Short- and Long-Term Environmental Changes in the Laptev Sea (Siberian Arctic) During the Holocene

Kurz- und langfristige Umweltveränderungen in der Laptev-See (sibirische Arktis) während des Holozäns

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Ber. Polarforsch. Meeresforsch. 424 (2002)
ISSN 1618 - 3193

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Die vorliegende Arbeit ist die inhaltlich unveränderte Fassung einer Dissertation, die 2001 der Mathematisch-Naturwissenschaftlichen Fakultät der Christian-Albrecht-Universität zu Kiel vorgelegt wurde.

Die in der vorliegenden Arbeit erhobenen Daten sind in der Datenbank PANGEA (http://www.pangaea.de) veröffentlicht.

ABSTRACT

Given the variability of seasonal, annual, and in particular longer time-scales, the dispersal and fate of the river discharge and its influence on the hydrographical and sedimentological settings are the central tasks in understanding the Holocene history of the Laptev Sea shelf. The main goal of this study was to investigate short- and long-term environmental changes in the strongly coupled land-shelf system of the Laptev Sea using isotopic evidence in sediments and biogenic carbonates.

In order to trace the modern spatial distribution of terrestrial organic matter, which is strongly affected by the riverine input and the thermal erosion of the ice-rich permafrost coast, stable carbon isotope ratios of total organic carbon in surface sediments were analyzed. The stable carbon isotope composition of surface sediments reveal a dominant impact of terrestrial organic matter on the modern depositional environment of the Laptev Sea shelf with distinct south to north and east to west gradients. Based on downcore $\delta^{13}C_{org}$ records in radiocarbon-dated sediment cores the spatial and temporal deposition of terrestrial organic matter during the past 12.7 ka is specified and can be related to depositional changes which occurred after the last glacial maximum when this region became flooded due to a global rising sea level. The major changes in the deposition of terrestrial organic matter occurred between 11 and 7 ka BP and comprise the main phase of the southward retreat of the coastline and river depocenters due to the postglacial sea level rise.

Stable oxygen and carbon isotope profiles from recent and fossil bivalve shells were investigated in order to trace modern and past hydrographical conditions and their changes during the postglacial history of the Laptev Sea. The serial dissection of bivalve shell valves along their growth axis from the umbo towards the ventral margin provides an isotopic record of hydrographical and physiological changes during the life of the individual specimen. The oxygen isotopic profiles of modern bivalve species of *Astarte borealis* exhibit amplitude cycles interpreted as recording annual hydrographical cycles. Regarding the well-known relationship between the carbonate $\delta^{18}O$, temperature, and the isotopic composition of water ($\delta^{18}O_w$), it is possible to relate isotopic phases to seasonal hydrographical phases like summer and winter. The within shell isotopic variations are mainly attributed to variations in the isotopic composition and in the salinity of bottom waters in the Laptev Sea. Seasonal temperature changes can be regarded of minor importance. Using a modern linear relationship between $\delta^{18}O_w$ and salinity of 0.50‰/salinity, salinity records are reconstructed from the oxygen isotope records of the bivalve shells and can be directly compared with hydrographical parameters at the investigated sites.

Persistent trends towards more negative $\delta^{13}C$ values are observed in all specimens and appear to be related to metabolic changes of the bivalves during ontogeny. In contrast, short-term fluctuations are likely linked to seasonal variabilities of the river water outflow patterns and enhanced phytoplankton productivity during summer. This is corroborated by a clear watermass-related distinction of the various $\delta^{13}C$ records made on the basis of water depth and distance from the riverine source.

Given a good conformance between isotope profiles from modern bivalve shells and oceanographic observations, oxygen isotope profiles of radiocarbon bivalve shells from a sediment core from northeast off the Lena Delta are used to obtain information about passt hydrological conditions. Although isotope profiles from fossil bivalves of the Laptev Sea shelf reflect only a brief interval of time, they may offer new important insights into the paleohydrography during snapshots of the last 8.4 ka and their relation to the Holocene transgression.

A reconstructed bottom water salinity of 29.5 at 8.4 ka BP indicates that the particular site was much more affected by riverine water than nowadays caused by the proximity to the coastline and to the paleo-river mouth. Due to the continuing southward retreat of the coastline and the Lena River mouth relative to the study site an increase in the bottom water salinity at 7.3 ka BP is reconstructed. The oxygen isotope shell profile at 7.3 ka BP gives an evidence of a bottom water hydrography which is characterized by a high variability of summer and winter conditions on the level of modern bottom water conditions. The following time slices at 3.6 ka and 1.6 ka BP reveal that modern hydrological conditions are fully established.

The presented salinity reconstruction enables us to make further presumptions on the relative proximity of the study site to the coast and to the river mouth during snapshot views of the Holocene history and thus can be related to the postglacial transgression of the Laptev Sea shelf.

ZUSAMMENFASSUNG

Zentrale Aspekte im Verständnis der holozänen Entwicklung des Laptev-See-Schelfs sind Veränderung in Ausbreitung und Intensität des Flusswassers auf unterschiedlichen Zeitskalen, sowie dessen Einfluss auf das hydrographische und sedimentologische Milieu. Ein Hauptanliegen der vorliegenden Arbeit ist es kurz- und langfristige Veränderungen zu untersuchen, wie sie sowohl in den Sedimenten als auch in biogenen Kalkschalern überliefert sind.

Zur Ermittlung der räumlichen Verteilung von terrestischem organischem Material auf dem Laptev-See-Schelf wurde die stabile Kohlenstoffsignatur der organischen Substanz in Oberflächenproben untersucht. Der moderne Eintrag von organischer Substanz ist stark terrestrisch beeinflusst und nimmt von Süden nach Norden, beziehungsweise von Osten nach Westen hin ab. Analysen zur Kohlenstoffsignatur in datierten Sedimentkernen konnten für eine Charakterisierung der räumlichen und zeitlichen Veränderungen im Eintrag von terrestrischem organischem Material während der letzten 12,7 ka herangezogen werden. Veränderungen im Ablagerungsmilieu stehen in direkter Beziehung zur postglazialen Überflutungsgeschichte des Laptev-See-Schelfs, bedingt durch den globalen Anstieg des Meeresspiegels. Drastische Veränderungen in der Ablagerung von terrestrischem organischem Material konnten für den Zeitraum zwischen 11 und 7 ka BP festgestellt werden. Dieses Zeitfenster beinhaltet die Hauptphase der Transgression auf dem Laptev-See-Schelf und ist gekennzeichnet durch das südlich gerichtete Rückschreiten der Küstenlinie und der Flussmündungen und somit auch durch eine Verlagerung der Sedimentationsräume der Flüsse.

Zur Identifizierung und Rekonstruktion von rezenten und vergangenen hydrographischen Bedingungen sowie deren Veränderungen während der postglazialen Entwicklung der Laptev-See wurden stabile Isotopenprofile an Schalen rezenter und fossiler Bivalven untersucht. Dezidierte Isotopenmessreihen entlang von Wachstumsprofilen an Bivalven bieten hochaufgelöste Informationen über hydrographische und milieubedingte Veränderungen während des Lebenszeitraums eines Individuums. Sauerstoffisotopenprofile an rezenten Bivalven zeigen deutliche Amplituden, die als saisonale hydrographische Veränderungen interpretiert werden können. Aufgrund der Abhängigkeit der Sauerstoffisotopenzusammensetzung im Karbonat der Bivalvenschale, der isotopischen Signatur des umgebenden Wassers ($\delta^{18}O_w$) sowie der

Umgebungstemperatur ist es möglich diese Amplituden den winter- und sommerlichen hydrographischen Gegebenheiten in der Laptev-See zuzuordnen. Isotopenänderungen innerhalb der Schale sind hauptsächlich den Variationen in der Isotopensignatur des Wassers zuzuschreiben, die wiederum eine lineare Abhängigkeit zur Salinität aufweisen. Jahreszeitlich bedingte Temperaturschwankungen im Bodenwasser können in der Laptev-See vernachlässigt werden. Unter der Annahme einer rezenten linearen Abhängigkeit von $\delta^{18}O_w$ und Salinität von 0,5‰/Salinitätseinheit lassen sich aus den Isotopenprofilen Salinitätsverläufe über den Lebenszeitraum der Bivalve rekonstruieren und mit gemessenen Werten an den jeweiligen Fundorten vergleichen.

Die gute Übereinstimmung der aus rezenten Bivalvenschalen rekonstruierten Salinitäten mit hydrographischen Beobachtungen bietet die Möglichkeit aus Isotopenprofilen von fossilen, datierten Schalen in einem Sedimentkern nordöstlich des Lena-Deltas Informationen über vergangene hydrographische Bedingungen und Veränderungen zu erhalten. Obwohl Isotopenprofile aus Bivalvenschalen immer nur einen kurzen Zeitrahmen hydrographischer Gegebenheiten während ihrer Lebensdauer wiedergeben können, so lassen sich daraus doch wertvolle Momentaufnahmen der Paläohydrographie und ihrer Beziehung zur holozänen Transgression gewinnen. Eine rekonstruierte Bodenwassersalinität von 29,5 zum Zeitpunkt 8,4 ka BP zeigt, dass die untersuchte Station zum damaligen Zeitpunkt verglichen mit heute unter erhöhtem Einfluss von Flusswasser stand. Dieser erhöhte Einfluss von Flusswasser ist in der damaligen Nähe zur Küste und zur ehemaligen Flussmündung der Lena zu suchen. Aufgrund des kontinuierlichen Rückschreitens der Küstenlinie infolge der Transgression verlagerte sich auch die Flussmündung relativ zur untersuchten Station nach Süden und führte zu erhöhten Bodenwassersalinität zum Zeitpunkt 7,3 ka BP. Die für diesen Zeitpunkt rekonstruierte Bodenwassersalinität ist mit der heutigen vergleichbar, jedoch mit wesentlich größeren jahreszeitlichen Amplituden. Die Zeitfenster 3,6 und 1,6 ka BP repräsentieren hydrographische Bedingungen, wie sie heutzutage an der untersuchten Station zu finden sind.

Die vorgestellten Salinitätsrekonstruktionen bieten außerdem die Möglichkeit Aussagen über die relative Lage der untersuchten Station zur Küstenlinie und vor allem zur Lage der Flussmündung während Momentaufnahmen der holozänen Transgressionsgeschichte des Laptev-See-Schelfs zu treffen.

1 INTRODUCTION

1.1 MAIN OBJECTIVES

As a part of the Russian-German multidisciplinary research project "Laptev Sea System 2000", the present study is focused on short- and long-term paleoenvironmental changes during the Holocene history of the Laptev Sea using isotopic evidence in sediments and biogenic carbonates.

It is now widely accepted that freshwater plays an important role in the hydrographical cycle of the Arctic Ocean because it is essential for the maintenance of the low-salinity surface water layer and for the formation of sea-ice (Aagaard and Carmack, 1989) (Fig. 1-1). Changes in the Arctic Ocean surface hydrography may be recognized as a major forcing mechanism that can perturb a particular climate mode. One of the most likely effects of the Arctic Ocean on global climate is the effect on thermohaline circulation through the export of cold freshwater and sea ice from the Arctic Ocean. For instance, an increase in freshwater and sea ice export through the Fram Strait has a significant impact on the deep-water formation gyres in the Nordic Seas and may induce a weakening of the thermohaline circulation (Aagaard and Carmack, 1994), thereby influencing the northerly directed heat transfer supplied by the North Atlantic current (Broecker, 1997).

In the context of growing concern about the response of Arctic regions to environmental changes and its impact on global climate the Laptev Sea and its adjacent hinterland are of particular interest. Here, large rivers are discharging freshwater onto the shelf, thereby constituting a key source of the Arctic halocline´s freshwater budget (Bauch et al., 1995). At present, the annual Arctic freshwater input reaches a total volume of 3300 km^3, which is equivalent to 10 % of the global runoff (Aagaard and Carmack, 1989; Gordeev et al., 1996). About 25 % of the total freshwater discharged into the Arctic Ocean is contributed by rivers draining onto the Laptev Sea shelf. The major freshwater source of the Laptev Sea is the Lena River, which alone contributes 75 % of the total annual freshwater discharge (Alabyan et al., 1995). This riverine discharge is characterized by a seasonal maximum between May and October with a flood peak period recorded in early summer. In contrast the winter discharge wanes down to only 15 % of the entire annual volume (Gordeev et al., 1996).

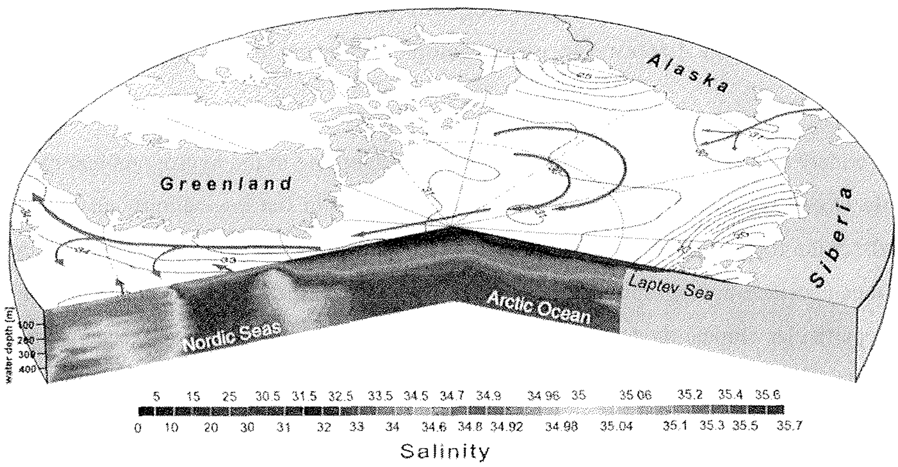


Fig. 1-1: Surface ocean circulation and average summer surface salinities in the Arctic Ocean, its shelf seas, and adjacent Nordic Seas. The oceanographic cross section of the upper 500 m across the Arctic Ocean from the Norwegian Sea to the Laptev Sea unveils the distinctive Arctic Ocean Halocline (summer average 1950-1990). Data from EWG (1998).

Together with the riverine waters enormous loads of suspended and particulate matter are being transported onto the shelf (Alabyan et al., 1995; Gordeev et al., 1996). While some of the terrestrial sediments remain on the shelf, others may be advected by shelf currents and/or entrained into sea ice (Eicken et al., 1997). Since these are important processes for the disposal and transfer of terrestrial material into the deep Arctic Ocean, the Laptev Sea shelf links the Arctic Ocean with the Siberian hinterland through the river discharge.

To better understand the present-day and past processes in the land-shelf system of the Laptev Sea, it seems particularly important to investigate its sediments. Since the modern shelf sediment budget is strongly dependent on the input of terrestrial material from rivers (Gordeev et al., 1996) and coastal erosion (Rachold et al., 2000), and on marine productivity (Heiskanen and Keck, 1996), the organic sediment fraction often comprises a mixture of terrestrial and marine components (Fahl and Stein, 1999). Thus, the analyses of the stable carbon isotope composition of the total organic sediment fraction ($\delta^{13}C_{org}$) in surface sediments, which is a widespread method to determine the terrestrial origin of the carbon (Sackett, 1964; Hedges and Parker, 1976; Naidu et al., 2000), can be used to trace the modern spatial distribution of terrestrial organic matter. The shelf sediments do not only contain information about the fluvial runoff, they are also sensitive recorders of those changes that occurred while the Laptev Sea region became flooded due to the last postglacial sea-level rise (Bauch et al., 1999; Bauch et al., 2001 [b]). The massive environmental changes that occurred, induced by the sea-level rise, such as a gradually southward retreat of the river mouths and their depocenters and an increased thermo-erosion of the ice-rich permafrost coast, should have affected the deposition of terrestrial organic matter. Using $\delta^{13}C_{org}$-downcore records in radiocarbon-dated sediment cores from the outer and central Laptev Sea shelf, this study makes an attempt to investigate temporal changes in the deposition of terrestrial organic matter during the transgressional history.

Beside the dominant impact of the river supply on the modern and past sedimentological settings, the hydrography of the Laptev Sea is itself strongly coupled with the annual river discharge and its characteristics. Given the variability of seasonal, annual, and in particular of longer time-scales, the dispersal and fate of the river discharge and its influence on the hydrographical settings are the central tasks in understanding changes in the Laptev Sea system.

A second focus of the present study therefore is the reconstruction of hydrographical conditions on modern and past timescales on the basis of stable oxygen and carbon isotope profiles of bivalve shells. Stable oxygen and carbon isotopic data from carbonate fossils have played an important role in paleoenvironmental reconstructions since the pioneering work of Urey et al. (1951). The oxygen isotopic composition of calcium carbonate is a function of the temperature and the oxygen isotopic composition of the ambient water (Epstein et al. 1953). Stable oxygen isotope data of bivalve shells are often used deciphering hydrographical aspects because isotopic changes can be related to changes in water temperature and/or salinity (e.g., Arthur et al., 1983; Hong et al., 1995; Khim et al., 2001). Because bivalves undergo accretionary growth, a serial carbonate sampling technique along the growth axis of the bivalve shells can provide isotopic records of hydrographical and environmental changes during the life span of the individual specimen (Krantz et al., 1987). Thus, isotope records of modern bivalves from the Laptev Sea shelf were used as a tool to trace modern temporal changes of hydrographical processes in the Laptev Sea system.

In order to reconstruct the paleohydrography in the eastern Laptev Sea during the Holocene, stable isotope profiles of fossil, radiocarbon-dated bivalve shells from a sediment core were established. Although reflecting only a brief interval of time during the life of the individual specimen their isotope profiles offer new important insights into temporal variability of the riverine freshwater discharge and its influence on the hydrography during snapshot views of the postglacial transgressional history of the eastern Laptev Sea shelf.

1.2 STUDY AREA: THE LAPTEV SEA

1.2.1 Physiography

The Laptev Sea as a part of the large Siberian shelves is located between the Kara and the East Siberian seas and bordered by the Taymyr Peninsula and the Severnaya Zemlya archipelago in the west and the New Siberian Islands in the east. Large parts of the Laptev Sea shelf are fairly shallow, with averaging water depths less than 50 m. The northern boundary of the Laptev Sea shelf is marked by the steep continental slope and the adjacent deep sea (Fig. 1-2). Its topography is characterized by a gently northward dipping plain, cut by submarine channels. These channels are connected to the mouths of the rivers and are clearly recognized as submerged river valleys formed during Late Pleistocene times of lowered sea level (Holmes and Creager, 1974; Kleiber and Niessen, 1999). Some channels run along tectonic structures which are related to rift zone extended from south to southeast from the shelf break to the mainland (Drachev et al., 1999).

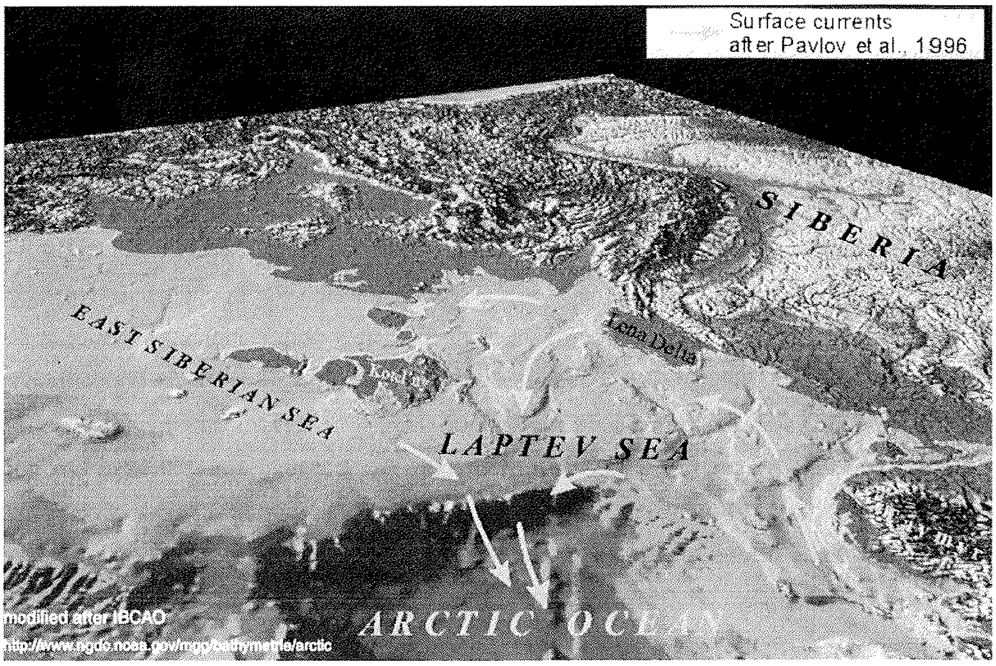


Fig. 1-2: Shaded relief of the Laptev Sea shelf and the adjacent hinterland, viewed from the northwest.

1.2.2 Hydrography

The modern hydrographical situation of the Laptev Sea results from the advection of Arctic water masses from the north and the annual river discharges of about 714 km^3 from the south (Global Runoff Data Center, 1998). The rivers Lena, Yana, Anabar, and Olenek drain an area of 3,643,000 km^2 (Treshnikov, 1985). 75 % of the total annual freshwater input to the Laptev Sea is contributed by the Lena River. In terms of freshwater discharge the Lena is the second largest among the Arctic rivers with a mean annual freshwater discharge of 532 km^3 (Global Runoff Data Center, 1998). Due to the extreme continental climate of East Siberia the water discharge of the Lena River exhibits strong seasonal and interannual variations. The surface waters are frozen each year from October to May until the river-ice breakup proceeds from south to north, reaching the Lena Delta in the mid of June. The Lena River shows a fortyfold increase from very low winter values to the peak flows of June and July, also the annual discharge is subject to interannual variations with 5-20 % of the annual mean (Aagaard and Carmack, 1989). As its mouth, the Lena River forms an extensive delta with many tributaries. The largest of these tributaries, Trofimovskaya and Bykovskaya, are responsible for ~60 and ~25 % of the total Lena River runoff, respectively, and their waters are discharged mainly to the eastern part of the Laptev Sea (Létolle et al. 1993; Ivanov and Piskun, 1995).

The enormous seasonal freshwater pulse has a great impact on the horizontal and vertical structure of the water column and affects a strong thermohaline stratification of the water in the shallow Laptev Sea. Although surface salinities within the shelf may vary yearly (Dmitrenko et al., 1999), the lowest values are always found in the southeastern part of the Laptev Sea. The Lena River waters progressively mix with the Laptev Sea waters, forming a large brackish surface plume extending northward. With increasing distance to the coastline and the river mouth the surface salinity increases and reflects the decreasing influence of riverine water. A typical feature for the Laptev Sea is a sharp halocline in water depths of 10 to 15 m, which separates less saline surface water from the subjacent colder and more saline bottom water.

1.2.3 Modern depositional environment

The riverine outflow is also responsible for a seasonally highly variable transport of significant amounts of suspended load onto the shelf. The total amount of suspended matter per year is estimated at about 24 million tons (Rachold et al., 2000). The main portion ($17.6 \cdot 10^6$ tons/year) of the sediments is transported by the Lena River (Gordeev et al., 1996). Other major rivers like the Yana ($3.5 \cdot 10^6$ tons/year), Khatanga ($1.7 \cdot 10^6$ tons/year), Olenyok ($1.1 \cdot 10^6$ tons/year) and Anabar ($0.1 \cdot 10^6$ tons/year) draining to the Laptev Sea have a less important sediment load (Gordeev et al., 1996). The sediments supplied by the rivers are mainly deposited on the Laptev Sea shelf (Kuptsov and Lisitzin, 1996), partly incorporated into sea ice and transported across the Arctic Ocean and through the Fram Strait via the Transpolar Drift (Eicken et al., 1997; Dethleff et al., 2000).

The importance of the eastern Laptev Sea as the main depositional center for modern fluvial input by the Lena and Yana rivers is related by the surface current system (Hölemann et al., 1999). In general, the western Laptev Sea surface current system is characterized by a southward inflow of cold saline water. The current is deflected to the east and mixes with low-salinity river water (Pavlov et al., 1996) (Fig. 1-2). The warm, low-salinity surface water leaves the Laptev Sea west of Kotel´ny. Previous investigations show that the surface sediments are relatively fine-grained ranging from silty clay to sandy silt (Washner, 1995). In general, the spatial grain-size distribution in surface sediments indicates a higher proportion of fine material in the eastern part, whereas more sandy sediments dominate the western part of the Laptev Sea shelf (Lindemann, 1995). A similar pattern is recognized in the content of organic matter, showing higher amounts in the east as opposed to the west (Hölemann et al., 1999; Stein et al., 1999). Indeed, the large rivers draining into the Laptev Sea transport substantial amounts of organic and other sedimentary material onto the shelf, but on the other hand the large amount of sediment input, caused by the thermal erosion of the ice-bearing permafrost coast should be taken into account. Rachold et al. (2000) calculated the sediment input by coastal erosion to $58.4 \cdot 10^6$ tons/year, which is more than twice the riverine input.

1.2.4 Holocene evolution of the Laptev Sea shelf

The extent of the Eurasian ice sheets during the Weichselian has recently been revised by Svendsen et al. (1999). They pointed out, that the eastern boundary of the large Eurasian ice sheet never extended further east than Taymyr Peninsula and the Central Siberian Uplands (Forman et al., 1999; Larsen et al., 1999, Möller et al., 1999; Svendsen et al., 1999). Therefore, sediment cores from the western Eurasian shelves (Barents and Kara seas) frequently show widespread glaciogenic sediments underneath marine sediments of Holocene age (Polyak et al., 1995; Lubinski et al., 1996; Hald et al., 1999) whereas the wide and shallow Laptev Sea shelf further east remained unaffected by glaciations and does not show such features.

The sea level on the shallow Siberian shelf seas, outside the limits of last glacial ice sheets is expected to have risen with some regional time differences compared to those shelves which came under the effect of postglacial vertical isostatic movements. Because of the inundation of formerly exposed landmasses, sediment records from the Laptev Sea shelf have been used to provide characteristic lithological features of the Holocene transgression (Bauch et al., 1999; Bauch et al., 2001 [b]). A first detailed insight into postglacial sedimentary evolution came from a few radiocarbon-dated cores from the Laptev Sea. They showed a distinctive, sea-level related change in the input of terrestrial-derived sediment material due to the gradual retreat of the paleocoastline (Bauch et al., 1999; Stein and Fahl, 2000; Mueller-Lupp et al., 2000). Based on more sediment cores, recovered from various water depths, ranging from the continental slope to the shallow inner shelf region, Bauch et al. (in press) established a chronology of the last transgression for the Laptev Sea shelf. On the basis of major changes in the average sedimentation rate in sediment cores and other sedimentological parameters, they reconstructed time slices of the postglacial-transgressional history of the Laptev Sea shelf. The observed sharp decrease in sedimentation rates is the direct result of the postglacial sea-level rise, which gradually diminished sedimentation from the outer to inner shelf due to an increasing distance between the shelf areas and the coast as the primary sediment source. They conclude that the general pattern in down-core sedimentation rates reflects the southward retreat of the coastline during the Holocene flooding of the Laptev Sea shelf.

Allowing for some uncertainties, they estimate that the inundation of the present 50 m, 43 m, and 31 m isobaths was concluded by about 11.1, 9.8, and 8.9 ka BP, respectively (Fig. 1-3). The Holocene sea-level highstand was reached near 5 ka BP. The rate of sea-level rise between these time constraints was calculated to 5.4 mm/yr, 13.3 mm/yr, and 7.9 mm/year.

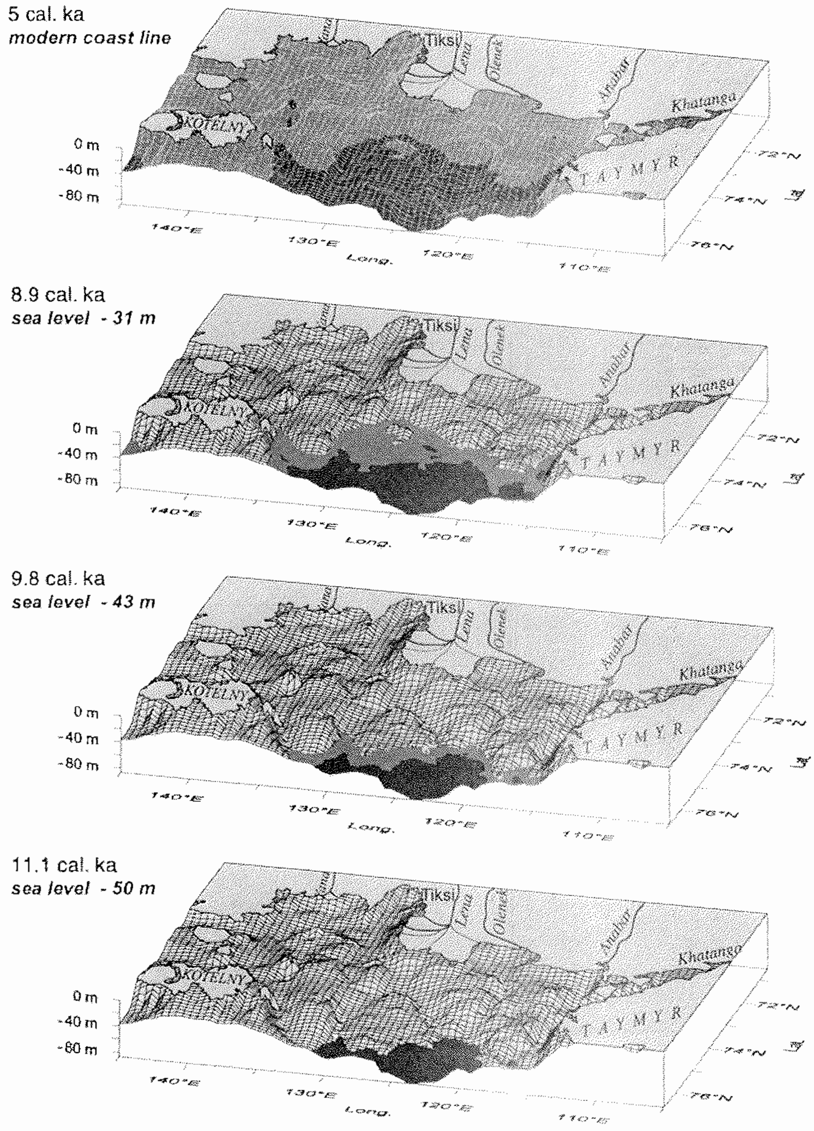


Fig. 1-3: Reconstruction of the Laptev Sea transgression (Bauch et al., 2001 [b]) showing the variation in areal flooding between each time interval investigated. The topographic map is based on Russian navigation charts and the bathymetric data obtained during several German-Russian expeditions. Note that the modern shelf topography does not reflect the actual paleosurface prior to inundation.

1.3 Material and Methods

1.3.1 Sediment samples

To cover a substantial part of the Laptev Sea shelf, at a total of 103 stations surface samples were taken from giant box cores during several expeditions to the Laptev Sea (Fig. 1-4).

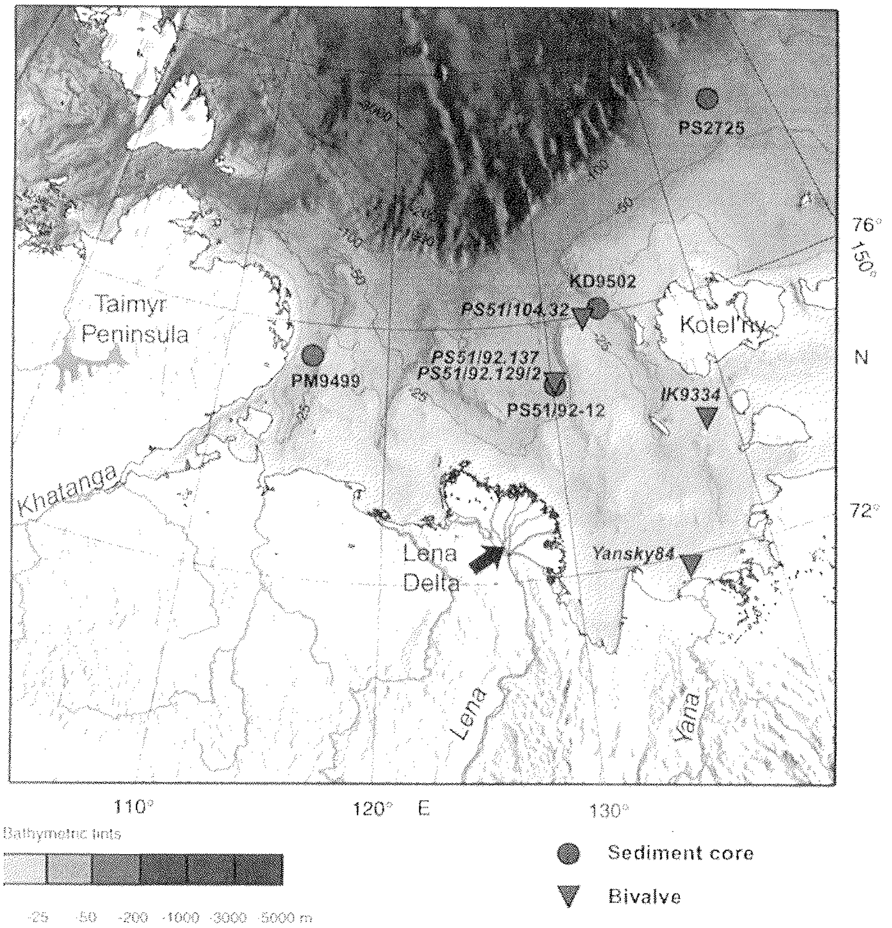


Fig. 1-4: Shaded relief of the Laptev Sea and the adjacent hinterland, showing the locations of the investigated sediment cores and bivalves. Datasource: IBCAO (International Bathymetric Chart of the Arctic Ocean). http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html. Projection: Lambert azimuthal equal-area projection (122 E/75 N).

The investigated sediment cores were recovered from the central and outer Laptev Sea shelf, covering a water depth of 32 to 77 m (Table 1-1; Fig. 1-4). Subsequent sediment samples for stable carbon isotope analyses and total organic carbon (TOC) measurements were taken with a resolution of 5 cm (KD9502-14) and 10 cm (PM9499-2, PS2725-5), respectively. All samples were freeze-dried and grinded using a hand-held agate pestle and mortar to provide a homogenized sample for the $\delta^{13}C_{org}$ and TOC measurements.

Table 1-1: Descriptions of the investigated sediment cores.

Core	Device	Long. [°E]	Lat. [°N]	Water depth [m]	Recovery [cm]	Cruise/ Reference
PS51/92-12	Kasten corer	130.140	74.592	32	589	PS51 ARK-XIVb / **1**
KD9502-14	Vibro corer	133.117	76.192	46	230	KD95 / **2**
PS2725-5	Gravity corer	144.135	78.657	77	478	PS27 ARK-XI/1 / **3**
PM9499-2	Kasten corer	115.545	75.501	48	235	PM94 / **4**

References: **1** Kassens and Dmitrenko (in press), **2** Kassens et al. (1997), **3** Rachor (1997), **4** Kassens and Dmitrenko (1995)

1.3.1.1 Stable carbon isotope analyses of the organic sediment fraction

The use of stable carbon isotope analyses of the total organic carbon in marine sediments to specify the provenance of the organic fraction is based on the general enrichment of ^{13}C by a few per mil on the delta scale in marine organic matter compared with terrestrial derived organic material. During photosynthesis carbon becomes depleted in ^{13}C. Plants using the C_3 photosynthesis pathway have a mean $\delta^{13}C$ of about –26 to –29‰ (Mook and Tan, 1991). Grasses and other plants using the C_4 pathway have $\delta^{13}C$ values between –10 and –20 (review by Deines, 1980).

The marine fraction of the sedimentary organic carbon is about –20‰, with some variation related to the oceanic province. Due to the dominance of C_3 plants in the catchment area of the Laptev Sea rivers, the terrestrial source is expected to provide a well defined isotope signature which reliably helps to identify the contribution of the terrestrial source of organic matter to the surface and downcore sediments of the Laptev Sea shelf. In contrast to more temperate regions the source of TOC from terrigenous C_4 plants to the drainage area of the Siberian rivers is insignificant because these plants do not exist in the northern latitudes (Teeri and Stowe, 1976; Teeri, 1988).

For stable carbon isotope measurements of the organic matter in the bulk sediments ($\delta^{13}C_{org}$) in the surface sediments as well as in the samples from the sediment cores, the samples were acidified with 2 % HCl (1h) at 40°C. Afterwards the samples were washed on a pre-combusted fiberglass filter to remove the carbonates. The filter was dried at 60 °C and combusted for 10 min. at 900°C in an excess of 4.5 grade oxygen. The yield of CO_2 was determined volumetrically and analyzed on a FINNIGAN-MAT Delta E isotope ratio mass spectrometer. The instrument was isotopically calibrated through the NBS 20 (carbonate) isotope standard ($\delta^{13}C$ = -1.06‰). The accuracy was checked using the IAEA NBS22 (oil) isotope reference material. The precision of the $\delta^{13}C$ results is 0.2‰ PDB or better. The isotope composition is given in the $\delta^{13}C$ vs. PDB notation: $\delta^{13}C\ [‰] = [(^{13}C/^{12}C_{sample} - {}^{13}C/^{12}C_{standard}) / (^{13}C/^{12}C_{standard})] \bullet 1000$.

1.3.1.2 TOC measurements

Measurements of $\delta^{13}C_{org}$ of the organic sediment fraction can provide an indication of the terrestrial origin of the total organic matter (TOC). Consequently TOC accumulation rates may give some indication of terrestrial or riverine input of organic matter through time.

The TOC contents (weight percentage) of the samples from cores PM9499-2 and KD9502-14 were measured at GEOMAR, Kiel, using a LECO C-200 carbon determinator. For TOC analyses the samples had to be decalcified prior to measurement. For this purpose a few drops of hydrochlorid acid were added until all the calcium carbonate was removed and no further reaction took place. Afterwards the sample was combusted at 1800°C and organic carbon, in terms of CO_2, was measured by an infrared detector. Each sample was measured twice to reduce measurement errors.

The TOC measurements for core PS2725 were taken from Fahl and Stein (1999) and were determined by the means of a Heraeus CHN-analyzer.

1.3.1.3 Chronology and accumulation rates

The age models of the core PM9499-2, KD9502-14, and PS2725-5 are based on established chronological frameworks (Bauch et al., 1999; Stein and Fahl, 2000) (Table 1-2). The age determinations were primarily based on radiocarbon dates of marine bivalves, obtained by means of an accelerator mass spectrometer (AMS) at the Leibniz Laboratory in Kiel (Germany). The lower part of core PM9499-2 contained no biogenic carbonate. Therefore, radiocarbon analyses were performed on bulk plant material (Bauch et al., 1999). The chronology of core PS51/92-12 is based on radiocarbon AMS-dates measured on marine bivalve shells at the Leibniz Laboratory in Kiel (Table 1-2; Fig. 1.5). A reservoir effect for the Laptev Sea shelf of 370±49 yrs was taken into account (Bauch et al., 2001 [a]) and was subtracted from each of the dated marine shells. All radiocarbon dates were converted into calendar years BP using the intercept method (Stuiver et al., 1998) in the program CALIB rev. 4.3 (Stuiver and Reimer, 2000).

Between the age tiepoints, the sedimentation was assumed to be constant and linear interpolation was applied to produce the depth-age relation of the measured proxies TOC and $\delta^{13}C_{org}$.

Taken into account for compaction of the sediment, the dry bulk density (DBS) was determined and multiplied with the linear sedimentation rate (LSR), according to the standard method of van Andel et al. (1975) to compute the total sediment accumulation (AR_{total}).

$$AR_{total}\ [g/cm^2/ka] = LSR\ [cm/ka] \bullet DBS\ [g/cm^3]$$

The accumulation rate (AccR) of TOC was calculated as a product of the total accumulation rate and the content of TOC: $AccR_{TOC}\ [g/cm^2/ka] = (TOC\ [\%]\ /100) \bullet AccR_{sediment}\ [g/cm^2/ka]$

Table 1-2: Radiocarbon dates and calibrated calendar years of the investigated sediment cores from the Laptev Sea shelf.

Core/ Lab#	Depth [cm]	^{14}C age [yrs]	Cal. age BP [yrs]	Core/ Lab#	Depth [cm]	^{14}C age [yrs]	Cal. age BP [yrs]
PM9499-2[1)]	0		0	**PS2725**[2)]			
KIA-1794	24	2140±30	1768	KIA-2747	0	bomb	0
KIA-3115	29.5	6510±50	7027	KIA-114	115	8340±60	8891
KIA-1793	122	8660±50	9047	KIA-115	207	9170±90	9828
KIA-1799	149	10090±50	11102	KIA-117	392	9280±60	9903
KIA-1817	157	10140±50	11120	KIA-118	430	9340±60	10073
KIA-1884*	184	10310±70	12213				
KIA-3120*	234	10650±110	12734				
KD9502-14[1)]	0		0	**PS51/92-12**	0		0
KIA-539	3	bomb	0	KIA-6877	2	590±25	273
KIA-540	23	6420±30	6930	KIA-6878	64	1505±35	1078
KIA-541	31	6440±50	6954	KIA-6879	160	1680±35	1267
KIA-544	85	6630±50	7203	KIA-12931	210	3810±35	3809
KIA-545	107	7340±50	7822	KIA-6880	300	6725±40	7270
KIA-546	119	7610±70	8104	KIA-6881	402	7280±45	7754
KIA-547	139	7700±70	8173	KIA-6882	500	7950±55	8408
KIA-548	157	7900±40	8335				
KIA-550	185	8300±60	8866				
KIA-551	225	8420±80	8936				

* plant material

^{14}C ages were taken from: 1) Bauch et al. (1999); 2) Fahl and Stein (1999)

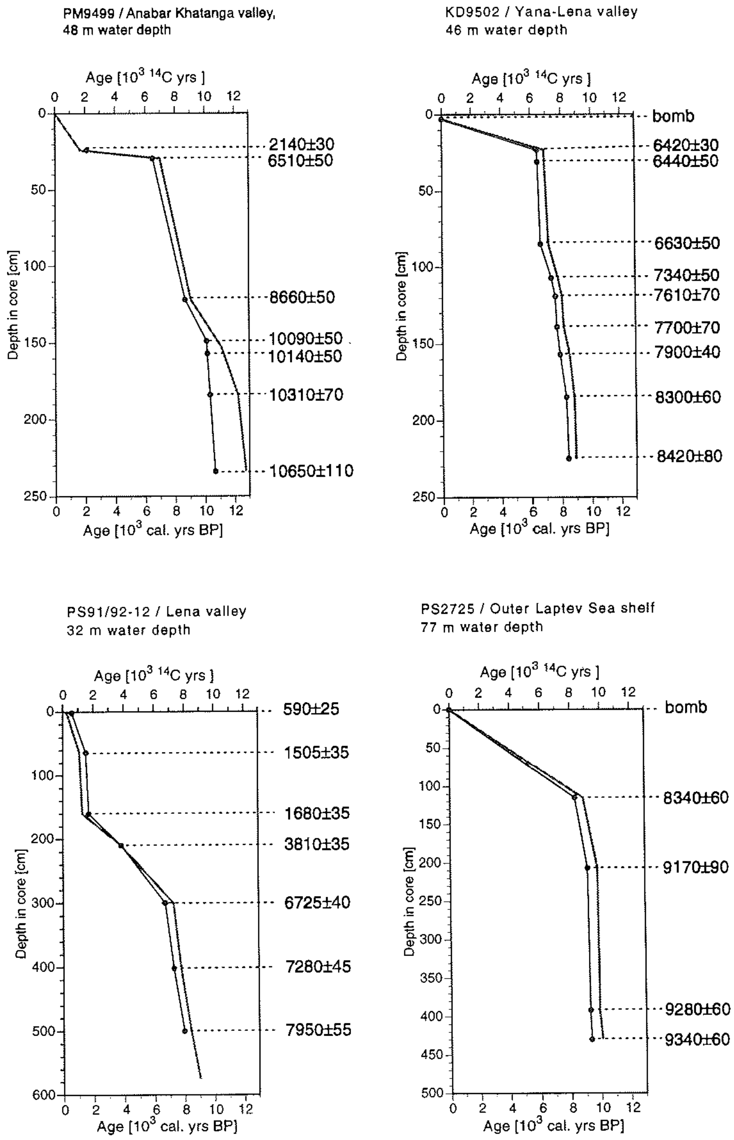


Fig. 1-5: Original radiocarbon dates and the reservoir-corrected age models as calculated in 10^3 cal yr. BP (gray line) of the investigated cores.

1.3.2 Bivalves

1.3.2.1 Bivalve species

While five modern bivalve specimens of *Astarte borealis* and *Macoma calcarea* were collected alive from the Laptev Sea for detailed stable isotope analyses, the four fossil bivalves of *Macoma calcarea* were obtained from a sediment core (PS51/92-12) northeast off the Lena Delta (Fig. 1-4). Collection sites, bivalves species, state of collection, collection date and age, respectively, of the investigated bivalves are presented in Table 1-3. The fossil bivalve shells were well preserved with no obvious signs of reworking. They were either found in situ with both valves in place, or the periostracum was still preserved, implying no significant lateral transport.

Table1-3: Description of the bivalve specimens used for the detailed stable isotope analyses.

Sample ID/ Lab #	Bivalve species	State of collection	Collection date/ Age [^{14}C years]	Water depth/ Core depth
PS51/104.32	*Astarte borealis*	alive	05.08.1998	32 m / surface
PS51/92.137[1)]	*Astarte borealis*	alive	03.08.1998	32 m / surface
IK9334 [2)]	*Astarte borealis*	alive	19.08.1993	22 m / surface
Yansky84 [3)]	*Astarte borealis*	alive	Summer 1984	11 m/ surface
PS51/92.129/2	*Macoma calcarea*	alive	03.08.1998	32 m / surface
PS51/92-12 120 cm	*Macoma calcarea*	fossil		32 m / 120 cm
PS51/92-12 210 cm KIA-12931	*Macoma calcarea*	fossil	3810±35	32 m / 210 cm
PS51/92-12 300 cm KIA-6880	*Macoma calcarea*	fossil	6725±40	32 m / 300 cm
PS51/92-12 500 cm KIA-6882	*Macoma calcarea*	fossil	7950±55	32 m / 500cm

We acknowledge
1) M. Schmidt (Institute for Polar Ecology, Kiel University)
2) I. Richling and V. Wiese (Malacological Museum "Haus der Natur-Cismar")
3) A. Gukov (Hydrometeorological Department Tiksi/Yakutia)

for providing the bivalves.

Modern bivalve species of *Astarte borealis* show a geographically widespread distribution in the Laptev Sea because of their tolerance to certain salinity and temperature environments (Gukov, 1999). The typical habitat is infaunal in waters with a salinity range of 15-34 and water depth of 15-50 m (Petryashov et al., 1999; Richling, 2000). *Macoma calcarea* is one of the typical representatives of deposit feeders in the Laptev Sea (Gukov, 1999). Burying themselves in the bottom by some centimeters, *Macoma calcarea* uses a tendril-like siphon to suck up fine-grained sediments and organic matter from the sediment-water interface.

1.3.2.2 Stable isotope analyses of bivalve shells

If the isotopic compositions within a shell are to be compared with environmental conditions, the samples must be taken along a profile in the direction of growth. Bivalves are suitable for this purpose because new material is added at the outer rim during their growth.

A serial sampling technique similar to that used in other studies (Erlenkeuser and Wefer, 1981; Krantz et al., 1987; Krantz et al., 1988; Bemis and Geary, 1996; Andreasson and Schmitz, 1998) was applied to derive high-resolution records from the shells. Prior to taking carbonate samples, the exterior of each shell was cleaned to remove the periostracum and any surficial contamination. Individual carbonate powder samples (>15 µg) were obtained from each specimen by milling consecutive grooves sequentially from the outer layer along the growth axis with a spatial resolution of approximately 0.15 to 0.3 mm (Fig. 1-6). Sample positions [mm] are reported as the distance from the umbo towards the ventral margin along the axis of maximum growth. To avoid a mixing of the sample with subjacent shell layers, the sample was milled surficially from the surface of the outer layer by using a diamond millingcutter under the microscope. The resulting carbonate powder sample was vacuumed on a little fiberglass filter. For isotope analysis, the carbonate powder on the filter was reacted with 100 % orthophosphoric acid under vacuum at 73°C in the Kiel carbonate device, which is coupled online to a Finnigan MAT 251 gas isotope mass spectrometer. Isotopic analyses of the CO_2 gas are recorded in standard delta (δ) notation in per mil (‰) relative to the PDB standard (NBS 20). The external error amounts to less than ±0.08‰ and ±0.05‰ for $\delta^{18}O$ and $\delta^{13}C$, respectively.

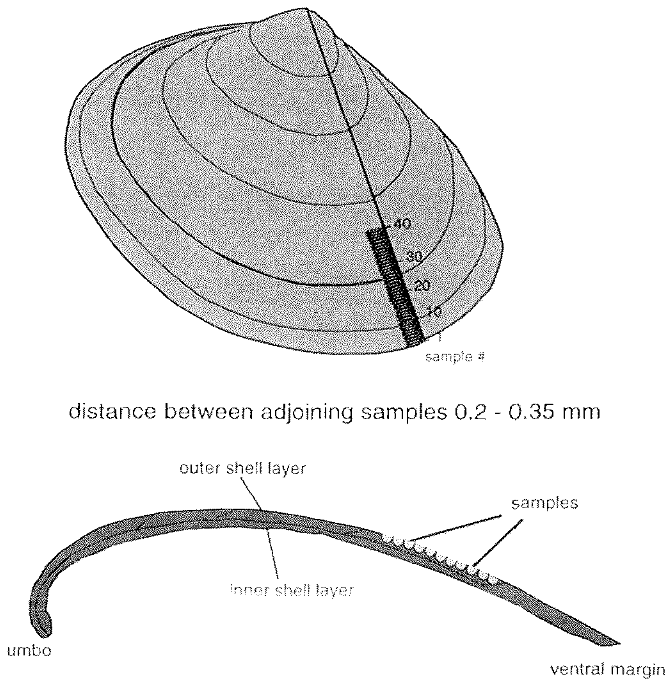


Fig. 1-6: A) Exemplary sample position along the growth axis. B) Schematic cross section of a bivalve shell illustrating that carbonate powder samples are millcutt only from the outer shell layer.

Having isolated the material, which was formed during a certain time under certain hydrographical and environmental conditions, that time must also be identified. Of course, the length of the period which corresponds to a sample is a function of growth rate and sample size. In the ideal case, the time period represented by a sample can be exactly dated in terms of calendar months, seasons, or years. This method is well established using the stable isotope profiles from corals and counting backwards the visually determinable growth layers from the time of collection. Unfortunately growth bands in the investigated bivalves shells are not clearly visually discernible, we tried to identify isotopic cycles and compared them to the seasonal hydrographical changes. Taking into account the relationship between the isotopic composition of the bivalve shell carbonate, the temperature, and the isotopic composition of the water, which is often related to salinity, the isotopic cycles can be interpreted as annual hydrological cycles with heavier $\delta^{18}O$ values indicating winter and lighter values indicating summer. The light values at the margin represent the summer in the year of collection. Because the modern bivalve specimens were collected alive, calendar years may be addressed directly by counting the annual isotope cycles backward from the margin. Since no hydrographical long-term monitoring exists so far, we are not able to establish a time scale with a resolution of days or months from the isotope profiles. But on the other hand seasonal hydrological conditions can be identified in the isotope profiles and give the possibility to reconstruct the hydrographical settings from the isotope profiles of the bivalve shells with a resolution of years.

1.3.2.3 X-ray diffraction

The mineralogy of the shell samples is important, because calcite and aragonite have slightly different fractionation factors as a function of temperature (Horibe and Oba, 1972; Grossmann and Ku, 1986).

Carbonate samples from the outer and inner shell layer were ground by hand in an agate mortar, homogenized and subsequently pressed into an aluminium sample holder. The X-ray diffraction analysis (XRD) was performed with a Phillips PW 1700 X-ray diffractometer with a Cobalt K-alpha anode at 40 kV and 35 mA. All samples were scanned with a scanning speed of 0.01° per second from 20° to 40°. The generated X-ray diffraction files were analyzed using the program Mac Diff 3.1.5 (Petschik, 1996) in order to determine whether the shell sample consists of Aragonite or Calcite, by measurement of peak areas (Milliman, 1974). All diffractograms only show a prominent Aragonite peak, whereas no Calcite peak was observed.

1.4 INDIVIDUAL STUDIES

This thesis comprises three manuscripts (CHAPTER 2-4) which have been published or submitted to peer-reviewed scientific journals. A short overview will be given in the following. Together with the references from CHAPTER 1 the references from each of this manuscripts have been merged into one reference list.

Chapter 2:

Changes in the deposition of terrestrial organic matter on the Laptev Sea Shelf during the Holocene: evidence from stable carbon isotopes.

In this study the stable carbon isotope composition of the total organic matter in surface sediments of the Laptev Sea was used to trace the modern spatial distribution of terrestrial organic matter. Downcore $\delta^{13}C_{org}$ records in AMS-dated sediment cores specify the spatial and temporal depositional changes of terrestrial organic matter during the past 12.7 ka and their relation to the Holocene history of the Laptev Sea shelf.

Chapter 3:

Seasonal and interannual variability of Siberian river discharge in the Laptev Sea inferred from stable isotopes in modern bivalves.

The purpose of this manuscript was to use the stable isotope profiles of bivalve shells as a tool to reconstruct the hydrographical conditions and changes in the Laptev Sea. The $\delta^{18}O$ and $\delta^{13}C$ cycles from growing profiles of recent bivalves of *Astarte borealis* indicate a correspondence to seasonal hydrographic changes and can be compared with synoptical data.

Chapter 4:

Paleohydrography of the Laptev Sea (Siberian Arctic) as recorded in stable isotope profiles of bivalve shells.

In this study, oxygen isotope analyses of shells from living and fossil bivalves were carried out to reconstruct hydrological changes and their correspondence to the Holocene history of the Laptev Sea shelf. Oxygen isotope profiles of AMS-dated bivalves of *Macoma calcarea* provide us an insight into the evolution of the bottom water salinity and temperature during snapshot views of the transgressional history of the Laptev Sea shelf.

2 CHANGES IN THE DEPOSITION OF TERRESTRIAL ORGANIC MATTER ON THE LAPTEV SEA SHELF DURING THE HOLOCENE: EVIDENCE FROM STABLE CARBON ISOTOPES

2.1 ABSTRACT

Stable carbon isotope ratios in the organic fraction of surface sediments from the Laptev Sea shelf were analyzed in order to study the modern distribution pattern of terrestrial organic matter. The $\delta^{13}C_{org}$ signature of surface sediments range from -26.6‰ near the coastal margin to -22.8‰ in the north towards the outer shelf. Characterizing the possible sources of organic matter by their $\delta^{13}C_{org}$ signature reveals that the terrestrial influence reaches further north into the eastern than in the western Laptev Sea.

Downcore records of the $\delta^{13}C_{org}$, measured on three AMS ^{14}C-dated cores from water depths between 46 m and 77 m, specify the spatial and temporal changes in the deposition of terrestrial organic matter on the Laptev Sea shelf during the past 12.7 ka. The major depositional changes of terrestrial organic matter occurred between 11 and 7 ka BP and comprised the main phase of the southward retreat of the coastline and of the river depocenters due to the postglacial sea level rise.

2.2 INTRODUCTION

The depositional environment of the broad and shallow Siberian shelf areas exert a strong impact through the vast river system and their discharge and particulates. More than 20 % of the total Arctic continental runoff (3300 km^3) is supplied by the rivers draining into the Laptev Sea (Aagaard and Carmack, 1989). About 520 km^3/yr of the total freshwater discharge of 700 km^3/yr to the Laptev Sea is contributed only by the Lena River (Alabyan et al., 1995). Approximately $21 \bullet 10^6$ tons per year of suspended particulate material (Alabyan et al., 1995) and up to $1.2 \bullet 10^6$ tons per year of particulate organic carbon (POC) (Rachold and Hubberten, 1999) are transported by the rivers, most of it by the Lena. However, the actual amount of sediment reaching the Laptev Sea is still under discussion because the portion of sediment that is deposited in the river deltas is not well-known. Furthermore, the amount of material released by thermal erosion of the ice-rich permafrost coastline has only been partially quantified (Are, 1999). The shelf sediments of the Laptev Sea do not only contain evidence of the modern fluvial runoff but also record the depositional changes in the past. Whereas most of the shelf was exposed during the last glacial maximum (LGM), the postglacial sea level rise led to a transformation of the shelf from a periglacial permafrost landscape into the modern shallow shelf sea (Bauch et al., 1999).

The $^{13}C/^{12}C$ ratio of the organic carbon in marine sediments has been used to specify the provenance of the organic fractions either derived from a terrestrial or a marine source (Hedges and Parker, 1976; Erlenkeuser, 1988, Tan and Edmond, 1993). This method is based upon a general enrichment of ^{13}C, by a few per mil on the delta scale, in marine organic matter compared to terrestrial material. Land plants using the C_3 pathway of photosynthesis reveal $\delta^{13}C$ values about –25 to –29‰ (Mook and Tan, 1991), while the marine fraction of the sedimentary organic carbon is about –20‰, with some variation related to the oceanic province. The intention of our studies is to trace the terrestrial organic matter using the organic stable carbon isotope composition in the sediments and to identify the depositional changes of terrestrial organic material during the Holocene history of the Laptev Sea. Due to the dominance of C_3 plants in the catchment area of the Laptev Sea rivers, the terrestrial source is expected to provide a well defined isotope signature which reliably helps to identify the contribution of the terrestrial source of organic matter to the surface and downcore sediments of the Laptev Sea shelf.

2.3 MATERIALS AND METHODS

2.3.1 Sediment material

Stable organic carbon isotope analyses were carried out on a total of 103 stations that cover a substantial part of the Laptev Sea shelf (Fig. 2-1). Three investigated sediment cores were obtained from the central (KD9502,PM9499) and outer shelf (PS2725). Core KD9502 from 46 m water depth and core PM9499 from 48 m water depth are located within the submarine channels of the Lena-Yana and Khatanga-Anabar rivers, respectively (Kassens et al., 1997; Kassens and Dmitrenko, 1995). Core PS2725 was recovered from 77 m water depth north of the New Siberian Islands (Rachor, 1997).

For organic carbon isotope analyses the bulk sediment samples were acidified with 2% HCl (1hr, 40°C) to remove carbonates, washed on a pre-combusted glass fiber filter, dried (60°C), and combusted for 10 min. at 900°C in an excess of 4.5 grade oxygen. The isotopically interfering NO_x were reduced over copper at 450°C. The yield of CO_2 was determined volumetrically and analyzed on a FINNIGAN-MAT Delta E isotope ratio mass spectrometer. The instrument was isotopically calibrated through the NBS 20 (carbonate) isotope standard ($\delta^{13}C$ = -1.06‰). The accuracy was checked using the IAEA NBS22 (oil) isotope reference material. The precision of the $\delta^{13}C$ results is 0.2‰ PDB or better. The isotope composition is given in the $\delta^{13}C$ vs. PDB notation: $\delta^{13}C\ [‰] = [(^{13}C/^{12}C_{sample} - {}^{13}C/^{12}C_{standard}) / (^{13}C/^{12}C_{standard})] \bullet 1000$.

To interpret the downcore carbon isotopic records in terms of paleoenvironmental changes, established chronological frameworks were used (Bauch et al., 1999; Stein and Fahl, 2000). The conventional ^{14}C ages were calibrated to calendar years (ka BP) using the intercept method in CALIB rev. 4.3 (Stuiver and Reimer, 2000; Stuiver and Reimer, 1993; Stuiver et al., 1998). A reservoir effect of 370±49 years for the Laptev Sea was applied (Bauch et al., 2001 [a]). Accumulation rates of total organic carbon (AccR TOC) were calculated on the basis of linear interpolation between the age points and consideration of the dry bulk density variations in the sediments.

2.4 Results

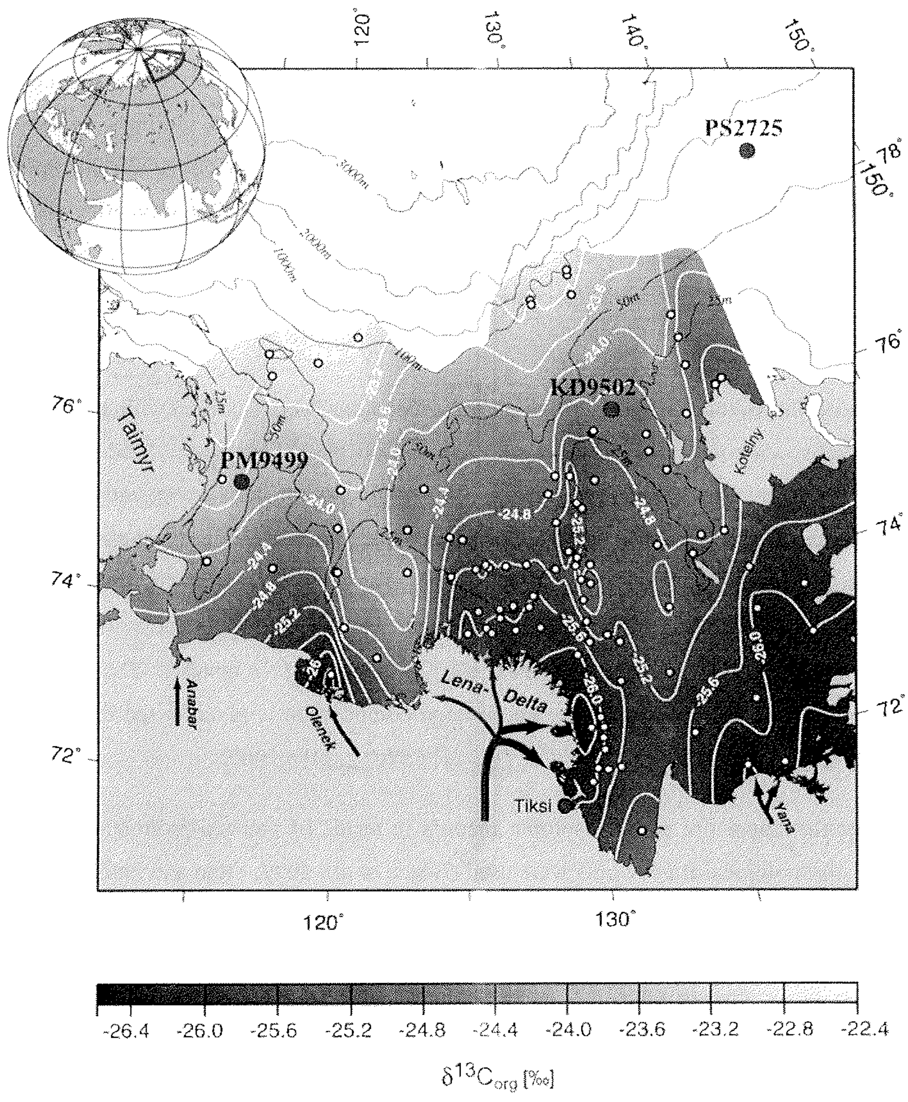


Fig. 2-1: $\delta^{13}C$ ratios of the organic fraction of the surface sediments from the Laptev Sea shelf. The distribution pattern was generated by gridding and linear interpolation between the data points (black dots).

2.4.1 $\delta^{13}C_{org}$ composition of the surface sediments

The $\delta^{13}C_{org}$ values of the surface sediments range from –26.6‰ near the Lena Delta to –22.8‰ on the continental slope, revealing a consistent trend towards isotopically heavier values from the south to the north (Fig. 2-1). The $\delta^{13}C$ signature is lightest near the river mouths and gradually increases northward following to some extent the submarine valleys, which run in a south to north direction (Kleiber and Niessen, 1999). The distribution pattern also reveals that lighter $\delta^{13}C_{org}$ values extend further north in the eastern part of the Laptev Sea than in the western part. This obvious east-west gradient in $\delta^{13}C_{org}$ values reflects the larger input of organic matter to the east (Rachold and Hubberten, 1999) as compared with the western Laptev Sea, where marine conditions are more dominant (Dmitrenko et al., 1999).

The lightest values of $\delta^{13}C$ observed near the mouths of the rivers Lena and Yana are in good agreement with the $\delta^{13}C$ composition of the river-born particulate organic matter (POM). For the Lena River, Rachold and Hubberten (1999) report an average value of -27.1‰ ± 0.8‰, which is close to the values found east off the Lena River delta (-26.6‰), where the main branches discharge. Samples from north of the Yana River yield -26.2‰, also matching the average isotopic composition of the riverine POM (-25.9‰ ± 0.4‰) (Rachold and Hubberten, 1999).

2.4.2 Accumulation of TOC and $\delta^{13}C_{org}$ composition during the Holocene

The $\delta^{13}C_{org}$ records in the two sediment cores from the central Laptev Sea (PM9499, KD9502) shelf show a distinct shift from isotopically lighter to heavier $\delta^{13}C_{org}$ values (Fig. 2-2a), which is dated back in both cores to approximately 7 ka BP. This suggests a thorough change of the depositional conditions on the central Laptev Sea shelf during this time. A dominantly terrestrial source of organic matter, indicated by low $\delta^{13}C_{org}$ values, is obvious in both cores prior to 7 ka BP. The increasing $^{13}C/^{12}C$ ratio coupled with decreasing accumulation rates of TOC underlines the decline of terrestrial organic matter supply to the central Laptev Sea shelf after 7 ka BP.

Also in the record of core PS2725 from the deeper outer shelf, this shift towards isotopically heavier $\delta^{13}C_{org}$ values and decreasing accumulation rates of TOC becomes evident 2 ka earlier.

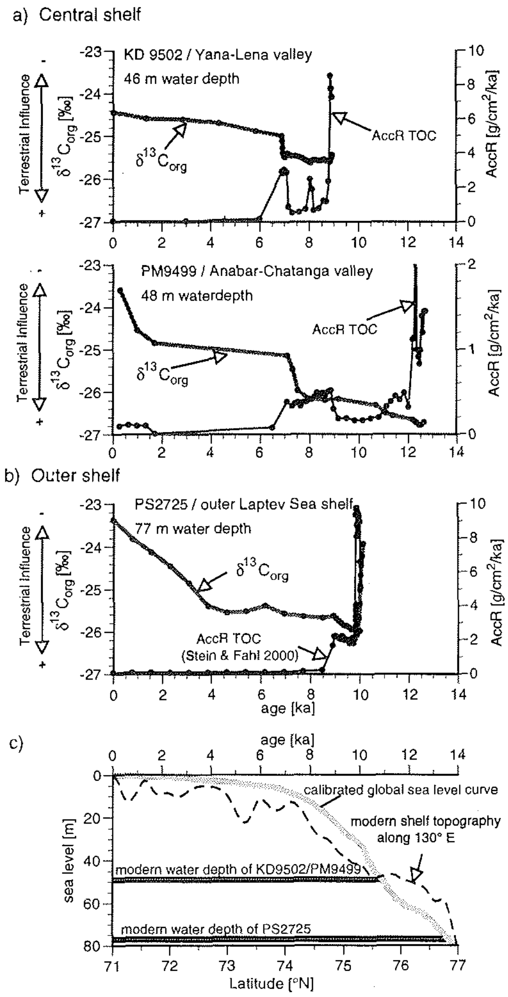


Fig. 2-2: $\delta^{13}C_{org}$ records and accumulation rates of TOC (AccR TOC) for three cores indicating the Holocene depositional changes on the central (a) and outer (b) Laptev Sea shelf. c) Profile of the modern Laptev Sea shelf topography (along 130° E) and the water depth of the investigated cores in comparison to the calibrated global sea level curve (Fairbanks 1989). The global sea level curve was calibrated to calendar years using the marine data set of CALIB 4.1.2 (Stuiver and Reimer 1993 ; Stuiver et al. 1998).

The development towards heavier $\delta^{13}C_{org}$ values seems to increase after 4 ka BP (Fig. 2-2b). However, a more precise dating of this younger change in the Holocene suffers from age uncertainties in this part of the core.

Prior 10 ka BP on the outer shelf, core PS2725 shows relatively heavy $\delta^{13}C_{org}$ values. Although this section is not dated, our data and those of others (Stein and Fahl, 2000) indicate that this part of the core must have been deposited under different environmental settings compared to the remaining part. According to the heavy $\delta^{13}C_{org}$ values this core section may contain much older, reworked marine deposits.

2.5 DISCUSSION

2.5.1 Distribution of terrestrial organic carbon in surface sediments

As revealed by our surface sediment data, the $\delta^{13}C$ signature seems a feasible method to trace the deposition of the terrestrial organic matter on the Laptev Sea shelf (Fig. 2-1). By this method it may also be possible to identify the main sources of organic matter by their $\delta^{13}C$ signature. On the basis of our data, the terrestrial source of organic matter is isotopically identified by a $\delta^{13}C_{org}$ of -26.6‰, which conforms to the average signature of POM, discharged by the main source, the Lena River. The river data of Rachold and Hubberten (1999) show that the signature of POM in the Siberian rivers is a mixture of two components, a detrital organic fraction with a $\delta^{13}C_{org}$ of -25.0‰ and an isotopically lighter component with an average of -31.0‰ that may be attributed to autochthonous riverine plankton. Rachold and Hubberten (1999) identified the detrital organic material as the main fraction of riverine POM, which is exported by the river runoff onto the Laptev Sea shelf. Besides, coastal material as another source of terrestrial input should not be neglected. Erosive processes, i.e. thermoabrasion and erosion of permafrost-affected coastal soils with a high content of organic carbon, should greatly imprint on the $\delta^{13}C_{org}$ signature in Laptev Sea sediments. According to Are (1999), the coastline of the Laptev Sea retreats with a rate of 2-6 m/y as a result of shore erosion. The amount of coastal erosion is estimated at $30 \bullet 10^{6}$ t/yr for the total coast of the inner Laptev Sea, which is similar to or even higher than the riverine input of sediment. Large parts of the coastal area of the Laptev Sea are dominated by peaty and organic-rich permafrost soils including long sections of ice complexes (Rachold and Grigoryev, 1999). Decomposition and mineralization of the organic matter in these soils are kept low by the harsh climatic conditions. Thus, the $\delta^{13}C$ signature of the original plant material remains well preserved (Gundelwein, 1998). Analyses of modern plant material from typical tundra vegetation show $\delta^{13}C_{org}$ values of -27.2‰ to -29.2‰ (Pfeiffer and Janssen, 1993; Gundelwein, 1998) and based on data from *Carex* sp. (-27.2‰), *Eriophorum vaginatum* (-28.6 ‰) and *Dryas punctata* (-29.2‰).

It is much more difficult to define a marine source of organic matter by its isotopic signature than the terrestrial source for the Laptev Sea region. The marine fraction of organic matter in the sediments is mainly derived from planktic organisms. Their isotopic composition ranges from –20‰ to –30‰ and is controlled by the isotopic fractionation between phytoplankton and the various fractions of dissolved inorganic carbon (DIC). The magnitude of this fractionation is related to temperature and to the CO_2 partial pressure in the water (Fortugne and Duplessy, 1981; Rau et al., 1992). Considering the generally low water temperature of the arctic waters, the stable carbon isotope signatures should be isotopically lighter than in low- and mid-latitude waters. However, surface sediments of deep-sea cores from the Central Arctic Ocean reveal $\delta^{13}C_{org}$ values between -21.4‰ to -22.9‰ (Erlenkeuser, 1988; Schubert, 1995). The comparatively heavy carbon isotope composition found in Arctic Ocean sediments may relate to the influence of diatoms in the planktic community, which partially use the C_4-cycle for carbon fixation (Voss, 1991). Also microbial degradation of the planktic organic detritus may lead to an increasing $\delta^{13}C_{org}$-level in the sediments (Voss, 1991). Despite the relatively heavy $\delta^{13}C_{org}$ values in these surface sediments, several investigations of biomarkers and bulk organic parameters suggest that Arctic Ocean sediments have a strong terrestrial overprint (Schubert, 1995, Schubert and Stein, 1996; Fahl and Stein, 1999; Stein and Fahl, 2000). For the Laptev Sea continental slope, Boucsein and Stein (2000) pointed out applying the maceral analysis as a organic-carbon-source indicator that only 20 to 40 % of the organic carbon appear to be of marine origin.

Due to the strong riverine contribution of organic matter to the modern Laptev Sea shelf, the marine source seems to play a minor role. This is in coincidence with previous surface sediment studies (Stein and Nürnberg, 1995; Stein et al., 1999; Fahl and Stein, 1999; Boucsein and Stein, 2000) which revealed that the Laptev Sea, especially the eastern part, is characterized by a strong overprint of the terrestrial organic fraction on the total organic input. The resulting $\delta^{13}C_{org}$ of the sedimentary mixture directly relates to the ratio of the two fractions, marine and terrestrial. The latter bears the greater potential of significant variations under the given settings of the Laptev Sea environment. Accordingly, we attributed the observed isotope variations to the effect of the sea level rise, which induced the southward retreat of the coastline and the depocenters of the rivers and accordingly reduced the fluviatile impact on the coring sites. This view is also consistent with the modern findings of the $\delta^{13}C_{org}$ in the surface sediments, which show lightest $\delta^{13}C_{org}$ values where the input rates of terrestrial matter are highest. Radiocarbon data from the bulk surface sediment of the eastern Laptev Sea reveal average radiocarbon ages of around 7 kyr. (Kuptsov and Lisitsin, 1996). Apparently these relatively old ages are due to a mixture of older and younger organic carbon, eroded from soils and deposits of the river catchment areas. These ages are not indicative for surficial relict sediments because various cores from the Laptev Sea shelf which were primarily dated on marine bivalves often reveal recent ages for the surface and show a continuous sediment accumulation up to the present (Bauch et al., 2001 [a]; Bauch et al., 2001 [b]).

2.5.2 Holocene input of terrestrial organic carbon

For the paleoenvironmental interpretation it is necessary to consider that significant depositional changes occurred on the Laptev Sea shelf after the last glacial maximum (LGM). Because the sea level was lowered by more than 100 m during the LGM (Fairbanks, 1989), huge areas of the shallow Laptev Sea shelf were exposed. With the postglacial sea level rise, the shelf became flooded and the coastline, the river mouths, and their depocenters gradually retreated southward. According to the calibrated global sea level curve (Fig. 2-2c), the sea level stood lower at 12.7 ka BP by about 70 m than today and rose by about 60 m within the next 6 kyr.

Based on our $\delta^{13}C_{org}$ studies, the Holocene input of terrestrial organic matter onto the Laptev Sea shelf can be interpreted in three phases. An early phase, characterized by mainly terrestrial conditions, is marked in the western Laptev Sea between 12.7 and 11 ka BP (Fig. 2-2a). The generally low $\delta^{13}C_{org}$ values with a high amount of terrestrial plant debris embedded in laminated sediment sequences found in this phase reflect a dominantly riverine depositional character (Bauch et al., 1999).

The first appearance of marine bivalves at 11 ka together with a slight increase of $\delta^{13}C_{org}$ mark the onset of the second phase. In this transitional phase from 11 to 7 ka BP, the shallow Laptev Sea shelf became widely flooded, probably resulting in large-scale shelf and coastal erosion and, simultaneously, enhancing the rate of terrestrial organic matter released to the shelf. Large amounts of organic carbon accumulated as documented by high accumulation rates of TOC. The central shelf environment probably remained influenced by riverine input during this period. This is corroborated by low $\delta^{13}C_{org}$ values (Fig. 2-2a), indicating continuously terrestrial fraction of organic matter and by abundances of freshwater algae (Kunz-Pirrung, 1998), both indicating the proximity to the riverine source of these central sites before 8 ka BP. Palynological investigations in northern Siberia indicate a climatic change to warmer and moister conditions at 8 ka BP (Naidina, 1995; Melles et al. 1996). Thus, warmer and moisture conditions and an expected enhanced river discharge could have additionally increased the input of terrestrial organic material. As a result of the continuing transgression and the climate optimum in the Mid-Holocene, wave-based erosion and thermoabrasion of the coastal permafrost deposits were strong, making more terrestrial organic material available for distribution on the shelf. With the retreat of the coastline, the depocenters of the rivers moved further southward, reaching the central shelf between 9 and 7 ka BP. During this time when accumulation of organic carbon was on maximum, the estimated paleo-water depth, at the site of KD9502, was about 25 m (Fig. 2-2c), a depth where maximum sediment accumulation occurs today in the Laptev Sea (Kuptsov and Lisitsin, 1996). On the deeper outer shelf the maximum accumulation of organic matter is recorded between 10 and 9 ka BP (Stein and Fahl 2000), due to the more northern position of the river mouths at this time.

The obvious decline in accumulation rates of TOC and the shift towards heavier stable carbon isotope composition after 7 ka BP on the central shelf (Fig. 2-2a) marks the onset of the third phase, which is now characterized by a reduced depositional rate of terrestrial material. At 5 ka

BP the sea-level rise reached the Holocene maximum in the Laptev Sea and the modern environmental situation became established (Bauch et al., 2001 [b]).

2.6 SUMMARY

The depositional history of the Laptev Sea shelf during the Holocene is strongly coupled with the postglacial sea level rise and the variations in the depositional environment. The $\delta^{13}C_{org}$ analyses of surface sediments and three radiocarbon-dated sediment cores from the central and outer shelf are used as indicators for spatial and temporal changes in the deposition of terrestrial organic material onto the Laptev Sea shelf during the past 12.7 ka BP.

- The modern distribution pattern of $\delta^{13}C_{org}$ in the Laptev Sea surface sediments is strongly influenced by the riverine input of terrestrial organic matter. Compared to the western Laptev Sea the terrestrial influence on the depositional realm of the eastern shelf reaches further north due to the high fluviatile discharge and input of terrestrial POM by the Lena and Yana rivers.
- In a downcore record from the western Laptev Sea shelf, the low values of $\delta^{13}C_{org}$ indicate that the source of organic carbon remained mainly terrestrial until 11 ka BP.
- The first appearance of marine bivalves, low $\delta^{13}C_{org}$ values alongside with high accumulation of organic carbon characterize a second interval between 11 and 7 ka BP. This interval reflects the main transgressional phase of the Laptev Sea shelf.

The shift towards relatively low accumulation rates of TOC and a significant increase of $\delta^{13}C_{org}$ on the central shelf marks the onset of a transition towards decreasing deposition of terrestrial organic matter at 7 ka BP. After this time the sea level reached its Holocene maximum and, as a consequence, the main depocenters of the rivers moved their position southward, leading to the modern depositional environment.

Acknowledgements

We thank V. Rachold, P. Meyers, and R. Stein for their constructive reviews and comments, which helped to improve the manuscript. H. Cordt and M. Wollny are gratefully acknowledged for analytical assistance. This study was financially supported by the German Ministry of Education, and Research within the bilateral Russian-German research project " Laptev Sea System 2000".

3 SEASONAL AND INTERANNUAL VARIABILITY OF SIBERIAN RIVER DISCHARGE IN THE LAPTEV SEA INFERRED FROM STABLE ISOTOPES IN MODERN BIVALVES

3.1 ABSTRACT

Stable oxygen and carbon isotope profiles from modern bivalve shells were investigated in order to reconstruct short-term hydrographical changes in the river-shelf system of the Laptev Sea.

Oxygen isotopic profiles obtained from the aragonitic species *Astarte borealis* exhibit amplitude cycles interpreted as annual hydrographical cycles. These records reflect the strong contrast between summer and winter bottom water conditions in the Laptev Sea. The seasonal variations in $\delta^{18}O$ are mainly controlled by the riverine freshwater discharge during summer with a ratio of 0.5‰ per salinity unit. Corrected for a defined species-dependent fractionation offset of –0.37‰, time-dependent salinity records were reconstructed from these $\delta^{18}O$ profiles. They indicate a good correspondence to seasonal hydrographic changes and synoptical data.

Persistent trends towards more negative $\delta^{13}C$ values are observed in all specimens and appear to be related to metabolic changes of the bivalves during ontogeny. In contrast, short-term fluctuations are likely linked to seasonal variabilities of the river water outflow patterns and enhanced phytoplankton productivity during summer. This is corroborated by a clear watermass-related distinction of the various $\delta^{13}C$ records made on the basis of water depth and distance from the riverine source.

3.2 INTRODUCTION

An essential part of our climate system is the northward-flowing ocean heat of the North Atlantic and its interaction with arctic water masses (Aagaard & Carmack, 1985). The outflow of cold and low-salinity surface waters from the Arctic Ocean is regarded a climate-sensitive mechanism potentially capable of directly reducing the intensity of thermohaline circulation in the subpolar North Atlantic (Rahmstorf 1995; Broecker 1997). As seen in stable oxygen isotope profiles, the low salinity content of the uppermost arctic water mass, the halocline, gains a considerable riverine freshwater contribution from the large Siberian rivers (Bauch *et al.* 1995). The Laptev sea shelf is a shallow marginal sea with open access to the Arctic Ocean and is influenced by several Siberian rivers with high outflow volumes (Gordeev *et al.* 1996). Because this riverine freshwater is directly fed into the Arctic Ocean, investigating the seasonal and interannual variability and the dispersal of this river discharge is a central task in understanding modern and past Arctic Ocean environments (Bauch *et al.* 2000).

A number of studies have dealt with stable oxygen and carbon isotope profiles of recent and fossil bivalve shells to reconstruct environmental and physiological changes (Arthur *et al.* 1983; Jones *et al.* 1986; Krantz *et al.* 1987, 1988; Israelson *et al.* 1994; Bemis & Geary 1996; Khim *et al.* 2000). These studies focused on within-shell variation and its relation to seasonal water temperature cycles, water masses, habitat and shell growth characteristics. Because bivalves grow accretionarily, $\delta^{18}O$ and $\delta^{13}C$ profiles along their growth direction provide time series of hydrographical and environmental information during a bivalve's lifetime. Thus, obtaining oxygen and carbon isotope records from modern marine bivalve shells appears to be a particularly feasible method to trace and reconstruct temporal changes of hydrographical processes, such as found in the strongly coupled land-shelf system of the Laptev Sea.

3.2.1 General hydrography of the Laptev Sea

The hydrographical settings in the Laptev Sea are the result of interaction between an advection of arctic water masses from the north and the riverine freshwater discharge from the south, especially from the Lena River. In terms of discharge volume, the Lena River is the second largest among all arctic rivers with an annual discharge of 532 km^3 (Global Runoff Data Centre 1998). This runoff is subject to strong seasonal and interannual variations. The Lena River shows a fortyfold increase from very low winter values to the peak flows in June and July, whereas interannual discharge rates vary between 5 and 20 % (Aagaard & Carmack 1989).

Laptev Sea waters are formed due to extreme seasonal contrasts. The surface water generally starts freezing in October (Eicken *et al.* 1997). After river breakup in early summer, a large brackish surface plume is formed that extends northward onto the shelf (Dmitrenko *et al.*,1999; Pivovarov *et al.* 1999).

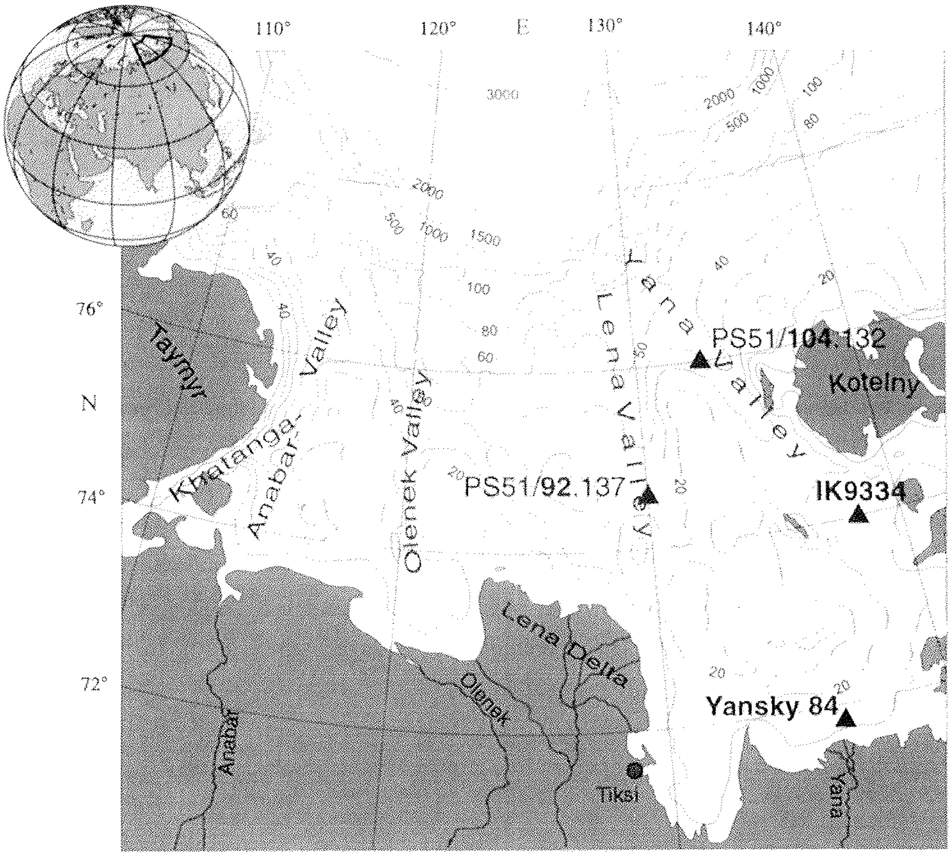


Fig. 3-1: Bathymetric map [m] of the Laptev Sea shelf showing the collection sites of the bivalves.

Table 3-1: Description of bivalve specimens and sites.

Sample ID /station	Collection date	Cruise **/Reference**	Water depth [m]	Salinity[4] Winter	Summer	Δ sal[5]	Temperature[4] [°C] Winter	Summer	Δ temp[5] [°K]
PS51/**104**.32	05.08.1998	PS51 / **A**	32 m	32.5	31.2	1.3	-1.6°C	-1.1°C	-0.5
PS51/**92**.137 [1]	03.08.1998	PS51 / **A**	32 m	32.5	31.6	0.9	-1.6°C	-1.3°C	-0.3
IK9334 [2]	19.08.1993	IK93 / **B**	22 m	28.4	26.5	1.9	-1.4°C	-0.9°C	-0.5
Yansky84 [3]	summer 1984	-	11 m	22.0	17.4	4.6[6]	-1.4°C	0.3°C	-1.76[6]

A) Kassens, H. & Dmitrenko, I., in press.

B) Kassens & Karpiy 1994

We acknowledge **1)** M. Schmidt (Institute for Polar Ecology, Kiel University), **2)** I. Richling and V. Wiese (Malacological Museum "Haus der Natur-Cismar"), and **3)** A. Gukov (Hydrometeorological Departement Tiksi/Yakutia) for providing the bivalves.

4) Temperature and salinity data of bottom water obtained from the "Russian Arctic Ocean atlas for winter and summer period" (1950-1990) of the Joint U.S.-Russian environmental working group (EWG, 1998)

5) Difference (Δ) between winter and summer data (w-s). If the temperature (Δ temp.) is negative, the water temperature is higher in summer than in winter. If the salinity (Δ sal.) is positive, the salinity is higher in winter than in summer.

6) Salinity and water temperature data were kindly provided by I. Dmitrenko and S. Kirillov (AARI, St. Petersburg, Russia)

The hydrography of our investigation sites (Fig. 3-1) is affected by strong seasonal variations due to the direct influence of riverine freshwater, mainly from the Lena River. While river discharge generally decreases over the course of the summer period, bottom salinity can slightly increases due to wind-driven penetration of more saline water into the middle shelf region from the north (Dmitrenko *et al.* 2001) as well as sea-ice formation processes beginning in October.

Long-term hydrographical data (1950-1990, EWG 1998) show for all investigated sites on average higher bottom water salinity in winter than in summer (Table 3-1). Average bottom water temperatures remain relatively constant, ranging between -1.1 and -1.6°C. Only at the near-coastal site there is a more variable temperature range throughout the year (0.3 to -1.4°C).

3.3 MATERIAL AND METHODS

3.3.1 Sampling techniques and isotopic analyses

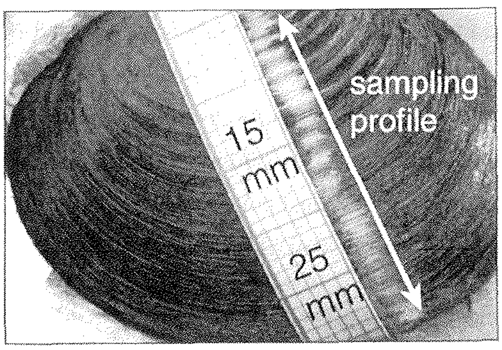
All water samples for stable oxygen isotope analysis were collected in summer 1994, during the TRANSDRIFT II cruise of RV "Prof. Multanovsky" (Kassens & Karpiy 1994). Usually, two samples were taken from each station; one from the surface water at 2 m water depth and one from below the pycnocline, which ranged in thickness from a few to more than 20 meters. Oxygen isotope measurements of the water samples were carried out at the Leibniz Laboratory in Kiel with a Finnigan-MAT Delta E mass spectrometer having a precision of 0.02‰. All results are reported relative to SMOW using the conventional $\delta^{18}O$ notation.

Bivalve species of *Astarte borealis* (Schumacher 1817) were collected alive from 32 to 11 m water depth during several expeditions to the Laptev Sea (Table 3-1; Fig. 3-1). While specimens 104 and 92 were gathered in summer 1998, specimens Yansky84 and IK9334 were collected in summer 1984 and 1993, respectively. Species of *Astarte borealis* were selected for isotopic analyses because of their widespread geographical distribution in the Laptev Sea, their relatively large shell size, and their tolerance to a wide salinity range (Gukov 1999). Their habitat in the Laptev Sea is characterized by polyhaline and poly-euhaline waters exhibiting salinities between 15 and 34 and water depths bewteen 15–50 m (Petryashov *et al.* 1999).

Using X-ray diffraction analysis (XRD), the carbonate shell of *Astarte borealis* was investigated for its mineralogic composition. It was found that the outer and inner shell layers consist of pure aragonite.

Because during bivalves' growth new material is continuously added to the ventral margin of the shell, samples were taken along a growth profile in order to obtain proper time series of shell carbonates deposited during the lifespan of the specimen (Fig. 3-2). Prior to taking carbonate samples, the exterior of each shell was thoroughly cleaned to remove any surface contamination. Individual carbonate powder samples (>15 μg) were sequentially millcut under a microscope from the outer shell layer along the axis of maximum growth. Spatial resolution of samples was approximately 0.15 to 0.3 mm. Sample positions along the profile are reported as distance from the umbo (0 mm) toward the ventral margin. To avoid possible contamination of the samples with material from subjacent shell layers, each sample was milled only from the surface of the outer layer. During sampling, the carbonate powder was vacuumed onto a fiberglass filter.

For isotope analysis, the carbonate powder on the filter was reacted with 100 % orthophosphoric acid under vacuum at 73°C in the KIEL carbonate device, which is coupled online to a Finnigan MAT 251 gas isotope mass spectrometer. Isotope values are reported as parts per mil (‰) in the usual δ-notation relative to the PDB standard (NBS20). The external error amounts to less than ±0.08‰ and ±0.05‰ for $\delta^{18}O$ and $\delta^{13}C$, respectively. Experiments were carried out on sample replicates. The average difference between replicates was 0.25±0.20‰ (n=55) on the $\delta^{18}O$-scale and 0.18±0.15‰ on the $\delta^{13}C$-scale.



Distance between adjoining samples: 0.2 - 0.35 mm

Fig. 3-2: *Astarte borealis,* specimen 104 showing the sampling profile from the umbo to the ventral margin.

3.4 RESULTS

3.4.1 Oxygen isotopes in Laptev Sea waters

A total of 65 water samples from water depths between 2 and 53 m having a salinity range from 4.7 near the Lena River mouth to 33.7 in the northern Laptev Sea were used for $\delta^{18}O$ analyses (Fig.3-3). The significant correlation between salinity and $\delta^{18}O_w$ (p-value 0.01; n=64; r=0.992) documents the mixing between freshwater, discharged by the rivers, and seawater. The resulting ratio of 0.50‰/salinity can be used in a two-component mixing model to identify possible end members. For zero salinity, a $\delta^{18}O_w$ value of –18.86‰ is obtained. Such a value for the freshwater end member is very similar to $\delta^{18}O_w$ values of -18.9‰ measured directly on water from the Lena River mouth (Létolle *et al.* 1993). Thus, the relationship between $\delta^{18}O_w$, salinity, and the freshwater end member value can be described with the following equation:

$$\delta^{18}O_w\ [‰\ SMOW] = salinity \bullet 0.50 - 18.86\ [‰\ SMOW] \qquad (1)$$

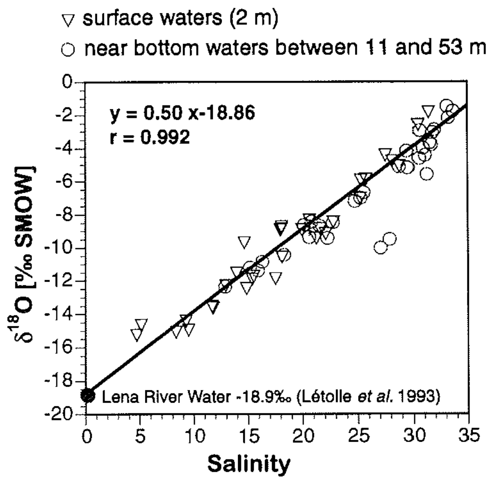


Fig. 3-3: $\delta^{18}O$ versus salinity data of the Laptev Sea water samples taken in August 1994. The relation of $\delta^{18}O_{water}$ and salinity is significant correlated (p-value 0.01; n=63) of r= 0.992 and can be expressed by a linear function: $\delta^{18}O$ [‰ SMOW] = sal•0.50-18.86 [‰ SMOW]

3.4.2 Stable isotopes in bivalve shells

Because the oxygen isotope composition of biogenic carbonate is controlled by the isotopic composition and temperature of the ambient water (Epstein *et al.* 1953, Grossman & Ku, 1986) the $\delta^{18}O$ results from the investigated bivalves shells should reflect the water mass conditions during their lifetime. All $\delta^{18}O$ profiles exhibit a cyclic nature (Figs. 3-4 – 3-7), which probably reflect annual cycles of hydrographical and, hence, environmental conditions. Since all specimens investigated were collected alive during August-September, the light values at the margin of the bivalve shell should represent the conditions of the final summer. Therefore, calendar years can be assigned directly by counting back the annual isotope cycles from the margin. For instance, in the $\delta^{18}O$ profile of specimen 104 there are 9 isotopic cycles recognized prior to the year of collection in 1998 (Fig. 3-4). Similarily, the oxygen isotope profile of specimen 92 represents hydrographical conditions from 1998 back to 1986 (Fig. 3-5).

The $\delta^{18}O$ profiles of specimens 104 and 92 show very similar characteristics (Table 3-2), suggesting the comparability of hydrographical conditions at these two sites. In specimen IK9334, a total of 10 cycles were identified as annual cycles, reflecting the hydrographical conditions between 1983 and 1993 (Fig. 3-6).

The characteristics of the $\delta^{18}O$ profile of specimen IK9334 are quite different from those of specimens 104 and 92. The mean $\delta^{18}O$ value of specimen IK9334 is about 2.20‰ lighter than the mean $\delta^{18}O$ values of specimens 104 and 92 (Table 3-2), which is in accordance with the shallower water depth and lower bottom water salinity at site IK9334.

Table 3-2: Characteristic $\delta^{18}O$ values of the bivalve isotope profiles; mean value, mean summer to winter amplitude, and the minimum and maximum of the summer and winter $\delta^{18}O$ values.

Specimen	Mean [‰]	mean ampl. [‰]	summer [‰] min / max		winter [‰] min /max	
PS51/**104**.32	1.47	1.17	0.25	1.62	1.92	2.52
PS51/**92**.137	1.31	1.23	-0.21	1.62	1.34	2.71
IK9334	-0.76	1.59	-3.51	-0.65	-0.58	1.29
Yansky84	-7.98	2.73	-10.97	-7.37	-7.80	-5.17

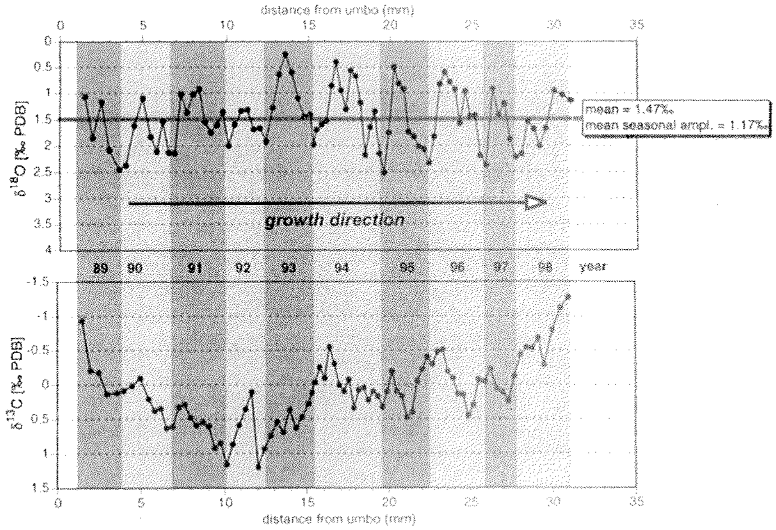


Fig. 3-4: Stable oxygen and carbon isotope profile of *Astarte borealis* (104), collected alive at 32 m water depth in summer 1998. The horizontal axis indicates the sampling profile in millimeters from the umbo to the ventral margin. The shaded subdivisions represent calendar years, calculated by counting back the annual isotope cycles from the ventral margin. The gray horizontal line indicates the mean $\delta^{18}O$ value of the profile.

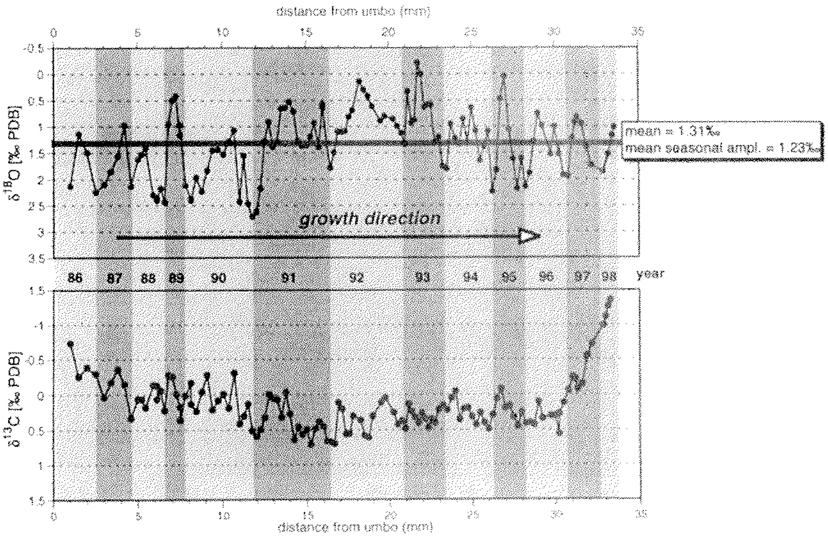


Fig. 3-5: Oxygen and carbon isotope profile of *Astarte borealis* (92) collected alive at 32 m water depth in summer 1998.

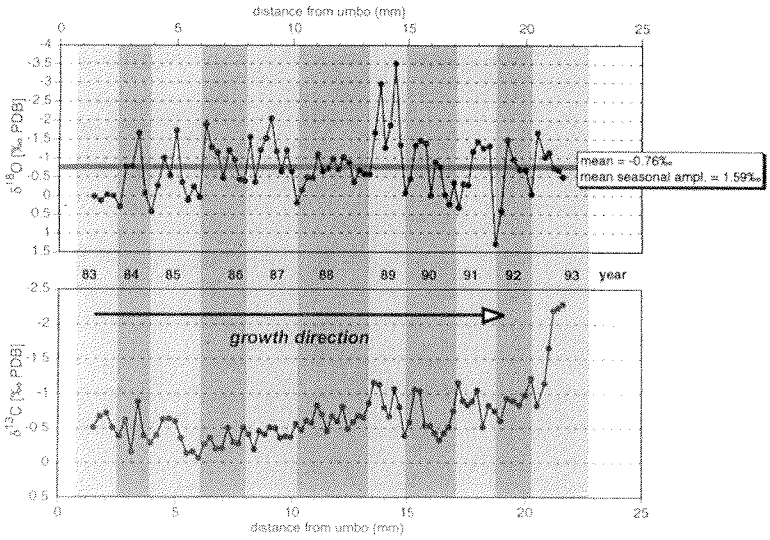


Fig. 3-6: Oxygen and carbon isotope profile of *Astarte borealis* (IK9334), collected alive at 22 m water depth in summer 1993.

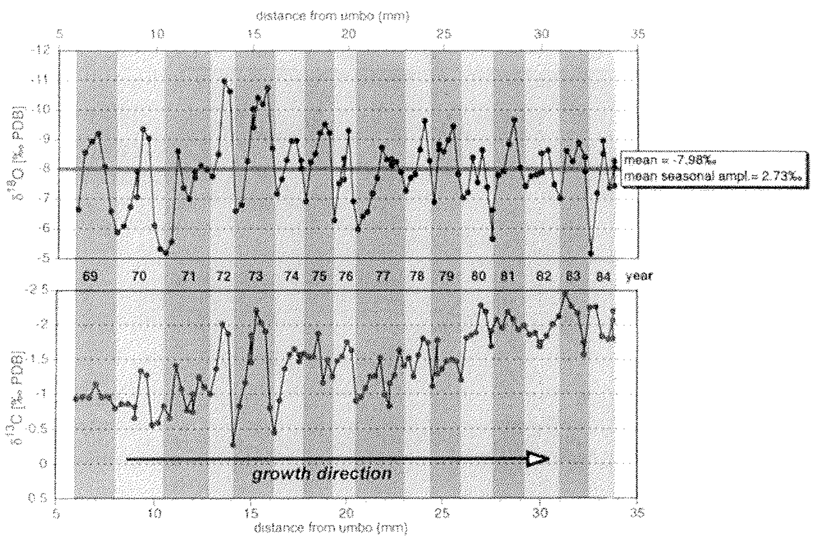


Fig. 3-7: Oxygen and carbon isotope profile of *Astarte borealis* (Yansky84), collected alive at 11 m water depth off the Yana Delta in summer 1984.

A total of 15 isotope cycles (from the year 1984 back to 1969) are recognizable in the $\delta^{18}O$ record from Yansky84 (Fig. 3-7). The profile from this site shows the most pronounced seasonal amplitudes of all investigated bivalves (Table 3-2). This is the result of a much stronger seasonal variation in both bottom salinity and temperature due to the proximity to the Yana Delta (Table 1).

Plotting all isotope data together unveils the watermass-dependent environmental differences between the various collection sites (Fig. 3-8). The $\delta^{18}O$ data of specimens collected from deeper water depth show isotopically heavier values than those from shallower water depth. The $\delta^{18}O$ difference between the mean $\delta^{18}O$ values of specimen 104 and 92 both from 32 m water depth and Yansky84 from 11 m water depth is more than 9‰, and reflects the different freshwater content of each site. For the carbon isotopes, a trend towards lighter $\delta^{13}C$ values with decreasing water depth and decreasing bottom water salinity is noticeable.

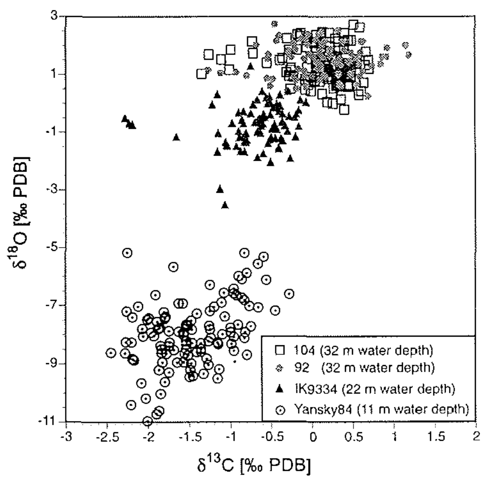


Fig. 3-8: Scatter-plot indicating all stable isotope measurements.

Although the $\delta^{13}C$ profiles of all specimens show no seasonal cyclicity, the $\delta^{13}C$ and the $\delta^{18}O$ data reveal concurrent decreases. Especially in the Yansky84 record (Fig. 3-7), this phenomenon is well pronounced showing most of the $\delta^{18}O$ peaks to coincide with corresponding decreases in $\delta^{13}C$. As with the $\delta^{18}O$, the short-term depletions in $\delta^{13}C$ values seem to be related to the riverine water, of which the $\delta^{13}C$ of the dissolved inorganic carbon (DIC) has values of about –5 to -6‰ PDB (Erlenkeuser 1995). This is in contrast to the general trend towards lighter $\delta^{13}C$ values observed in all $\delta^{13}C$ records with increasing distance from the umbo (Figs. 3-4 - 3-7).

3.5 DISCUSSION

As the hydrographic conditions in the Laptev Sea vary considerably during the year, an understanding of growth season and habitat of the bivalve species is important. *Astarte borealis* is an infaunal filter feeder with a siphon adapted for extracting food particles from the bottom water and water-sediment interface (Khim *et al.* 2001). In spite of a seasonal biomass production in the Laptev Sea (Tuschling 2000), the availability of food for bivalves is by no means seasonally restricted because of the permanent existence of a bottom nepheloid layer with high contents of particulate organic matter (Gukov 1999; Wegner *et al.* 2001). It can be therefore assumed that the analyzed shells were formed during all season.

In order to determine the species-dependent fractionation offset for *Astarte borealis* we calculated an expected $\delta^{18}O$ value for aragonite percipitated in equilibrium condition using actual bottom water temperature and $\delta^{18}O$ composition of the porewater at the time of the bivalve collection. The porewater $\delta^{18}O$ signature of the upper 5 cm in the sediment was used because of the infaunal habitat of *Astarte borealis*. A fractionation offset was calculated by subtracting the expected $\delta^{18}O$ value from the measured isotopic values at the ventral margin, i.e., from the youngest part of the shell formed before collection (Table 3-3). The results indicate that the oxygen isotopes of shell carbonate of *Astarte borealis* reveal an average fractionation offset of about –0.37‰.

Table 3-3: Fractionation offset calculation by subtracting the $\delta^{18}O_{ar}$ expected from the measured $\delta^{18}O_{ar}$. $\delta^{18}O_{ar}$ (expected) is calculated for two bivalve shells of *Astarte borealis* using equation 2, where $\delta^{18}O_{water}$ and T were replaced by the porewater $\delta^{18}O$ and the bottom water temperature (Bude unpublished data), at the date of collection. The $\delta^{18}O_{ar}$ (measured) is the $\delta^{18}O$ value at the ventral margin, which represents the youngest part of the shell, formed just before collection

Station/ specimen	T seafloor [°C]	$\delta^{18}O$ (porewater) [‰ SMOW]	$\delta^{18}O_{ar}$ (measured) [‰ PDB]	$\delta^{18}O_{ar}$ (expected) [‰ PDB]	Offset [‰ PDB]
104	-1.23	-3.25	1.14	1.46	**-0.32**
92	-1.24	-3.26	1.02	1.45	**-0.43**

3.5.1 Salinity reconstruction

To reconstruct the hydrographical environment of the Laptev Sea from oxygen isotope profiles of bivalve shells we used the following equation of Grossman & Ku (1986) for aragonitic mollusks:

$$T\ [°C] = 21.8 - 4.69\cdot(\delta^{18}O_{aragonite}\ [PDB]) - \delta^{18}O_{water}[SMOW]) \quad (2)$$

Because the seasonal bottom water temperature variation of 0.3 to 0.5°K would affect the oxygen isotopes in aragonite only by 0.07 to 0.10‰, the within-shell variations in the oxygen isotopic profiles of *Astarte borealis* in the Laptev Sea are primarily controlled by variations in $\delta^{18}O_{water}$, that is salinity. Therefore, more negative $\delta^{18}O$ values in the shell profiles reflect the less saline bottom waters during summer, and more positive values indicate increased salinity during winter.

After correcting for the species-dependent fractionation offset, a time-dependent salinity record was calculated from the oxygen isotope profile of each specimen (Fig. 3-9). The reconstructed annual and interannual variations of bottom water salinity of specimens 92 and 104 show a consistent trend and document the affinities of the hydrographical conditions at these two sites. Mean winter and summer salinity data (1950-1990) for the investigated stations as well as individual bottom water salinity measurements, carried out during several expeditions in the 90's, corroborate a good precision of our reconstruction (Fig. 3-9). Similar to the bivalve isotope profiles from sites 92 and 104, the $\delta^{18}O$ record of specimen IK9334 is in good accordance with mean annual salinity variations (EWG, 1998).

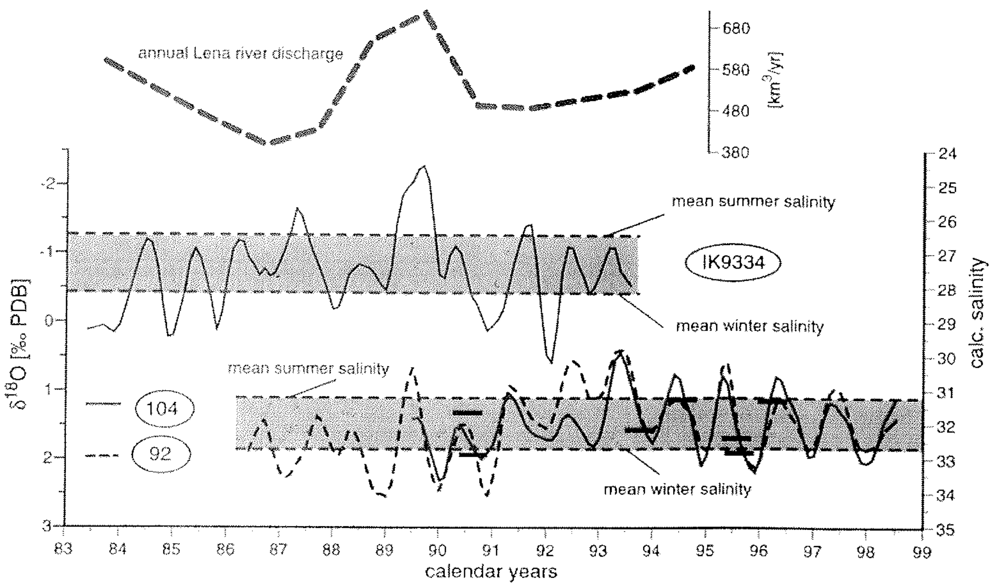


Fig. 3-9: Smoothed (2 point) $\delta^{18}O$ and reconstructed salinity records of specimens 104, 92, and IK9334 between 1983 and 1998. Mean summer and winter salinities (dashed horizontal lines) for each site were obtained from the "Joint U.S.-Russian Arctic Ocean atlas for winter and summer period (1950-1990)" (EWG, 1998); individual salinity measurements carried out on several expeditions are marked with a black dash; the data having been kindly provided by I. Dmitrenko and S. Kirillov (Arctic and Antarctic Research Institute, St. Petersburg, Russia). Annual Lena River discharge data obtained from the Global Runoff Data Centre (1998).

Although the $\delta^{18}O$ record of IK9334 is, in general, isotopically lighter than those of sites 92 and 104 due to lower bottom water salinity, there are some notable similarities. For instance, the pronounced peak in 1989 is evident in the salinity records of specimens 92 and IK9334, and seems to correlate with a prominent freshwater discharge event from the Lena River recorded in the year 1989 (Fig. 3-9). This event in the year 1989 was an absolute maximum in annual Lena River discharge (record from 1935-1995) and the result of anomalously high summertime precipitation in the drainage area of the Lena River (Semiletov *et al.* 2000).

An interpretation of the bottom water salinity record from specimen Yansky84 seems more complicated (Fig. 3-10). Here, in the proximity of the Yana Delta, besides salinity also water temperature shows significant seasonal variations (Table 3-1). While a seasonal temperature variation of 1.7°K at this site affects the shell $\delta^{18}O$ variations by 0.35‰, the mean seasonal salinity change of 4.6 leads to a change of 2.3‰ in the $\delta^{18}O$ of the shell. The resulting expected seasonal $\delta^{18}O$ amplitude totals 2.65‰, a value which is very similar to the observed mean seasonal $\delta^{18}O$ amplitude of 2.73‰ (Table 3-2). Therefore, it can be concluded that the $\delta^{18}O$ variations of Yansky84 are also primarily controlled by salinity whereas the effect of water temperature changes remains small.

Although the mean seasonal $\delta^{18}O$ amplitude is comparable to the expected amplitude, there remains a total offset of more than -3‰ between the mean $\delta^{18}O$ values in the record of Yansky84 and the expected values as calculated from the hydrographical data (Fig. 3-10). This large offset may be the result of inaccuracies in the $\delta^{18}O_w$/salinity relation for this site in front of the Yana Delta. Our $\delta^{18}O_w$ to salinity ratio was calculated on the basis of water samples from the Laptev Sea shelf and fits well with the freshwater end member $\delta^{18}O_w$ signal of the Lena River water. Because of the higher continentality of the drainage area of the Yana River, an isotopically lighter $\delta^{18}O_w$ freshwater signal is expected (Dansgaard 1964; Létolle *et al.* 1993) and therefore a different $\delta^{18}O_w$/salinity ratio.

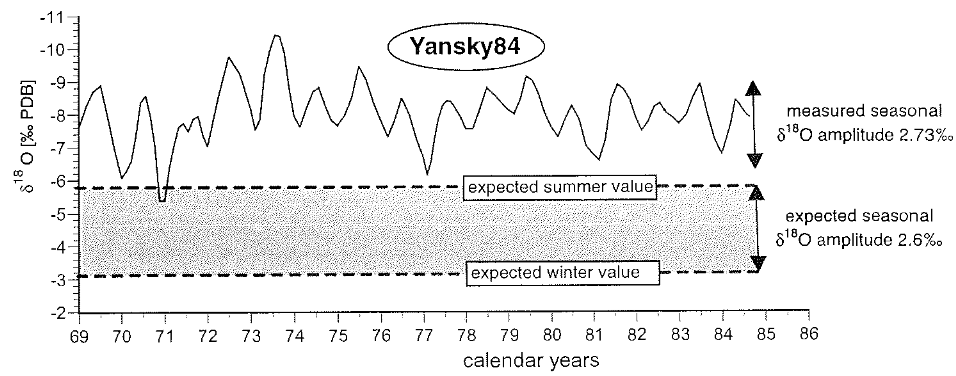


Fig. 3-10: Smoothed (2 point) $\delta^{18}O$ record of Yansky84 between 1969 and 1984. The expected summer and winter $\delta^{18}O$ values (dashed horizontal lines) were calculated using mean summer and winter temperature and salinity data (kindly provided by I. Dmitrenko and S. Kirillov).

Since all investigated $\delta^{18}O$ profiles reveal similar trends, a qualitative reflection of the seasonal influence on the bivalves' oxygen isotope profiles in the Laptev Sea is reconstructed in Figure 3-11. The decreasing salinity and corresponding light $\delta^{18}O$ values in the oxygen isotope profile are the result of the large amount of riverine freshwater output during summer. This trend towards lighter $\delta^{18}O$ values can be weakened by the episodical advection of more saline water and thus isotopically heavier water from the Arctic Ocean as a result of upwelling currents in the near-bottom layer below the pycnocline from the north. During the ice-free season strong southerly winds can cause a deformation of the sea level and result in reversal, southerly currents in the near-bottom water layer (Dmitrenko *et al.* 2001). During winter, an enhanced influence of water from the Arctic Ocean due to low riverine outflow may result in slightly heavier $\delta^{18}O$ values. However, the exact timing and magnitude of these events will vary from year to year depending on the volume of riverine discharge and the specific meteorological conditions in the Laptev Sea during summer. Although major seasonal events, like the freshwater input in summer, are identifiable in all our records, it is not possible to resolve a more accurate time scale because of the uncertainty in the seasonal growth rate of the bivalves.

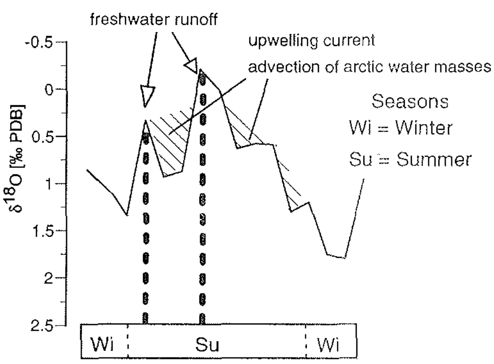


Fig. 3-11: Schematic presentation of the influence of hydrographic processes on the $\delta^{18}O$ profiles of a bivalve shell in the eastern Laptev Sea. Data are from isotope profiles of specimen 92 from 20.25 to 23.75 mm (distance from umbo).

3.5.2 Stable carbon isotopes

In contrast to the oxygen isotope composition, the reasons for the differences and variations in the $\delta^{13}C$ records of the bivalve shells are less certain because the shell $\delta^{13}C$ responds to the interaction of both, physical and biological processes (McConnaughey 1989; Hong et al. 1995; Hikson *et al.* 1999). The fact that all our $\delta^{13}C$ shell profiles show no clear cyclicity but an overall decreasing trend away from the umbo may be best explained with ontogenetic effects (Wefer 1985; Wefer & Berger 1991). It is reported that during the onset of sexual maturity and reproduction a bivalve uses primarily metabolic energy, which is then manifested in light shell $\delta^{13}C$ (Erlenkeuser & Wefer 1981; Krantz *et al.* 1987; Klein *et al.* 1996). As all our specimens show similar trends during their lifetime other possible environmental factors, e.g., changes of bottom water ventilation (*cf.* Brey & Mackensen 1997) can be disregarded for the Laptev Sea.

The inherently low $\delta^{13}C$ values of -5 to -6‰ PDB (DIC) inferred for riverine water in the Laptev Sea region (Erlenkeuser 1995) implicate that the marked depletion noted in the $\delta^{13}C$ record of the bivalves is also associated with river-induced salinity changes. This assumption is corroborated by coeval changes noted in the $\delta^{18}O$ records.

Remineralization of ^{13}C-depleted riverine organic matter and oxidation of phytoplankton organic matter (Arthur *et al.* 1983; Krantz *et al.* 1997, 1988) are other processes that add to the observed decreases in bottom water DIC $\delta^{13}C$ at our sites (Erlenkeuser 1995). Since most negative shell $\delta^{13}C$ values are found in specimen Yansky84 (Fig. 3-8), which was found near the river mouth, these values reflect the combined effect of riverine DIC and organic remineralization. In such an environment, increased biological productivity and enhanced deposition of fresh organic matter is expected (Erlenkeuser 1995).

3.6 SUMMARY

Detailed oxygen and carbon isotope time series taken along the growth direction of modern bivalve shells of *Astarte borealis* were used to reconstruct water mass conditions in the shallow river-shelf system of the Laptev Sea.

All $\delta^{18}O$ records exhibit a pronounced cyclicity induced by seasonal changes in riverine freshwater discharge. Because the $\delta^{18}O$ composition of the aragonitic shells is predominantly controlled by the $\delta^{18}O$ composition of the ambient water, for which a high correlation with salinity is shown, the variability in the $\delta^{18}O$ records of the shells are interpreted as annual hydrological cycles with heavier $\delta^{18}O$ values indicating winter and lighter values indicating summer conditions. Compared to salinity, the influence of temperature on the $\delta^{18}O$ of the bivalve shells is an order of magnitude smaller. Thus, a clear distinction of the hydrological conditions at each collection site could be made on the basis of both seasonal $\delta^{18}O$ amplitudes and mean $\delta^{18}O$ values.

The bivalve shells were also investigated to determine whether their carbonate is precipitated in isotopic equilibrium. A mean fractionation offset of -0.37‰ in $\delta^{18}O$ was found for *Astarte borealis*. Corrected for this species-dependent fractionation offset, salinity records were calculated from shell data. The resulting salinity records correspond well with seasonal hydrographical conditions and synoptical water measurements, implying that $\delta^{18}O$ profiles from the shells of *Astarte borealis* are a reliable tool to reconstruct past salinity changes in the bottom waters of the Laptev Sea.

Short-term fluctuations in the $\delta^{13}C$ profiles of the bivalve shells show coeval trends with $\delta^{18}O$ and therefore seem to be associated with riverine freshwater discharge and increased phytoplankton productivity during summer. In contrast, differences in the $\delta^{13}C$ of the shell carbonate between the various sites appear to be controlled by the admixture of riverine DIC, while an overall decreasing trend observed in all $\delta^{13}C$ profiles is more likely related to the ontogeny of the bivalves.

4 PALEOHYDROGRAPHY OF THE LAPTEV SEA (SIBERIAN ARCTIC) AS RECORDED IN STABLE ISOTOPE PROFILES OF BIVALVE SHELLS

4.1 ABSTRACT

Oxygen isotope profiles along the growth axis of modern and fossil bivalve shells of *Macoma calcarea* were established to reconstruct hydrological changes in the eastern Laptev Sea since 8.4 ka BP. The variability of the oxygen isotopes in the individual records is mainly attributed to variations in the isotopic composition ($\delta^{18}O_w$) and in the salinity of bottom waters in the Laptev Sea. Seasonal temperature changes can be regarded of minor importance. Using a modern linear relationship between salinity and $\delta^{18}O_w$ of 0.50 ‰/salinity, seasonal salinity changes are reconstructed and directly compared with hydrographical parameters at the investigated site.

Given the good conformance between isotope profiles from recent bivalve shells and modern oceanographic observations, oxygen isotope profiles of radiocarbon-dated bivalve shells from a sediment core from northeast off the Lena Delta give insight into past hydrological conditions. The changes in the data not only provide subdecadal records of seasonal variations, they also provide evidence of the Holocene transgression. If, as is assumed, the relationship between $\delta^{18}O_w$ and salinity was constant throughout the time, the results would suggest that at 8.4 ka BP bottom water salinity at the investigated site was reduced by ~3. Reconstruction of the inundation of the Laptev Sea shelf indicated a sea level ~ 27 m below present at this time and a proximity of the site to the coastline and thus to the paleoriver mouth of the Lena River. Due to a rising sea level and a further southward retreat of the river mouth, bottom water salinity increased at 7.2 ka BP showing a high seasonal variation. Conditions comparable to the modern hydrography were at last found at 3.6 ka BP.

4.2 INTRODUCTION

The Arctic Ocean and its hydrographic structure plays an important role in influencing the global thermohaline circulation through the export of freshwater and sea-ice to the Nordic Seas (Aagaard and Carmack, 1989). Changes in the export rates of Arctic freshwater and sea ice could result in a perturbation of the thermohaline circulation (Aagaard and Carmack, 1994; Broecker, 1997) thereby effecting the heat transport towards northern latitudes.

The low-salinity layer of the Arctic Ocean is mainly fed by riverine freshwater from Siberia and within this system the Laptev Sea is recognized as one of the key sources for the Arctic halocline´s freshwater budget. The shallow Laptev Sea is influenced by large quantities of freshwater supplied during summer by several rivers, especially by the Lena River. In terms of freshwater discharge the Lena River is the second largest among Arctic rivers with a mean annual discharge of 532 km^3 per year (Global Runoff Data Center, 1998). This freshwater runoff is subject to strong seasonal and annual variations and causes strong stratification in the shallow Laptev Sea (Dmitrenko et al., 1999).

Given the variability of seasonal, annual, and in particular longer timescales, the dispersal and fate of the river discharge and its influence on the hydrographical settings are a central task in understanding changes in the Laptev Sea system. The major objective in this study is to use stable oxygen isotopes from living and fossil carbonates to reconstruct past hydrological changes. The oxygen isotopic composition of marine carbonates is controlled by the isotopic composition of the water from which the carbonates precipitated and the temperature of the surrounding water (Epstein et al., 1953; Grossman and Ku, 1986). By establishing $\delta^{18}O$ profiles along the axis of maximum growth of bivalve shells it is possible to obtain substantial hydrographical information of the bivalves' habitat (Jones et al., 1986; Krantz et al., 1988; Israelson et al., 1994; Bemis and Geary, 1996; Andreasson and Schmitz, 1998; Khim et al., 2001). Using oxygen isotope profiles from modern and fossil bivalves in a sediment core northeast off the Lena Delta, which is the largest source of freshwater, this study investigates changes in the bottom water hydrography during snapshot views of the last 8.4 ka and how these temporal variations are related to the Holocene transgression.

4.3 MATERIAL AND METHODS

4.3.1 Bivalves

Modern and fossil bivalve specimens of *Macoma calcarea* were collected from site PS51/92 northeast off the Lena Delta (Fig. 4-1). While the modern shell was collected alive from the near surface, fossil shells were well preserved with no obvious signs of reworking. The fossil bivalves were either found in situ with both valves in place, or the periostracum was still preserved, implying no significant lateral transport. *Macoma calcarea* shows a Panarctic distribution and is found widespread in the Laptev Sea between water depths of 10 to 300 m (Gukov, 1999; Richling, 2000).

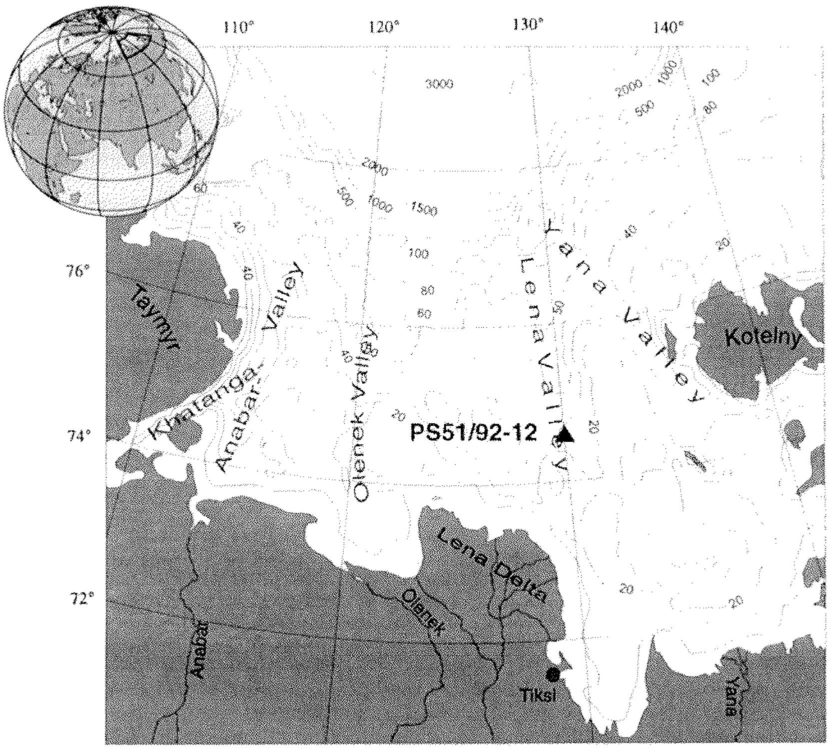


Fig. 4-1: Bathymetric chart [m] of the Laptev Sea shelf and location of the studied site.

A serial sampling technique similar to that used in other studies (Erlenkeuser and Wefer, 1981; Krantz et al., 1988; Krantz et al., 1987; Bemis and Geary, 1996; Andreasson and Schmitz, 1998) was applied to derive high-resolution isotope records from the shells. Prior to taking carbonate samples, the exterior of each shell was cleaned to remove any surface contamination. Individual carbonate powder samples (>15 μg) were millcut under the microscope sequentially from the outer layer along the axis of maximum growth with a spatial resolution of approximately 0.15 to 0.3 mm. Sample positions are reported as distance from the umbo to the ventral margin along the sampling profile. To avoid a contamination of the sample with material from subjacent shell layers, the sample was milled only from the surface of the outer layer. During sampling, the carbonate powder was vacuumed on a little fiberglass filter.

For isotope analysis, the carbonate powder on the filter was reacted with 100 % orthophosphoric acid under vacuum at 73°C in the KIEL carbonate device, which is coupled online to a Finnigan MAT 251 gas isotope mass spectrometer. Isotope values are reported as parts per mil (‰) in the usual δ-notation relative to the PDB standard (NBS 20). The external error amounts to less than ±0.08‰. Experiments carried out on sample replicates showed that the average (n=38) difference between replicates was 0.17‰ on the $\delta^{18}O$-scale.

4.3.2 Sediment core

The chronology of core PS51/92-12 is based on radiocarbon dates measured on bivalve shells using the accelerator mass spectrometer at the Leibniz Laboratory in Kiel (Table 4-1).

Assuming linear sedimentation rates between the age tiepoints, an age model was constructed by interpolating in between the age tiepoints (Fig. 4-2). The conversion of the given ^{14}C year into calendar years (yrs. BP) was carried out using the intercept method of the marine data set (Stuiver et al., 1998) from the program CALIB rev. 4.3 (Stuiver and Reimer, 2000). A reservoir effect for the Laptev Sea shelf of 370±49 yr was taken into account (Bauch et al., 2001 [a]). A total of 7 bivalves were used for the AMS-datings, which belong to the species of *Macoma calcarea*, *Leionucula bellotii*, and *Macoma moesta*. The radiocarbon-dated bivalves of *Macoma calcarea* from 210, 300, and 500 cm core depth were used for the oxygen isotope profile analysis (Fig. 4-2). The age of the specimen at 120 cm core depth was calculated from the age model.

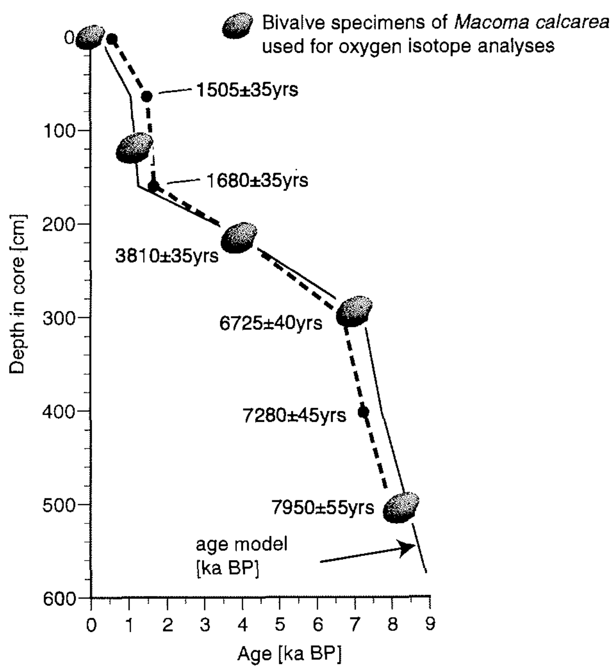


Fig. 4-2: Chronology and age model of core PS51/92-12. The bivalve symbol indicates the bivalves of *Macoma calcarea,* which were used for the oxygen isotope analyses.

Table 4-1: Bivalve species, radiocarbon dates, calibrated calendar years used for the chronology, and age model of core PS51/92-12 from the Laptev Sea shelf.

Depth [cm]	Lab#	Bivalve species	Age [^{14}C years]	Age [cal. yr BP]	Age range 1 Sigma [cal. yr BP]
0		*Macoma calcarea*	**collected alive**	**0**	-
2	KIA-6877	*Leionucula bellotii*	590±25	273	301-246
64	KIA-6878	*Leionucula bellotii*	1505±35	1078	1164-1009
120		***Macoma calcarea***	**no AMS-dating**	**1188***	-
160	KIA-6879	*Macoma moesta*	1680±35	1267	1302-1223
210	**KIA-12931**	***Macoma calcarea***	**3810±35**	**3809**	**3866-3695**
300	**KIA-6880**	***Macoma calcarea***	**6725±40**	**7270**	**7333-7230**
402	KIA-6881	*Leionucula bellotii*	7280±45	7754	7830-7681
500	**KIA-6882**	***Macoma calcarea***	**7950±55**	**8408**	**8515-8361**

^{14}C years were converted (intercept method) into calendar years using the marine data set of Stuiver et al. (1998) in the program CALIB rev.4.3 (Stuiver and Reimer, 2000). A local reservoir age of 370±49 years was used (Bauch et al., 2001 [a]). The bold marked specimens were used for the oxygen isotope analyses.

* age calculated according to the age model

4.4 RESULTS

4.4.1 Application of oxygen isotope profiles from bivalve shells in the Laptev Sea

The oxygen isotopic composition ($\delta^{18}O$) of bivalve shell carbonate is controlled by the temperature and the isotopic composition of the water at the time of precipitation (Epstein et al., 1953). Accurate reconstruction of environmental conditions from the $\delta^{18}O$ records of fossil bivalves requires measuring or constraining as closely as possible the analogous modern setting of several parameters. These include the seasonal range of temperature and salinity, and the relationship between salinity and $\delta^{18}O$ of the water (Khim et al., 2001).

Further shell mineralogy is important because calcite and aragonite have slightly different fractionation factors as a function of temperature (Horibe and Oba, 1972; Grossman and Ku, 1986). Since XRD-analyses of shells of *Macoma calcarea* reveal that they consist of aragonite we can use the paleotemperature equation of Grossman and Ku (1986).

$T\ [°C] = 21.8 - 4.69*(\delta^{18}O_{aragonite} - \delta^{18}O_{water})$

$\delta^{18}O_w$ measurements (Erlenkeuser, 1999) in surface and bottom water samples from the Laptev Sea document a linear relation (r^2=0.93) with salinity, from which a $\delta^{18}O_w$ to salinity ratio of 0.50‰/salinity was calculated. This relationship implies a freshwater $\delta^{18}O$ end member of −18.86‰ [SMOW], which is consistent with measured $\delta^{18}O_w$ values of 18.9‰ (Létolle et al., 1993) for the Lena River water, the primary freshwater source in the Laptev Sea.

Temperature data obtained from the "Joint U.S. Russian Arctic Ocean atlas for winter and summer period (1950-1990)" (EWG, 1998) reveal that for the investigated station 92 the bottom water temperature remains relatively constant throughout the year at −1.2 to −1.5°C with a summer to winter variation of 0.36°K. The relative effect of this summer to winter variation on the shell $\delta^{18}O$ is only -0.08‰ and thus exerts a negligible influence on the shell isotope variations. Transferring the mean annual winter to summer salinity variations to the $\delta^{18}O_{aragonite}$ signal would effect an isotope variation of 0.45‰. Therefore the main forcing factor of the within-shell isotope variations is the isotopic composition of the water and according to the $\delta^{18}O_w$ to salinity relationship the variations in the bottom water salinity.

Although most studies that deal with the dependency of carbonate $\delta^{18}O$ on temperature, salinity, and $\delta^{18}O_w$ have shown that both calcitic and aragonitic mollusks deposit shell carbonate in oxygen isotopic equilibrium (Wefer and Berger, 1991), it still seems to be necessary for an accurate interpretation of the oxygen isotope profiles in our bivalves to quantify the vital offset of the species (Table 4-2).

We compared the measured $\delta^{18}O_{aragonite}$ at the ventral margin, which represents the youngest part of the bivalve with an expected $\delta^{18}O_{aragonite}$ value. For the calculation of the expected $\delta^{18}O_{aragonite}$ we used the actual bottom water temperature (S.O. Bude, unpublished data) at the collection date and the actual $\delta^{18}O$ signature of the surrounding porewater. The porewater $\delta^{18}O$ (H. Erlenkeuser, unpublished data) in 2.5 cm core depth was used because of the infaunal habitat of *Macoma calcarea*. An offset of 0.01‰ reveals that *Macoma calcarea* appears to calcify near the equilibrium (Table 4-2). For the hydrographic reconstruction from fossil bivalves we assume that the vital offset for the modern specimen of *Macoma calcarea* is equivalent to the vital offset of the fossil specimens.

Table 4-2: Offset calculation by subtracting the $\delta^{18}O_{ar}$ measured from $\delta^{18}O_{ar}$ expected. The $^{18}O_{ar}$ expected is calculated solving the equation of Grossman and Ku (1986) to $\delta^{18}O_{aragonite}$, where temperature is replaced by the actual bottom water temperature and $\delta^{18}O_{w}$ by the $\delta^{18}O$ of the porewater.

Station	T bottom water [°C]	$\delta^{18}O$ porewater [‰ SMOW]	$\delta^{18}O$ expected [‰ PDB]	$\delta^{18}O$ measured [‰ PDB]	Offset [‰ PDB]
92	-1.24[1)]	-3.26[2)]	1.45	1.46	0.01

1) S.O. Bude, unpublished data.

2) H. Erlenkeuser, unpublished data.

4.4.2 Bivalve oxygen isotope profiles

Oxygen isotope profiles of modern bivalve specimens from the Laptev Sea exhibit amplitude changes that can be addressed to annual cycles with more negative (isotopically lighter) values indicating summer and more positive (heavier) values indicating winter season (CHAPTER 3). In the modern bivalve from site 92, 2.5 seasonal cycles were identified with mean summer to winter variations of 1.3‰ (Fig. 4-3, Table 4-3). The light $\delta^{18}O$ values at 18 mm, which is equivalent to the ventral margin, represents the collection date in August 1998. Employing the equation of Grossman and Ku (1986) together with an in situ bottom water temperature of −1.24°C and a $\delta^{18}O_{w}$ to salinity relationship of 0.50‰/salinity, we calculated a salinity record from the oxygen isotope values of this bivalve (Fig. 4-3). The variability in the calculated salinity record is remarkably consistent when compared with the mean summer to winter salinity range obtained from the Joint U.S. Russian Arctic Ocean atlas for winter and summer period (1950-1990) (EWG, 1998) (Fig. 4-3).

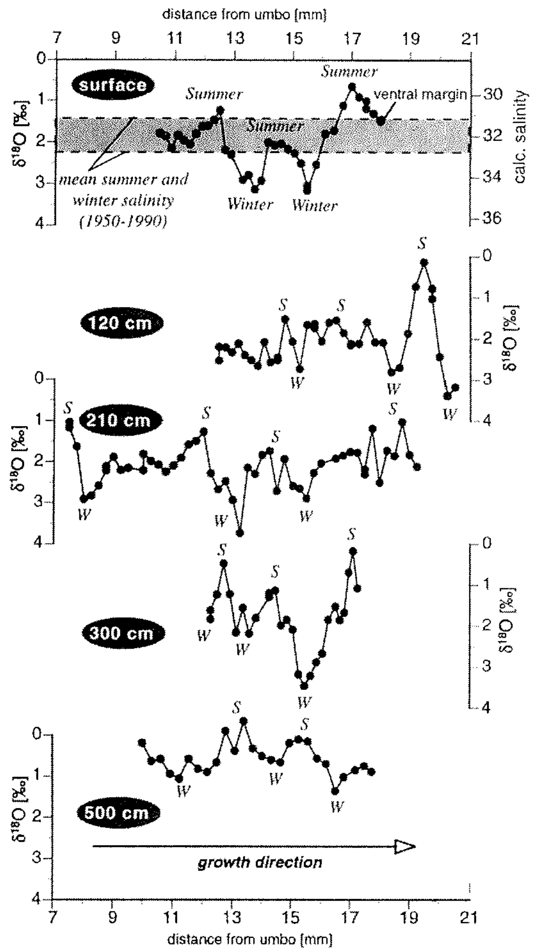


Fig. 4-3: Oxygen isotope shell profiles of modern and fossil bivalve shells collected from site PS51/92 from a water depth of 32 m. The sample positions [mm] are measured as distance from the umbo toward the ventral margin along the axis of maximum growth. The profiles are plotted with the y-axis reversed so that the more negative $\delta^{18}O$ values visually represent the summer (S).

Table 4-3: Core depth, age, mean $\delta^{18}O$, and mean seasonal variations of the investigated bivalves.

Core depth [cm]	Age [cal. ka BP]	Mean $\delta^{18}O$ [‰]	Mean seasonal $\delta^{18}O$ variation [‰]
0	0	1.97	1.3
120	1.6	2.06	1.3
210	3.6	2.08	1.0
300	7.3	1.78	1.6
500	8.4	0.58	0.7

The oxygen isotope record of the specimen collected from 120 cm core depth with a mean $\delta^{18}O$ value of 2.06‰ (Table 4-3) shows two seasonal cycle; one with a very prominent winter to summer variation of ~3 ‰ and a second, less pronounced cycles with an amplitude of ~1.2‰ (Fig. 4-3). In the shell profile from 210 cm core depth 2.5 annual cycles are discernible from the $\delta^{18}O$ profile with a mean of 2.08‰. The $\delta^{18}O$ profile of a *Macoma calcarea* from 300 cm sediment depth with a mean $\delta^{18}O$ of 1.78‰ shows also 2.5 seasonal cycles but reveals a higher seasonal amplitude of 2 to 3.5‰. The oxygen isotope profile of the lowermost bivalve shows reduced seasonal variations and its mean $\delta^{18}O$ value of 0.58‰ is significantly depleted compared to the records of the bivalves in the upper section of the core (Fig. 4-3, Table 4-3).

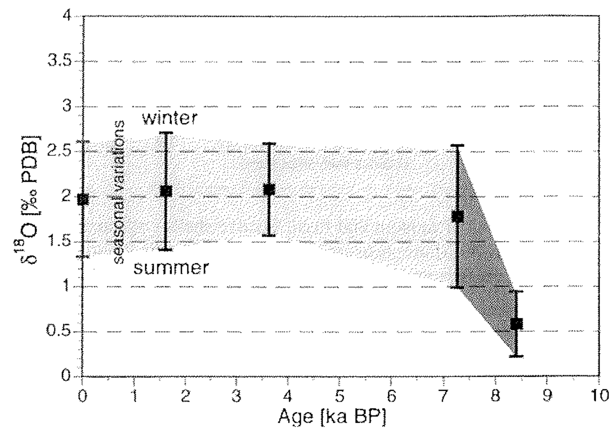


Fig. 4-4: Mean $\delta^{18}O$ in the shell profiles and their seasonal variations.

A comparison of all $\delta^{18}O$ shell profiles as snapshot views of the Holocene hydrographical history at site 92 is shown in Figure 4-4. It is obviously seen that the average $\delta^{18}O$ value of the shell profiles at 3.6 ka BP, 1.6 ka BP, and of the modern bivalve are rather similar. In comparison the average $\delta^{18}O$ value of the shell profile at 7.3 ka BP is slightly depleted. Furthermore a distinctive increase of the seasonal amplitudes in the $\delta^{18}O$ profile is observed in this bivalve implying more pronounced hydrographical variations between the summer and the winter regime at this time. In contrast to all younger bivalves the isotope shell profile at 8.4 ka BP reveals a mean value of 0.58‰ and a weak seasonal variation of 0.36‰ (Table 4-3). When comparing the mean $\delta^{18}O$ value of the modern and of the oldest bivalves, a depletion of −1.35‰ is discernible (Fig. 4-4). Because of the uncertainty whether this depletion of −1.35‰ is induced by changes in bottom water temperature and/or salinity, we present a model in which we calculated possible salinity and temperature combinations to obtain the mean $\delta^{18}O$ value of the investigated bivalve shell profiles (Fig. 4-5).

4.5 PALEOHYGRAPHICAL IMPLICATION

Our temperature and salinity model (Fig. 4-5) suggests two extreme possibilities to interpret the observed isotopic shift of −1.35‰, either a warmed bottom water by 6.3°K at 8.4 ka BP or a salinity reduction of 2.8. Both interpretations require that either of the two factors, temperature or salinity, would remain constant. Although this time marks the onset of the Holocene climate Optimum in the Laptev Sea region (Laing et al., 1999; Pisaric et al., 2001) it is hard to accept a bottom water temperature increase by more than 6°K without a change in salinity. Water temperatures of ~5°C are found today only in surface waters near the Lena River mouth during summer, where salinity remains < 6 (Dmitrenko et al., 1995; Dmitrenko et al., 1999). Therefore we favor the latter possibility of reduced bottom water salinity. If we assume bottom water temperatures of −1.2 to -1.5°C (EWG, 1998; Bude, unpublished data), which are rather typical modern bottom water temperatures on the eastern Laptev Sea shelf (S. Kirillov, pers. com., 2001), we can reconstruct a bottom water salinity of 29.4 to 29.6 at 8.4 ka BP (Fig. 4-5). In the case of a relatively warm bottom water temperature of -0.6°C, which is only found in direct proximity to the Lena Delta the reconstructed salinity increases only by 0.2 (Fig. 4-5). This indicates, that in comparison with a modern salinity of ~32 (EWG, 1998; Kirillov, unpubl. data) site 92 was more influenced by freshwater than at present.

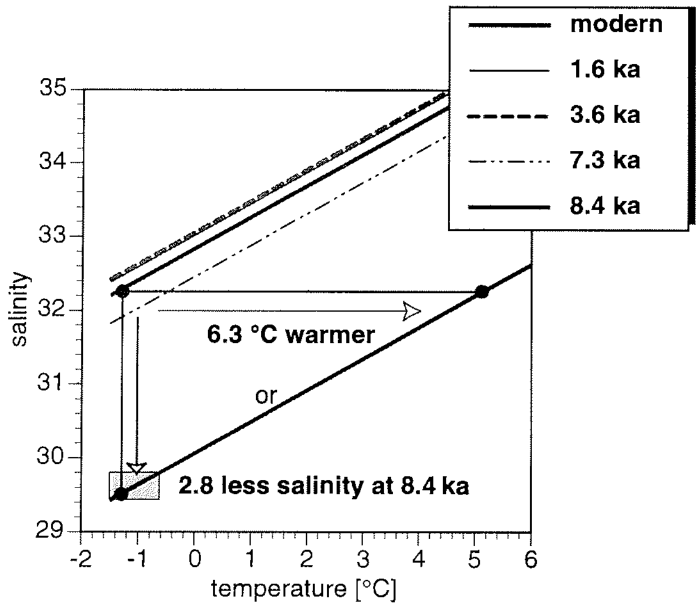


Fig. 4-5: Temperature and salinity model for the interpretation of the different bivalve shell $\delta^{18}O$ values. The lines are representing the possible salinity and temperature combinations to obtain the mean $\delta^{18}O$ value of the dated bivalves. The gray shaded box indicates the reliable reconstructed temperature and salinity range for the 8.4-ka-old bivalve.

Because the Laptev Sea region evolved into a shallow shelf sea only during the postglacial sea level rise, the southward transgressing sea had a major impact on the shelf environment (Bauch et al., 1999). On the basis of major changes in the average sedimentation rate in sediment cores and other sedimentological parameters Bauch et al. (in press) reconstructed time slices of the postglacial-transgressional history of the Laptev Sea shelf and estimated that the inundation of the present 31 m isobath was concluded by about 8.9 ka BP whereas the Holocene sea level maximum was reached near 5 ka BP. Using this time frame of the sea-level rise between 8.9 and

5 ka BP a sea level 27 m below that of today is estimated for site 92 at 8.4 ka BP. This means that the site 92 was located close to the paleocoastline and in a valley which Kleiber and Niessen (1999) identified as the main paleovalley of the Lena River (Fig. 4-6). On the assumption of a linear sedimentation up to the present in core 92, which Bauch et al. (2001) pointed out for a core further east on the inner Laptev Sea shelf, we can estimate a paleo water depth of ~ 10 m at 8.4 ka BP for site 92. For the verification of our reconstructed salinity for site 92 with a paleo water depth of ~10 m at 8.4 ka BP we compared the reconstructed salinity to modern bottom water salinities of stations with a water depth of 10 m, which were located in the proximity of the Lena Delta. Modern bottom water salinities do not exeed values of 26 to 27 (Kirillov, unpublished data) and are thus reduced by 3.5 to 2.5 salinity units in comparison to our reconstructed salinity.

A paleohydrological interpretation on the basis of reconstructed bottom water salinities remains incomplete without discussing possible changes in surface water salinities. On the basis of a correlation between freshwater diatoms in core top sediments and summer surface water salinities from the Kara Sea, Polyakova and Bauch (subm.) reconstructed surface water salinities for core 92. Their reconstructed surface water salinity of 8 to 9 in combination with our estimated bottom water salinity of 29.5 reveals that at 8.4 ka BP the water column of site 92 was likely under the influence of strong stratification, which is rather more intensive than found today in the Laptev Sea.

The modern topography in the area of site 92 is characterized by a submarine channel that is clearly recognized as the submerged Lena River valley formed during times of lowered sea level (Holmes and Creager, 1974; Kleiber and Niessen, 1999). It may be assumed from the nature of the modern bathymetry at site 92 that no delta system existed at a time with a lowered sea level. Because of the channel-like submarine topography the Lena paleoriver mouth at this time resembled an eastuarine system. This situation probably caused a southward reversed bottom current of more saline water below low-density river water and could explain our relatively high bottom water salinity reconstructed. Such reversed currents are also registered today in the submerged Yana and Lena valleys. They occur occasionally and are caused by wind forced deformations of the sea level due to strong offshore winds from the southeast (Dmitrenko et al., 2001).

The distinct increase in the mean $\delta^{18}O$ of the shell profiles from 8.4 to 7.3 ka BP gives evidence for significant changes in the bottom water salinity due to increasing distance of the site 92 relative to the Lena River mouth. According to our reconstruction mean bottom water salinity changed from 29.5 to 32, which is quite the actual mean bottom water salinity for site 92 today. This time interval with increasing bottom water salinity is also time-coeval with a major decrease in freshwater diatom abundance in this core (Polyakova and Bauch, subm.) and with major changes in the depositional environment recognized in other cores, obtained from a similar water depth as the site of core PS51/92-12 (Bauch et al., 2001 [b]).

In dependence of the southward retreat of the coastline, the river depocenters also shifted, both leading to a stepwise decrease in sedimentation and accumulation rates and in riverine influence. A decrease of the accumulation of total organic carbon contemporaneously with a significant increase of $\delta^{13}C_{org}$ in the sediments of the central Laptev Sea shelf marks a transition from a near-coastal and fluvial environment to the modern depositional environment between 8 and 7 ka BP (Mueller-Lupp et al., 2000). The reconstructed bottom water salinity of 32 at 7.3 ka BP gives clear evidence of the end of this transitional phase, as this bottom water salinity is already similar to the modern one. But a higher summer-to-winter variation in the bottom water salinity at 7.3 ka BP probably provides an indication of stronger seasonal climatic contrasts. Several paleoclimatic reconstructions pointed out more continental climatic conditions for the Laptev Sea region during that time (Monserud et al., 1998; MacDonald et al., 2000). Unfortunately, no isotope shell profile exists for the time between 6 and 4 ka BP when the sea level reached its Holocene maximum. But the paleohydrological reconstruction at 3.6 ka BP reveals that modern hydrographical conditions were fully established at this time. This is in accordance with paleoclimatic reconstructions that also indicate stable modern conditions in the Laptev Sea region during the last 3-4 ka BP (Laing, 1999; MacDonald et al., 2000; Pisaric et al., 2001; Naidina and Bauch, in press).

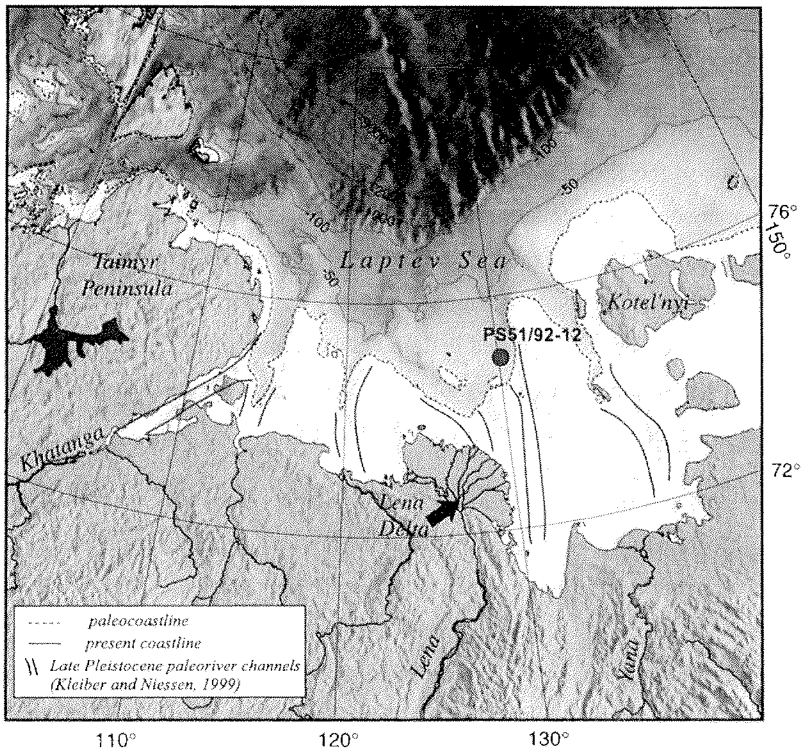


Fig. 4-6: Paleoenvironmental scenario at 8.4 ka BP of the Laptev Sea region. The sea level was 27 meter below that of today. Note that the topographical data obtained from the IBCAO (2000) and does not reflect the actual paleosurface prior to the inundation.

4.6 SUMMARY

Paleohydrographical changes on the eastern Laptev Sea shelf during the last 8.4 ka were reconstructed from oxygen isotope profiles of bivalve shells collected from a well-dated sediment core from northeast off the Lena Delta. Detailed profiles of fossil shells are compared with an isotopic record of a modern specimen of *Macoma calcarea*, which reflects the modern hydrographical conditions of the bottom water at the investigated site.

Although isotope profiles from fossil bivalves of the Laptev Sea shelf reflect only a brief interval of time, they may offer new important insights into the paleohydrography during snapshots of the last 8.4 ka and their relation to the Holocene transgression.

The isotope profile of the 8.4 ka old specimen shows $\delta^{18}O$ values that are on average by 1.35‰ depleted in comparison to the modern specimen from the same site. Under the assumption that the $\delta^{18}O_w$ to salinity relationship in the Laptev Sea remained constant throughout the time, we can interpret this depletion as the result of a reduced salinity at 8.4 ka BP, indicating a near coastal and fluvial environment. A reconstructed bottom water salinity of 29.5 in comparison with the reconstructed surface water salinity of 8 (Polyakova and Bauch, subm.) shows a clear evidence for a stronger stratification of the water column at 8.4 ka BP.

Because of the Holocene transgressional history of the Laptev Sea shelf, the increasing sea level was the most influencial factor on the paleoenvironment, with prominent impacts on the locality of the paleoriver mouth and thus on the hydrographical conditions. Due to the continuing southward retreat of the coastline and the Lena River mouth relative to the study site an increase in the bottom water salinity at 7.3 ka BP is reconstructed. The oxygen isotope shell profile at 7.3 ka BP gives an evidence of a bottom water hydrography which is characterized by a high variability of summer and winter conditions on the level of modern bottom water conditions. The following time slices at 3.6 ka and 1.6 ka BP reveal that modern hydrological conditions are fully established.

The presented salinity reconstruction enables us to make further presumptions on the relative proximity of the study site to the coast and to the river mouth during snapshot views of the Holocene history and thus can be related to the postglacial transgression of the Laptev Sea shelf.

5 SUMMARY AND CONCLUSIONS

The rationale of this study was to give insights into hydrographical and sedimentological changes on the Laptev Sea shelf on annual, decadal, and in particular longer timescales and their connections to the riverine input and its characteristics.

In order to determine variations in the deposition of terrestrial organic matter on the Laptev Sea shelf, which are strongly affected by the riverine input and the thermal erosion of the ice-rich permafrost coast, stable carbon isotope ratios of the organic matter in surface sediments and radiocarbon dated sediment cores were analyzed.

- The modern distribution pattern of $\delta^{13}C_{org}$ in surface sediments reveals a strong impact of terrestrial organic matter on the modern depositional environment of the Laptev Sea shelf with distinctive south to north and east to west gradients. Although there are some uncertainties in defining a marine source of organic matter from the stable carbon isotope ratios for the Laptev Sea, the terrestrial isotope signals contributed by the river discharge and coastal erosion can be identified and traced in their distribution over the shelf.

- Given the modern distribution of terrestrial organic matter on the Laptev Sea shelf, changes in the sediment cores can be related to the input of terrestrial organic matter during the postglacial transgression and can be divided into three major phases.

  - *Until 11 ka BP*: the source of organic carbon the was mainly terrestrial, implying that the central Laptev Sea shelf was not flooded until that time.

  - *11 – 7* ka *BP*: a significant shift in the stable carbon isotope ratios and decreasing accumulation rates of TOC mark the transition towards decreasing deposition of terrestrial organic matter. It is interpreted that these drastic changes in the deposition were caused by the erosion and redistribution of formerly terrestrial shelf sediments and by the contemporaneous southward retreat of the fluvial depocenters.

- *after 7 ka BP*: the main depocenters of the rivers moved their position southward, leading to the modern depositional environment after the sealevel reached its Holocene maximum at 5 ka BP.

The study suggests that the isotopic composition of sediment TOC has potential application in reconstructing changes in delivery and accumulation of terrestrial organic matter resulting from postglacial changes in sea level and environment.

For the reconstruction of short-term hydrographical changes in the modern, strongly coupled land-shelf system of the Laptev Sea, stable oxygen and carbon isotope profiles of from recent bivalve species of *Astarte borealis* were investigated.

- Their oxygen isotope profiles exibit amplitude cycles, which can be interpreted as recording annual hydrographical cycles. Thus in a first step it was necessary to unveil the factors that control the isotopic composition in bivalve shells. The main forcing factor of within shell oxygen isotope variations is the isotopic composition of the habitat´s water and its salinity changes. Because of the relatively constant bottom water temperature on the Laptev Sea shelf, the effect of temperature on the carbonate percipitation can be neglected. For the accurate interpretation in terms of hydrographical changes a vital offset for the species *Astarte borealis* of -0.37‰ was calculated.
- Salinity reconstructions carried out from oxygen isotope profiles of modern bivalve shells reveal good correspondence to seasonal hydrographical conditions.

Given the good conformance between isotopic profiles from living bivalves to modern hydrographical conditions, the oxygen isotope profiles of fossil bivalve shells can be used to trace past hydrographical changes.

- The salinity reconstruction from the oxygen isotope shell profiles at 8.4 ka BP, would suggest that the investigated site was under stronger riverine influence than at present.
- The fossil bivalve at 7.3 ka BP reveals an increased bottom water salinity with strong seasonal variations.

- Conditions comparable to the modern hydrographical settings were established at 3.6 ka BP.

The presented salinity reconstructions enable us to make further assumptions on the relative proximity of the study site to the coast and to the river mouth during snapshot views of the Holocene history and thus can be related to the postglacial transgression of the Laptev Sea.

All presented results suggest that the increasing sea level, caused by the Holocene transgression of the Laptev Sea shelf, was the most influencial factor on the paleoenvironment, with prominent impacts on the locality of the paleoriver mouth and thus on the hydrographical and sedimentological conditions.

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7 Danksagung

Herrn Prof. Dr. Jörn Thiede danke ich recht herzlich für die Vergabe und Betreuung dieser Arbeit.

Ein besonderer Dank geht an Henning Bauch, der durch sein stetiges Interesse und seine unermüdliche Diskussionsbereitschaft wesentlich zum Gelingen dieser Arbeit beigesteuert hat. Ein aufmunterndes "Sieh zu ...." und "Na, weißt Bescheid !?" haben stets für Motivation gesorgt.

Ein großer Dank gebührt Heidemarie Kassens für ihr persönliches Engagement, das nicht nur wesentlich zum Gelingen der Expeditionen in die Laptev-See beigetragen hat, sondern auch mir immer wieder den Geist der russisch-deutschen Zusammenarbeit vermittelte.

Mein herzlicher Dank geht auch an Herrn Dr. Erlenkeuser sowohl für die zahlreichen Isotopenmessungen als auch für wertvolle Anregungen und Diskussion über das isotopische Leben von Muscheln. Ebenso sei dem Team des Leibniz-Labors für die Unterstützung bei den Laborarbeiten gedankt.

Meinen Freunden und Kollegen Sven-Ole Bude, Claudia Didié, Jan Helmke, Jens Höleman, Thorben Klagge, Niels Nørgaard-Petersen, Bernhard Peregovich, Michael Schmidt, Johannes Simstich, Robert Spielhagen und Carolyn Wegner danke ich für zahlreiche Diskussionen, Anregungen, Unterstützungen und vor allem für das angenehme Arbeitsklima während meiner Zeit am GEOMAR. Nicht zu vergessen für die montäglichen Bundesligadiskussionsrunden.

Ein herzliches Dankeschön an Ortrud Runze und Karen Volkmann-Lark für die Durchsicht und Korrektur der vorliegenden Arbeit.

Allen russischen und deutschen Kolleginnen und Kollegen im Projekt „System Laptev-See 2000" sei für die wunderbare und erfolgreiche Zusammenarbeit sowohl von fachlicher als auch von menschlicher Seite gedankt.

Dem Kapitän und der Besatzung der „Polarstern" sowie den Piloten der Flugstaffel Tiksi sei an dieser Stelle für ihren unermüdlichen Einsatz gedankt, der den Erfolg der Expeditionen ermöglichte.

Meinen Eltern möchte ich einen besonderen Dank für ihre mentale Unterstützung während der Promotion aussprechen.

Für ein Leben neben der Polarfoschung und vor allem für die Einsicht, dass es neben der Laptev-See Down Under noch weitere „key regions" auf unserem Planeten gibt, möchte ich mich bei meiner Frau Wiebke ganz herzlich bedanken.

Die vorliegende Arbeit ist im Rahmen des deutsch-russischen Verbundvorhaben „System Laptev-See 2000" entstanden. Für die Finanzierung möchte ich mich beim BMBF bedanken. Der ESF danke ich für die Teilnahmen an den QUEEN-Workshops in Lund und Straßburg.

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