporadically a faintly lamination occurs. The bioturbated grey silty clays show TOC contents below 1 wt. % and C/N ratios between 12-17. The HI values vary between 25-75 mgHC/gTOC. Only the two basal HI values of the bioturbated grey silty clays intercalating the lower massive diamicton range between 125 and 150 mgHC/gTOC. The bioturbated grey silty clays show the highest CaCO3 content of all units ranging between 6-15 wt. %. The IRD layer intercalating the bioturbated grey silty clays consists of small mud clasts.
Lithostratigraphic unit 4 consists of a brown streaked, dark or olive grey, bioturbated, massive pebbly silty clays. Overall high contents of IRD with peak values consisting of mud clasts, scattered cm-sized cobbles and occasionally coal fragments (PS2446-4, PS2447-4) characterize the massive pebbly silty clays. TOC contents vary from 0.3-1.6 wt. % whereas the C/N ratios range from 11 to >30. HI values are between 35 and 150 mgHC/gTOC. The CaCO3 content varies considerably between 2 and 17 wt. %.

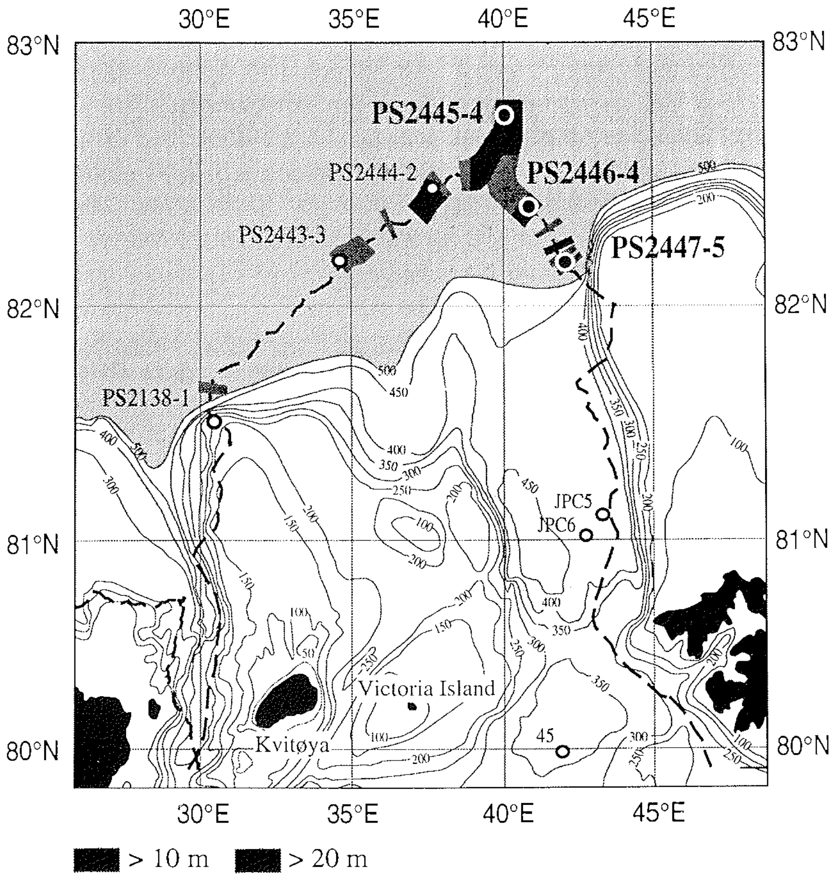

Fig. 5.6. Bathymetric map of the study area showing the distribution of the debris flow lobes identified in the PARASOUND profile.

Lithostratigraphic unit 5 represents the uppermost core section that also comprises recent surface sediments. It consists of a very dark brown to olive grey, bioturbated mud. The entire unit is rich in organic matter and only sporadically faintly laminated. The uppermost 20 cm of core PS2445-4 show a high abundance of *Pyrgo* sp. (Fütterer, 1994). The IRD proportion is only represented by a few individual coarse sand grains. TOC contents vary in core PS2446-4 from 0.8-1.4 wt. %, C/N ratios range from 6-11, whereas the HI values vary between 40-85 mgHC/gTOC. The CaCO3 content increases in core PS2446-4 from 1.5 at the base of the unit to 8 wt. % at the top.

5.5.3 Chronostratigraphy and sedimentation rates

The chronology of the sediment cores is based on 9 AMS ^{14}C dates (Table 1). The dates show increasing ages with sediment depth. Furthermore, the stratigraphic framework of core PS2446-4 is supported by the stable oxygen isotope record of planktic foraminifera *Neogloboquadrina pachyderma* sin. (Fig. 5.7).
The final deposition of the lower massive diamicton on the lower and middle continental slope took place is approximated 23 ^{14}C ka. This age was deduced from a sample of the bioturbated grey silty clay layer intercalating the massive diamicton in core PS2446-4 (Fig. 5.7). On the upper continental slope (PS2447-5) the deposition of the diamictons prevailed until approximated to 13.4 ^{14}C ka. The deposition of the lower massive pebbly silty clay in core PS2446-4 has occurred between 21.1 and 19.3 ^{14}C ka. The distinct decrease in $\delta^{18}O$ (1.3 ‰) after 15.4 ^{14}C ka marks the beginning of the transition from the last glacial period to the Holocene interglacial period (Termination I). Termination I is defined by two characteristic low-$\delta^{18}O$ spikes associated with distinct $\delta^{13}C$ minima values, interpreted to reflect meltwater influx (cf. Stein et al., 1994), and a distinct IRD-input. The age of 12.4 ^{14}C ka marks the onset of marine isotope stage (MIS) 1, which is characterized by relatively low $\delta^{18}O$ values and heavy $\delta^{13}C$ values.
Hence, the dates were as well used to assume sedimentation rates by linear interpolation. Whereby the thickness of the upper diamicton in core PS2446-4, interpreted as slump deposit (Fütterer, 1994), was subtracted for the sediment core. The linear sedimentation rates (LSR) on the middle continental slope in front of the FVT vary between 9.1 and 49.3 cm/ky (Table 2). During the glacial period of MIS 2 the LSR are higher (20.2-49.3 cm/ky) than during the Holocene interglacial period (<10 cm/ky). In general, the interpolated LSR are comparable with LSR from the northern Barents Sea continental margin (Knies and Stein, 1998), the St. Anna Trough (Hald et al., 1999) and the

Core	Sample interval [cm]	^{14}C years interval	Sedimentation rates [cm/1000 yr]
PS2445-4	131-191	14400-19280	12.3
PS2446-4	0-6	0-660	9.1
PS2446-4	0-150	0-12420	12.1
PS2446-4	150-180	12420-15430	10.0
PS2446-4	180-357	15430-19290	20.2
PS2446-4	357-420	19290-21550	27.9
PS2446-4	420-520	21550-23580	49.3

Table 5.2: Sedimentation rates from core PS2446-4 in front of the Franz Victoria Trough based on AMS radiocarbon dates (Table 1).

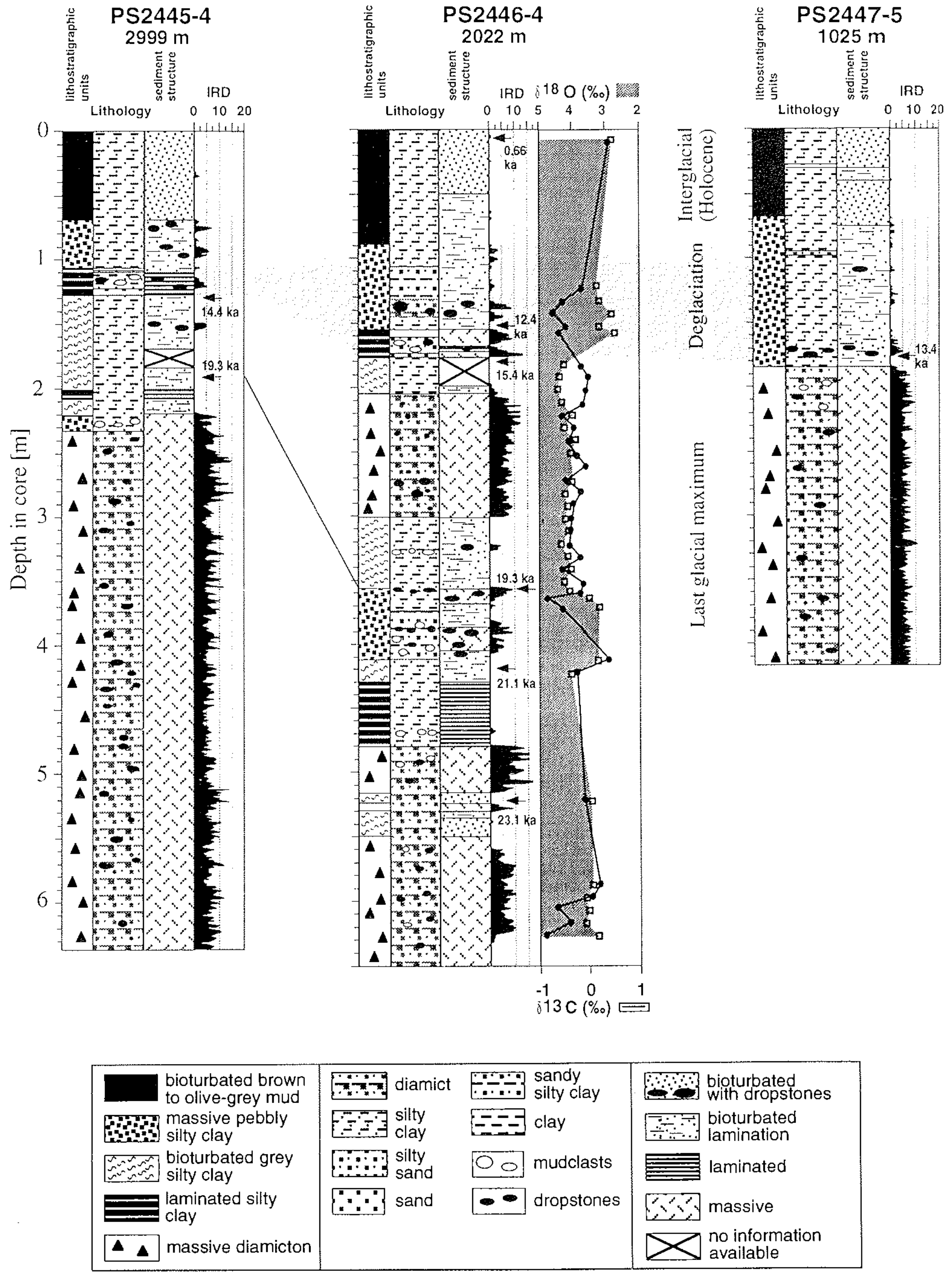

Fig. 5.7. Lithostratigraphic units, lithology, sedimentary structure and IRD content (numbers of detritus >2 mm in cm core intervals) of sediment cores PS2445-4, PS2446-4 and PS2447-5. Oxygen and carbon isotopes of core PS2446-4 are also displayed. AMS ^{14}C ages shown have been reservoir corrected using an age of 440 yrs (see table 1).

Laptev Sea continental margin (Bauch et al., 1996; Spielhagen et al., 1996; Weiel, 1997; Stein et al., 1999).

5.6 Discussion

5.6.1 Last Glacial Maximum (LGM)

The glaciation of the Franz Victoria Trough
The PARASOUND profile (4 kHz) from the continental slope in front of the FVT reveals that the top of the transparent lenses and layers of the third seismic unit correspond with the lower diamictons in cores PS2445, PS2446 and PS2447. Transparent lenses were first interpreted by Damuth (1978) in 3.5 kHz records from the Bear Island and North Sea trough mouth fans, as debris flow deposits. In high latitudes, submarine fans constructed of stacked debris flow deposits and glacimarine diamictons reflect a periodic or continuous high sediment input from a fast-flowing glacier/ice sheet directly onto the upper continental slope, as described by e.g. Damuth (1978), Vogt et al. (1993), Laberg and Vorren (1996), Vorren et al. (1989) for the Bear Island Trough or by Solheim et al. (1992) for the Isfjorden Fan on the Svalbard continental margin. The transparent layers represent according to Fütterer (1994) diamictons deposited at high sedimentation rates during the last or previous glaciations on the Barents Sea shelf. Therefore, we suggest that the thick sequence of debris flow lobes and diamicton layers were deposited when the grounding line of a SBIS reached the shelf break of the FVT (Fig. 5.9). The AMS^{14}C age of 23.1 ka in the hemipelagic sequences intercalating the lower glacial diamicton in PS2446-4 approximates the advance of the grounding SBIS to the shelf break.
The sheet-like geometry, the absence of characteristic sediment lenses, the very limited acoustic penetration and the morainal ridges are strong evidence for interpreting the acoustically transparent, third seismic as basal till (cf. Lubinski et al. 1996). The identification of the key seismic reflector overlying the transparent third seismic unit in the PARASOUND profile of the FVT, supports the extent of the basal till to the shelf edge and thus the grounding of the northern SBIS in the entire FVT. The lack of morainal ridges in the PARASOUND profile in the northern FVT is a further indication that the grounding line of the SBIS reached the shelf edge (cf. Laberg and Vorren 1996). Continuously high TOC values (up to 1.5 wt. %) in association with C/N ratios >20 and low HI-values (<100 mgHC/gTOC) reveal the terrigenous character of the debris flow sediments and are indicative for a Svalbard/Barents Sea source area (Knies and Stein, 1998).
The restricted distribution of the gravity flow lobes in front of the FVT (Fig. 5.7) suggest that the trough acted as conduit for the fast-flowing ice stream as proposed by Elverhøi et al. (1995b) for the Isfjorden. A canalization of the terminal ice zone in flow-parallel troughs descending 300-400 m below sea level is proposed by Boulton (1990), based on a simple numerical model. An increase in ice thickness by more than 200 m, compared to the adjacent shelf, will result in an enhanced flow and the tendency for an ice stream to develop (Boulton, 1990). An enhanced flow associated with an earlier glaciation, as suggested for the eastern Svalbard Islands by Elverhøi et al. (1995a), may help to explain the early advance of the northern SBIS to the shelf edge of FVT compared to western Svalbard. There, the SBIS reached the coast by ~22 ^{14}C ka (Andersen et al., 1996) and the maximum extension probably between 19.4

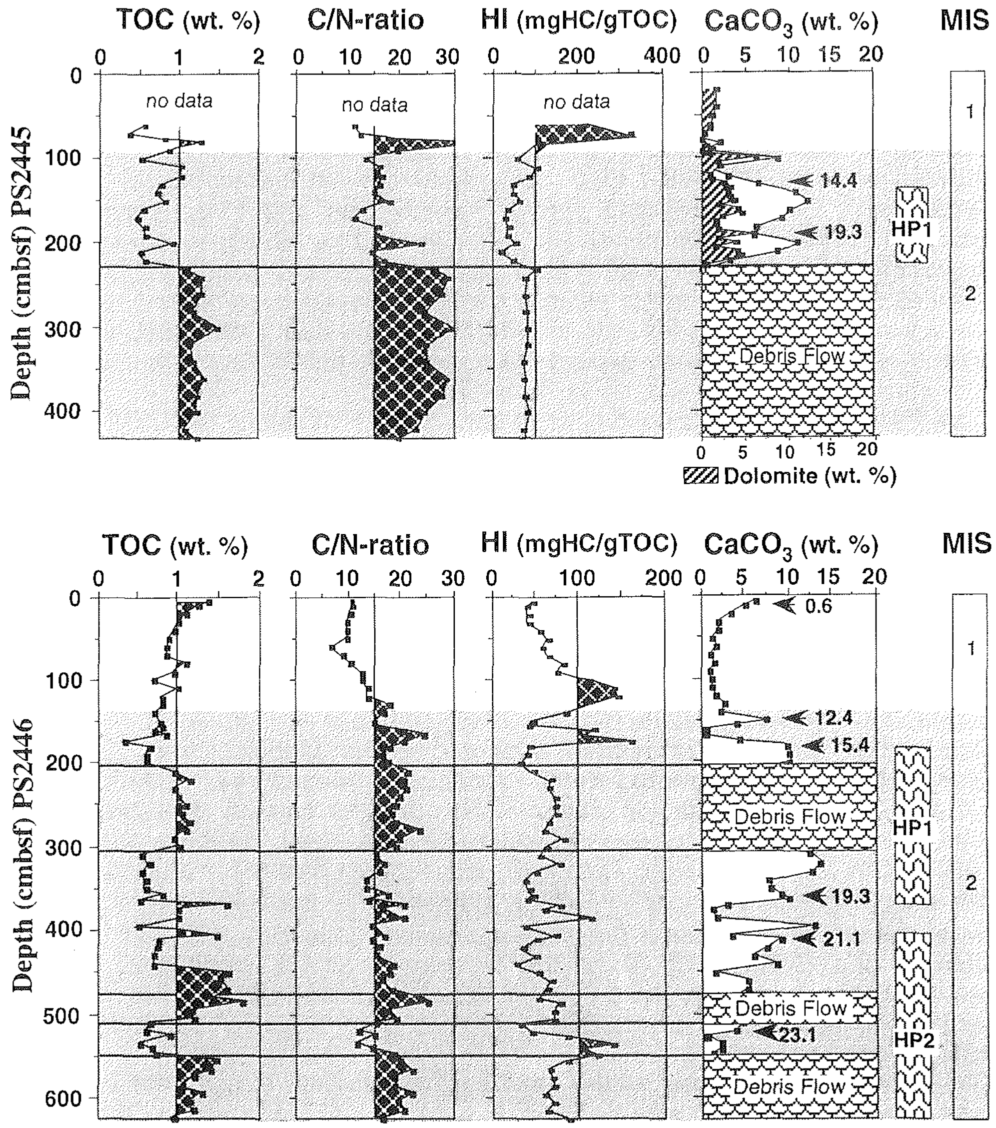

Fig. 5.8. Compilation of the total organic carbon, carbonate and dolomite content (all wt. %), C/N ratios and hydrogen index (HI) data versus core depth. Dolomite content in core PS2445-4 was published by Vogt (1997). Enrichment of carbonate rather than dolomite in core PS2445-4 indicates high amounts of planktic and benthic foraminifers. AMS^{14}C datings and marine isotope stages (MIS) are shown on the right. HP1 and 2, high productive zones, are defined according to Dokken and Hald (1996).

to 15 ^{14}C ka (cf. Elverhøi et al., 1995a; Landvik et al., 1998). In addition, a rather early extension of the northern SBIS into the FVT can be assumed from the vicinity to the hypothesized center of the ice sheet on Kong Karls Land, Svalbard (Forman et al., 1995), from there the ice flowed unhindered by bathymetric impediments to the FVT (Polyak and Solheim, 1994).
Furthermore, the distribution of the debris flow deposits in the PARASOUND profiles (Fig. 5.6) and the general lack of glacial fans off the northern Svalbard margin (Solheim et al., 1996) indicate that the continental margin west of the

FVT is not directly influenced by a fast-flowing ice stream reaching the shelf edge. This is supported by Österholm (1990), who argued based on marine limits on northern Nordaustlandet (Fig. 5.1) at about 50 m a.s.l., that the SBIS extended only to the coast line during the Late Weichselian. However, a steep increase in bulk accumulation rates (up to 50 g/cm^2/ky) and highest rates of kaolinite in core PS2138-1 (Fig. 5.1), likely derived from glacially eroded bedrocks in the northern and central Barents Sea and thus, indicate ice-proximal conditions west of the FVT after 23 ^{14}C ka (cf. Knies et al., 1999). According to Dowdeswell et al. (1998), these ice-proximal conditions point to a more stable ice sheet margin west of the FVT. Because compared to a fast-flowing ice stream, the sediment delivery of a more stable ice sheet margin is greatly reduced, which may explain the absence of debris flow deposits.

5.6.2 Paleoceanographic conditions in front of the FVT during the LGM

Hebbeln et al. (1994) suggested that relatively warm Atlantic derived water masses from the North Atlantic Ocean advected into the Greenland-Iceland-Norwegian seas (GIN) in short term events between 27-22.5 and 19.5-14.5 ^{14}C ka and that the resulting seasonally ice-free waters acted as important regional moisture sources for the build-up of the SBIS. The bioturbated grey silty clay intercalating the lower massive diamicton in sediment core PS2446-4 exhibit bioturbation and an increased CaCO3 contents (up to 5 wt. %), referring to high abundances of coccolithes as well as subpolar planktic and benthic foraminifera (Andersen et al., 1996; Hebbeln and Wefer, 1997). In the study area, periods associated with increased bioproductivity point to seasonally overall ice-free water conditions caused by Atlantic water surface/subsurface advection and/or local polynyas caused by upwelling of relatively warm Atlantic subsurface water (Kellogg, 1980; Hebbeln and Wefer, 1991; Kohfeld et al., 1996). Therefore, we suggest that the bioturbated grey silty clay, approximated to 23.1 ^{14}C ka, indicates that the North Atlantic Ocean water inflow, which caused the high productive zone HP2 (29-22.5 ^{14}C ka; Dokken and Hald, 1996) along the western Svalbard continental margin, prevailed as far east as the FVT and acted as important regional moisture source for the build-up of the SBIS onto the shelf edge (cf. Hebbeln et al., 1994, Knies et al., 1999).

The terrigenous character of the laminated sediments, directly overlying the lower debris flows deposits in core PS2446-4, is indicated by high TOC contents (up to 1.7 wt. %) , C/N ratios >15 and low HI values (<75 mgHC/gTOC). The lack of bioturbation points to high sedimentation rates likely in relation with dense, turbid meltwater plumes draining the ice sheet located at the shelf edge directly on the continental margin (Fig. 5.9).

Severe bioturbation of the grey silty clay overlying the laminated sequence in association with CaCO3 contents up to 9 wt. % indicates that seasonally ice-free water conditions prevailed until approximately 21 ^{14}C ka. These seasonally ice-free water conditions also confirmed by an enhanced supply of MOM indicated by low TOC contents (0.75 wt %), a drop in C/N ratios (<17) and slightly increasing HI values (up to 75 mgHC/gTOC), are likely related to a coastal polynya triggered by katabatic winds from the growing SBIS and an inflow of subsurface Atlantic water masses (cf. Knies et al., 1999).

The lower massive pebbly silty clay is characterized by a high IRD input indicating an increased calving rates of the SBIS between ~21 and 19.3 ^{14}C ka. The predominantly terrigenous origin of the sedimentary organic matter is documented by high C/N ratios (up to 20), variable TOC contents

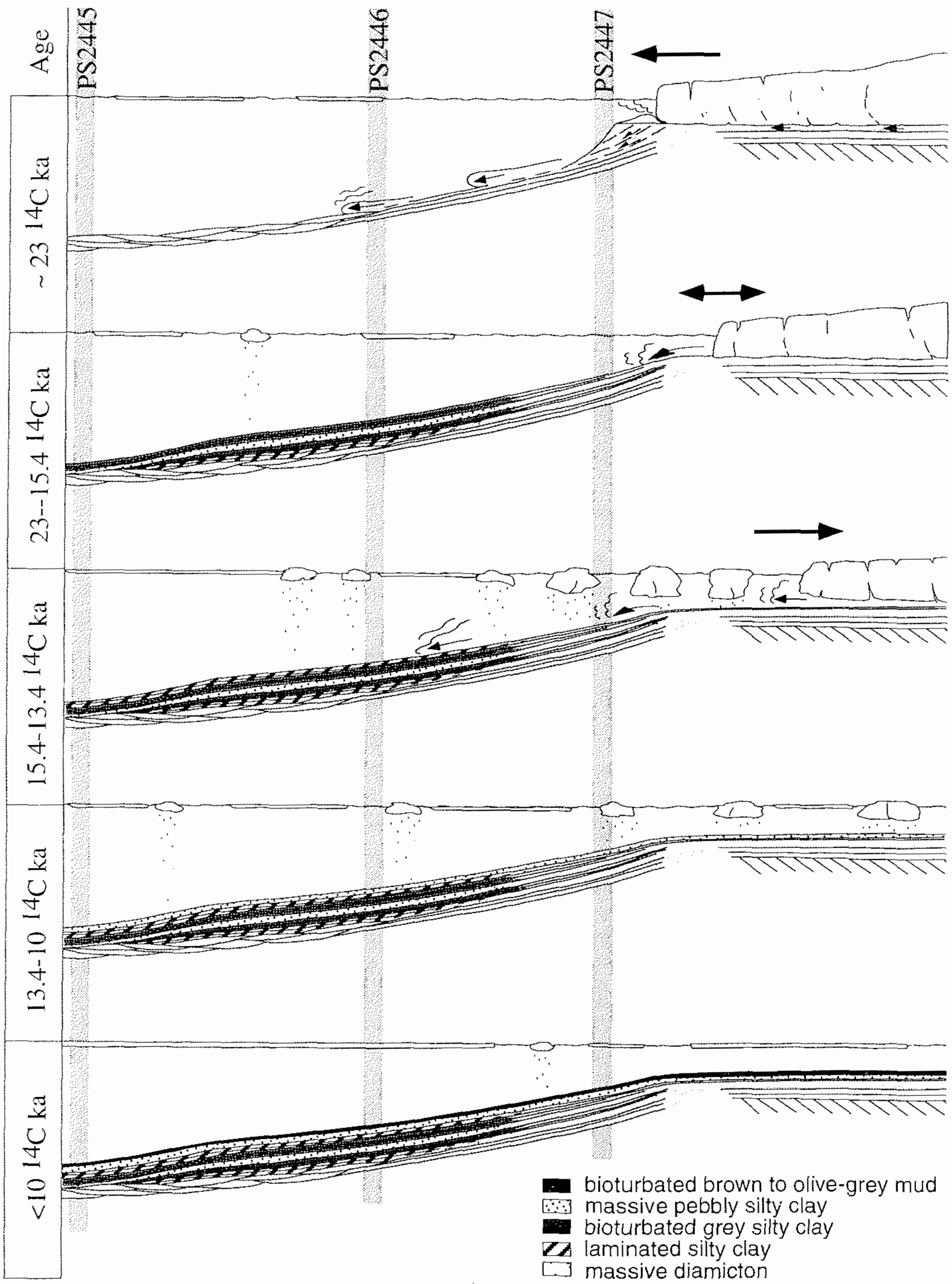

Fig. 5.9. Schematic models of the evolution of the northern Barents Sea continental margin during the Late Weichselian Glaciation showing the main processes on the shelf edge and the continental slope in relation to the behaviour of the ice sheet at the shelf edge.

(0.5-1.5 wt %) and generally low HI values (<80 mgHC/gTOC). Because no further stacked gravity flow deposits occur on the lower continental slope north of the FVT, indicate a major grounding line displacement, we suggest that the low $\delta^{18}O$ values (3.5 ‰) and $\delta^{13}C$ minima values (-0.5 ‰), interpreted as

meltwater signal, in association with significant IRD pulses refer to a temporary instability of the northern SBIS. This temporary instability coincides with the enormous discharge of icebergs to the North Atlantic (Heinrich Event H2: 21.6-19.4 ^{14}C ka) (Broecker et al., 1994; Bond et al., 1992; Andrews and Tedesco, 1992 ; Andrews et al., 1994).
The upper bioturbated grey silty clay in cores PS2445-4 and PS2446-4 is characterized by a high CaCO3 (up to 7.5 wt. %) and a low TOC content (up to 0.8 wt %. Based on low dolomite contents in core PS2445-4, the increased CaCO3 content is interpreted as biogenic calcite, although C/N-ratios around 15 and HI-values <100 mgHC/gTOC point to a predominantly terrigenous origin. The deposition of the upper bioturbated grey silty clay is approximated between 19.3 and 15.4 ^{14}C ka in core PS2446-4 and between 19.3 and 14.4 ^{14}C ka in core PS2445-4, respectively. Thus, the deposition coincides with the high productive zone HP1 (Dokken and Hald, 1996) and is therefore likely related to at least seasonally open water conditions caused by Atlantic water surface/subsurface advection to the Arctic Ocean (Hebbeln et al., 1994).

5.6.3 Deglaciation and Holocene

The initial disintegration of the northern SBIS (Termination I) marked in the cores from the middle and lower continental slope (PS2445-4, PS2446-4) by a significant increase in IRD and a pronounced meltwater signal, displayed by $\delta^{18}O$ minina (3.2 ‰) and reduced $\delta^{13}C$ values (-0.57 ‰) (Fig. 5.7). The predominately terrigenous origin of the sediments is supported by increasing TOC values (up to >1 wt %), high C/N ratios (up to 25) and very low carbonate contents (<5 wt %). This initial disintegration is approximated in core PS2446-4 to 15.4 ^{14}C ka. The first phase of disintegration until 12.4 ^{14}C ka is characterized by two distinct IRD peaks (Fig. 5.7). A decrease in IRD input during the first phase of deglaciation may be related to a stabilization of ice sheet after the initial, huge input of icebergs (e.g. Vorren et al. (1996). The subsequent cooling of the surface water after the first iceberg input promotes sea ice preservation and increases thereby the albedo. This in turn leads to a halt/readvance of the ice sheet and a reduced input of IRD. A cooling and temporary absence of open water conditions is supported by the contemporary deposition of laminated sediments. Their lack of bioturbation may indicate a poor ventilation of the water column (Phillips and Grantz, 1997). The occurrence of only one IRD event in the laminated sediments of core PS2445-4 on the lower continental slope signifies most likely that icebergs were blocked by permanent sea-ice and thus supports the transition from cold to warm conditions (Nam, 1996) (Fig. 5.9). If the single IRD peak in core PS2445-4 at 1.5 m represents a short-time instability of the ice sheet or even correlates with the initial disintegration cannot be verified based on our datings and core data. An initial meltwater event at 15.4 ^{14}C ka is in rather good correspondence with the first light-oxygen-isotope event in the eastern Arctic Ocean (Stein et al., 1994; Nørgaard-Pedersen et al., 1998), the Fram Strait (Jones and Keigwin, 1988), the western Svalbard margin (Jones and Keigwin, 1988; Hebbeln et al., 1994; Elverhøi et al., 1995a) and the northeastern Atlantic Ocean (Duplessy et al., 1981) and coincides with the cooling cycle predating the Heinrich event H1 (14.6-15.0 to 13.2-13.6 ^{14}C ka; McCabe and Clark, 1998). Therefore, we suggest that initial disintegration of the northern SBIS more likely reflects a climatic influence through a reduction in precipitation (McCabe and Clark, 1998) and/or a response to increased summer insolation than a responds to the collapse of the Laurentide or other

ice sheets in the northern hemisphere (cf. Dowdeswell et al., 1999). Furthermore, we suggest that the marine based nature of the SBIS in addition with the morphology of the FVT made it very susceptible to decoupling of the glacier bed either caused by an eustatically or isostatically induced rise in sea level (Jones and Keigwin, 1988, Andersen et al., 1996). If the isostatical depression of the SBIS continued after the LGM it may have reached a critical level initiating the destruction of the ice sheet by marine downdraw through the FVT without external forcing, as described by Jones and Keigwin (1988) for the Bear Island and Storfjord troughs. The lack of the morainal ridges in the northern FVT supports a decoupling of the glacier bed during deglaciation. The change from massive to stratified diamicton on the middle and upper continental slope is interpreted as increased meltwater discharge of the grounded SBIS at the shelf edge of the FVT (e.g. Elverhøi et al., 1990, 1995b). Thus, the transition of the stratified diamicton to the massive pebbly silty clay approximated to ~13.4 ^{14}C ka (PS2447-5) may reflect the retreat of the northern SBIS from the shelf edge of the FVT (Fig. 5.9). This age is constrained in the northern FVT by the initial deposition of the ice proximal laminated clay at 13 ^{14}C ka overlying the diamicton, which is interpreted as a till (Lubinski et al., 1996; Polyak and Solheim, 1994). The prominent IRD pulses recorded in the upper massive pebbly silty clay indicate a discontinuous retreat of the SBIS. The onset of the first major IRD input is approximated in core PS2446 to ~12.4 ^{14}C ka. In core PS2445 the two major IRD events are dated based on linear interpolation to 12.3 and 10.7 ^{14}C ka, respectively. Therefore the two IRD pulses are in rather good correlation with distinct iceberg rafting events in the central FVT (Lubinski et al., 1996), on the Yermak Plateau (Vogt, 1997), the Saint Anna Trough (Polyak et al., 1997) and pulses of glacimarine sedimentation in the southeastern Barents Sea (Polyak et al., 1995). This ice rafting events are coeval with a period of increasing surface-water and air temperatures in the northern Atlantic region and accelerated eustatic sea-level rise, suggesting that the remaining retreat of the SBIS was paced by these factors (Polyak et al., 1995).
The bioturbated brown to olive-grey mud resembles in color, increased organic content, and very low IRD content sediments in the northern and central Barents Sea whose deposited began at ~10 ^{14}C ka (Elverhøi and Solheim, 1983; Elverhøi, 1989; Polyak and Solheim, 1994; Lubinski et al., 1996; Polyak et al., 1997). Apparently, the brown to olive-grey mud marks the end of the marine phase of deglaciation and points to the retreat of the SBIS to the present shore line. Terrestrial evidences from Franz Josef Land and eastern Svalbard support this interpretation (Forman et al., 1995 and references therein). On basis of its thickness we suggest that the bioturbated brown to olive-grey mud, which in all cores represents the uppermost lithostratigraphic unit, corresponds to the uppermost, transparent seismic unit of draping character in the entire study area.

5.7 Summary and conclusions

Stacked, acoustic transparent lenses and layers in front of the FVT, interpreted as debris flow deposits and layers of glacimarine diamicton, indicate that large quantities of sediments were directly deposited by the northern SBIS onto the upper continental slope at approximately 23 ^{14}C ka. A grounding of the SBIS in the entire FVT is supported by the identification of the basal key seismic reflector overlying the acoustically transparent unit, interpreted as basal till

near the shelf break. The distribution of the gravity flow deposits on the continental slope suggests that the FVT acted as conduit and led to an enhanced flow of the northern SBIS. An enhanced flow in association with an earlier glaciation may help explaining the early advance of the northern SBIS to the shelf edge, compared to west Svalbard. The initial disintegration of the northern SBIS (Termination I), indicated by an intensive increase of IRD to the continental slope and a pronounced meltwater signal, occurred at around 15.4 ^{14}C ka. This initial disintegration may reflect a climatic influence through a reduction of precipitation in association with the cooling cycle predating the Heinrich event H1, the decoupling of the glacier bed due to an eustatically or isostatically induced rise in sea level and/or a response to increased summer insolation. The grounding line retreat of the northern SBIS from the shelf edge of the FVT, indicated by a drastic change in sedimentary pattern on the upper continental slope is approximated to 13.4 ^{14}C ka. The stepwise deglaciation of the northern SBIS is documented by distinct IRD-pulses which appear to be contemporaneous with the onset of distinct pulses of IRD and glacimarine sedimentation in the adjacent areas between 13 and 9.4 ^{14}C ka.
Bioturbation indicated that seasonally open water conditions prevailed along the northern Barents Sea at least as far east as the FVT during the last glacial/interglacial cycle.

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