

**Planktic foraminifer ecology and stable isotope geochemistry
in the Arctic Ocean: implications from water column and
sediment surface studies for quantitative reconstructions
of oceanic parameters**

**Ökologie planktischer Foraminiferen und stabile Isotope
im Arktischen Ozean: Anwendbarkeit für die quantitative
Rekonstruktion von ozeanischen Parametern**

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Für Locke und Paulina

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Summary

Planktic foraminiferal assemblages and shell isotope-geochemistry have for long been used to recognize variations of past water mass composition in the oceans. The focus of this study is to determine the factors controlling the distribution and abundance of living and fossil planktic foraminifers in the outer Laptev Sea and the Fram Strait and the stable O- and C-isotope ratio of their calcite shells. A decrease in absolute abundances of living planktic foraminifers in the water column by a factor of 8 from the Fram Strait to the outer Laptev Sea is controlled by high river-water discharge from the Siberian shelves, the lower food supply, and permanent ice coverage. The biocoenosis of planktic foraminifers is dominated by the polar species *Neogloboquadrina pachyderma* (sinistral coiling) EHRENBERG, 1861, and the subpolar species *Turborotalita quinqueloba* NATLAND, 1938, and their distribution pattern reflects the complex hydrographic regime. In the cold Polar Water, *N. pachyderma* (sin.) comprises >70 % of the total assemblages, while *T. quinqueloba* yielded abundances of >80 % in warmer and more saline Atlantic Water.

The planktic foraminiferal assemblages in the ocean-surface sediments show significant enrichments of *N. pachyderma* (sin.), when compared with living assemblages, predominantly caused by selective carbonate dissolution. Nevertheless, in the Fram Strait, the occurrence of fossil *T. quinqueloba* is an indicator for the paleo-position of the summer sea-ice margin and can be used to reconstruct the distribution of Polar and Atlantic waters. In ice-free areas, *N. pachyderma* (sin.) lives as a "deep-water" species at and below 100 m water depth. *T. quinqueloba* dwells slightly shallower at ice-free stations and migrates into deeper waters at the sea-ice margin. Under a permanent ice cover, *N. pachyderma* (sin.) and *T. quinqueloba* are forced to dwell shallower because of food availability.

The depth habitat is a major control for the stable isotope composition of both species. In the outer Laptev Sea and the western Fram Strait, low oxygen isotope values of living individuals reflect the influence of the low saline surface layer in the upper 50 m. The good correlation between $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) and salinity underlines the importance for paleoceanographic reconstructions. Oxygen isotope offsets between living and fossil individuals are explained by salinity variations during the last centuries and by secondary calcification, which continued below 200 m water depth. Highest differences were calculated for the outer Laptev Sea and the western Fram Strait, where the observed vertical salinity differences are >4 psu.

The carbon isotope composition of *N. pachyderma* (sin.) is largely controlled by metabolism and the carbon isotopes of dissolved inorganic matter of the ambient sea water. Species-specific and size class-dependent offsets are caused by kinetic and metabolic fractionation processes. *N. pachyderma* (sin.) from surface sediments are enriched in ^{13}C compared to living individuals. In the outer Laptev Sea, highest offsets between living and fossil individuals indicate anthropogenic CO_2 uptake of surface waters in the well-ventilated shelf regions. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of living nonencrusted *N. pachyderma* (sin.) are consistently depleted in comparison to the isotope values for equilibrium calcite by 1.3 ‰ and 2.0 ‰, respectively. These vital effects decrease with increased encrustation and are reduced by 0.7 ‰ $\delta^{18}\text{O}$ and 0.5 ‰ $\delta^{13}\text{C}$ in encrusted shells from the surface sediments.

Kurzfassung

Vergesellschaftungen planktischer Foraminiferen und isotope-geochemische Untersuchungen ihrer Schalen stellen eine Standardmethode zur Rekonstruktion von Wassermassenparametern in allen Ozeanen des Weltmeeres dar. Der Arktische Ozean nimmt wegen seiner Eisbedeckung und hohen Frischwasserzufuhr gegenüber anderen Ozeanen eine Sonderstellung ein. Ziel der vorliegenden Arbeit ist die Bestimmung dieser Einflußfaktoren auf die Verbreitung und Häufigkeit lebender und fossiler planktischer Foraminiferen und auf die stabilen Sauerstoff- und Kohlenstoffisotopen Werte der kalkigen Gehäuse in der äußeren Laptevsee und der Framstraße. Die absoluten Häufigkeiten der lebenden planktischen Foraminiferen nehmen von der Framstraße zur äußeren Laptevsee aufgrund hoher Flußwasserzufuhr von den sibirischen Schelfen, geringem Nahrungsangebot und einer permanenten Eisbedeckung um den Faktor 8 ab. Die Lebendgemeinschaft der planktischen Foraminiferen wird von der polaren Art *Neogloboquadrina pachyderma* (links gewunden) (EHRENBERG) 1861 und der subpolaren Art *Turborotalita quinqueloba* (NATLAND) 1938 vertreten und spiegelt die verschiedenen Wassermassen des Arktischen Ozeans wider. *N. pachyderma* (sin.) ist mit > 70 % die dominierende Art in kaltem Polarwasser, während *T. quinqueloba* mit >80 % in warmem und salzreichem Atlantikwasser vorherrscht.

Die fossile Gemeinschaft in Sedimentoberflächenproben weist im Gegensatz zur Lebendgemeinschaft infolge von Kalklösung eine starke Anreicherung von *N. pachyderma* (sin.) auf. Das Vorkommen von *T. quinqueloba* im Sediment gibt Aufschluß über die sommerliche Eisrandlage und kann zur Unterscheidung von kaltem Polarwasser und warmem, salzreichen Atlantikwasser genutzt werden. In jahreszeitlich eisfreien Gebieten lebt *N. pachyderma* (sin.) in Wassertiefen um 100 m. *T. quinqueloba* hingegen lebt oberflächennah und wandert nur am Eisrand in tiefere Wässer ab. Unter einer permanenten Eisdecke zwingt das geringe Nahrungsangebot beide Arten in oberflächennahes Wasser.

Das Tiefenhabitat beider Arten in der Wassersäule wirkt sich erheblich auf die Zusammensetzung der stabilen Isotopen in den Kalkschalen aus. Die geringe saline Oberflächenschicht in der äußeren Laptevsee und der westlichen Framstraße spiegelt sich in niedrigen Sauerstoffisotopen der Gehäuse wider. Die Differenz der Sauerstoffisotopenwerte von *N. pachyderma* (sin.) aus der Wassersäule und dem Oberflächensediment lassen auf Salzgehaltsschwankungen während der letzten Jahrhunderte und auf zunehmende Verkrustung der Gehäuse in Wassertiefen unterhalb von 200 m schließen. Höchste Differenzen werden durch vertikale Salzgradienten von >4 psu in der äußeren Laptevsee und der westlichen Framstraße bedingt.

Die Zusammensetzung stabiler Kohlenstoffisotope von *N. pachyderma* (sin.) hängt im wesentlichen vom Stoffwechsel der Individuen und von den Kohlenstoffisotopenwerten des Wassers ab. Abweichungen zwischen beiden Arten und verschiedenen Größenklassen resultieren aus kinetischen- und stoffwechselbedingten Fraktionierungsprozessen. Die größten Differenzen zwischen den Kohlenstoffisotopenwerten von *N. pachyderma* (sin.) aus der

Wassersäule gegenüber dem Sediment in der äußeren Laptevsee lassen einen hohen Eintrag von anthropogenem CO₂ über die gut durchlüfteten Schelfwässer erkennen. Die Vitaleffekte von unverkrusteten *N. pachyderma* (sin.) betragen 1.3 ‰ für Sauerstoffisotope und 2.0 ‰ für Kohlenstoffisotope und sind bei verkrusteten Individuen im Sediment um 0.7 ‰ beziehungsweise 0.5 ‰ reduziert.

1. INTRODUCTION

Since ecological awareness increased in the last decades, the Earth's modern climate in conjunction with natural and man-made climate change are more and more of special interest. In order to predict future climate more reliable, the knowledge and understanding of climate history are fundamental principles. The high northern latitude oceans have a high relevance for the global climate and its change through time (Aagaard et al., 1985; Aagaard and Carmack, 1994). The Arctic Ocean sea ice and freshwater budget are sensitive elements of the global environment (Rudels, 1989), and even small changes could alter the present conveyor belt circulation and northern climatic zonation (Aagaard and Carmack, 1989; Swift, 1986).

Deep-sea sediments can provide undisturbed high-resolution records of the past, and are a primary source for understanding the climate variations on earth (e.g., Hebbeln and Wefer, 1997; Hebbeln et al., 1998). Calcite shells of planktic foraminifers are major components in pelagic sediments and are important tools for paleoceanographic reconstructions (Vincent and Berger, 1981; Hemleben et al., 1989; Wefer et al., 1999). Distribution and stable isotope composition of planktic foraminifers are often used to establish or verify a stratigraphy for Quaternary sequences (e.g., Spiegler, 1996; Nørgaard-Pedersen et al., 1998). They are valuable proxies for studies of the earth climate history of e.g., the Arctic Ocean (Stein et al., 1994a; Nørgaard-Pedersen et al., 1998; Poore et al., 1999) and provide quantitative estimates for sea-surface temperature (SST) and sea-surface salinity (SSS) reconstructions during the past (e.g., Duplessy et al., 1991; Hale and Pflaumann, 1999).

The planktic foraminifer *Neogloboquadrina pachyderma* (sin.) is the most abundant species in Quaternary and recent sediments of the high latitudes (Vilks, 1975; Kennett and Srinivasan, 1983; Pflaumann et al., 1996). *N. pachyderma* (sin.) is usually used as a proxy for extremely cold water conditions (Bond et al., 1992, 1993, Bauch, 1997). The species *Turborotalita quinqueloba* has proven to be a reliable proxy for subpolar waters and for the influx of Atlantic waters into the Arctic Ocean (Carstens and Wefer, 1992; Hebbeln et al., 1994; Bauch, 1994). However, little is known about the species' ecology and life cycle and how these factors affect the isotopic composition of its shells.

For the interpretation of environmental information conveyed by species distribution and stable isotope composition, the species' physiology, depth habitat, life cycle, and seasonality have to be known. Therefore, the living community has to be described and factors controlling the diversity and abundance have to be determined. The incorporation of stable isotopes in the calcite shell needs to be investigated to prevent distortion of paleoceanographic interpretations, because several factors, e.g., species-specific vital effects, vertical migration during life cycle, and global sea-water $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ variations can complicate the interpretation (e.g., Spero et al., 1997). Such studies on living planktic foraminifers have mainly concentrated on tropical to temperate climate regions, but they are rare in the polar latitudes. Carstens and Wefer (1992) and Carstens et al. (1997) presented results on

planktic foraminifers in the Nansen Basin and the Fram Strait, but did not distinguish between living and fossil individuals. Bauch et al. (1997, in press.) published oxygen and carbon isotope data of *N. pachyderma* (sin.) from core top sediments and the water column in the Nansen Basin and suggested a significant difference between the average depth of habitat and calcification and an imprint of anthropogenic CO₂ in the Arctic Ocean. However, little knowledge exists about reasons for differences between living and fossil assemblages. Stable oxygen and carbon isotopic records are often difficult to interpret due to the lack of recent studies on the influence of variable environmental parameters on the isotopic composition of living individuals in northern high latitudes.

In this study, the distribution of living and fossil planktic foraminifers at the Laptev Sea continental margin is presented for the first time and compared to the distribution pattern in the hydrographically different Fram Strait. The planktic foraminifer distribution in the upper water column and the underlying ocean surface sediments and their oxygen and carbon isotope composition were presented with emphasis on the dominant features of the Arctic Ocean: the high freshwater discharge from the Siberian rivers, the permanent ice cover with its seasonally variable ice margin, and the vertically stratified water column.

1.1. Planktic foraminifers in paleoceanography

Since D'Orbigny (1826) described planktic foraminifers for the first time, and Murray (1897) defined a climatic based biogeographic zonation, planktic foraminifers have been used extensively in paleoceanography and biostratigraphy. Schott (1935) reported first quantitative data of living planktic foraminifers in tropical waters and noted glacial-interglacial changes in assemblages of Quaternary sediments. The use of oxygen isotopes to deduce the paleotemperature of the foraminiferal environment has been first recognized by Emiliani (1954) and has become the most important tool for paleoceanographic studies. In the following decades, many paleotemperature equations have been published (for review see Bemis et al., 1998) and individually used for e.g., cold or warm water environments. Planktic foraminiferal biostratigraphy has expanded enormously with the Deep Sea Drilling and Ocean Drilling Project, which provided important data from deep-sea deposits for more than thirty years. Based on biogeographic zonation, Imbrie and Kipp (1971) introduced factor regression equations to reconstruct quantitatively sea-surface temperatures, which became widely used to analyze Quaternary sequences in tropical and temperate latitudes (CLIMAP, 1976).

Simultaneous, numerous studies dealt with biogeographic and water mass distributional patterns (for overview see Vincent and Berger, 1981; Hemleben et al., 1989) in the Pacific, Indian, and North Atlantic oceans, and provided a sound basis for biologic-ecological (e.g., Bijma et al., 1990a; Schiebel et al., 1997), seasonal flux (e.g., Reynolds-Sautter and Thunell, 1989; Donner and Wefer, 1994), and culturing studies (Spindler et al., 1984; Bijma et al., 1990b, 1992). Efforts to apply the stable isotope composition of living planktic foraminifers indicated complex mechanisms affecting the shells' isotope ratio

(e.g., special issue of Palaeogeography, Palaeoclimatology, Palaeoecology, volume 30, 1981), later itemized by McConnaughey (1989), Ortiz et al. (1996), and Spero et al. (1997).

In the Arctic Ocean, first precise planktic foraminiferal distribution and stable isotope patterns were given by Vilks (1975) and Aksu and Vilks (1988). During the 1990s, detailed studies on the recent planktic foraminiferal distribution have been carried out (Carstens and Wefer, 1992; Carstens et al., 1997). Further studies on planktic foraminiferal isotope composition in the Arctic Ocean revealed some inconsistencies and indicate that further studies on living planktic foraminifers are needed (Spielhagen and Erlenkeuser, 1994; Bauch et al., 1997; Bauch et al., in press).

1.2. Objectives of this study

The principle goal of this study was to determine how the extreme environmental conditions in the modern Arctic Ocean are reflected in the stable isotope composition of planktic foraminifers, especially of *N. pachyderma* (sin.), which is predominantly used for paleoceanographic reconstructions in the high latitudes. Therefore, the initial step was the investigation of the biocoenoses of planktic foraminifers and the incorporation of stable isotopes in the calcite shells. These results than should be linked to the Past in the sense "the Present is the key to the Past". The study was mainly initiated by $\delta^{18}\text{O}$ data of *N. pachyderma* (sin.) in sediment surface samples on the Laptev Sea continental margin, which show a seaward decrease in contrast to an increase of sea-surface salinity (Spielhagen and Erlenkeuser, 1994). Both parameters are expected to be roughly positive linear related. In this context two major questions arise:

- Which water mass is reflected in the isotope signal measured in deep-sea sediments, and does *N. pachyderma* (sin.) calcify in equilibrium with the ambient sea water?
- What controls the distribution and shell chemistry of living planktic foraminifers in the modern Arctic Ocean?

An answer to these questions will improve the application and interpretation of the stable isotope signal in deep-sea sediments. Therefore, the major objectives of this study were:

- to describe the vertical and lateral distribution of living planktic foraminifers in surface waters of the outer Laptev Sea and the Fram Strait and to compare the results of these hydrographically different areas with regard to possible transport in water masses of Atlantic origin.
- to decipher the influence of the ice coverage, freshwater signal, food, and nutrients on the foraminiferal depth habitat with emphasis on species' reproduction cycles.
- to provide stable isotope data of living planktic foraminifers and *in situ* measurements of temperature and salinity, and data of actual water $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of DIC (dissolved inorganic carbon) and to identify how these parameters influence the shell isotope signal.

- to determine the significance of physiological factors probably altering the foraminiferal isotope composition and to compare living and fossil foraminiferal assemblages and isotope data to identify mechanisms which are responsible for possible differences.
- to assess paleoceanographic implications.

1.3. Outline of this study

This thesis comprises three chapters (2 to 4), which are in press or submitted for publication. In chapter 2 (Planktic foraminifers in the outer Laptev Sea and the Fram Strait - Modern distribution and ecology. Volkmann, R., in press), the abundance, diversity, and distribution of living planktic foraminifers in the upper 500 m of the water column in the outer Laptev Sea and the Fram Strait were described in detail. In addition to the vertically stratified plankton tows, hydrographic data of chlorophyll *a* and phosphate concentrations were used to determine the controlling factors. Presumptions are given for the reproduction and calcification depth of both dominant species.

Chapter 3 (Stable isotope composition ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) of living planktic foraminifers in the outer Laptev Sea and the Fram Strait. Volkmann, R. and Mensch, M.) was written in cooperation with co-author M. Mensch, who provided water $\delta^{18}\text{O}$ data. Stable isotope compositions of living planktic foraminifers *N. pachyderma* and *T. quinqueloba* are compared to water $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ of DIC, water temperature and salinity. Different physiological factors affecting the absolute isotope values have been identified and depletions from inorganic calcite precipitated in equilibrium with sea water were determined. According to paleoceanographic reconstructions, evidence is given for the significance of foraminiferal isotope data as quantitative proxies.

The major part of chapter 4 (Planktic foraminifers in the Arctic Ocean: Biogeography and stable isotopes - Results from plankton tows and ocean surface sediments. Volkmann, R. and Spielhagen, R.F.) includes the planktic foraminiferal distribution and stable isotope compositions from sediment surface samples at the Laptev Sea continental margin and the Fram Strait. R. Spielhagen provided multinet and sediment surface samples from the Laptev Sea continental margin (ARK-XI/1) and H. Erlenkeuser the stable isotope measurements. The assemblages of living and fossil planktic foraminifers are discussed with regard to calcium carbonate dissolution, surface water mass characterization, and ice coverage. The environmental conditions of the Little Ice Age, the average depth of habitat, and the calcification process are used to explain the spatial and temporal oxygen isotope distribution of *N. pachyderma* (sin.). The relevance of anthropogenic CO_2 , air-sea exchange, and isotopically light river outflow is discussed for foraminiferal carbon isotopes. According to paleoceanographic reconstructions, different environmental facies as determined from foraminiferal assemblages and stable isotopes could be mapped for the modern Arctic Ocean.

2. PLANKTIC FORAMINIFERS IN THE OUTER LAPTEV SEA AND THE FRAM STRAIT - MODERN DISTRIBUTION AND ECOLOGY

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2.1. ABSTRACT

Planktic foraminifera were studied in the Arctic Ocean in the outer Laptev Sea (76-80°N, 100-150°E) in 1995, in the Fram Strait (81-82°N, 10°W-15°E) and in the western Barents Sea (76-78°N, 30-33°E) in 1997. Five depth intervals were sampled vertically between 500 m water depth and the sea surface. In the 125-250 µm size class, highest abundances of living individuals were present in the western Fram Strait (17 ind./m³) and the Barents Sea (14 ind./m³), decreasing to 4 ind./m³ near Severnaya Zemlya and less than 2 ind./m³ at the eastern Laptev Sea continental margin. The most common species *Neogloboquadrina pachyderma* (sinistral coiling) occurred in cold Polar water masses between 50 and 100 m water depth, where they accounted for >70 % of all shells. A synodic lunar reproductive cycle is demonstrated in all sampled areas, where reproduction takes place around full moon. In warmer Atlantic water masses of the West Spitzbergen Current and the Barents Sea, *Turborotalita quinqueloba* contributes >80 % to the total assemblage. Most individuals were obtained between 50 and 200 m water depth. In the western Fram Strait affected by the East Greenland Current and at the outer Laptev Sea relative abundances decrease to 2-10 %. All other species combined make up only 5 % of the total fauna. In general, empty tests are most abundant in water depths deeper than 200 m as a result of gametogenesis and due to high juvenile mortality. The strong gradient in absolute abundances seems to be determined by the availability of food, low salinity due to freshwater discharge from the Siberian rivers and the ice coverage of the Arctic Ocean. The relative abundances, however, reflect the complex hydrographic interaction between relatively warm Atlantic water inflow and cold polar water export in the Arctic Ocean.

2.2. INTRODUCTION

Planktic foraminifera are one of the most powerful tools in paleoceanography. The composition of assemblages and stable oxygen and carbon isotopes are used to reconstruct sea-surface conditions, e.g., distribution of water masses and ventilation (e.g., Mulitza et al., 1998), to calculate sea surface temperatures (SST) and salinities (SSS) (Duplessy et al., 1991) and to provide a stratigraphic frame work for deep-sea sediments.

Studies of Arctic living planktic foraminifera contribute to our understanding of high latitude marine faunas, and their distribution provides recent analogues for the interpretation of planktic foraminifer assemblages in the late Quaternary. The species *N. pachyderma* (sinistral) is the most common planktic foraminifer in polar regions (Bé and Tolderlund, 1971), and dominates the planktic foraminiferal flux to the ocean floor (Vilks, 1975; Hilbrecht, 1997).

The modern Arctic Ocean, however, is a comparatively hostile environment for planktic life and little is known how habitat and species distribution of planktic foraminifers respond to the extreme conditions of almost permanent ice coverage, cold surface waters, Atlantic water inflow and freshwater input.

Early studies in northern high latitudes concentrated on the Canadian Archipelago (Vilks, 1975) and Baffin Bay (Stehmann, 1972). Recently, living planktic foraminifers were sampled in the Nansen Basin (Carstens and Wefer, 1992), the Northeast Water Polynya (Kohfeld et al., 1996), the Fram Strait (Carstens et al., 1997), and the Norwegian-Greenland Sea (Jensen, 1998). These investigations revealed that two species (*N. pachyderma* (sin.) and *T. quinqueloba*) dominate planktic foraminiferal assemblages at the sea floor, and pronounced the seasonal occurrence in the upper 500 m of the water column with highest abundances at the sea-ice margin. However, both living and dead foraminifers were included in these investigations and may lead to a different depth habitat calculation for living species. Little knowledge exists of the distribution of living species and their biological rhythms such as the lunar reproduction cycle. Lunar and semi-lunar periodicities were only described for some spinose planktic foraminifers (e.g., Spindler et al., 1978; Bijma et al., 1990a, 1994; Schiebel et al., 1997).

In this study, living and dead planktic foraminifers, sampled with vertically-stratified nets, were compared in two hydrographically different areas of the Arctic Ocean: (I) The outer Laptev Sea (sampling time: August 1995), where a strong freshwater inflow from the Siberian rivers results in a low saline surface water layer (~ 29 psu: salinity units on the "Practical Salinity Scale 1978"), and (II) the Fram Strait (July 1997), with the inflow of relatively warm Atlantic water in the east, and sea ice and cold surface water export to the Nordic Seas in the west. The vertical distribution, the reproduction, the lateral transport, and paleoceanographic implications will be discussed.

2.3. HYDROGRAPHY OF THE ARCTIC OCEAN

The Arctic Ocean is characterized by a strong stratification of water masses, which almost completely inhibits vertical mixing, while advective processes dominate the water mass distribution (Rudels, 1989). The sea surface in the eastern Arctic region is ice covered in winter, while in summer marginal areas of the outer Laptev Sea and the Fram Strait between the East Greenland and northern Svalbard are ice free (Fig. 2.1.).

The uppermost Arctic Ocean is characterized by a thin (<5 m) low salinity surface layer (<30 psu) caused by ice melting and river run-off from the shelf areas during summer. This layer is heated by solar radiation in summer (Rudels et al., 1997), while the 10-50 m thick Polar Mixed Layer (PML) extends to the surface in winter. Temperatures in the PML are close to the freezing point (~ -1.8 °C) and salinities range between 33 and 34 psu. The main surface currents in this layer are the Transpolar Drift in the Eurasian Basin flowing from the Siberian shelves to the Fram Strait, and the Beaufort Gyre in the Amerasian Basin. The PML is underlain by a 100-200 m thick saltier halocline (Aagaard et al., 1981; Anderson et al., 1989), which separates the

cold surface waters from the warm Arctic Intermediate Water (AIW) and prevents thermal convection. The AIW has its origin in the North Atlantic water that flows into the Arctic Ocean via the West Spitsbergen Current (WSC). By this current, Atlantic water masses are transported through the eastern Fram Strait into the Arctic Ocean following the Svalbard continental margin, submerge beneath the PML (Rudels et al., 1994), and establish a temperature and salinity maximum at 200-500 m water depth there (Rudels et al., in press a). Part of this current is deflected and follows the ridge topography poleward north of the Laptev Sea (Rudels et al., 1994). Bourke et al. (1988) suggest a splitting of the WSC into two branches; one entering close to Svalbard and one passing west of the Yermak Plateau, possibly recirculating westward in the Fram Strait.

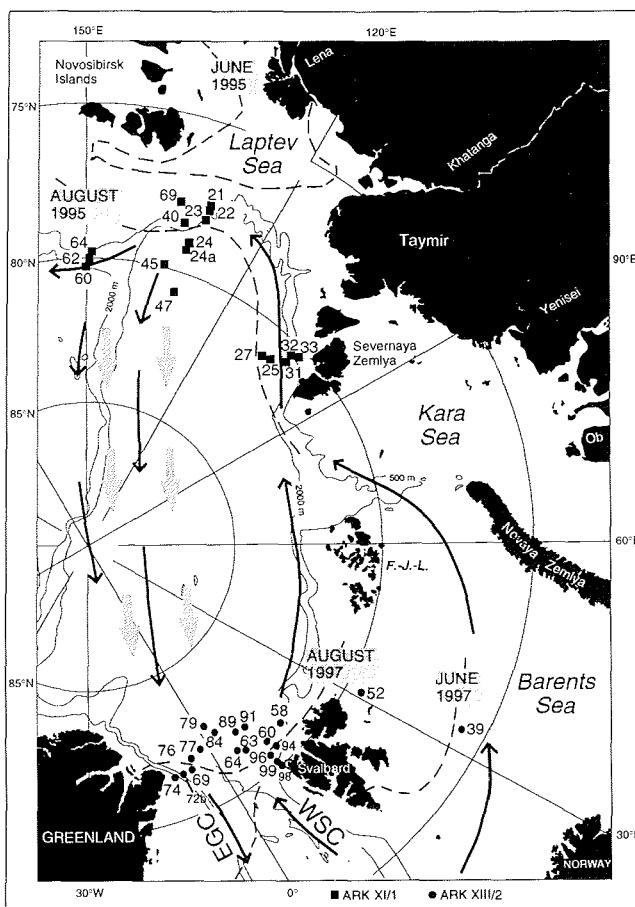


Fig. 2.1. Sampling area and hydrographic setting in the Arctic Ocean. Broken lines mark summer sea ice margins as indicated by shipboard observation and SSM-I evaluation (Special Sensor Microwave/Imager). Note different dates and years of samples. Multinet tows are performed during ARK-XI/1 in 1995 and ARK-XIII/2 in 1997. Grey arrows denote the Transpolar Drift, black arrows the movement of Atlantic derived water; WSC: West Spitzbergen Current, EGC: East Greenland Current.

A second Atlantic water pathway through the Barents Sea results in fresher and colder waters with higher density, while the warmer, more saline Fram Strait branch dominates at lower density (Rudels et al., 1994). With the merging of the two pathways north of the Kara Sea, the temperature of the Atlantic Layer becomes lower, supported by the incorporation of dense, cold descending shelf waters further to the east.

During the "Polarstern" expeditions ARK-XI/1 (1995) and ARK-XIII/2 (1997) hydrographic data were sampled with a high resolution CTD (Rudels et al., in press a, b). The Atlantic Layer at the western Laptev Sea continental margin occurs between 130 and 600 m water depth and is characterized by salinities higher than 34.9 psu and temperatures up to 2.7 °C, decreasing eastwards to the eastern Laptev Sea continental margin. The 150 m thick halocline water and the up to 30 m thick PML shows temperatures between -1.6 and -1.8 °C, while the surface layer in the uppermost meters of the water column is warmer with temperatures up to -0.5 °C at the ice margin. North of the Lena delta, low salinities of less than 30 psu in the surface layer indicate the Lena outflow. To the west, salinities increase reaching more than 33 psu north of Severnaya Zemlya. The vertical distribution shows a steady increase up to 34.9 psu, thus a strong gradient in salinity is observed in the upper 200 m.

In the western Fram Strait the East Greenland Current (EGC) carries cold and relatively fresh Polar Water southward. Enhanced by the summer ice melt, the surface waters at the East Greenland continental slope have extremely low salinities of 31.8 psu in summer. A distinct halocline is observed between 20 and 170-260 m water depth on the entire shelf. The underlying Atlantic Layer occurs down to 600 m water depth with temperatures above 0.5 °C. North of Svalbard the temperature of the Atlantic Layer increases up to 2.5 °C in water depth between 20 and 600 m, indicating Atlantic water entering from Fram Strait and a halocline is less developed there or completely absent.

2.4. MATERIALS AND METHODS

Sixteen plankton tows were taken during "Polarstern" expedition ARK-XI/1 in August 1995 (Rachor, 1997) and fifteen plankton tows during ARK-XIII/2 in July 1997 (Stein and Fahl, 1997) in the Arctic Ocean (Fig. 2.1.). Samples were collected by multinet casts on three transects in the outer Laptev Sea and on two transects from the eastern slope of the Yermak Plateau to the East Greenland Shelf and the southern Nansen Basin to the continental slope north of Svalbard, respectively. Two stations (39 and 52) were sampled in the Barents Sea. Sea ice samples were obtained from the lower 20 cm of some sea ice cores and checked for planktic foraminifers on board. Sampling data for each station are listed in Table 2.1. Temperature and salinity distribution of the upper water column are based on *in situ* conductivity, temperature, and depth (CTD) measurements (Rudels et al., in press a, b), collected directly before the plankton tows. Data of total ice cover and change of ice concentration were obtained by Special Sensor Microwave/Imager (SSM-I) (J. Kolatschek, unpubl. data) and shipboard observations.

The nets of 63 μm mesh size were towed vertically with a maximum winch speed of 0.5 m/s at regular depth intervals (0-50 m, 50-100 m, 100-200 m, 200-300 m, and 300-500 m). The volume of filtered water was calculated for each sample as a product of towed intervals and the square-shaped net opening (0.25 m²). Every catch was preserved in a 4 % borax-buffered formalin seawater solution, stored at 2 °C and treated with bengal-rose-ethanol solution for distinguishing "living" (protoplasma-containing) and "dead" (empty or filled with various amounts of protoplasm remnants) tests. All foraminifers were picked out by pipette and counted under wet conditions. The species identification was carried out for individuals greater than 125 μm using the species concept of Kennett and Srinivasan (1983) and Hemleben et al. (1989).

Table 2.1.: Sampling locations, depth intervals, sampling time, sea ice conditions, and lunar day from multinet tows and chlorophyll *a* maximum values from water samples. The water depths of chlorophyll *a* maximum are in parentheses. Asterisks (*) mark stations, where sea ice samples were collected. All samples were obtained during a period of four weeks (ARK-XI/1) and five weeks (ARK-XIII/2), respectively.

Station	Latitude	Longitude	Water depth (m)	Depth range (m)	Date	Time (GTM)	Ice cover	Lunar day	Chlorophyll <i>a</i> max. ($\mu\text{g/l}$)
ARK-XI/1									
36/022	77°55.8N	130°02.7E	1811	0-50-100-200-300-500	03.08.95	4:22	ice margin	22	
36/023	78°09.6N	129°58.7E	2289	0-50-100-200-300-500	03.08.95	19:45	ice margin	22	
36/024*	79°07.8N	131°26.5E	3061	0-50-100-200-300-500	04.08.95	23:37	ice covered	23	0.3 (10 m)
36/024a	79°19.2N	131°33.4E	3102	0-50-100-200-300-500	05.08.95	19:20	ice covered	24	
36/025	81°08.5N	105°38.9E	2507	0-50-100-200-300-500	07.08.95	19:02	ice margin	26	0.8 (10 m)
36/027	81°13.0N	106°58.7E	3129	0-100-200-300-400-50	09.08.95	1:16	ice covered	28	0.4 (10 m)
36/031	80°46.2N	103°21.6E	1177	0-50-100-200-300-500	11.08.95	8:35	no ice	2	0.3 (150 m)
36/032	80°38.5N	103°03.2E	546	0-50-100-200-300-500	11.08.95	20:15	no ice	2	
36/033	80°25.9N	101°58.7E	245	0-50-100-150-200-245	12.08.95	6:06	no ice	3	2.3 (20 m)
36/040a	78°30.5N	133°49.7E	1738	0-50-100-200-300-500	15.08.95	17:20	ice margin	6	0.7 (10 m)
36/045*	79°59.7N	134°59.9E	3353	0-50-100-200-300-500	18.08.95	22:07	ice covered	9	0.2 (10 m)
36/047*	80°55.6N	131°16.6E	3846	0-50-100-200-300-500	20.08.95	21:32	ice covered	11	0.4 (10 m)
36/060	80°17.2N	150°18.4E	1710	0-50-100-200-300-500	28.08.95	22:22	ice covered	19	0.3 (10 m)
36/062	80°04.5N	149°50.0E	1035	0-50-100-200-300-500	29.08.95	19:20	ice covered	20	0.3 (10 m)
36/064	79°52.7N	149°49.2E	509	0-50-100-200-300-500	30.08.95	5:40	ice covered	21	0.7 (10 m)
36/069	78°23.3N	134°55.4E	1161	0-50-100-200-300-500	01.09.95	15:28	no ice	23	
ARK-XIII/2									
44/039	75°59.9N	32°58.8E	310	0-50-100-150-200-290	27.06.97	10:47	ice margin	8	1.4 (50 m)
44/052	79°26.7N	38°29.6E	325	0-50-100-150-200-300	30.06.97	0:56	ice covered	11	0.6 (0-20 m)
44/058*	81°05.9N	16°56.5E	970	0-50-100-200-300-500	04.07.97	10:50	ice covered	15	0.5 (20 m)
44/060	80°58.2N	11°50.8E	2001	0-50-100-200-300-500	06.07.97	16:30	ice covered	17	
44/063*	81°05.6N	7°00.7E	861	0-50-100-200-300-500	10.07.97	3:00	ice covered	21	0.3 (0-10 m)
44/069	81°27.2N	5°23.3W	3596	0-50-100-200-300-500	15.07.97	10:30	ice margin	26	0.4 (10 m)
44/074	81°35.3N	10°00.7W	524	0-50-100-200-300-500	18.07.97	4:05	ice margin	29	2.1 (10 m)
44/076	81°52.8N	4°34.7W	4185	0-50-100-200-300-500	18.07.97	16:50	ice covered	29	
44/077	81°59.9N	2°25.8W	2584	0-50-100-200-300-500	19.07.97	11:50	ice covered	30	
44/079*	82°39.1N	1°24.4E	3228	0-50-100-200-300-500	20.07.97	23:30	ice covered	1	0.2 (10-20 m)
44/084*	82°19.3N	3°42.1E	2092	0-50-100-200-300-500	24.07.97	6:48	ice covered	5	2.3 (0 m)
44/089*	81°54.0N	7°50.2E	846	0-50-100-200-300-500	27.07.97	12:45	ice covered	8	0.3 (10-30 m)
44/091*	81°39.8N	10°26.9E	1544	0-50-100-200-300-500	29.07.97	0:35	ice covered	10	0.5 (10 m)
44/096	80°31.9N	10°22.7E	782	0-50-100-200-300-500	02.08.97	5:50	ice margin	14	2.3 (10 m)
44/099	80°11.5N	10°24.1E	517	0-50-100-200-300-500	04.08.97	15:30	ice margin	15	1.2 (0 m)

To evaluate the lunar periodicity of *N. pachyderma* (sin.), residuals were calculated by subtracting the average relative abundance of tests from the actual relative abundance for different size classes according to Schiebel et al. (1997).

The faunal composition is shown for both living and dead individuals. The vertical distribution patterns of living *N. pachyderma* (sin.) and *T. quinqueloba* are expressed as the proportions in per cent at a station for both species (standing stock), in absolute abundances for each sampled depth interval, and as an integrated value of the upper 500 m in individuals (ind.) per cubic metre.

Neogloboquadrina pachyderma (dextral coiling) and all other specimens except *N. pachyderma* (sin.) and *T. quinqueloba* were assigned to "other species" (Table 2.2.). Encrusted and kummerform individuals of *N. pachyderma* (sin.) are combined and assigned as carrying reproductive features. Data are available from the PANGAEA data base of the Alfred Wegener Institute, Bremerhaven (<http://www.pangaea.de>).

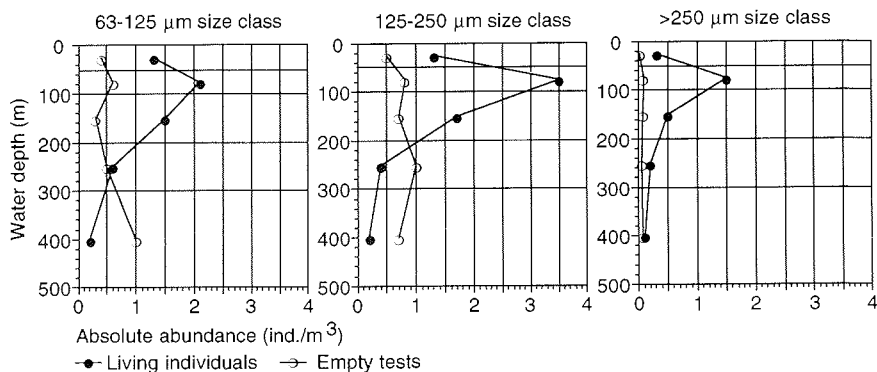
Table 2.2.: Species of planktic foraminifers in the Arctic Ocean. Species concept is after Kennett and Srinivasan (1983) and Hemleben et al. (1989). Values in parentheses are absolute numbers of species found in the whole investigation areas. The average composition of the assemblages in the 3 areas studied are listed for the 125-250 µm and >250 µm size class (in *italic* letters for >250 µm). The residues are unidentified and broken specimens.

Planktic foraminifera	Relative abundances (%)					
	Outer Laptev Sea		Fram Strait		Barents Sea	
<i>Neogloboquadrina pachyderma</i> (EHRENBERG) 1861 (sinistral coiling)	77.7	<i>95.6</i>	70.0	<i>97.0</i>	7.0	<i>95.8</i>
<i>Turborotalita quinqueloba</i> (NATLAND) 1938	11.4	<i>0.2</i>	25.4	<i>0.4</i>	87.7	
<i>Neogloboquadrina pachyderma</i> (EHRENBERG) 1861 (dextral coiling)	6.5	<i>3.4</i>	1.9	<i>2.0</i>	0.9	
"other" species	<i>Globigerinita glutinata</i> (EGGER) 1893	1.0	<i>0.1</i>	0.2		
	<i>Globigerinita uvula</i> (EHRENBERG) 1881	0.5		0.1	1.2	
	<i>Globigerinella aequilateralis</i> (BRADY) 1897	(1)				
	<i>Globigerina falconensis</i> BLOW 1959	(1)				
	<i>Globigerina rubescens</i> HOFKER 1956	(2)				
	<i>Globigerinoides ruber</i> (d'ORBIGNY) 1839	0.2				
	<i>Globoturborotalita tenella</i> (PARKER) 1958	(1)				
total	97.5	<i>99.3</i>	97.6	<i>99.4</i>	96.5	<i>95.8</i>

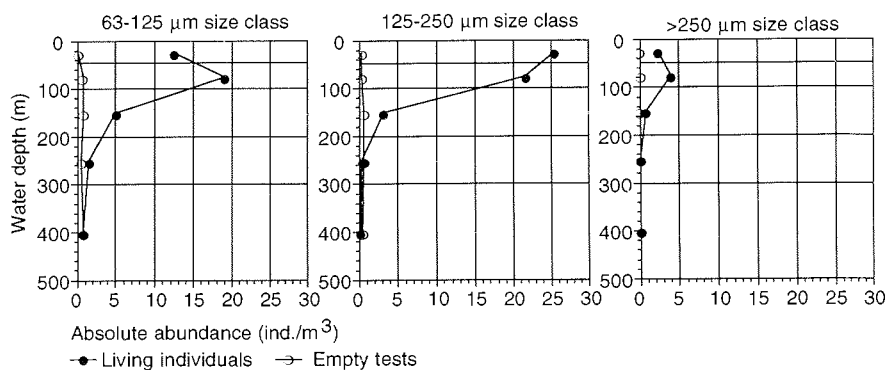
2.5. RESULTS

In this study ten species of planktic foraminifers could be distinguished. Results are given in Table 2.2. Most individuals occur in the 125-250 µm size class (Fig. 2.2.) which is almost completely identified and thus used to describe the occurrence and vertical distribution in the Arctic Ocean. No planktic foraminifers were found in sea ice samples. Highest abundances of living species in each size class occur in the upper 200 m in the outer Laptev Sea and the Barents Sea and in the upper 100 m in the Fram Strait. Empty tests occur in smaller abundances except below 200 m in the two size classes <250 µm in the outer Laptev Sea. The absolute abundances of empty tests increase with depth, with highest abundances in the outer Laptev Sea below 200 m and in the Fram Strait and the Barents Sea below 100 m.

Outer Laptev Sea



Fram Strait



Barents Sea

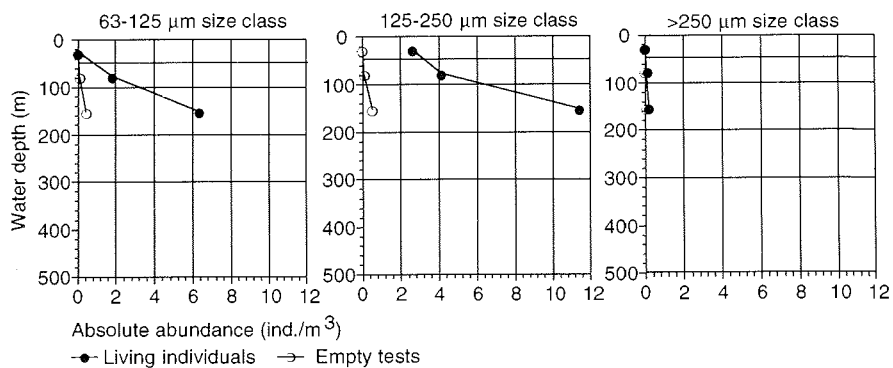


Fig. 2.2.: Average depth distribution of living individuals and empty tests of planktic foraminifers for different size classes in the outer Laptev Sea, the Fram Strait and the Barents Sea. Note different scales. Horizontal lines show boundaries between tow intervals.

2.5.1. Outer Laptev Sea

Average faunal composition in the upper 500 m

The planktic foraminiferal assemblages in the 125-250 μm size class at all water depths are characterized by high amounts (62-87 %) of *N. pachyderma* (sin.) (Fig. 2.3.a). Less than 15 % are kummerform phenotypes, representing fully grown adult individuals (Ollson, 1973; Bijma et al., 1990a) or attributed to environmental stress (Kennett, 1976).

The relative abundance of *T. quinqueloba* varies between 1 and 20 %. The ratio between sinistral and dextral coiling specimens is 3:1. Right-coiling *N. pachyderma* comprises mean values of 2 to 10 %, being most abundant at the sea-ice margin (station 23, 25, 31, and 32). The proportions of the subpolar species *Globigerinita uvula* and the cosmopolitan species *Globigerina glutinata* are relatively small, the average value is 2 % of the total fauna, but high amounts up to 14 % occur at four stations in water depth between 300 m and 500 m (station 22, 23, 24a, and 25). At these stations dead specimens of *Globigerinella aequilateralis*, *Globigerina falconensis*, *Globigerina rubescens*, *Globigerinoides ruber*, and *Globoturborotalita tenella* occur in the same depth interval.

The 250-500 μm size class is also dominated by *N. pachyderma* (sin.) with mean relative abundances of 85-100 % (see Appendix 2.1.). 39 % of *N. pachyderma* (sin.) are kummerform phenotypes at station 31, and 18-34 % of kummerform types are found at the adjacent stations (station 25, 27, 32, and 33). Most of these individuals show a secondary calcite crust. The remaining individuals are *N. pachyderma* (dex.).

Absolute abundances

The absolute abundance of living *N. pachyderma* (sin.) in the upper 500 m of the water column in the 125-250 μm size class reaches maximum values northeast of Severnaya Zemlya (Fig. 2.4., transect C) up to 4.2 ind./m³. Under permanent ice coverage on transects A and B, the abundances vary between 0.5 and 1.1 ind./m³ and between 1.5 and 1.8 ind./m³ at the sea-ice margin. At the ice-free stations close to the Lena outflow the values decrease to 0.6 and 0.3 ind./m³, respectively.

The absolute abundance of *T. quinqueloba* shows a similar distribution, but is less than 0.5 ind./m³ in general. Highest values of *N. pachyderma* (sin.) in the 250-500 μm size class up to 2 ind./m³ are also observed north of Severnaya Zemlya, where all samples were taken in a period of five days around full moon, while remaining stations show values less than 0.3 ind./m³ (Appendix 2.1.).

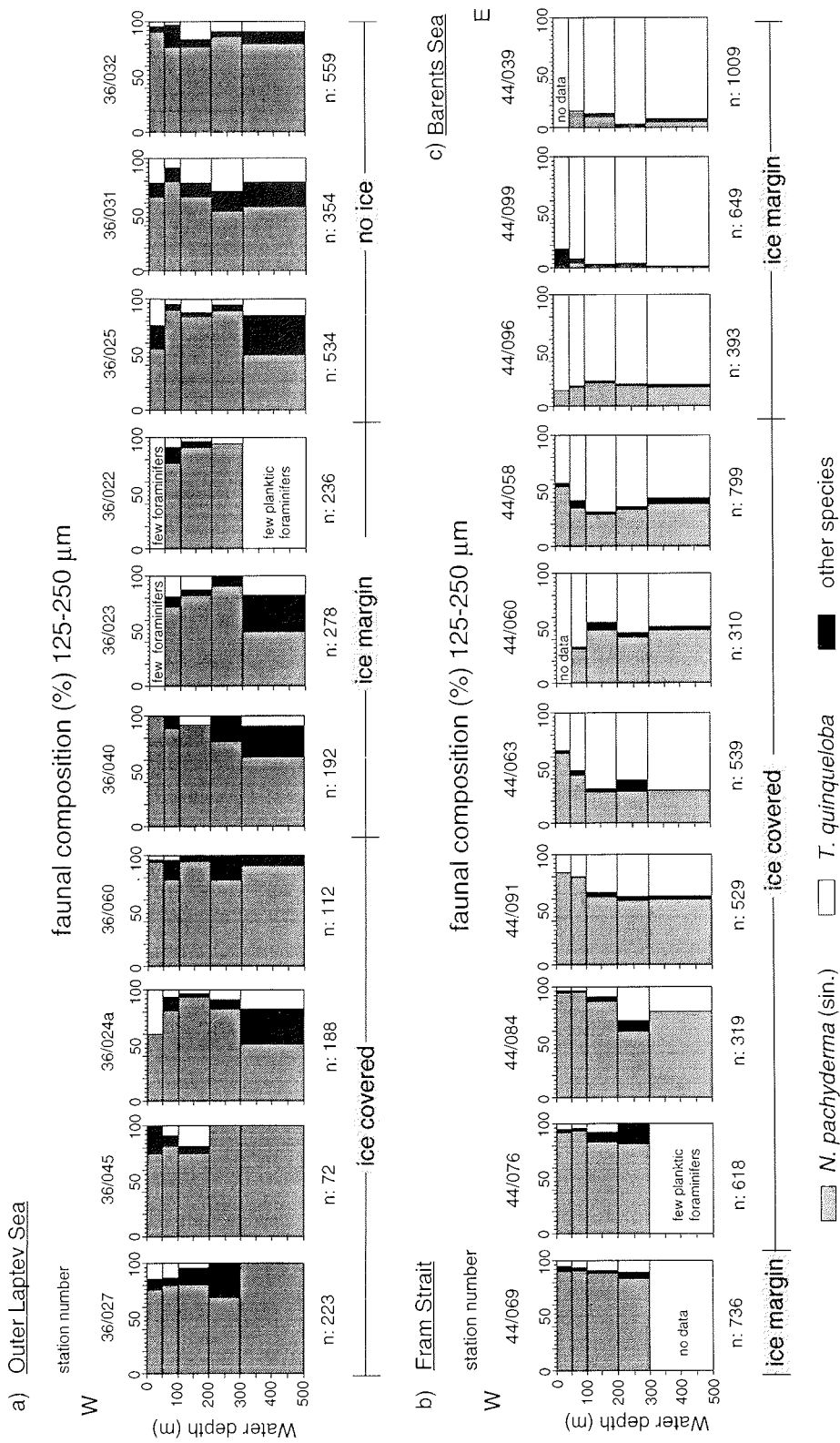


Fig. 2.3.: Faunal composition of selected stations at the (a) outer Laptev Sea, (b) Fram Strait and (c) Barents Sea in the upper 500 m of the water column. n gives the total number and counted amount of living and dead planktic foraminifers per station.

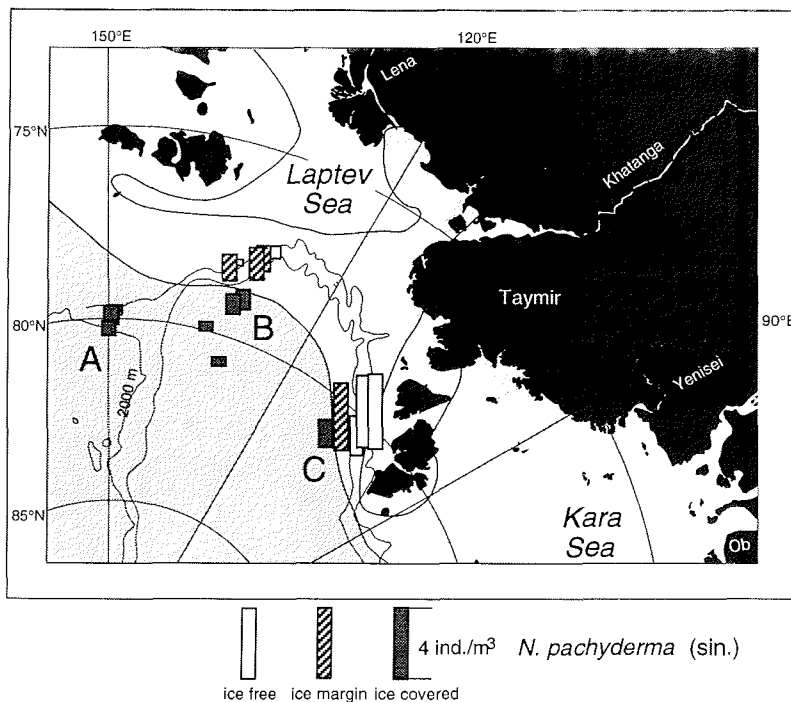


Fig. 2.4.: Absolute abundance of *N. pachyderma* (sin.) in the 125-250 μm size class in the upper 500 m of the water column in the outer Laptev Sea. The grey area shows the sea ice cover in June 1995, the dark grey area only in August 1995. The sampling period was August. Capital letters mark different transects (A: eastern Laptev Sea continental margin; B: outer Laptev Sea, central part; C: northeast of Severnaya Zemlya). Near Severnaya Zemlya the location of the sea ice margin is relatively stable.

Depth distribution

The depth distribution of *N. pachyderma* (sin.) in the 125-250 μm size is plotted as absolute abundance for living specimens and empty tests and as standing stock for living specimens. Most stations show maximum abundances of living *N. pachyderma* (sin.) in halocline water between 50 m and 100 m (Fig. 2.5.). At station 47, 60 and 64 under permanent ice coverage, the maximum abundance is observed between 0 and 50 m (Appendix 2.2.) and at the shallow station 33 between 100 and 150 m. Below 200 m water depth, low numbers of living individuals were observed at most stations. Empty tests are abundant below 200 m water depth, except at station 22, 25, 40a, and 47, where most individuals without protoplasm occur between 50 and 100 m.

Outer Laptev Sea

Absolute abundance (ind./m³) ● Living individuals ○ Empty tests

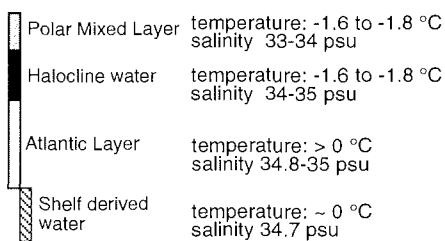
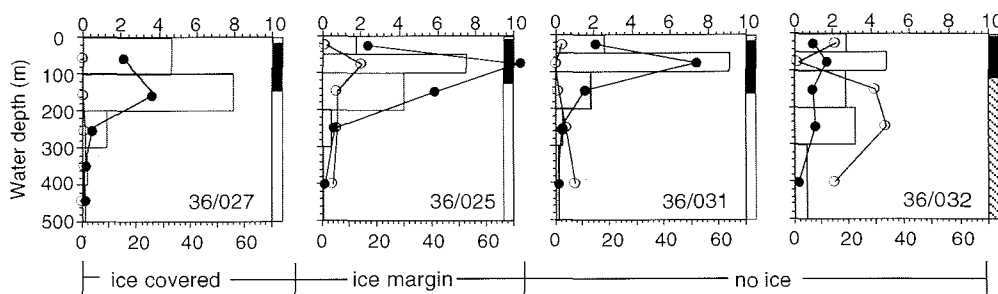
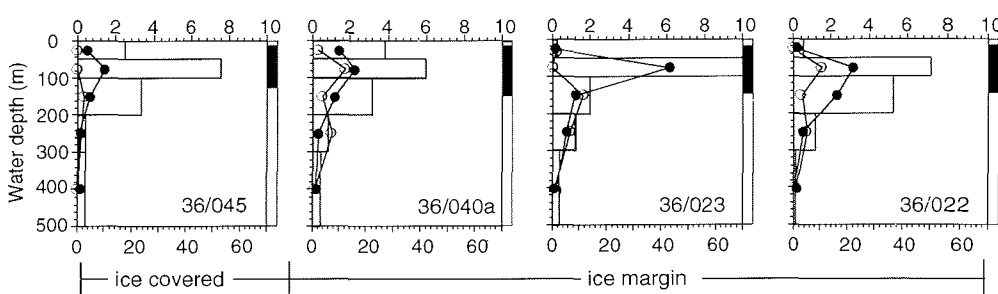
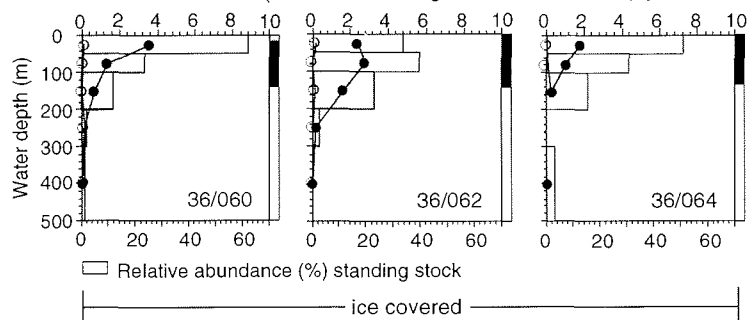


Fig. 2.5.: Absolute abundance (living individuals and empty tests) and relative depth distribution as standing stock (living individuals) of *N. pachyderma* (sin.) (125-250 μm) in the upper 500 m of the water column at the outer Laptev Sea. Shaded columns on the right mark different water masses. Station numbers are shown in the diagrams. Data of stations not plotted are shown in Appendix 2.2.

2.5.2. Fram Strait and Barents Sea

Average faunal composition in the upper 500 m

The faunal composition of planktic foraminifers in the Fram Strait in the 125-250 μm size class is dominated by *N. pachyderma* (sin.) and *T. quinqueloba* (Fig. 2.3.b). Additional species are *N. pachyderma* (dex.), *G. uvula*, and *G. glutinata*, contributing less than 7 % to abundances. The cold waters in the west yielded between 71 % and 88 % and the warm water masses close to the Atlantic water inflow 5-44 % relative abundance of *N. pachyderma* (sin.). Most specimens have a thin shell with well-developed globular chambers. For *T. quinqueloba* the abundance varies between 8 % and 10 % and between 54 % and 93 % for cold and warm regimes, respectively. For the other species no water mass dependence can be deduced.

The mean value of relative abundance of *N. pachyderma* (sin.) in the 250-500 μm size class ranges from 96-100 % (Appendix 2.1.). Small percentages of *N. pachyderma* (dex.) occur in the colder water masses in the western Fram Strait. *T. quinqueloba* is only found at Stat. 74. Both size classes are lacking kummerform phenotypes of *N. pachyderma* (sin.), except few stations in the 250-500 μm size class reveal up to 14 % (station 74, 76, 79, and 91). A secondary calcite crust is in most cases weakly developed.

Absolute abundances

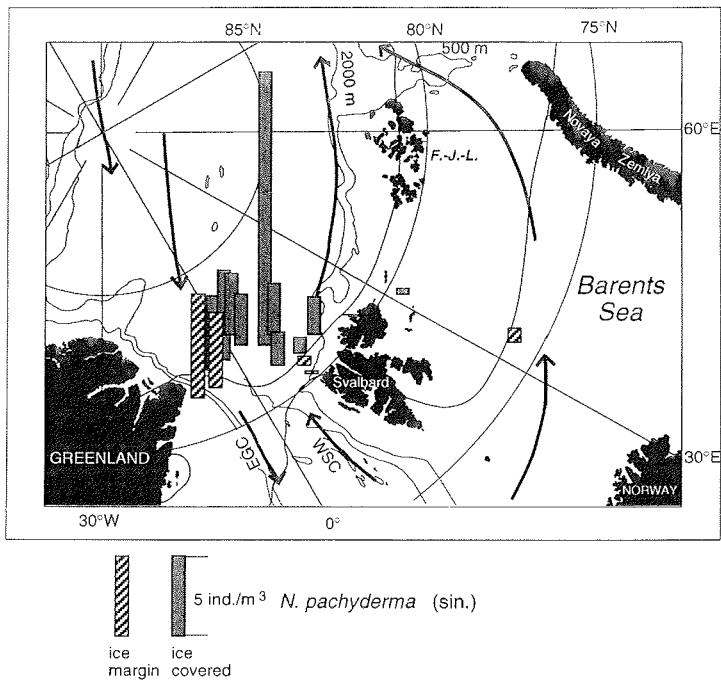
The absolute abundance of *N. pachyderma* (sin.) in the upper 500 m of the water column in the 125-250 μm size class generally decreases from the East Greenland Shelf from 6.4 ind./m³ eastwards to <1 ind./m³ northeast of Svalbard and the Barents Sea (Fig. 2.6.). Maximum values of *N. pachyderma* (sin.) are recorded at station 89 under permanent ice cover (16.6 ind./m³).

Turborotalita quinqueloba, however, shows low values in the west (<0.5 ind./m³) and a consistent increase to the east to 5 ind./m³ (Fig. 2.6.), with highest abundances in the Barents Sea (11.6 ind./m³). The ratio between sinistral and dextral coiling specimens is 4:1. In the 250-500 μm size class the absolute abundance of *N. pachyderma* (sin.) has a maximum value at the westernmost station 76 (2.3 ind./m³) and decreases continuously to <0.5 ind./m³ at the eastern stations (Appendix 2.1.).

Depth distribution

The depth distributions of living *N. pachyderma* (sin.) and living *T. quinqueloba* in the 125-250 μm size class are plotted in Fig. 2.7. Both species show similar trends. The data reveal maximum abundances of living individuals between 0 and 100 m water depth. High relative abundances of living *N. pachyderma* (sin.) are obtained in the halocline water between 50 and 100 m water depth at station 74, 76, and 91, while at station 69, 77, 79, and 84 the depth maximum is found in the upper 50 m in Polar water masses (Appendix 2.3.). *T. quinqueloba* shows the same trend as *N. pachyderma* (sin.) in depth distribution.

a



b

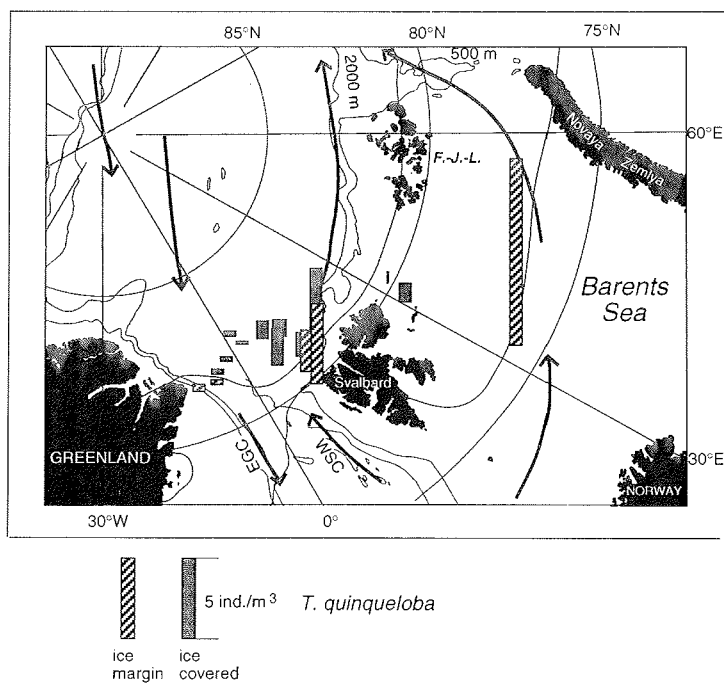
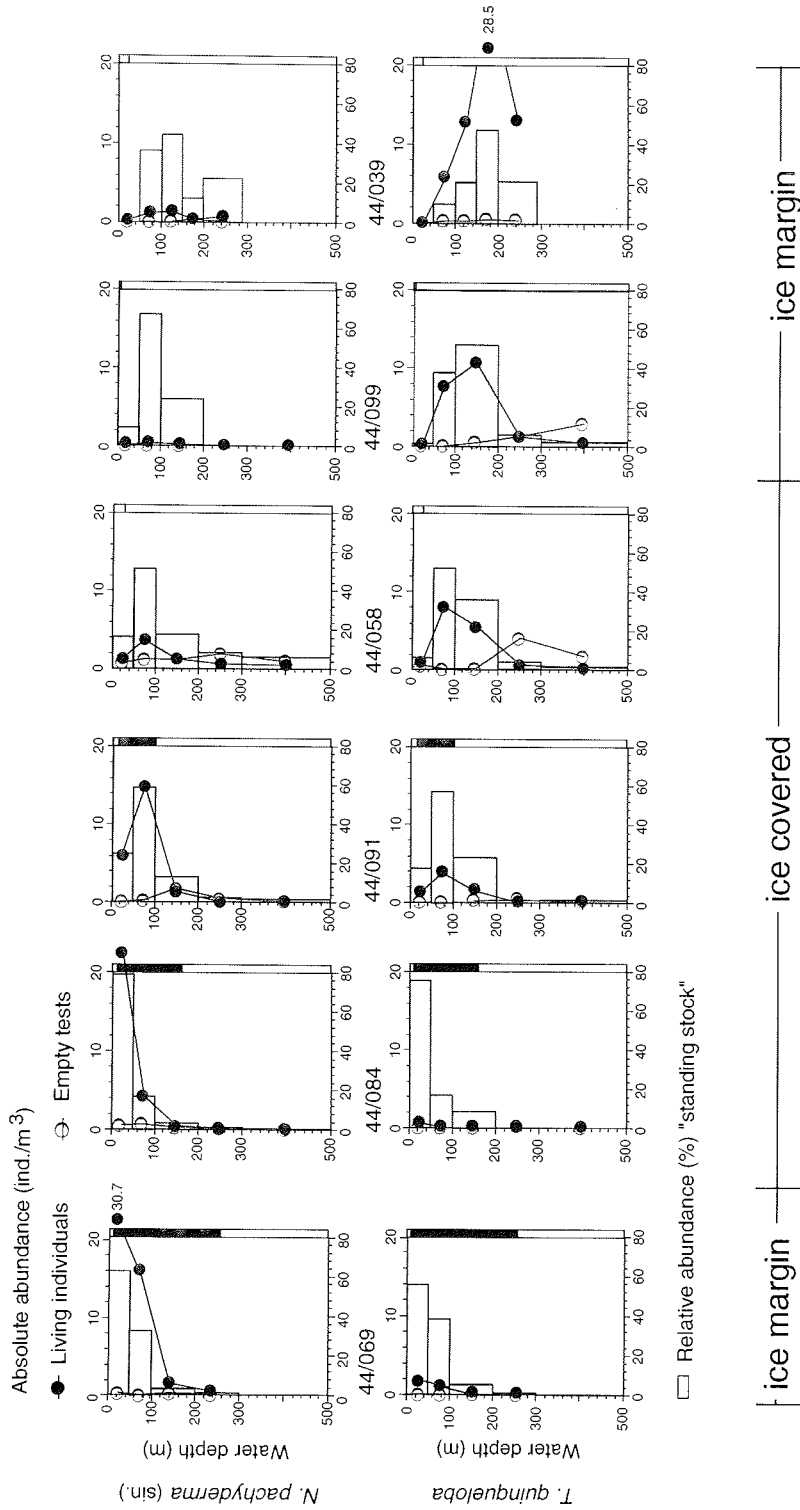


Fig. 2.6.: Absolute abundance of (a) *N. pachyderma* (sin.) and (b) *T. quinqueloba* in the upper 500 m of the water column of the Fram Strait. The grey area marks sea ice cover in June 1997, the dark grey area only in August 1997. The sampling period was June to August. Black arrows show the pathway of Atlantic derived water.

Fram Strait



Barents Sea

Fig. 2.7.: Absolute abundance (living individuals and empty tests) and relative depth distribution as standing stock (living individuals) of *N. pachyderma* (sin.) and *T. quinqueloba* (125-250 μm) in the upper 500 m of the water column in the Fram Strait and the Barents Sea (station 39). Shaded columns mark different water masses (for explanation see Fig. 2.5.). Station data not plotted are listed in Appendix 2.3.

Highest amounts of *N. pachyderma* (sin.) are found at station 89 in the depth interval 0-50 m (83 ind./m³). In the western Fram Strait the depth maximum for both species is between 50 and 100 m (station 60, 96, and 58) under the thin low salinity layer. At station 63 *N. pachyderma* (sin.) prefers the upper 50 m of the water column, while *T. quinqueloba* dominates between 50 and 100 m. Station 99 and station 39 (Barents Sea) are characterized by high surface temperatures (>3 °C) and the absence of halocline water. Here maximum abundances of *N. pachyderma* (sin.) occur between 50 and 100 m and 100 and 150 m, respectively. *T. quinqueloba*, however, prefers deeper waters between 100 and 200 m at station 99 and between 150 and 200 m with maximum abundances of 28.5 ind./m³ at station 39 and no differences in depth habitat exist between the two coiling types. At ice covered station 52 (Barents Sea) with a water depth of about 300 m, planktic foraminifers are generally rare. Here, individuals of both species prefer a water depth between 100 and 200 m.

2.5.3. Significance of the mesh size

Carstens et al. (1997) gave a detailed description of the use of different mesh sizes and revealed significant differences in the species composition compared to earlier studies. Carstens et al. (1997) used a 63 µm mesh and calculated that coarser meshes >150 µm or >200 µm only caught 30-10 % of the population obtained with a 63 µm mesh. In this study, planktic foraminifers >125 µm were used to describe the living community in the upper water column to allow comparison with results from the same mesh size used in surface sediment studies (e.g., Spielhagen and Erlenkeuser, 1994). Species <125 µm are often unidentifiable juvenile specimens (Bé et al., 1985). Usually, *T. quinqueloba* is distinguished from the juvenile stage of *N. pachyderma* on the basis of having fine spines and a thinner wall (Bé and Hamlin, 1967), but it is common for spinose species to shed their spines during the recovery period (Hemleben et al., 1989). Less than 60 % of the individuals <125 µm could be identified to species which were mostly well developed specimens of *T. quinqueloba* with short or well preserved spines. The remaining individuals are juvenile and neanic stages, probably of *N. pachyderma* and microperforate species.

2.6. DISCUSSION

The diversity of planktic foraminifers is generally rare in polar and subpolar regions and a maximum of five species reaches significant abundances (Table 2.2.). In temperate to tropical regions, biodiversity of planktic foraminifers increases gradually and comprises more than 35 species (Vincent and Berger, 1981; Hemleben et al., 1989). The biocoenosis of planktic foraminifers in the Arctic Ocean is dominated by the polar species *N. pachyderma* (sin.) and the subpolar species *T. quinqueloba*. The predominance of *N. pachyderma* (sin.) in other high northern latitude cold-water environments has also been reported by Stehmann (1972), (used mesh size >200 µm), Vilks (1975) (>200

µm), Carstens and Wefer (1992) (>63 µm), Kohfeld et al. (1996) (>150 µm), Carstens et al. (1997) (>63 µm), and Jensen (1998) (>63 µm) and for the Southern Ocean by Donner and Wefer (1994) (>125 µm) and Berberich (1996) (>20 and <100 µm). If not comparable size fractions were counted, the use of different mesh sizes will make comparison almost impossible and standardisation of mesh size for future plankton studies will be urgently required.

2.6.1. Correlation between foraminiferal abundances and hydrography

The distribution pattern of planktic foraminifers in the Arctic Ocean reflects the complex hydrographic regime. The faunal contribution of *N. pachyderma* (sin.) reaches >70 % in the outer Laptev Sea and in the western Fram Strait, where a distinct halocline is developed, while significant amounts of *T. quinqueloba* (>80 %) were found in the relatively warm Atlantic water (station 39, 96, and 99) in the eastern Fram Strait and the Barents Sea. To reveal the preferred water masses of the two dominant species in the 125-250 µm size class, the absolute abundances of each depth maxima for each station is plotted versus mean temperature and salinity (Fig. 2.8.).

In the outer Laptev Sea, most stations show maximum number of living *N. pachyderma* (sin.) in halocline waters between -1.3 and -1.7 °C and salinities between 32.7 and 34.4 psu with highest values up to 10.4 ind./m³ between 50 and 100 m. Living individuals of *T. quinqueloba* have their maximum abundance between 100 and 200 m and the absolute abundances are a factor of ten lower than for *N. pachyderma* (sin.) (Fig. 2.9.).

At station 33 near Severnaya Zemlya under ice-free conditions, the water column is less stratified than in the interior of the Arctic basin (Rudels et al., in press a) and no underlying Atlantic water is present. Here *N. pachyderma* (sin.) prefers warmer and more saline water between 100 and 200 m below the poorly developed halocline at water depths between 20 and 80 m. At station 32 with a similar water mass distribution, highest abundances are observed between 50 and 100 m water depth, but a second maximum with relatively high abundances occurs below 100 m water depth with temperatures around 0 °C and salinities >34.5 psu. These are in the range of the optimal environmental conditions, reported from plankton tows in the North Atlantic (Bé and Tolderlund, 1971).

Similar distributions were described by Bé and Tolderlund (1971) and Carstens et al. (1997), where *N. pachyderma* (sin.) lives in ice-free areas as a “deep-water” species (Bé, 1977) below 100 m water depth. Under a permanent ice coverage, *N. pachyderma* (sin.) migrates into shallower waters between 0 and 50 m water depth. The uppermost low saline (<30 psu) surface layer of about 5 m is expected to be avoid of the planktic foraminifers. This assumption fits well with the observation that no individuals were found in sea ice samples. Although Spindler and Dieckmann (1986) found numerous *N. pachyderma* (sin.) in sea ice of the Weddell Sea, the lack of planktic

foraminifers in Arctic Ocean sea ice has already been described in previous studies (e.g., Spindler, 1990). Differences in sea ice properties are suggested to influence the abundance and diversity of species living in the sea ice system both in the Arctic and Antarctic (Spindler, 1990).

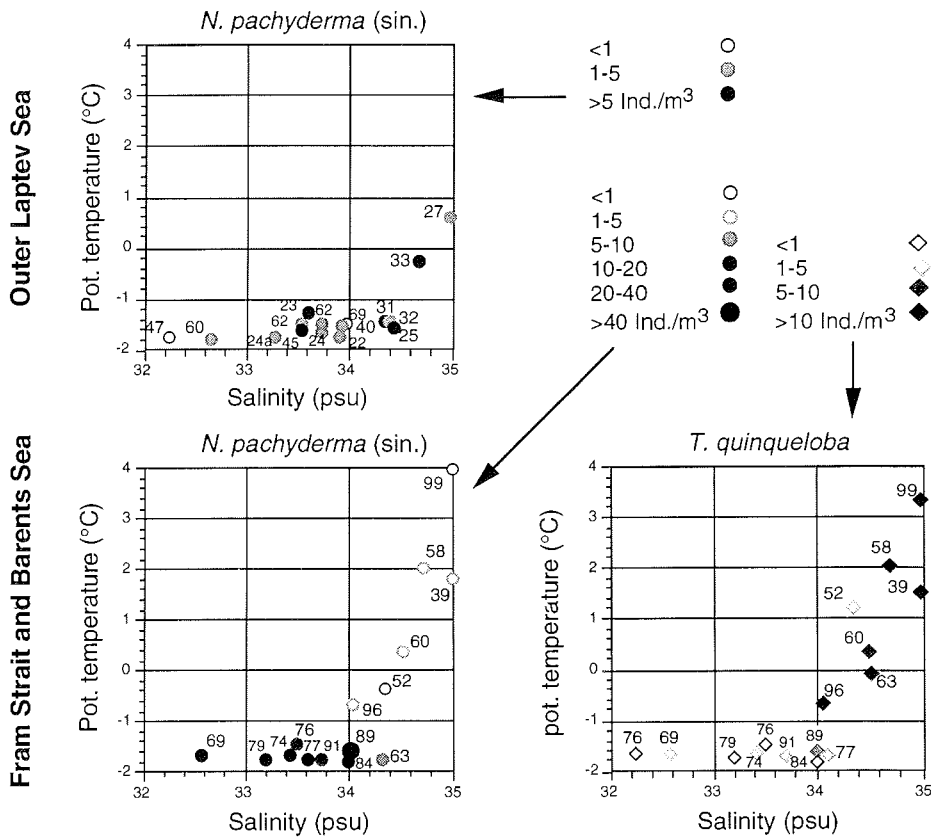


Fig. 2.8.: Absolute abundances of living *N. pachyderma* (sin.) and living *T. quinqueloba* versus potential mean temperature and mean salinity in depth interval with maximum individuals. Values are shown in legend. The station numbers are given in the diagram. Note that maximum abundances of *N. pachyderma* (sin.) are found in a narrow temperature and wide salinity range (PML and halocline), while maximum abundances of *T. quinqueloba* occupy a narrow salinity and wide temperature range (Atlantic water).

The distribution pattern in the Fram Strait is more clearly developed. Here *N. pachyderma* (sin.) shows maximum abundances in a small temperature range between -1.5 and -1.8 °C, but in a wide salinity range between 32.6 and 34.0 psu in the upper 100 m (Fig. 2.8.). This is caused by the shallow depth habitat which *N. pachyderma* (sin.) prefers under the permanent ice cover, where cold surface waters overly the halocline with a wide range of salinities.

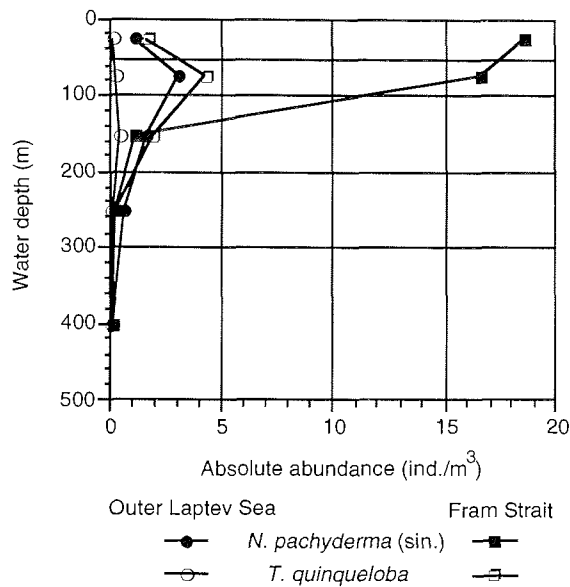


Fig. 2.9.: Average abundances of living planktic foraminifers per cubic metre and depth interval (125-250 µm) in the outer Laptev Sea and the Fram Strait.

Due to the extreme oceanographic conditions in the Arctic Ocean, *N. pachyderma* (sin.) seems to prefer colder and fresher water masses. This depth habitat and the decreased abundance of subpolar and right-coiling species are well developed north of 81°N in the outer Laptev Sea and around north of 82°N in the Fram Strait. Carstens and Wefer (1992) described such a latitudinal boundary near 83°N north of the Barents Sea at 30°E.

At the subpolar ice margin in the eastern Fram Strait and the Barents Sea no halocline is developed. Here the depth habitat of *N. pachyderma* (sin.) is similar to that found in the outer Laptev Sea (0-50 m) and the western Fram Strait (0-100 m). Only in regions of permanent ice cover is this species forced to dwell in shallower water masses.

The depth distribution of *T. quinqueloba* in the Fram Strait is similar to that of *N. pachyderma* (sin.), but *T. quinqueloba* displays lower abundances in general (Fig. 2.10.). At the sea-ice margin *T. quinqueloba* dwells slightly deeper, because of low salinities in the upper water column. At ice-free stations *T. quinqueloba* migrates into shallower water (Carstens et al., 1997). Maximum abundances of *T. quinqueloba*, however, are located in a wide temperature range between -0.7 and 3.4 °C and salinities between 34 psu and almost 35 psu (Fig. 2.8.).

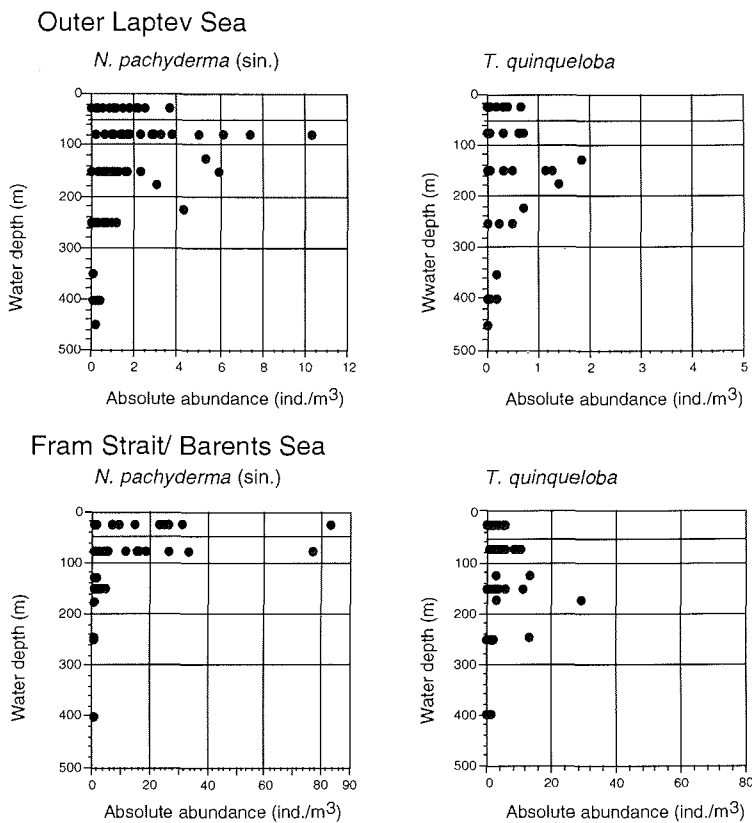


Fig. 2.10.: Absolute abundance of living *N. pachyderma* (sin.) and living *T. quinqueloba* in sampled depth intervals between sea surface and 500 m in the 125-250 μm size class in the outer Laptev Sea, the Fram Strait and the Barents Sea. Note different scales.

2.6.2. Location of the sea-ice margin and food availability

In the Arctic Ocean, primary productivity is largely restricted to the summer season, when light is available and the ice cover is receding (Grahl et al., 1999). Thus, the foraminiferal flux in the Nordic Seas shows a strong seasonality (Jensen, 1998), with high fluxes occurring in late summer and autumn. Kohfeld et al. (1996) observed that the flux of *N. pachyderma* (sin.) was confined to a brief period of two weeks to one month (August), likely tied to phytoplankton blooms. In the Southern Ocean, the foraminiferal flux is also restricted to short periods during the year (Donner and Wefer, 1994), where maximum foraminiferal flux occurs during austral summer in the Bransfield Strait and due to ice-cover somewhat later in the year in the northern Weddell Sea. Accordingly, in this study with sample periods of four and five weeks in the Arctic summer, nets were towed in the period of high productivity of planktic foraminifers.

In summer, melting at the stable ice margin causes stratification in the upper water column. A stable ice situation is well developed near Severnaya Zemlya (the ice movement to the north is lower than 2.5 km per day). Here the absolute abundance of *N. pachyderma* (sin.) reaches maximum values of about 4 ind./m³ in the upper 500 m of the water column. *T. quinqueloba* shows highest abundances of up to 0.5 ind./m³ as well. This could be the result of increased primary production reflected by high chlorophyll *a* values (>2 µg/l) in surface waters northeast of Severnaya Zemlya (Kattner et al., 1999). In contrast, due to the extensive ice coverage, wide areas of the Laptev Sea were low in chlorophyll *a* (see Table 2.1.). These low levels of productivity are reflected in the low absolute abundances of foraminifers as well (1-2 ind./m³).

A correlation between the ice margin in the Barents Sea and the easternmost Fram Strait with highest abundances of *T. quinqueloba* (Fig. 2.6.) is also apparent. However, in the western Fram Strait, *N. pachyderma* (sin.) shows high values at the ice margin (station 69 and 74) and at ice covered stations as well (see Table 2.1.). North of Svalbard, the sea ice movement is relatively slow (1 km per day) and high chlorophyll *a* values for the sampling period were measured in surface waters (>2 µg/l, E.-M. Nöthig, unpubl. data). Lower values are present under ice covered conditions. The vertical distribution of both species supports a weak relationship to the chlorophyll *a* concentration.

Previous studies have shown that planktic foraminifers are most abundant near the chlorophyll *a* maximum (Fairbanks and Wiebe, 1980) and adapt their preferred depth habitat to the seasonal changing chlorophyll *a* maximum. Kohfeld et al. (1996) reported in the Northeast Water Polynya highest abundances of *N. pachyderma* (sin.) at or just below the chlorophyll *a* maximum between 20 and 80 m water depth. However, the chlorophyll *a* concentrations in the studied area of the Arctic Ocean are <4 µg/l, ranging at the lower limit of values measured in the Northeast Water Polynya. In the sampling periods of this study, the chlorophyll *a* maximum mostly occurred above the halocline in the upper 30 m of the water column (see Table 2.1.), whereas *N. pachyderma* (sin.) and *T. quinqueloba* preferred water depths predominantly between 50 and 100 m which is below the chlorophyll *a* maximum. Under a permanent ice cover, a foraminiferal depth habitat between 0 and 50 m is coincident with the chlorophyll *a* maximum, suggesting that it might be a controlling factor.

Carstens et al. (1997) reported strong variations in abundances with numbers of planktic foraminifers along the ice margin "among the highest found in the world ocean" (1250 ind./m³). This observation could not be found in my samples. The differences may be caused by several factors: Carstens et al. (1997) did not distinguish between living and dead individuals and between size classes. Physical properties (e.g., adhesion) might prevent the flux of small tests out of the water column and could feign higher abundances. The strong seasonality of planktic foraminifers and the patchiness of distribution could be an explanation: Surely Carstens et al. (1997) just captured a huge bloom of foraminifers. The movement of the sea ice cover is also different from year to year and Carstens et al. (1997) reported a very stable ice margin in

their sampling period with high chlorophyll *a* values. In my study, the abundances of individuals <125 µm show no correlation to the ice margin in the western Fram Strait and the Barents Sea due to the fast sea ice movement (5-10 km per day) to the north.

Additionally, the distribution pattern of *T. quinqueloba* may follow the occurring other zooplankton as well. Calanoid copepods are the main food source of spinose planktic foraminifers (Spindler et al., 1984). Copepods dominate the zooplankton community in the Laptev Sea and the adjacent Nansen Basin (>90 % of all zooplankton) (Hanssen, 1997), and species distribution is water-mass dependent. Compared to the Barents Sea and regions affected by the West Spitsbergen Current, the copepod biomass in the Laptev Sea is low, and *T. quinqueloba* is almost near absent. The faunal contribution of *T. quinqueloba* increases at the ice margin and in ice-free areas, especially on the Barents Sea shelf. Unfortunately, the preferred food source of *T. quinqueloba* is not really known. *T. quinqueloba* is found in association with Atlantic species of copepods (e.g., *Calanus finmarchicus*), suggesting that these species could be a preferred prey. While *C. finmarchicus* might be too large to serve as a food source for the small *T. quinqueloba*, previous studies have shown that the spinose *Globigerinoides sacculifer* actually needs more time to digest smaller calanoids than larger species (Spindler et al., 1984), and thus prey somewhat larger is no problem for spinose species or a limiting factor.

While chlorophyll *a* concentrations serve as an indicator of algal biomass, they provide no information about the species composition, which may be important to the foraminiferal distribution. In the Fram Strait, the distribution pattern reveals a dominance of diatoms associated with a maximum of chlorophyll *a* concentration in the western part (station 69-74). Flagellates like *Phaeocystis pouchetii* and *Dinobryon balticum* dominate in the southeastern part (station 94-99) (E.-M. Nöthig, pers. comm., 1999). In the central part of the Fram Strait much lower algal biomass was found with other diatom and flagellate species dominating (Bauerfeind and Okolodkov, 1997; Okolodkov, 1997). In the outer Laptev Sea and in the Barents Sea (station 39), where *N. pachyderma* (sin.) shows low abundances, flagellates dominate the phytoplankton community (Okolodkov, 1997). The availability of food, in this case the presence of diatoms, is a further limiting factor for the abundance of *N. pachyderma* (sin.), but until now, investigations of the food source (e.g., content of vacuoles, culturing) are absent. Nevertheless, the correlation between chlorophyll *a* and individual planktic foraminifers needs a differentiation of phytoplankton organisms.

2.6.3. Absolute abundances of planktic foraminifers in the Arctic Ocean

The absolute abundances of planktic foraminifers in the outer Laptev Sea are by a factor of 4 lower than in the Fram Strait (Fig. 2.9.). A correlation between the amount of *N. pachyderma* (sin.) and the supply of diatoms, as main food source of non-spinose species (Spindler et al., 1984) is the most reasonable explanation for this change in *N. pachyderma* (sin.) abundances. The permanent ice coverage might also be a controlling factor, although under the thick ice cover in the Fram Strait higher abundances of planktic foraminifers than in the ice covered outer Laptev Sea could be found. All other parameter such as nutrients (G. Kattner, unpubl. data), temperature, and chlorophyll *a* are similar in both areas. North of the Lena delta, lowest abundances of planktic foraminifers (<1-2 ind./m³), about half that found near Severnaya Zemlya, correspond to the inflow of low saline river waters. Here the salinity is about 29 psu in the surface waters, which is lower than the salinity minimum of 30.5 psu that Boltovskoy and Wright (1976) suggested for both dominant species. The low salinity due to freshwater discharge ranges out of the salinity tolerance for both species. Under this conditions, only few individuals might be able to grow and to carry out their life cycle, resulting in extremely low numbers of planktic foraminifers.

2.6.4. Reproduction

The reproductive cycle has a strong influence on the occurrence and distribution of planktic foraminifers and it is difficult to compare catches of planktic foraminifers sampled during different periods of the synodic cycle. The density of living *N. pachyderma* (sin.) at station 89 in the Fram Strait is unusually high for this sampling period (eight days after full moon), but similar abundances have been reported from ice-covered stations in the northern Nordic Seas (Carstens et al., 1997). It is thought that in early stages of ontogeny, chambers grow very rapidly (Hemleben et al., 1989). Assuming a lunar reproductive cycle for *N. pachyderma* (sin.), the high abundances at station 89, found mainly in the 125-250 µm size class, could represent a generation few ontogenetic stages after reproduction. A synodic reproduction is suggested from plotting the residual values of the size classes 125-250 µm and 250-500 µm versus lunar day (Fig. 2.11.). As expected, the test size spectrum changes over time with high relative proportions of individuals >250 µm around full moon in both sample areas and negative residual values near new moon.

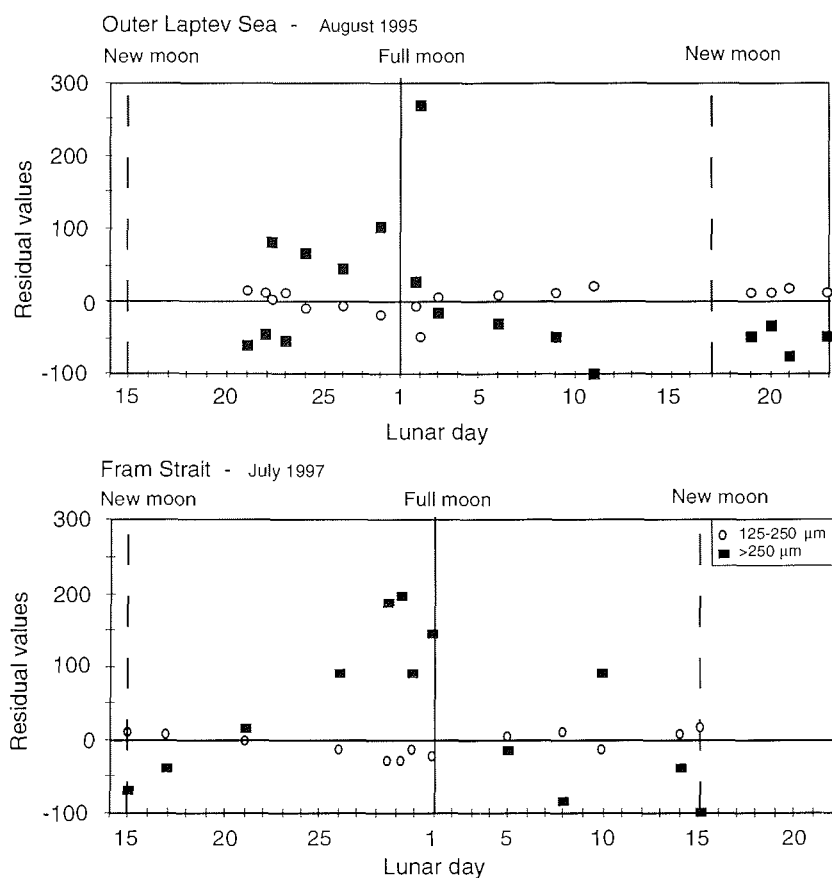


Fig. 2.11.: Residual values, describing the difference between the average relative abundance and the actual relative abundance of the test size classes 125-250 μm and >250 μm of living *N. pachyderma* (sin.) in the outer Laptev Sea and the Fram Strait. Data between 50 and 200 m water depth were used only, because planktic foraminifers are too sparse below 200 m to calculate relative abundances. Stat. 27 includes 0 to 200 m.

This suggests that reproduction takes place around or just before full moon. This hypothesis is supported by the high number of kummerforms in these samples, as the formation of this morphotype has been associated with reproduction (Bijma et al., 1990a). The relative proportions of the 125-250 μm size class show an opposite, but less distinct trend (Fig. 2.11.) (e.g., maximum residuals associated with new moon). Hence maturity is reached mainly in the >250 μm size class.

A lunar reproductive cycle is also assumed for *T. quinqueloba*, and maturity is reached in the 125-250 μm size class. Station 58 and 60 in the Fram Strait show a faunal contribution of *T. quinqueloba* of 54-60 % and fits well with data of Carstens et al. (1997). The similar population pattern despite coarser meshes used in this study might be the result of the population dynamics: Carstens et al. (1997) used samples (>63 μm mesh) taken in a period of seven

days after full moon. Assuming a lunar reproductive cycle of spinose planktic foraminifers (Hemleben et al., 1989; Bijma et al., 1994; Schiebel et al., 1997), these samples might include a lot of juvenile and neanic specimens. Station 58 and 60 were sampled in a period of three days after new moon, where high abundances of adult individuals were obtained (>125 µm mesh). Thus, the faunal distribution in plankton tows is only a snapshot of the life cycle and high variations have to include in the population patterns and the species depth habitat.

2.6.5. Lateral transport

Except the “true” polar species *N. pachyderma* (sin.), all planktic foraminifers in the Arctic Ocean were transported by water masses of Atlantic origin. The preferred depth habitat of living *N. pachyderma* (dex.) between 50 and 100 m water depth is quite constant, with similar abundances in the two studied areas. Empty tests are most abundant below 200 m water depth in the outer Laptev Sea. Regardless of the discussion about genetic or temperature control of coiling direction (e.g., Hemleben et al., 1989), *N. pachyderma* (dex.) is most abundant in subpolar water masses (Bé, 1977). A few right-coiling individuals are most likely transported with water masses of Atlantic origin (Carstens and Wefer, 1992). These individuals might be able to grow in the Arctic Ocean, but reproduction seems to be unlikely, as indicated by the low amounts of kummerform individuals. Despite the fact that *N. pachyderma* (dex.) prefers warmer water masses, the living individuals found in this study seem to be adapted to the extreme environment and dwell slightly shallower under permanent ice cover conditions than *N. pachyderma* (sin.). The distribution pattern of *G. glutinata* and *G. uvula* does not show a regular pattern.

A considerable number of these species and some “exotic” empty tests of *G. aequilateralis*, *G. falconensis*, *G. rubescens*, *G. ruber*, and *G. tenella* in a water depth between 300 and 500 m at the outer Laptev Sea deserve mention. These specimens are relatively well-preserved and show no redeposition features, excluding the possibility that they are derived from reworked older sediments along the eastern shores of the Laptev Sea (Bauch, 1999). In the Fram Strait and the Barents Sea no individuals of these species were observed and the relative abundances of *G. glutinata* and *G. uvula* show low values (Table 2.2.). A possible explanation is the transport of empty tests with Atlantic water masses into the Arctic Ocean. Atlantic-derived water submerges beneath the Polar Mixed Layer and reaches the catchment area of sampled water depth in the outer Laptev Sea. Assuming high influx (3.7 Sv) of Atlantic water (Aagaard and Carmack, 1989), carried by the WSC, high influx (2.4 Sv) to the Barents Sea, and a sinking speed of 100 to 300 m per day for tests >150 µm (Takahashi and Bé, 1984), the “exotic” species could have lived somewhere in the Norwegian-Greenland Sea. The theoretically possible, shorter way from the Pacific Ocean via inflow over the 45 m-deep Bering Strait seems unlikely because of the shallow sill depth. In addition, several studies about Holocene and glacial deposits in the Barents and Kara Sea yielded “exotic” planktic foraminifers (Blaschishin et al., 1985; Khusid et al., 1995).

Carstens and Wefer (1992) discuss a transport of subpolar species with water masses of Atlantic origin into the Nansen Basin, where they might be able to grow and few might be able to release gametes. The subpolar and "exotic" foraminifers might be indicators for the relatively warm Atlantic water inflow.

Furthermore, *Globigerina bulloides* was absent in the samples studied, a species usually occurring in temperate water masses (Kennett and Srinivasan, 1983), but reported by Carstens et al. (1997) and Bock (1990) for the Nordic Sea in the sphere of influence of Atlantic water masses and for the Baffin Bay (Stehmann, 1972) with similar oceanographic conditions. The absence of *G. bulloides* in the Arctic Ocean corresponds to results of other plankton tow investigations in the northern high latitudes (Bé and Tolderlund, 1971; Jensen, 1998), although warmer water masses were sampled. The transport of *G. bulloides* with Atlantic water masses may be a sporadic process, following annual and/or lunar periodicity, or is probably linked to food availability or water column stratification. Therefore, the catch of *G. bulloides* is possibly pure chance.

2.6.6. Calcification depth of *N. pachyderma* (sin.)

Assuming that living individuals calcify approximately in the depth interval where they were sampled, a calcification weighting factor was calculated for some stations by the proportions of living individuals (standing stock) and the proportions of individuals with a secondary calcite crust (Appendix 2.4.). While the average depth of calcification lies between 100 and 200 m water depth in the Fram Strait as well as in the outer Laptev Sea, the average depth of habitat lies between 50-100 m at ice covered and cold Polar Water affected stations and descends downward to about 100 m water depth at the ice margin and at stations affected by warm Atlantic water masses (Fig. 2.12.).

This is in accordance with calculations made on *N. pachyderma* (sin.) in the Nansen Basin (Bauch et al., 1997), although no ice cover dependence, but Polar water mass influence at the shallower depth habitat was observed. A similar average depth of habitat as for *N. pachyderma* (sin.) is calculated for living *T. quinqueloba* (Fig. 2.12.).

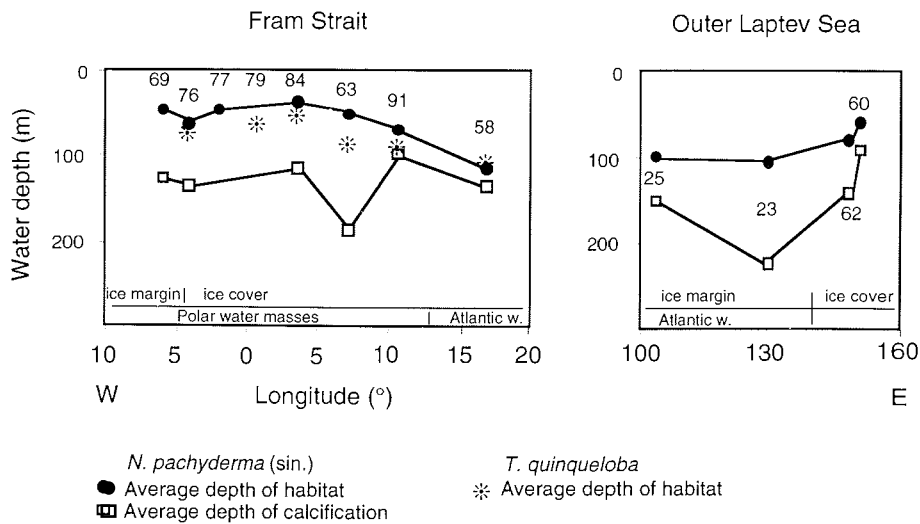


Fig. 2.12.: Average depth of habitat of living *T. quinqueloba* and *N. pachyderma* (sin.) and average depth of calcification of living *N. pachyderma* (sin.) vs. longitude in the 125-250 μm size class. Station numbers are given in the diagram. Atlantic w. marks stations, where the temperature in the Atlantic Layer is greater than 2 °C.

2.6.7. Paleoceanographic implications

Reconstructions of past polar ocean environments are often based on faunal compositions and chemical properties of planktic foraminifers in deep-sea sediments. At present, the occurrence of both dominant species in the Arctic Ocean is well correlated to the hydrographic regime and provides a reliable proxy for water mass characterisations. The depth habitat of both species is influenced by a vertical migration due to the rhythmic life cycle and food supply. Furthermore, the perennial ice cover forces *N. pachyderma* (sin.) to dwell shallower between 0 and 50 m water depth, as observed in the western Fram Strait and in the ice covered outer Laptev Sea, as also in the central Arctic Ocean (e.g., Carstens and Wefer, 1992) and its distribution demonstrates a small range in temperature of about -1.3 to -1.8 °C. In contrast, the open water conditions lead this species to descend into water depths between 100 and 200 m, where temperature and salinity are generally higher. These species-specific depth habitats are fundamental preconditions for reconstructing past polar environments from planktic foraminiferal stable isotope composition. Therefore, to reconstruct sea-surface temperature (SST) and salinity (SSS) in high latitudes from stable isotope compositions of *N. pachyderma* (sin.) in deep-sea sediments, the ice coverage has to be known to calculate the apparent depth habitat. Except of a species-specific vital effect (e.g., Bauch et al., 1997), the oxygen isotope composition of planktic foraminifers reflects the ambient water mass properties and is recorded in fossil specimens.

Paleotemperature estimates from planktic foraminiferal assemblages in the cold extremes of the temperature range worsen, because of mono-specific assemblages of *N. pachyderma* (sin.) (Wefer et al., 1999). The extent of the ice coverage and water mass boundary characterisation may be given by appropriate amounts of *T. quinqueloba*, which reaches worth mentioning abundances in Atlantic water masses at the sea-ice margin and under ice-free conditions. However, preferably delicate species (e.g., Vincent and Berger, 1981) such as *T. quinqueloba*, are selectively dissolved, while the compact test of *N. pachyderma* (sin.) is more resistant. The biogeographic distribution of living planktic foraminifers probably do not match sediment foraminiferal assemblages, because nonencrusted *N. pachyderma* (sin.) are completely absent in surface sediments of the Northeast Water Polynya (Kohfeld et al., 1996), but common in plankton tow samples. The flux of planktic foraminifers to the ocean floor is important to understand the relationship between recent and past marine environments, but studies on planktic foraminiferal assemblages in the 125-250 µm size class of surface sediments of the Arctic Ocean are not available yet. To interpret paleoenvironmental changes, diverse planktic foraminifer assemblages in sediments are needed, as suggested for the Nordic Seas (Jensen, 1998).

2.7. CONCLUSIONS

The distribution pattern of living planktic foraminifers in the Arctic Ocean indicates a strong relation to the hydrographic regime. The cold Polar waters yielded high abundances of *N. pachyderma* (sin.) (>70 %), while *T. quinqueloba* dominates in warm Atlantic water (>80 %). The ratio between absolute abundances of planktic foraminifers in the Fram Strait, the open ocean near Severnaya Zemlya and the less saline outer Laptev Sea is 8:2:1. In the cold Polar waters the subpolar *T. quinqueloba* is a factor of ten less abundant than the polar *N. pachyderma* (sin.).

The typical depth habitat of *N. pachyderma* (sin.) in permanent ice covered areas of the Arctic Ocean is the uppermost water column with cold and fresh water masses (between 5 and 50 m water depth). Under ice-free conditions, *N. pachyderma* (sin.) lives deeper in warmer and more saline water masses. The availability of diatoms as a main food source may influence their absolute abundances and might be the main controlling factor. *T. quinqueloba* adapt to the extreme oceanographic conditions as well and lives shallow under the permanent ice cover, but migrates into deeper water masses at the ice margin. The position of the sea-ice margin significantly influences the abundances of planktic foraminifers, when slow ice movement permits a stable stratification, usually resulting in higher primary production.

Neogloboquadrina pachyderma (sin.) reproduces around full moon below 100 m water depth, and maturity is reached mainly in the >250 µm size class. Comparative studies indicate a lunar reproductive cycle for *T. quinqueloba* as well. Close to the synodic life rhythm, the planktic foraminifers migrate through different water depths and each catch is just a snapshot. The life horizons and the size class distributions change during the reproduction cycle and have to be included in the interpretation of the species depth habitat.

3. STABLE ISOTOPE COMPOSITION ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) OF LIVING PLANKTIC FORAMINIFERS IN THE OUTER LAPTEV SEA AND THE FRAM STRAIT

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3.1. ABSTRACT

The upper water column in the Fram Strait and the outer Laptev Sea was sampled for living planktic foraminifer species *Neogloboquadrina pachyderma* (sin.) and *Turborotalita quinqueloba*. Their shell $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are compared to water oxygen and dissolved inorganic carbon isotope data to determine the environmental influence on the foraminifers' isotopic ratio. Major controls on the oxygen isotope composition of both species are the shallow depth habitat under permanent ice coverage, the low salinity surface layer, and the rate of metabolic activity. None of the specimens precipitated its shell in isotopic equilibrium with the ambient sea water. They are all depleted in ^{13}C and ^{18}O , attributed to a species-specific vital effect. For nonencrusted *N. pachyderma* (sin.) in the 125-250 μm size class, this vital effect amounts to 1.3 ‰ in $\delta^{18}\text{O}$ and 2.0 ‰ in $\delta^{13}\text{C}$. It increases to higher values in waters under permanent ice cover. *Turborotalita quinqueloba* reveal a mean vital effect of about 1.3 ‰ in $\delta^{18}\text{O}$ and 2.6 ‰ in $\delta^{13}\text{C}$. The general isotopic trends are similar for *N. pachyderma* (sin.) and *T. quinqueloba*. Differences in the species' isotope ratio at the same sites are caused by different calcification depths and metabolic activity. The oxygen isotope composition of *N. pachyderma* (sin.) shows a relationship to salinity measurements and indicates that it is a good quantitative proxy for salinity reconstructions, while no relationship exists between oxygen isotopes and water temperature.

3.2. INTRODUCTION

Oxygen and carbon isotope data of planktic foraminifers are powerful tools for paleoceanographic reconstructions. For an accurate interpretation of the isotope signature in deep-sea sediments, factors controlling the isotope ratio have to be identified and quantified. Stable isotope studies of living planktic foraminifers have demonstrated that many species show significant variability in their oxygen and carbon isotope composition (e.g., Fairbanks et al., 1980; Sautter and Thunell, 1991; Bauch et al., 1997; Simstich, 1999). Most of this variability is attributed to the vertical migration of foraminifers during their life cycle (Emiliani, 1971; Hemleben et al., 1989; Kohfeld et al., 1996). Factors such as water chemistry and biological fractionation make the interpretation of stable isotope values more difficult.

The non-spinose species *Neogloboquadrina pachyderma* (sinistral coiling) dominates the planktic foraminifer assemblages in polar regions, and provides continuous isotope records in high latitude sediment cores (e.g., Nørgaard-

Pedersen, 1997; Knies, 1999). The spinose and symbiont-bearing species *T. quinqueloba* is most common in subpolar water masses (e.g., Carstens et al., 1997; Jensen, 1998; Volkmann, in press), and is the most abundant and widespread subpolar foraminifer in Holocene sediments of the Nordic Seas (Bauch, 1993). In the ice covered Arctic Ocean, both species' life habitats are restricted to the uppermost Polar water. While open water conditions lead *N. pachyderma* (sin.) to migrate into water depths greater than 100 m (Carsten et al., 1997; Volkmann, in press), symbionts confine the habitat of *T. quinqueloba* to the photic zone (Bé, 1977). Relative to the World's Ocean, the modern Arctic Ocean is of special interest due to the perennial ice cover and high freshwater input. Little knowledge exists how the shell chemistry of planktic foraminifers reflects these extreme oceanographic conditions (Bauch et al., 1997; Spielhagen and Erlenkeuser, 1994).

In this paper, we present oxygen and carbon isotope data of living and dead *N. pachyderma* (sin.) and *T. quinqueloba* in the upper water column of the Arctic Ocean (Fig. 3.1.). They are compared to direct isotope measurements of seawater and equilibrium calcite values. Physiological effects in the isotopic ratio are discussed, and factors controlling the absolute isotope signature are determined.

3.3. HYDROGRAPHIC OVERVIEW

The Arctic Ocean is characterized by a perennial sea ice coverage, high freshwater discharge onto the Siberian shelves, and a strong stratification in the upper water column (Rudels et al., 1994) (Fig. 3.2.). Summer sea-ice melt and river run-off from the continents cause a thin low salinity surface layer (salinity < 30 psu: salinity units on the "Practical Salinity Scale 1978"), e.g., north of the Lena outflow. The underlying Polar Mixed Layer (PML) (potential temperature = -1.6 to -1.8 °C, salinity 33-34 psu) is about 10-50 m thick. The Transpolar Drift carries sea ice and river run-off from the Siberian shelves across the Arctic Basin, and eventually feeds into the East Greenland Current (EGC) which transports cold Polar water southward in the western Fram Strait.

A distinct halocline with temperatures close to the freezing point (~ -1.8 °C) is observed throughout the Arctic Ocean: in the outer Laptev Sea between 20 m and maximal 170 m water depth and at the East Greenland continental slope between 20 m and maximal 260 m. Atlantic water flows into the Arctic Ocean in the West Spitsbergen Current (WSC) from the Norwegian Sea in several cores through the eastern Fram Strait and over the Barents Sea (Rudels et al., in press a). North of Svalbard, the halocline is only weakly developed and the Atlantic Layer (AL) reaches temperatures up to 2.5 °C.

Northeast of Severnaya Zemlya the water column is less stratified due to shelf derived waters (Rudels et al., in press b). At the Laptev Sea continental margin, the AL is observed between 130 and 600 m water depth where the temperatures are slightly above 2 °C and the salinities are higher than 34.9 psu. In the western Fram Strait, the AL underlies the halocline down to 600 m water depth with temperatures above 0.5 °C.

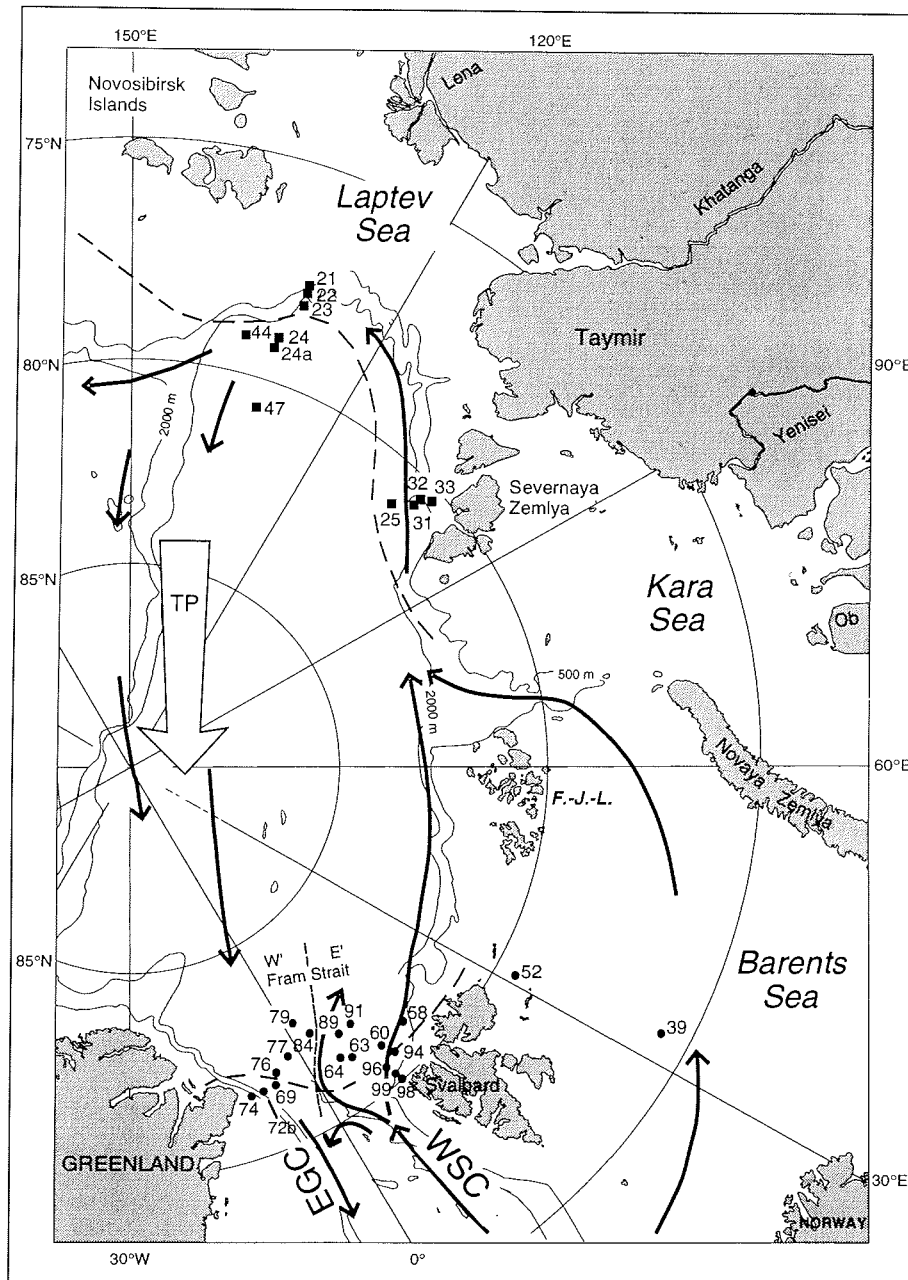


Fig. 3.1.: Sampling area and hydrographic setting in the Arctic Ocean. Broken lines mark summer sea ice margins (August) as indicated by shipboard observations and SSM-I evaluation (Special Sensor Microwave/Imager). Note different dates and years of samples. Multinet tows were performed during ARK-XI/1 (■) in August 1995 and ARK-XIII/2 (●) in July 1997. Black arrows denote the movement of Atlantic derived water; WSC: West Spitzbergen Current, EGC: East Greenland Current; TP: Transpolar Drift. The dotted line in the Fram Strait separates the western from the eastern part.

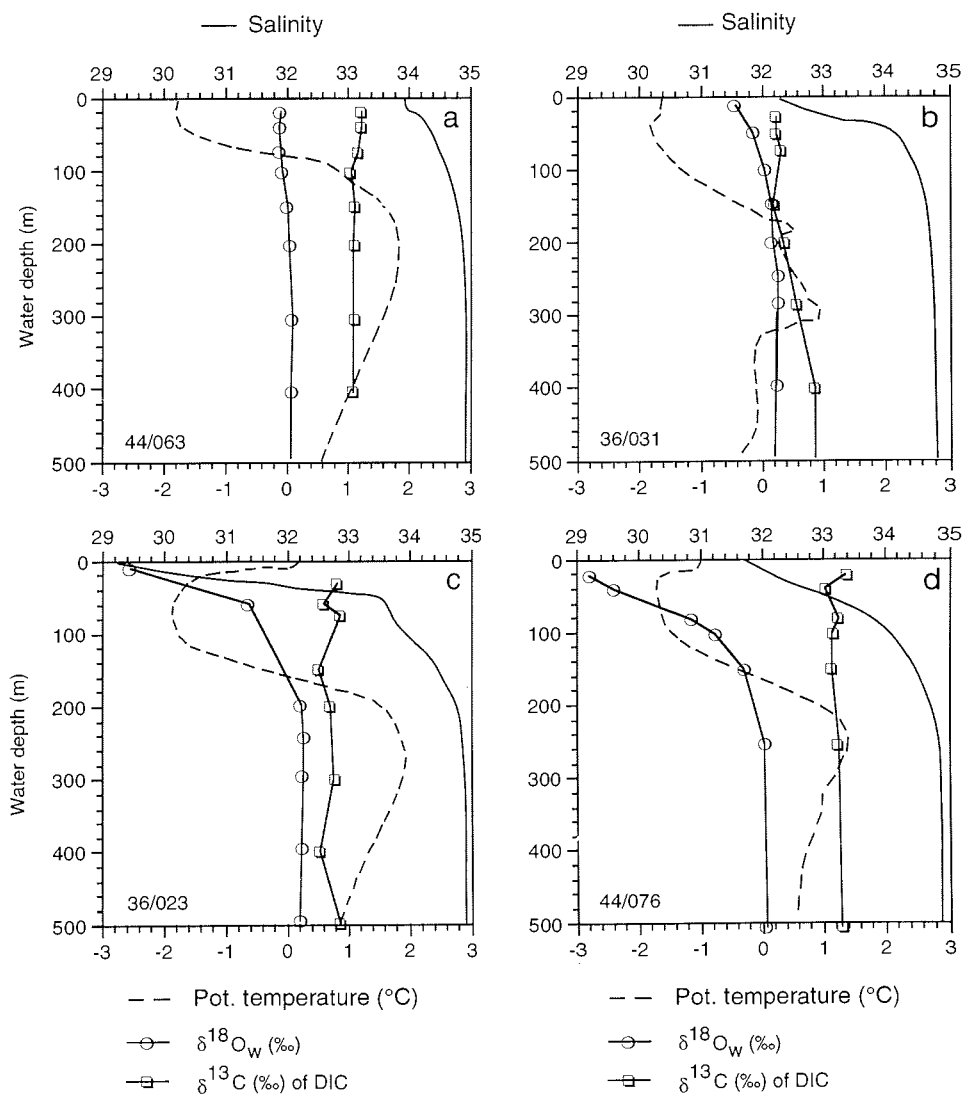


Fig. 3.2.: Potential temperature, salinity, water $\delta^{18}\text{O}$, and $\delta^{13}\text{C}_{\text{DIC}}$ profiles from stations (a) in the eastern Fram Strait, (b) northeast of Severnaya Zemlya, (c) the outer Laptev Sea, and (d) the western Fram Strait. Panels are arranged along the Atlantic Water inflow. Temperature and salinity profiles are based on CTD-data by Rudels et al. (in press a, b).

3.4. MATERIALS AND METHODS

Plankton tows and samples of the ambient seawater used in this study were obtained during “Polarstern” expedition ARK-XI/1 in August 1995 (Rachor, 1997) and during ARK-XIII/2 in July 1997 (Stein and Fahl, 1997) (Fig. 3.1.) in the Arctic Ocean. Plankton samples were collected by multinet casts in the outer Laptev Sea, the Fram Strait, and the western Barents Sea. The nets of 63 μm mesh size were towed vertically on regular depth intervals (Table 3.1.).

All plankton samples were preserved in a 4 % buffered formalin seawater solution, and stored at 2 °C. To distinguish living and dead individuals, plankton samples were treated with bengal-rosa-ethanol solution. All foraminifers were picked by pipette, rinsed with tap water and methanol to remove organic material and water, respectively. Faunal contribution and species abundances have been published by (Volkman, in press, Journal of Foraminiferal Research). Specimens of nonencrusted forms of *N. pachyderma* (sin) in the 125-250 µm, and encrusted individuals in the >250 µm size class, and *T. quinqueloba* (sin.) and *T. quinqueloba* (dextral) in the 125-250 µm size class were roasted in vacuo at 200 °C for 1 hour.

The oxygen and isotope mass ratios of the planktic foraminifers were measured using a Finnigan-MAT 251 mass spectrometer (Leibniz Laboratory Kiel University and University Bremen). Isotopic composition is given in the usual δ -notation and is calibrated to Vienna Pee Dee Belemnite (V-PDB) standard. Measurement errors are ± 0.08 ‰ and ± 0.05 ‰ for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, respectively. Standard error on the average difference is calculated from the standard deviation divided by the square root of measured number of samples (n).

Temperature and salinity distribution of the upper water column are based on in situ conductivity, temperature, and depth (CTD) measurements (Rudels, in press a, b) and were collected directly before the tows. According to the warm Atlantic water branches entering the Arctic Ocean in the WSC through the Fram Strait, station 44/069 to 44/084 are assigned to the western Fram Strait, and the other stations to the eastern Fram Strait (Fig. 3.1.).

Water samples for stable isotope analyses were taken directly after the rosette sampler had returned to the ship's deck to minimize loss of CO_2 and exchange with atmospheric CO_2 . For the $\text{H}_2^{18}\text{O}/\text{H}_2^{16}\text{O}$ analyses, water samples were drawn into glass bottles, sealed by plastic screw-on caps with polyethylene inserts, and analyzed using a Finnigan MAT252 mass spectrometer (Institut für Umweltp Physik, University Heidelberg). Water samples for carbon isotope analyses were filled slowly into 100 ml ground glass bottles and 0.2 ml HgCl_2 were added to stop biological activity. Handling procedure for the carbon isotope measurements of water samples (Leibniz Laboratory) is described in detail by Erlenkeuser et al. (1999). The reference standard is Vienna Standard Mean Ocean Water (SMOW). Accuracy for water $\delta^{18}\text{O}_w$ is better than 0.03 ‰, for $\delta^{13}\text{C}$ of DIC (Dissolved Inorganic Carbon) better than 0.02 ‰.

The oxygen "equilibrium calcite value", δ_c , was calculated between sea surface and 500 m water depth from actual $\delta^{18}\text{O}$ (δ_w) and temperature (T) measurements according to the paleotemperature equation of O'Neil et al. (1969) and Shackleton (1974):

$$T = 16.9 - 4.38 (\delta_c - \delta_w) + 0.1 (\delta_c - \delta_w)^2$$

The conversion factor between $\delta^{18}\text{O}_w$ from the V-SMOW to the V-PDB scale is

$$\delta_w = 0.9998 \delta^{18}\text{O} (\text{V-SMOW}) - 0.2 \text{ ‰} \quad \text{Bemis et al. (1998)}$$

Cruise	Station	Latitude	Longitude	Bottom depth (m)	Depth-range (m)	Date	Time (GMT)	Ice cover	average depth of habitat <i>N. pachyderma</i> (sin.) (in m water depth)
Outer Laptev Sea									
ARK-XI/1	36/021	77°51.0N	130°03.8E	1153	0-50-100-200-300-500	02.08.95	13:55	no ice	
	36/022	77°55.8N	130°02.7E	1811	0-50-100-200-300-500	03.08.95	4:22	ice margin	120
	36/023	78°09.6N	129°58.7E	2289	0-50-100-200-300-500	03.08.95	19:45	ice margin	110
	36/024	79°07.8N	131°26.5E	3061	0-50-100-200-300-500	04.08.95	23:37	ice covered	100
	36/024a	79°19.2N	131°33.4E	3102	0-50-100-200-300-500	05.08.95	19:20	ice covered	140
	36/025	81°08.5N	105°38.9E	2507	0-50-100-200-300-500	07.08.95	19:02	ice margin	100
	36/031	80°46.2N	103°21.6E	1177	0-50-100-200-300-500	11.08.95	8:35	no ice	80
	36/032	80°38.5N	103°03.2E	546	0-50-100-200-300-500	11.08.95	20:15	no ice	140
	36/033	80°25.9N	101°58.7E	245	0-50-100-150-200-245	12.08.95	6:06	no ice	140
	36/040a	78°30.5N	133°49.7E	1738	0-50-100-200-300-500	15.08.95	17:20	ice margin	100
	36/047	80°55.6N	131°16.6E	3846	0-50-100-200-300-500	20.08.95	21:32	ice covered	40
Fram Strait									
ARK-XIII/2	44/039	75°59.9N	32°58.8E	310	0-50-100-150-200-290	27.06.97	10:47	ice margin	180
	44/052	79°26.7N	38°29.6E	325	0-50-100-150-200-300	30.06.97	0:56	ice covered	200
	44/058	81°05.9N	16°56.5E	970	0-50-100-200-300-500	04.07.97	10:50	ice covered	120
	44/060	80°58.2N	11°50.8E	2001	0-50-100-200-300-500	06.07.97	16:30	ice covered	110
	44/063	81°05.6N	7°00.7E	861	0-50-100-200-300-500	10.07.97	3:00	ice covered	50
	44/064	81°07.7N	5°36.9E	632	0-50-100-200-300-500	11.07.97	1:14	ice covered	
	44/069	81°27.2N	5°23.3W	3596	0-50-100-200-300-500	15.07.97	10:30	ice margin	50
	44/072b	81°34.9N	8°10.5W	1980	0-50-100-200-300-500	17.07.97	15:45	ice margin	
	44/074	81°35.3N	10°00.7W	524	0-50-100-200-300-500	18.07.97	4:05	ice margin	60
	44/076	81°52.8N	4°34.7W	4185	0-50-100-200-300-500	18.07.97	16:50	ice covered	60
	44/077	81°59.9N	2°25.8W	2584	0-50-100-200-300-500	19.07.97	11:50	ice covered	50
	44/079	82°39.1N	1°24.4E	3228	0-50-100-200-300-500	20.07.97	23:30	ice covered	40
	44/084	82°19.3N	3°42.1E	2092	0-50-100-200-300-500	24.07.97	6:48	ice covered	40
	44/089	81°54.0N	7°50.2E	846	0-50-100-200-300-500	27.07.97	12:45	ice covered	50
	44/091	81°39.8N	10°26.9E	1544	0-50-100-200-300-500	29.07.97	0:35	ice covered	70
	44/094	80°43.9N	11°51.3E	1020	0-50-100-200-300-500	01.08.97	10:53	ice margin	
	44/096	80°31.9N	10°22.7E	782	0-50-100-200-300-500	02.08.97	5:50	ice margin	90
	44/098	80°00.1N	10°52.3E	258	0-50-100-150-200-254	02.08.97	19:44	ice margin	
	44/099	80°11.5N	10°24.1E	517	0-50-100-200-300-500	04.08.97	15:30	ice margin	100

Table 3.1.: Station locations, sampled depth intervals, ice coverage, and average depth of habitat of *N. pachyderma* (sin.) from multinet tows.

3.5. DISTRIBUTION OF LIVING PLANKTIC FORAMINIFERS IN THE ARCTIC OCEAN

The absolute abundances of living planktic foraminifers in the 125-250 μm size class in the upper 500 m of the water column decrease from 17 ind./ m^3 in the Fram Strait and 14 ind./ m^3 in the Barents Sea to 4 ind./ m^3 northeast of Severnaya Zemlya and less than 2 ind./ m^3 in the eastern part of the outer Laptev Sea. This strong gradient as well as the almost complete absence of planktic foraminifers from the central and eastern Laptev Sea continental margin close to the Lomonosov Ridge is caused by the nearly permanent ice coverage, low availability of food, and the low salinity surface layer due to freshwater discharge from the Lena river (Volkman, in press).

In cold Polar waters ($T < 0\text{ }^\circ\text{C}$) high abundances (>70 %) of the polar species *N. pachyderma* (sin.) are observed, while the subpolar species *T. quinqueloba* dominates in the warmer Atlantic derived water masses of the WSC and the Barents Sea (80 %). The preferred depth habitat of living *N. pachyderma* (sin.) is between 50 and 100 m in the outer Laptev Sea, but single specimens still live down to 500 m water depth. In contrast, in the Fram Strait living *N. pachyderma* (sin.) is almost exclusively found in the upper 300 m. While the average depth of calcification, as defined by Bauch et al. (1997), lies between 100 and 200 m water depth in the Fram Strait as well as in the outer Laptev Sea, the average depth of habitat lies between 50-100 m at stations that are ice covered and affected by cold Polar waters, and increases to about 100 m water depth at the ice margin and stations affected by warm Atlantic water masses (Volkman, in press). *Turborotalita quinqueloba* is confined to the photic zone (Bé, 1977) in ice covered areas and under ice-free conditions. It migrates into deeper water masses at the ice margin (Carstens et al., 1997; Volkman, in press).

The planktic foraminifers >250 μm showed highest abundances of up to 2 ind./ m^3 near Severnaya Zemlya and in the western Fram Strait, in agreement with the lunar reproductive cycle of *N. pachyderma* (sin.), which account for >85 % of all planktic foraminifer shells >250 μm , and revealed high relative proportions around full moon (Volkman, in press). Ontogeny of *N. pachyderma* (sin.) is size-correlated, and maturity is reached at sizes >175 μm (Berberich, 1996), therefore the last, terminal ontogenetic stage, can occur in both analysed size classes. The formation of kummerforms (last chamber of the whorl) (Bijma et al., 1990a), or a secondary calcite crust (Kohfeld et al., 1996) are possible features for fully-grown individuals. Encrustation could be a gradual process beginning near the surface and continuing while descending in the water column (Kohfeld et al., 1996), whereas Simstich (1999) suggests that growth and encrustation of single individuals occur at different, but well defined, small scale depth intervals.

3.6. ISOTOPE RESULTS

The stable isotope results of *N. pachyderma* (sin.) and *T. quinqueloba* are presented separately for both investigated areas. Oxygen and carbon isotope

values of both planktic foraminifers are shown in Figures 3.3. and 3.4. for selected representative stations (for all data see Appendix 3.1. and 3.2.).

3.6.1. Outer Laptev Sea and northeast of Severnaya Zemlya

The $\delta^{18}\text{O}$ composition of living *N. pachyderma* (sin.) in the outer Laptev Sea covers a range between 1.0 and 3.13 ‰ (Appendix 3.1.) with a mean value of 2.40 ‰ (± 0.61 , $n=26$) for individuals in the 125-250 μm size class. In the >250 μm size class $\delta^{18}\text{O}$ values show a mean value of 3.08 ‰ (± 0.48 , $n=18$). The $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) in the 125-250 μm size class are generally lower of 0.52 ‰ (± 0.36 , $n=14$). Northeast of Severnaya Zemlya $\delta^{18}\text{O}$ values are generally about 0.6 ‰ higher than in the outer Laptev Sea. The vertical variation of the $\delta^{18}\text{O}$ values is relatively high (Fig. 3.3.), caused by a few extremely low values (1.0-1.3 ‰) measured at station 22 and 32 in the 50-100 m depth interval.

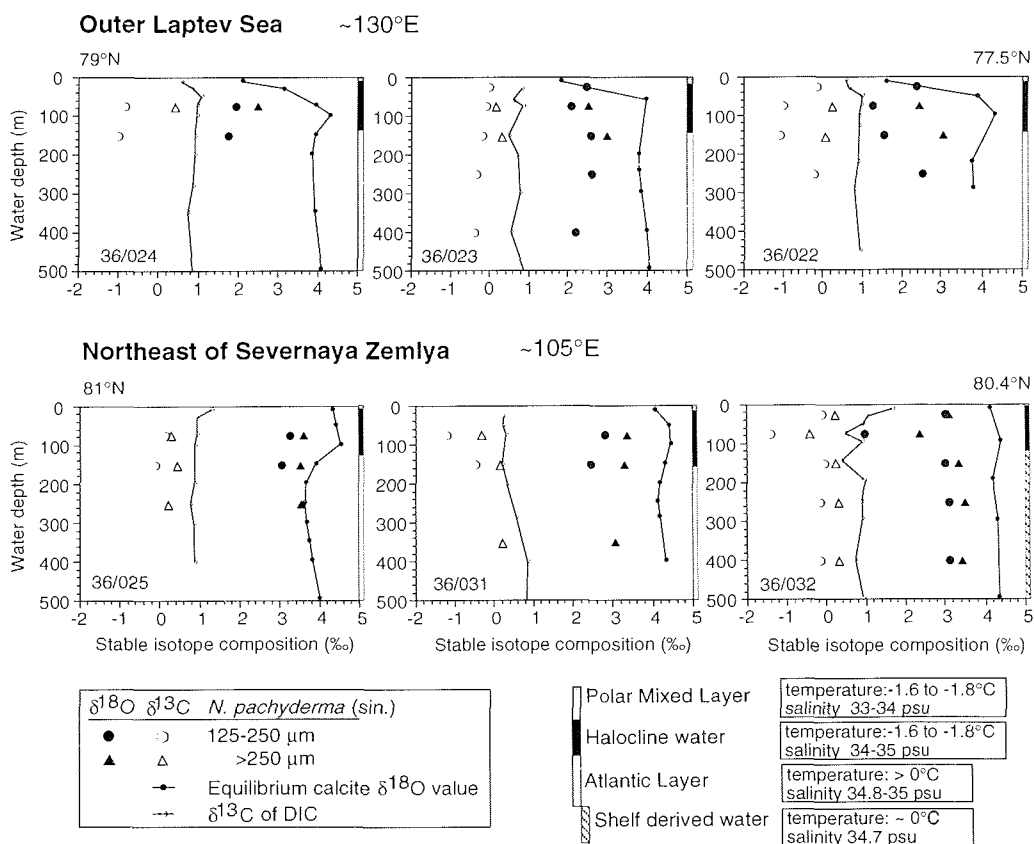


Fig. 3.3.: Stable isotope composition of living *N. pachyderma* (sin.) in the upper water column of the outer Laptev Sea (station 22-24) and north of Severnaya Zemlya (station 25-32) for the 125-250 μm size class (circles) and the >250 μm size class (triangles). The stations are roughly arranged along north-south transects.

The $\delta^{13}\text{C}$ of living *N. pachyderma* (sin.) range between -1.39 and 0.26 ‰ in the 125-250 μm size class and between -0.41 and 0.56 ‰ in the >250 μm size class (Appendix 3.1.). The offset between both size classes is 0.92 ‰ (± 0.49 , $n=6$) in the outer Laptev Sea and 0.52 ‰ (± 0.27 , $n=8$) northeast of Severnaya Zemlya (station 25-33). The $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) in both size classes vary strongly throughout the upper 500 m of the water column with some very low values at station 22, 24, 31 and 32 (Fig. 3.3.).

3.6.2. Fram Strait

The stable isotope composition of *N. pachyderma* (sin.) and *T. quinqueloba* in the upper 500 m of the water column in the Fram Strait shows significant deviation between the relatively fresh western part (station 69-84), and the warmer and more saline eastern part (station 58-64, 89-99) (see Fig. 3.1.). In the western Fram Strait, living *N. pachyderma* (sin.) in the 125-250 μm size class show a mean $\delta^{18}\text{O}$ value of 1.34 ‰ (± 0.36 , $n=19$, range: 0.61-1.87 ‰), while in the eastern Fram Strait, the mean $\delta^{18}\text{O}$ value is 2.90 ‰ (± 0.2 , $n=16$, range: 2.62-3.36 ‰). The living individuals in the >250 μm size class show the same trend in $\delta^{18}\text{O}$ composition: a mean of 1.57 ‰ (± 0.34 , $n=18$, range: 0.65-2.17 ‰) in the western part and a mean of 3.07 ‰ (± 0.29 , $n=10$, range: 2.60-3.46 ‰) in the eastern part of the Fram Strait. The individuals in the >250 μm size class are about 0.18 ‰ (± 0.24 , $n=16$) heavier in the western Fram Strait and about 0.35 ‰ (± 0.21 , $n=6$) in the eastern Fram Strait. The vertical variation of $\delta^{18}\text{O}$ values in both size classes shows a decrease towards the sea surface of up to 1.2 ‰ in the western part and an increase of up to 0.4 ‰ in the eastern part of the Fram Strait, reflecting the trends of the equilibrium calcite values (Fig. 3.4.).

The $\delta^{13}\text{C}$ values for *N. pachyderma* (sin.) in the 125-250 μm size class average 0.32 ‰ (± 0.14 , $n=17$) in the western part and -0.11 ‰ (± 0.19 , $n=16$) in the eastern part of the Fram Strait. In the >250 μm size class the difference in $\delta^{13}\text{C}$ values between the western and the eastern part is less pronounced with average $\delta^{13}\text{C}$ values of 0.48 ‰ (± 0.15 , $n=18$) and 0.31 ‰ (± 0.12 , $n=10$), respectively. The vertical variation of $\delta^{13}\text{C}$ is rather small for *N. pachyderma* (sin.) in both size classes, and the offset between both size classes is about 0.13 ‰ (± 0.07 , $n=7$) in the western and 0.51 ‰ (± 0.21 , $n=3$) in the eastern Fram Strait.

For *T. quinqueloba* we distinguished sinistral and dextral coiling types. The results show no significant difference between the two coiling types. Like *N. pachyderma* (sin.) the $\delta^{18}\text{O}$ composition of living *T. quinqueloba* shows lower values of 1.53 ‰ (± 0.33 , $n=6$, range: 0.99-1.74 ‰) in the western Fram Strait and higher values of 2.65 ‰ (± 0.53 , $n=27$) in the eastern Fram Strait. In the Barents Sea average $\delta^{18}\text{O}$ values are 2.81 ‰ (± 0.39 , $n=9$) for *T. quinqueloba*. The vertical variation of $\delta^{18}\text{O}$ composition for living *T. quinqueloba* shows roughly similar trends like *N. pachyderma* (sin.) (Fig. 3.4.). The absolute $\delta^{13}\text{C}$

values of *T. quinqueloba* decrease from the western Fram Strait with 0.41 ‰ (± 0.05 , n=6, station 69-84) to 0.02 ‰ (± 0.08 , n=7, station 63 and 91) to -1.07 ‰ (± 0.49 , n=30, station 58, 60, 94-99) north of Svalbard and in the Barents Sea. In contrast to oxygen isotopes, vertical variation of $\delta^{13}\text{C}$ composition for *T. quinqueloba* is small (except station 98 and 99, Appendix 3.2.).

Fram Strait

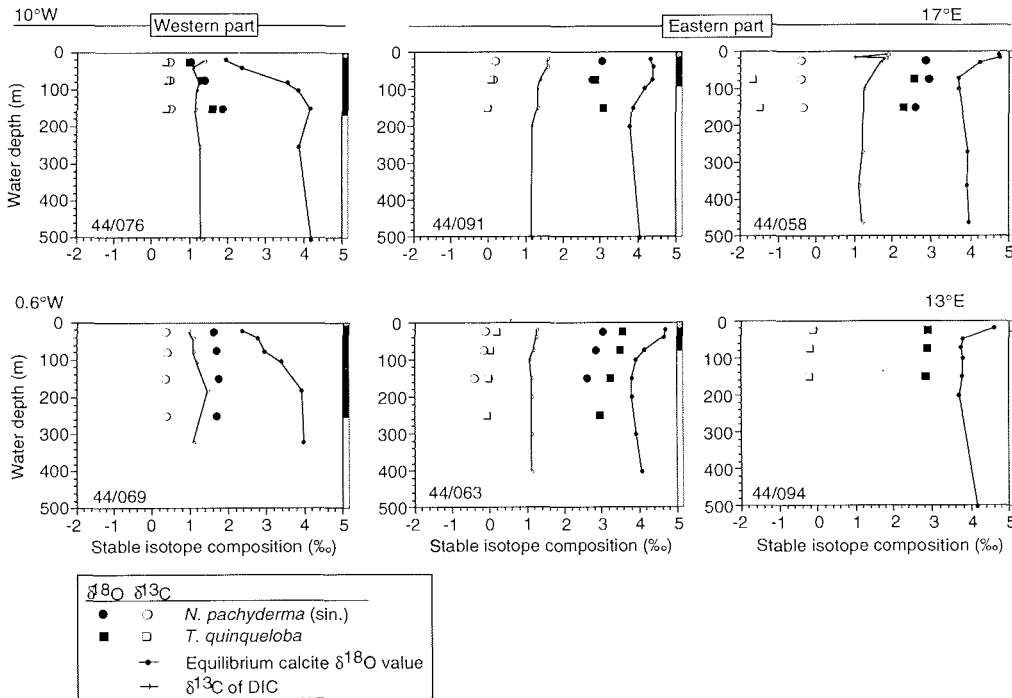


Fig. 3.4.: Stable isotope composition of *N. pachyderma* (sin.) and *T. quinqueloba* in the upper water column of the Fram Strait. Stations are arranged along two parallel roughly east-west transects between 81° and 82°N. Because of the high correlation coefficient between the 125-250 μm and >250 μm size class for *N. pachyderma* (sin.) ($r= 0.95$ for $\delta^{18}\text{O}$ and 0.71 for $\delta^{13}\text{C}$), stable isotope composition of individuals >250 μm is not shown. Shaded columns mark different water masses (for explanation see Fig. 3.3.).

3.6.3. Equilibrium calcite values

Vertical profiles of equilibrium calcite values ($\delta^{18}\text{O}_c$) in the Arctic Ocean calculated after O'Neil et al. (1969) and Shackleton (1974) show regionally different patterns (Figs. 3.3. and 3.4.). The equilibrium calcite values decrease from about 4 ‰ to less than 2 ‰ towards the sea surface in the outer Laptev Sea north of the Lena Delta, and in the western Fram Strait. In the eastern Fram Strait, $\delta^{18}\text{O}_c$ values increase from about 4 ‰ up to 4.8 ‰ towards the sea surface. Northeast of Severnaya Zemlya, vertical variation of $\delta^{18}\text{O}_c$ values is between 3.8-4.6 ‰.

3.7. DISCUSSION

3.7.1. Modern water

Stable isotope composition

The water $\delta^{18}\text{O}_w$ and salinity in the Arctic Ocean is not linearly related (Fig. 3.5.). Their relationship is a mixture of isotopically light riverwater, meltwater, and salt enrichment during brine release (Östlund and Hut, 1984; Bauch et al., 1995). Sea ice melting, precipitation, and freshwater inflow in the outer Laptev Sea are visible in lower salinities in the surface layer relative to linearity. Sea-ice formation, however, releases brines into the water column, and is indicated by higher salinities. Bauch et al. (1995) calculated relatively high contributions of river run-off and sea-ice, the latter associated with brine release in the Transpolar Drift. In the eastern Fram Strait, where Atlantic water dominates in the upper 500 m of the water column, the average $\delta^{18}\text{O}_w$ value of 0.28 ‰ is determined for salinities >34.8 psu. Lower salinities and $\delta^{18}\text{O}_w$ values between 0.1 and 0.3 ‰ as measured in the surface waters are due to ice melting.

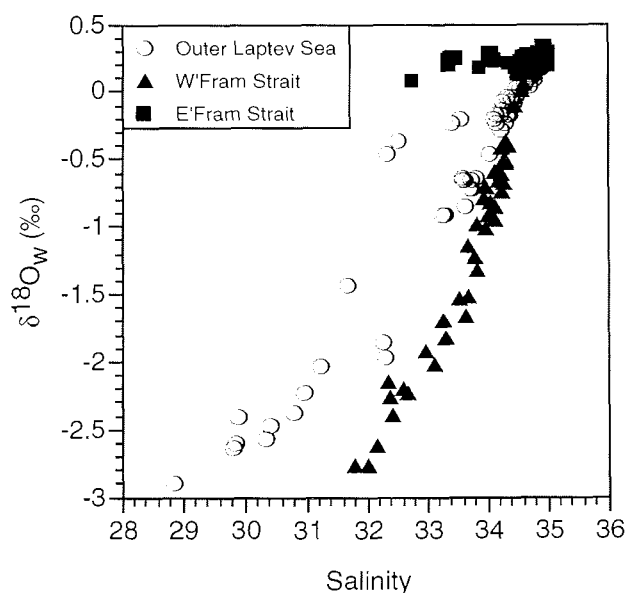


Fig. 3.5.: Relationship between salinity and $\delta^{18}\text{O}_w$ data in the outer Laptev Sea and the Fram Strait. All data, where plankton tows are taken, have been used (see Table 3.1.).

The carbon isotope composition of the DIC in the outer Laptev Sea ranges between 0.19 and 1.71 ‰ (Fig. 3.6.) in the upper 1000 m of the water column, and reveal some scatter in the upper 200 m. Low $\delta^{13}\text{C}_{\text{DIC}}$ of riverine-waters discharged into the Laptev Sea (Erlenkeuser et al., 1995), remineralisation of organic matter, and well ventilated Arctic shelf regions with respect to CO_2 (Bauch et al., in press.) can be related to relatively low $\delta^{13}\text{C}_{\text{DIC}}$ values. In the

Fram Strait, the $\delta^{13}\text{C}$ values are higher, most probably due to a lower freshwater signal and the larger distance to the shelf regions, and range between 0.93 and 1.90 ‰. Increased $\delta^{13}\text{C}_{\text{DIC}}$ in surface water samples might also reflect a better ventilation but $\delta^{13}\text{C}_{\text{DIC}}$ values are still far from equilibrium fractionation with the atmosphere. The extent of isotopic fractionation relatively to the atmosphere strongly depends on temperature. The $\delta^{13}\text{C}_{\text{DIC}}$ increases by 0.11 ‰ per degree of temperature cooling (Mook, 1994; Zhang et al., 1995), and values of $\delta^{13}\text{C}_{\text{DIC}}$ in complete equilibrium with the atmosphere might be 2.5 ‰ for modern conditions and about 4.0 ‰ for pre-industrial conditions in the Arctic Ocean (Bauch et al., in press). In the eastern Barents Sea (station 39), a $\delta^{13}\text{C}_{\text{DIC}}$ value of 3.86 ‰ in 20 m water depth may be caused by high productivity associated with ^{12}C consumption by planktic algae or possible bloom event.

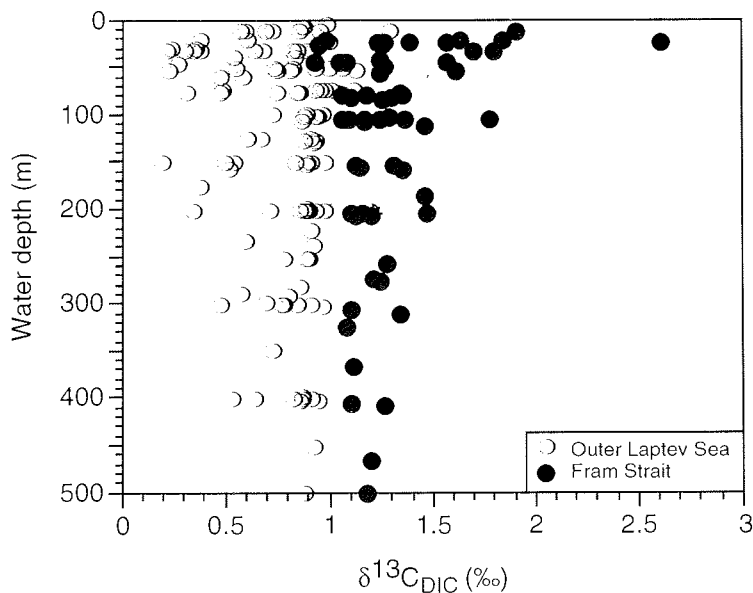


Fig. 3.6.: Depth distribution of $\delta^{13}\text{C}_{\text{DIC}}$ in the outer Laptev Sea and the Fram Strait. In the outer Laptev Sea, data are available from all plankton stations. In the Fram Strait, data are available from station 58, 63, 68, 69, 74, 76, 84, and 91.

3.7.2. Planktic foraminifers

Living Neogloboquadrina pachyderma (sinistral) $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values

The stable isotope composition of *N. pachyderma* (sin.) in the 125-250 μm size class in the outer Laptev Sea and the Fram Strait reflects the different hydrographic regimes in the Arctic Ocean. The isotope composition of living *N. pachyderma* (sin.) in the outer Laptev Sea reveal some scatter, but can be roughly divided in two separate clusters (Fig. 3.7.a): (I): $\delta^{18}\text{O}$ values >2 ‰, reflecting a habitat depth at and below 100 m water depth, with $\delta^{13}\text{C}$ values of

-0.5 to 0.4 ‰, influenced by low $\delta^{13}\text{C}_{\text{DIC}}$ from water of the Lena river. Heaviest $\delta^{18}\text{O}$ values (3.3-3.7 ‰) near Severnaya Zemlya reflect saline, and relatively cold shelf derived waters.

Lower isotope values (cluster II) of samples from the upper 100 m reflect the fresh near surface waters depleted in $\delta^{18}\text{O}$ or a preformed signature of the ambient water mass, e.g., the high freshwater discharge of the Lena River with $\delta^{13}\text{O}_{\text{DIC}}$ values down to -4 ‰ (Erlenkeuser et al., 1995) and $\delta^{18}\text{O}_w$ of -20.6 ‰ (Bauch et al., 1995). The relatively low isotope values occur predominantly in halocline water, where in fact higher values due to low water temperatures were expected. The vertical $\delta^{18}\text{O}_w$ and $\delta^{13}\text{C}_{\text{DIC}}$ profiles do not show a depletion in this depth interval.

In the Fram Strait the stable isotope composition of living *N. pachyderma* (sin.) also shows two distinct, clearly separated clusters (Fig. 3.7.b): (I): the eastern Fram Strait with higher $\delta^{18}\text{O}$ values (2.6-3.4 ‰) but lower $\delta^{13}\text{C}$ (-0.4 to 0.2 ‰), and (II): the western Fram Strait (station 69-84) with $\delta^{18}\text{O}$ about 0.6-2.0 ‰ and $\delta^{13}\text{C}$ about 0.1-0.5 ‰ for individuals in the 125-250 μm size class. Lower oxygen isotope values in the western Fram Strait are affected by the low salinity surface layer, where most of the primary calcite has been built. Due to the deeper average depth of habitat in the eastern Fram Strait (Volkman, in press), higher $\delta^{18}\text{O}$ values are attributed to increased salinities and $\delta^{18}\text{O}_w$ values.

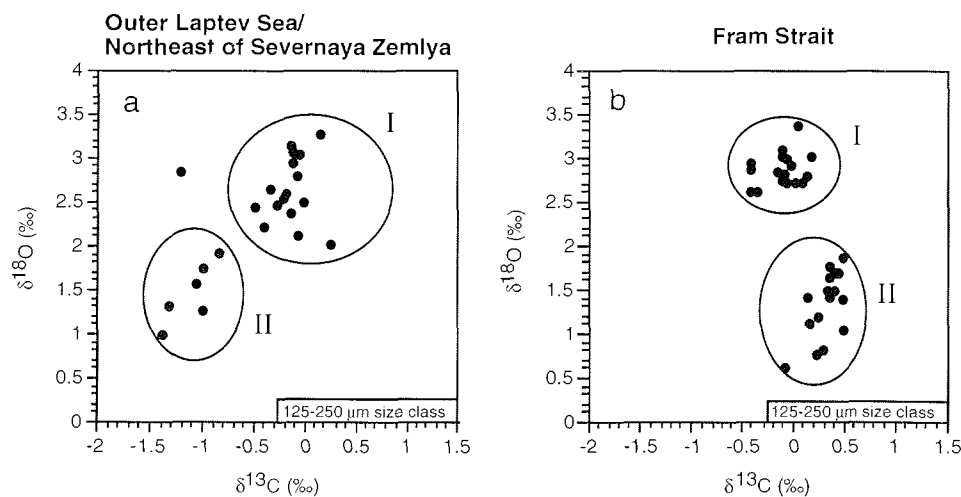


Fig. 3.7.: Oxygen and carbon isotope composition of *N. pachyderma* (sin.) in (a) the outer Laptev Sea and (b) the Fram Strait. (a) Cluster I indicates a depth habitat of 100 m water depth, while Cluster II reflects a shallower habitat and influence of isotopically light river water. (b) Cluster I characterizes a deeper habitat as Cluster II, which reflects a shallow depth habitat affected by the low saline surface layer.

Living *Turborotalita quinqueloba* $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values

The depth habitat and metabolic activity of living *T. quinqueloba* are reflected in the stable isotope composition of the calcite shells. The distribution pattern of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ reveal three different cluster (Fig. 3.8.): (I): the Atlantic-water affected stations around Svalbard, where no halocline is developed. High metabolic activity, probably caused by favorable environmental conditions, e.g., warm and saline Atlantic water, results in low $\delta^{13}\text{C}$ values (-1.7 to 0.2 ‰). (II): the ice covered area in the eastern Fram Strait with high $\delta^{18}\text{O}$ values of up to 3.5 ‰ (station 63). Here, *T. quinqueloba* lives predominantly between 50 and 100 m water depth, reflecting the low temperatures of the Arctic halocline. (III): the ice covered western Fram Strait, where *T. quinqueloba* dwells shallower in the 0-50 m depth interval. Its $\delta^{18}\text{O}$ values down to 1.0 ‰ are attributed to low $\delta^{18}\text{O}_w$ in the surface waters.

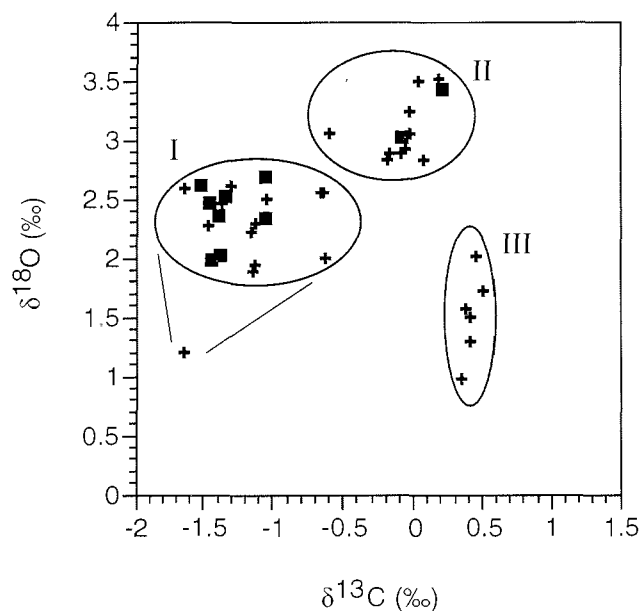


Fig. 3.8.: $\delta^{18}\text{O}$ values of living *T. quinqueloba* in the Fram Strait. Crosses mark sinistral coiled individuals, squares dextral coiled individuals.

Calcification depth

The primary and secondary calcification depths are most important for the interpretation of the stable isotope composition of living and dead planktic foraminifers. In the Arctic Ocean most of the nonencrusted *N. pachyderma* (sin.) lived in the upper 100 m of the water column (Carstens et al., 1997; Volkman, in press), characterized by the Polar Mixed Layer and the halocline. Here, *N. pachyderma* (sin.) probably builds its primary calcite shell. Assuming that the planktic foraminifers calcified at that depth where they were caught, the average depth of calcification of *N. pachyderma* (sin.) lies between

100 and 200 m water depth (Bauch et al., 1997; Volkmann, in press). The isotope composition of the secondary calcite crust of *N. pachyderma* (sin.) will have a significant effect on the total isotope composition of the test, because this crust can account for approximately 50 % to 75 % of the total shell mass (Bé, 1980; Kohfeld et al., 1996; Simstich, 1999). The measured isotope value of mature individuals is an average of the different growth stages.

Living *T. quinqueloba* shows less encrustation. For reproduction it descends downwards (Arikawa, 1983), sheds its spines, and closes the spine holes with gametogenetic calcite (Simstich, 1999). The difference between calcification and habitat depth is rather small for this species, and the isotope composition is less affected by secondary calcite.

To verify, how and in which water depth individuals of *N. pachyderma* (sin.) calcify, two different models proposed by Simstich (1999) were used. Model 1 assumes a calcification in a restricted depth range, while model 2 uses a gradual calcification during assumed downward migration (formula and calculated values are given in Appendix 3.3.). The secondary calcite crust (M_s) amounts to 50 % (Arikawa, 1983). In the outer Laptev Sea, northeast of Severnaya Zemlya and in the western Fram Strait, for oxygen isotopes both models yield comparable data between absolute $\delta^{18}\text{O}$ values and equilibrium calcite values and do not differ significantly from each other (Fig. 3.9.). In contrast, in the eastern Fram Strait the gradual calcification (model 2) yields too high $\delta^{18}\text{O}$ values greater than the equilibrium calcite value, and a small scale calcification between 100 and 200 m water depth becomes more probable.

Calculating with 75 % for the proportion of the secondary calcite crust as observed by Kohfeld et al. (1996) in the Northeast Water Polynya on the Greenland shelf, the gradual calcification is also probable as the small scale calcification in a well defined depth interval. Additionally, the correlation of $\delta^{18}\text{O}$ values of living *N. pachyderma* (sin.) in the investigation areas to its average depth of habitat (see Table 1) is much stronger ($r=0.7$) than for its average depth of calcification ($r=0.4$).

The fact that both models by Simstich (1999) yield reasonable values, also for $\delta^{13}\text{C}$ values (Appendix 3.3.), and the correlation to the average depth of habitat, suggests a calcification of the primary crust of *N. pachyderma* (sin.) in a narrow depth interval around the average depth of habitat as well as most portions of the secondary calcite crust. Only part of the secondary calcite crust will be formed while descending through the water column.

The oxygen isotope values of living *N. pachyderma* (sin.) thus roughly reflect the average depth of habitat, which on the other hand depends on ice coverage and water mass distribution (Volkmann, in press).

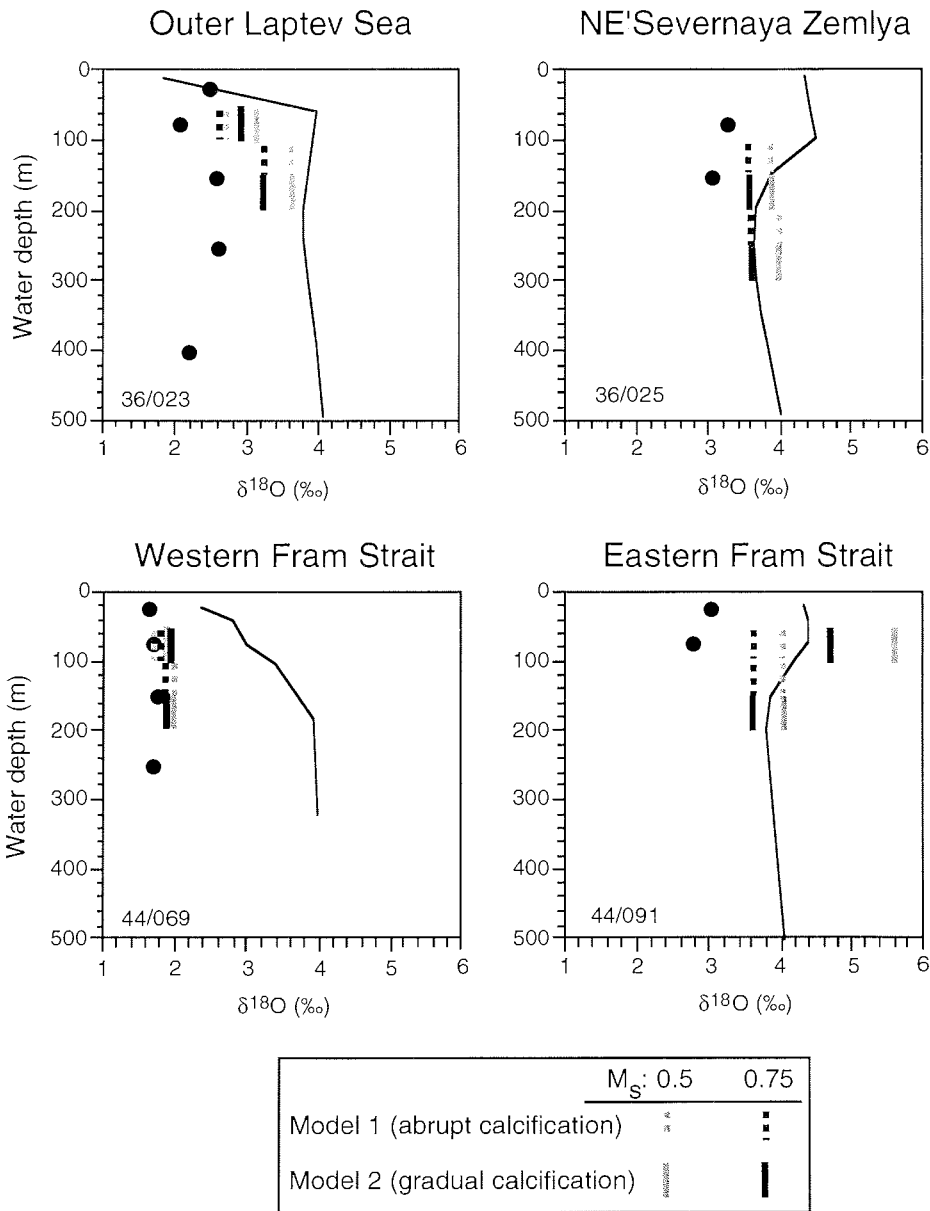


Fig. 3.9.: Theoretical stable isotope values of *N. pachyderma* (sin.) in the 125-250 μm size class, calculated for an abrupt calcification between 100 and 200 m water depth (model 1), and a gradual calcification during downward migration (model 2) after Simstich (1999). The total mass M_t of the calcite test is expected to consist of the primary calcite M_p and the secondary calcite M_s , where $M_t = 1 = M_p + M_s$. Both models are calculated assuming a secondary calcite crust of 50 % (Arikawa, 1983), where $M_s = 0.5$ and of 75 % (Kohfeld et al., 1996), where $M_s = 0.75$. Formula are given in Appendix 3.3. The solid lines are equilibrium calcite profiles.

Physiological effects on stable isotope composition

Different ontogenetic stages of *N. pachyderma* (sin.) and *T. quinqueloba* can be biometrically defined (Berberich, 1996; Brummer et al., 1987), but also small-sized individuals at maturity are recognized (Brummer et al., 1987), and size variations due to temperature changes are known (Bijma et al., 1990b; Hommers, 1998). Because of the similar depth distribution of living *N. pachyderma* (sin.) from the 125-250 μm and $>250 \mu\text{m}$ size classes and changes in the test size spectrum over time associated with a lunar reproductive cycle (Volkman, in press), we assume that ontogeny is the major determining factor for the size increase of *N. pachyderma* (sin.) and *T. quinqueloba* in the modern Arctic Ocean. In other words, larger planktic foraminifers in this study are most probably older and more mature than the smaller individuals.

The stable isotope values of *N. pachyderma* (sin.) in the 125-250 μm and $>250 \mu\text{m}$ size classes show a good correlation in the Fram Strait ($\delta^{18}\text{O}$: $r=0.95$, $\delta^{13}\text{C}$: $r=0.71$) and in the outer Laptev Sea ($\delta^{18}\text{O}$: $r=0.81$, $\delta^{13}\text{C}$: $r=0.71$). The isotope values of individuals in the $>250 \mu\text{m}$ size class are consistently higher by 0.2-0.5 ‰ in $\delta^{18}\text{O}$ and by up to 1.1 ‰ in $\delta^{13}\text{C}$. This is in accordance with previous results on stable isotope compositions of *N. pachyderma* (sin.) in northern high latitudes (Aksu and Vilks, 1988; Bauch et al., 1997; Simstich, 1999). This size dependence is also described from living *Globorotalia menardii* and *N. dutertrei* in the Indian Ocean (Bouvier-Soumagnac and Duplessy, 1985), from *N. pachyderma* (sin.) in sediment traps in the Southern Ocean (Donner and Wefer, 1994), and from individual planktic foraminifers in sediment cores of the equatorial Atlantic (e.g., Billups and Spero, 1995).

Growth rate and metabolic activity might be the most important factors, assuming that ontogeny of *N. pachyderma* (sin.) is size-correlated. In early ontogenetic life stages of planktic foraminifers, the individuals calcify faster and respire at higher rates (Berger et al., 1978; Hemleben et al., 1989). A rapid HCO_3^- precipitation to CaCO_3 is associated with kinetic fractionation, and a discrimination against the heavy isotopes ^{18}O and ^{13}C (McConnaughey, 1989), when metabolic CO_2 is used for chamber formation. Respired CO_2 has a lower $\delta^{18}\text{O}$ value relative to the ambient sea water, and oxygen equilibrium is attained with the surrounding fluid by diffusion to the boundary membrane (McConnaughey, 1989). This isotopic equilibrium time is approximately 10^4 seconds at mean seawater pH, and the disequilibrium may result from precipitation before isotopic equilibrium is reached. A similar mechanism affects shell $\delta^{13}\text{C}$ values (Spero and Lea, 1996). Here, the $\delta^{13}\text{C}$ is a mixture of seawater HCO_3^- and metabolic CO_2 with low $\delta^{13}\text{C}$ values. Spero and Lea (1996) suggested that for juvenile individuals a greater portion of metabolic CO_2 is available at higher precipitation rates and when the distance between precipitation site and cytoplasm is small as in very small chambers.

Another relevant feature is the host and symbiont relationship. Symbiont photosynthesis is the primary physiological parameter controlling the $\delta^{13}\text{C}$ of symbiont-bearing, spinose planktic foraminifers (Spero et al., 1997).

Increasing symbiont density during ontogenetic development enriches the ^{13}C with foraminiferal shell size. Small living *T. quinqueloba* in the Fram Strait are consistently depleted in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$. An offset in size with differences of 1.01 ‰ (± 0.11 , $n=2$) for $\delta^{18}\text{O}$ and 0.33 ‰ (± 0.01 , $n=2$) for $\delta^{13}\text{C}$ is given between the 63-125 μm and the 125-250 μm size class, considerably higher for oxygen due to fractionation mass ratio.

Species-specific effects

Both the oxygen and carbon isotope compositions of living nonencrusted *N. pachyderma* (sin.) and *T. quinqueloba* in the 125-250 μm size in the Fram Strait class show a good relationship for the same depth intervals ($r=0.89$ for $\delta^{18}\text{O}$, $r=0.74$ for $\delta^{13}\text{C}$). Species-specific offsets (Table 3.2.) can be a result of different metabolic activity. Higher metabolic rate associated with lower $\delta^{13}\text{C}$ values is assumed for *T. quinqueloba* in the eastern Fram Strait, where it finds better living conditions than in the western Fram Strait. Temperatures about 2-4 °C and salinities >34.6 psu seem to be an environment which activate the metabolism resulting in higher growth rate and isotopically lighter calcite shells. In the western Fram Strait *T. quinqueloba* appears to level out the metabolic activity at minimum due to lower food concentration (Volkman, in press), resulting in slower growth and higher, relatively constant $\delta^{13}\text{C}$ values.

Table 3.2.: Average differences between isotopic composition of living *N. pachyderma* (sin.) and *T. quinqueloba* from multinet tows in the Fram Strait for the test size 125-250 μm .

Area	<i>N. pachyderma</i> (sin.) - <i>T. quinqueloba</i>	
	$\Delta\delta^{18}\text{O}$ (‰)	$\Delta\delta^{13}\text{C}$ (‰)
Eastern Fram Strait (Stas. 58, 60)	0.32 (± 0.03)	1.01 (± 0.25)
(Sta. 63)	-0.60 (± 0.06)	-0.01 (± 0.14)
Western Fram Strait	-0.12 (± 0.32)	-0.28 (± 0.08)

Another possibility for species-specific offsets are different calcification depths for *N. pachyderma* (sin.) and *T. quinqueloba*. Due to the high vertical gradient in equilibrium calcite values, a difference in calcification of about 10 m can be attributed to a difference of about 0.1 ‰ in $\delta^{18}\text{O}$. Although both species have a similar depth distribution, the calcification depth for *N. pachyderma* (sin.) appears to lie approximately 30 m shallower at station 58 and 60 in the eastern Fram Strait, while at station 63, higher $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) suggest a deeper calcification depth of about 60 m compared to *T. quinqueloba*. These three stations in the eastern Fram Strait show similar hydrographic conditions, therefore the different behavior in depth of calcification might be subject to changes in food and nutrient availability rather than differences in physical properties of the water masses. A low specific

offset in $\delta^{18}\text{O}$ in the western Fram Strait can be attributed to a similar calcification depth for both species.

Comparison of $\delta^{18}\text{O}_w$ and $\delta^{18}\text{O}_{\text{foram}}$ values and the vital effect

Relative to $\delta^{18}\text{O}_w$, the $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) and *T. quinqueloba* from plankton tows show similar offsets. In Polar Water (0-100 m), *N. pachyderma* (sin.) and *T. quinqueloba* are 3.1 ‰ (± 0.54 , $n=39$) higher than average $\delta^{18}\text{O}_w$ values, while in deeper water, the offset is lower (2.66 ± 0.39 ‰, $n=23$, for *N. pachyderma* (sin.) and 2.49 ± 0.6 ‰, $n=12$, for *T. quinqueloba*).

Usually, $\delta^{18}\text{O}$ values of planktic foraminifers are compared to equilibrium calcite, calculated from specific paleotemperature equations. The temperature: $\delta^{18}\text{O}$ relationship of O'Neil et al. (1969) and Shackleton (1974) based on inorganic calcite and has been used for cold water environments (e.g., Bauch et al., 1997; Kohfeld, 1998; Simstich, 1999). The absolute difference between measured and calculated $\delta^{18}\text{O}$ is called vital effect (e.g., Wefer and Berger, 1991) and means that planktic foraminifers do not build their shells in equilibrium with the ambient sea water. The vertical variation of $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) and *T. quinqueloba* is determined by the variation of $\delta^{18}\text{O}_c$, but none of the $\delta^{18}\text{O}_{\text{foram}}$ values are in equilibrium with the theoretical oxygen isotope value, and are lower than the equilibrium calcite values.

While the scattered $\delta^{18}\text{O}_c - \delta^{18}\text{O}_w$ values of living *T. quinqueloba* show a regression line ($r=0.6$) with a slope approximately similar to the paleotemperature equation of O'Neil et al. (1969) and Shackleton (1974) (Fig. 3.10.), $\delta^{18}\text{O}_c - \delta^{18}\text{O}_w$ values of living *N. pachyderma* (sin.) do not show any pattern compared to water temperature. Both species precipitate their shell out of isotopic equilibrium predicted for anorganic calcite, and due to the regression line $\delta^{18}\text{O}$ values of *T. quinqueloba* can provide temperature estimates when the vital effect is taken into account, while this is hardly probable for *N. pachyderma* (sin.).

The absolute differences between $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) and equilibrium calcite values (vital effect) are not consistent within the Arctic Ocean (Table 3.3.). Highest deviations are calculated in the negative temperature range for living *N. pachyderma* (sin.) in the western Fram Strait. The vital effect shows a roughly increasing trend with decreasing temperature and salinity, according to observations made by Bauch et al. (1997) in the Nansen Basin. An increased calcification rate is associated with a decrease in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values (McConnaughey, 1989) and shifts the skeleton's isotopic composition further from equilibrium (Ortiz et al., 1996). This might be a possible explanation for the increased vital effect in a low temperature and salinity environment, where the unfavourable conditions lead the individuals to grow faster for survival of the species.

Average vital effect for living, nonencrusted *N. pachyderma* (sin.) in the Arctic Ocean is 1.51 ‰ in the 125-250 µm size class (Table 3.3.). This high value can be attributed to early ontogenetic stages. Bauch et al. (1997) measured living, encrusted *N. pachyderma* (sin.) >160 µm and >250 µm, representing fully-grown stages, and calculated a vital effect of about 1 ‰ and 0.86 ‰, respectively.

Table 3.3.: Vital effect for $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{terram}} - \delta^{18}\text{O}_c$) of *N. pachyderma* (sin.) and *T. quinqueloba* in the Arctic Ocean.

Investigation area	<i>N. pachyderma</i> (sin.)						<i>T. quinqueloba</i>	
	125-250 µm		>250 µm				125-250 µm	
	Normalform		Normalform		Kummerform		living	dead
	living	dead	living	dead	living	dead		
Outer Laptev Sea	1.27‰	1.72‰	1.29‰		1.16‰			
N'Severnaya Zemlya	1.52‰	1.25‰	0.93‰	0.82‰	0.74‰	0.75‰		
whole Laptev Sea	1.35‰	1.46‰	1.02‰	0.82‰	0.86‰	0.75‰		
			±0.44	±0.33	±0.06			
Western Fram Strait	2.07‰		1.94‰				2.01‰	
Eastern Fram Strait	1.15‰	1.02‰	1.05‰				1.38‰	1.26‰
whole Fram Strait	1.61‰	1.02‰	1.50‰				1.29‰	1.26‰
							±0.46	±0.37
whole Arctic Ocean	1.51‰	1.38‰	1.35‰					
	±0.78	±0.48	±0.56					

Fully-grown individuals in the whole Laptev Sea like the dead and kummerform *N. pachyderma* (sin.) >250 µm show a vital effect of about 0.8 ‰, possibly due to a slower growth rate, which fits well with the data of Bauch et al. (1997). The relatively high statistical deviation is caused by the average of all samples in different hydrographic regimes.

The physiological component of the species-specific $\delta^{18}\text{O}$ vital effect of living *N. pachyderma* (sin.) (>250 µm size class) in the Arctic Ocean is about 1.0 ‰ for encrusted individuals under ice-free conditions. After subtracting these 1.0 ‰ and additionally 0.3 ‰ for the difference between nonencrusted and encrusted individuals (Kohfeld et al., 1996) from each $\delta^{18}\text{O}$ vital effect of living *N. pachyderma* (sin.) in the 125-250 µm size class, most samples are approximately in equilibrium with the theoretical oxygen isotope value. Changes in temperature, salinity, freshwater discharge, percentage of ice cover, and food availability control specimen's metabolism and have a direct influence on the vital effect of living individuals.

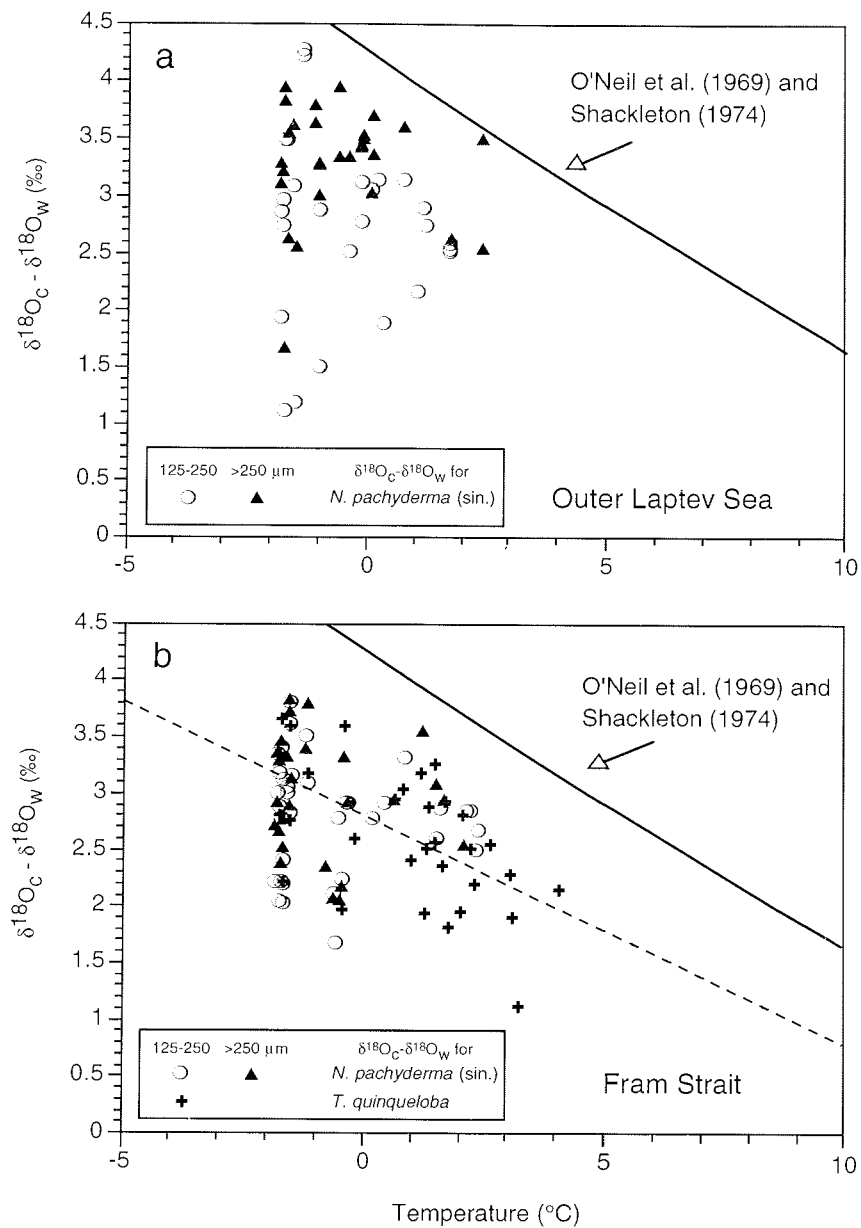


Fig. 3.10.: Comparison of temperature: $\delta^{18}\text{O}$ relationships with the paleotemperature equation by O'Neil et al. (1969) and Shackleton (1974) for (a) the outer Laptev Sea and (b) the Fram Strait. The dotted line indicates the regression line of *T. quinqueloba* ($r=0.6$).

The combination of low water temperature with ice coverage increases the $\delta^{18}\text{O}$ vital effect for living *N. pachyderma* (sin.) from 1.3 ‰ to 1.5 ‰ at the ice margin and to 1.6 ‰ under permanent ice coverage (Fig. 3.11.). Downward migration during ontogeny carries the isotope signal from upper to deeper waters, and the isotope signal is only slightly modified for nonencrusted individuals. In the outer Laptev Sea and the western Fram Strait, growth and primary calcification of *N. pachyderma* (sin.) occur in shallow water, and individuals descend downward into subsurface waters without or little further calcification. A comparison of $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) in greater depths with the corresponding equilibrium calcite values may lead to an overestimation of the vital effect.

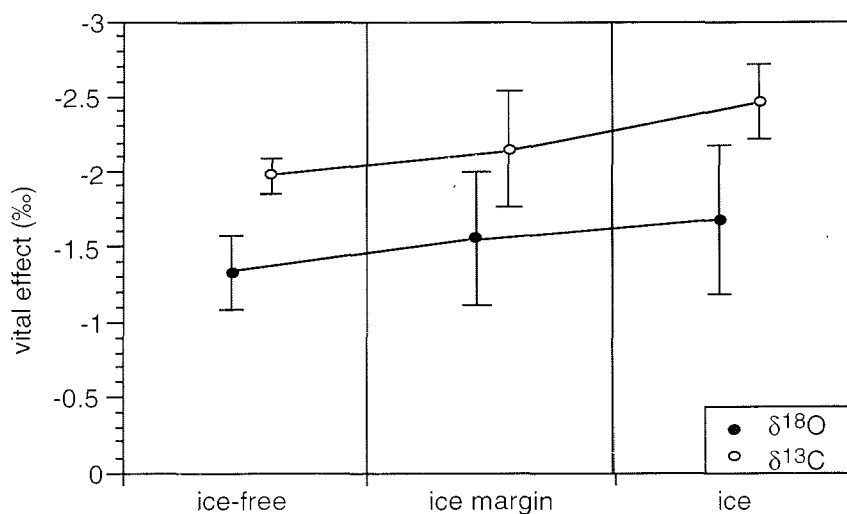


Fig. 3.11.: Mean difference between measured and calculated $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values for living and nonencrusted *N. pachyderma* (sin.) in the 125-250 μm size class, averaged for ice-free, ice margin, and ice covered areas. The vertical bars reflect the standard deviations.

The vital effect calculated for *T. quinqueloba* of about 1.3 ‰ at the ice margin and ice covered stations are higher than suggested by Simstich (1999) for the Nordic Seas, and is the result of different hydrographic regimes.

Comparison of $\delta^{13}\text{C}_{\text{DIC}}$ and $\delta^{13}\text{C}_{\text{foram}}$ values and the vital effect

For carbon, a strong disequilibrium is calculated for *N. pachyderma* (sin.) and *T. quinqueloba*, and $\delta^{13}\text{C}$ values are generally lower than $\delta^{13}\text{C}_{\text{DIC}}$ (Table 3.4.). The vertical variations of $\delta^{13}\text{C}$ values in both planktic foraminifers are a factor of two higher than the variation in $\delta^{13}\text{C}_{\text{DIC}}$ and metabolism might be the controlling factor. Romanek et al. (1992) found inorganic precipitated calcite to be 1 ‰ (± 0.2) heavier than $\delta^{13}\text{C}_{\text{DIC}}$, and the deviation of this $\delta^{13}\text{C}_c$ from $\delta^{13}\text{C}_{\text{foram}}$ is the species-specific vital effect.

Table 3.4.: Difference between $\delta^{13}\text{C}_{\text{foram}}$ and $\delta^{13}\text{C}_{\text{DIC}}$ of *N. pachyderma* (sin.) and *T. quinqueloba* in the Arctic Ocean. The vital effect is about 1 ‰ higher than these calculated values (Romanek et al., 1992).

Investigation area	<i>N. pachyderma</i> (sin.)						<i>T. quinqueloba</i>	
	125-250 μm		>250 μm				125-250 μm	
	Normalform		Normalform		Kummerform		living	dead
	living	dead	living	dead	living	dead	living	dead
Outer Laptev Sea	1.23‰	1.17‰	0.63‰	-	0.51‰	-		
N'Severnaya Zemlya	0.92‰	0.96‰	0.41‰	0.61‰	0.49‰	-		
whole Laptev Sea	1.14‰	1.10‰	0.51‰	0.61‰	0.49‰	-		
				± 0.41	± 0.42			
Western Fram Strait	0.90‰		0.73‰				0.90‰	
Eastern Fram Strait	1.49‰	1.31‰	0.88‰				1.82‰	2.47‰
whole Fram Strait	1.15‰	1.31‰	0.78‰				1.56‰	2.47‰
							± 0.79	± 0.18
whole Arctic Ocean	1.14‰	1.15‰	0.67‰					
	± 0.44	± 0.40	± 0.28					

High metabolic activity, associated with considerable low $\delta^{13}\text{C}$ values, increases the vital effect for the symbiont-bearing living *T. quinqueloba* of up to 2.6 ‰. $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) averaged over all stations reveal a vital effect of 2.1 ‰ and 1.7 ‰ in the 125-250 μm and >250 μm , respectively. As for oxygen isotopes, the vital effect increases from ice-free stations to ice covered stations (Fig. 3.11.) due to an increased calcification rate.

The species-specific vital effects can be modified from region to region. For living encrusted *N. pachyderma* (sin.) in the 125-250 μm size class, Kohfeld et al. (1996) and Bauch et al. (in press) discussed a vital effect in $\delta^{13}\text{C}$ of 1 ‰ and 2 ‰, respectively. This may be caused by several factors: $\delta^{13}\text{C}_{\text{calcite}}$ decreases with increasing seawater CO_3^{2-} (Spero et al., 1997), and temperature (Ortiz et al., 1996; Kohfeld, 1998), with high and rapid calcification rates (McConnaughey, 1989; Spero and Lea, 1996), and is affected by dietary $\delta^{13}\text{C}$ (Spero and Lea, 1996).

3.7.3. Paleoceanographic implications

The results of the present study underline that the stable isotope composition of living planktic foraminifers in the Arctic Ocean is determined by a complex combination of physiological and environmental factors. Although the primary crust of *N. pachyderma* (sin.) is built in the upper 100 m of the water column, and may reveal a strong isotope signal of the low salinity surface layer, sea surface temperature and salinity are not generally recorded in the specimens' $\delta^{18}\text{O}$ values. The $\delta^{18}\text{O}$ values roughly reflect first off all the average depth of habitat, although the depth habitat of living *N. pachyderma* (sin.) is influenced by vertical migration (Volkman, in press). Under a permanent ice cover in the outer Laptev Sea and the western Fram Strait, *N. pachyderma* (sin.) lives in the Arctic halocline and reveals $\delta^{18}\text{O}$ values lower than 2 ‰. In the eastern

Fram Strait and northeast of Severnaya Zemlya, $\delta^{18}\text{O}$ values are between 2.5-3.7 ‰ due to the deeper average depth of habitat mostly in Atlantic derived waters. The secondary calcite crust partly affects the isotope composition of encrusted individuals, which predominantly becomes fossilized in deep sea sediments. Decreased metabolic activity in later ontogenetic stages explains higher $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values for encrusted adult specimens, when lower calcite precipitation enriches the heavy isotopes and shifts the isotope composition closer to the equilibrium calcite values.

For paleoceanographic reconstructions it should be noted that oceanographic and hydrographic conditions during ARK-XI/1 and ARK-XIII/2 expeditions differed significantly from those of previous years by remarkably high temperatures in the northern hemisphere (Mann et al., 1998) and an extreme northern position of the ice-edge in 1995 (Aleksandrov and Kolatschek, 1997). Therefore, the calculated vital effects describe the special conditions in these years and regions and should be carefully used for paleoceanographic reconstructions.

The $\delta^{18}\text{O}$ values of living *N. pachyderma* (sin.) show a relationship to salinity (Fig. 3.12.) and demonstrate that oxygen isotopes can be used as a quantitative proxy for salinity, although a salinity range of 1 salinity unit implies a $\delta^{18}\text{O}$ range of about 2 ‰. However, the lack of a clear relationship between temperature and $\delta^{18}\text{O}$ values demonstrates that oxygen isotopes of living *N. pachyderma* (sin.) in the outer Laptev Sea and the Fram Strait can not serve as a reliable proxy for water temperature. The low degree of correlation could be explained by the low range in temperature of the preferred depth habitat of *N. pachyderma* (sin.) of 4 °C, and need to be examined in regions where the temperature gradients are higher.

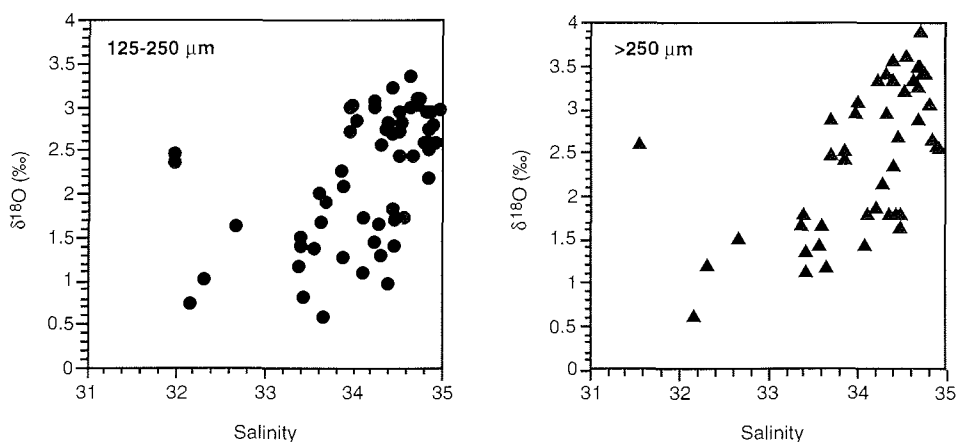


Fig. 3.12.: $\delta^{18}\text{O}$ values of living *N. pachyderma* (sin.) in the outer Laptev Sea and the Fram Strait vs. salinity, shown for the 125-250 μm and >250 μm size class. Salinities are averaged over the sampled depth intervals.

The $\delta^{13}\text{C}$ of planktic foraminifers is routinely used as a proxy for $\delta^{13}\text{C}_{\text{DIC}}$, but the $\delta^{13}\text{C}_{\text{DIC}}$ values are strongly influenced by biological processes. Such alteration might be recorded in the phosphate concentration as well as in the $\delta^{13}\text{C}_{\text{DIC}}$, generally viewed to be inversely correlated. Photosynthesis leaves the ocean surface waters depleted in nutrients with high $\delta^{13}\text{C}$ values, while the nutrients enriched deep waters show low $\delta^{13}\text{C}$ values. However, this relationship is not perfect, because nutrients circulate only through the sea, while carbon circulates through the atmosphere as well (Broecker and Maier-Reimer, 1992). Air-sea exchange removes ^{12}C preferentially to the atmosphere and is partially decoupling $\delta^{13}\text{C}_{\text{DIC}}$ and phosphate. In the outer Laptev Sea, the water masses are enriched in ^{12}C , affected by the relatively well ventilated Arctic shelf regions (Bauch et al., in press). High $\delta^{13}\text{C}_{\text{DIC}}$ values up to 1.9 ‰ found in surface waters of the eastern Fram Strait are associated with very low phosphate concentrations (0.2 $\mu\text{mol}/\text{kg}$) (G. Kattner, unpubl. data) and suggest high biological consumption rather air-sea exchange. Fig. 3.13. demonstrates that the carbon isotope compositions of living *N. pachyderma* (sin.) are roughly correlated to $\delta^{13}\text{C}_{\text{DIC}}$ and therefore may provide a tool for nutrient changes in the past polar oceans.

Both oxygen and carbon isotope compositions of living *N. pachyderma* (sin.) and *T. quinqueloba* record environmental parameters of the ambient sea water, and a good relationship exists between their isotope values. Previous studies on deep sea sediments in the Nordic Seas have shown strong discrepancies between isotope compositions of both species (Bauch, 1993). This fact may depend on the different calcification behaviour, because *N. pachyderma* (sin.) adds parts of the crust while descending through the water column and predominantly thick, encrusted individuals occur in deep sea sediments (Kohfeld et al., 1996), whereas fossil specimens of *T. quinqueloba* are less encrusted (Simstich, 1999).

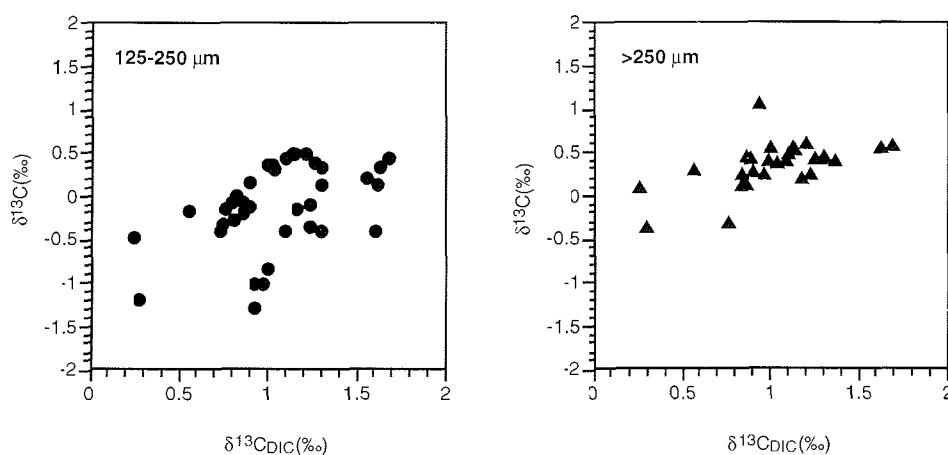


Fig. 3.13.: $\delta^{13}\text{C}$ values of living *N. pachyderma* (sin.) in the outer Laptev Sea and the Fram Strait vs. $\delta^{13}\text{C}_{\text{DIC}}$, shown for the 125-250 μm and >250 μm size class.

3.8. CONCLUSIONS

From our data set the following conclusions can be drawn:

-The precipitation of the calcite crust of living *N. pachyderma* (sin.) is suggested to have taken place in a narrow depth interval around the average depth of habitat, which depends on ice coverage and water mass distribution. Only part of the secondary calcite crust is added when the individuals descend downwards, because model results of abrupt calcification fit equally or better to the data than the model with gradual calcification.

-The modern distribution of $\delta^{18}\text{O}$ values of living *N. pachyderma* (sin.) and *T. quinqueloba* in the Fram Strait and the outer Laptev Sea reflects the different hydrographic regimes and is additionally controlled by the interplay of their average depth of habitat, growth rate and metabolic activity.

-Under a permanent ice cover, where *N. pachyderma* (sin.) dwells shallow in the upper 50 m of the water column, an increased calcification rate is associated with an increased vital effect (difference between equilibrium calcite values and $\delta^{18}\text{O}$ values of planktic foraminifers) between 1.3 ‰ and 1.6 ‰. Living *T. quinqueloba* in the Fram Strait reveal a vital effect of 1.3 ‰ (only ice-covered and ice-margin stations).

-Relative to $\delta^{13}\text{C}_c$ ($=\delta^{13}\text{C}_{\text{DIC}} + 1$ ‰), $\delta^{13}\text{C}$ values of living nonencrusted *N. pachyderma* (sin.) and living *T. quinqueloba* are consistently lower by about 2.1 ‰ and 2.6 ‰, respectively. Larger and encrusted *N. pachyderma* (sin.) reveals a lower vital effect of about 1.7 ‰. The vertical variation of $\delta^{13}\text{C}_{\text{foram}}$ is in first order determined by metabolic activity rather than being due to $\delta^{13}\text{C}_{\text{DIC}}$ of the ambient water.

-Species-specific differences in $\delta^{18}\text{O}$ values in the Fram Strait reflect different depth of calcification. A difference in calcification of about 10 m causes a difference of about 0.1 ‰ in $\delta^{18}\text{O}$. Higher metabolic activity due to better environmental conditions associated with lower $\delta^{13}\text{C}$ values is suggested for *T. quinqueloba* in the eastern Fram Strait.

-The stable isotopes in planktic foraminifers of the Arctic Ocean are strongly size-dependent, with depletions of 0.2-0.5 ‰ in $\delta^{18}\text{O}$ and of up to 1 ‰ in $\delta^{13}\text{C}$ for living *N. pachyderma* (sin.) in the 125-250 μm size class relatively to the >250 μm size class. For living *T. quinqueloba*, lower values of 1 ‰ in $\delta^{18}\text{O}$ and of 0.3 ‰ in $\delta^{13}\text{C}$ are found in the smaller size class.

4. PLANKTIC FORAMINIFERS IN THE EASTERN ARCTIC OCEAN: BIOGEOGRAPHY AND STABLE ISOTOPES - RESULTS FROM PLANKTON TOWS AND OCEAN SURFACE SEDIMENTS

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4.1. ABSTRACT

Living planktic foraminifera in the upper water column and sediment surface samples of the Arctic Ocean were investigated with regard to species diversity, abundance, and stable oxygen and carbon isotopes and were isotopically compared with the water column. Samples were obtained on the Laptev Sea continental margin in August 1995 and the Fram Strait in July 1997. The planktic foraminiferal distribution is controlled by the contribution of Polar and Atlantic waters and the position of the summer sea-ice margin. Strong deviations in foraminiferal diversity between the water column and sediment surface samples are caused by selective calcium carbonate dissolution due to corrosive bottom water. The oxygen and carbon isotopes of living and fossil *N. pachyderma* (sin.) are compared to determine how the extreme Arctic Ocean environmental conditions are reflected in the isotope signal measured in deep-sea sediments. The oxygen isotopes show a relationship to the apparent depth habitat and salinity of the given water mass, but they have a limited use for delineating temperatures. Possible reasons for the $\delta^{18}\text{O}$ offsets between fossil and living *N. pachyderma* (sin.) are salinity variations during the last centuries and ontogenetic changes. Offsets are highest where a salinity gradient of about 5 psu is present in the upper 300 m of the water column. A locally deeper paleo-habitat of *N. pachyderma* (sin.) is suggested and explains isotopically heavier values in the sediment samples, e.g., in the western Fram Strait, compared to lower oxygen isotope ratios of living individuals which reflect the modern low saline surface layer. The carbon isotopes of fossil *N. pachyderma* (sin.) are also generally higher if compared to the living individuals. Highest offsets at the Laptev Sea continental margin can be attributed to large amounts of anthropogenic CO_2 entering the Arctic waters through the well-ventilated shelf regions. The lateral distribution pattern of $\delta^{13}\text{C}$ values is mainly determined by isotopically light river water from the Siberian shelves. The relationship between $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) from surface sediments and $\delta^{13}\text{C}_{\text{DIC}}$ values of surface water suggests that carbon isotope data can be used to determine the large-scale degree of air-sea exchange and also might reflect the nutrient signature of past surface waters.

4.2. INTRODUCTION

The Arctic Ocean plays a key role for the global climate and the dynamics of the world ocean and atmosphere (Alley, 1996). Therefore, efforts have been undertaken to decipher and evaluate changes in the Arctic in order to

determine the natural climatic variability, which forms the background for anthropogenic effects. Analyses of abundances and stable isotope compositions of planktic foraminifers are fundamental in paleoceanographic studies, and are routinely used to correlate sedimentary sequences and unravel the paleoclimatic history. The faunal composition can be linked to specific surface water masses and provides valuable environmental information (e.g., Hemleben et al., 1989; Johannessen et al., 1994). Oxygen isotopic records from deep-sea sediment cores have become a standard tool to deduce glacial/interglacial cycles and to estimate values and variability of sea surface temperatures and salinities (e.g., Broecker, 1982; Duplessy et al., 1991). The $\delta^{13}\text{C}$ records of fossil foraminifers are used to estimate changes in the $^{13}\text{C}/^{12}\text{C}$ ratio of oceanic ΣCO_2 and to infer paleoproductivity and past states of the oceanic carbon cycle (e.g., Lynch-Stieglitz et al., 1995).

There is a general agreement that the planktic foraminifer abundance is influenced by temperature, salinity, food supply, and predation. In the Arctic Ocean, diversity and distribution of planktic foraminifers are largely controlled by the permanent ice coverage, the high freshwater discharge from the Siberian rivers, and nutrient and food availability (Volkman, in press). The stable isotope composition of their calcite tests is controlled by numerous biological and physical factors (Bemis et al., 1998; Spero and Lea, 1996; Romanek et al., 1992; McConnaughey, 1989). For the northern high latitudes the basic assumption that planktic foraminifers, in this case *Neogloboquadrina pachyderma* (sinistral coiling), most common in polar regions, calcify the shells in equilibrium with the ambient seawater or have predictable offsets was discussed in detail by Bauch et al. (1997, in press), Kohfeld (1998), Simstich (1999), and Volkman and Mensch (subm.). The results indicate regional differences in the controlling factors. However, little is known about reasons for differences between living and fossil assemblages. Stable oxygen and carbon isotopic records are often difficult to interpret due to the lack of modern studies on the influence of variable environmental parameters on the isotopic composition of living individuals in northern high latitudes.

The principle goal of this study is to determine how changes of Arctic Ocean hydrography, ice coverage, atmospheric CO_2 , and water isotope composition are reflected in polar planktic foraminifers. To reach this objective, we analyzed the faunal distribution and oxygen and carbon isotopic compositions of living and fossil specimens along with the isotopic situation in the modern waters from the Laptev Sea continental margin and the Fram Strait to discuss the significance of foraminiferal assemblages and their spatial isotope distribution for paleoceanographic reconstructions.

4.3. THE ARCTIC OCEAN - GEOGRAPHIC AND HYDROGRAPHIC OVERVIEW

The Arctic Ocean is a well-stratified enclosed sea and consists of the Arctic deep basins, extensive shallow continental shelves, and marginal plateaus (Fig. 4.1.). The Lomonosov Ridge divides the Arctic basins into the Eurasian and Amerasian Basin, both up to 4500 m deep. The Eurasian Basin north of the wide Laptev Sea, Kara Sea, and Barents Sea shelves is subdivided by the

Gakkel Ridge into the Nansen and Amundsen basins. The only deep water connection to the Atlantic Ocean is through the Fram Strait between Greenland and Spitsbergen. Shallower passages connect the Atlantic Ocean through the Barents Sea and the Davis Strait, while the exchange with the Pacific Ocean is confined to the shallow Bering Strait.

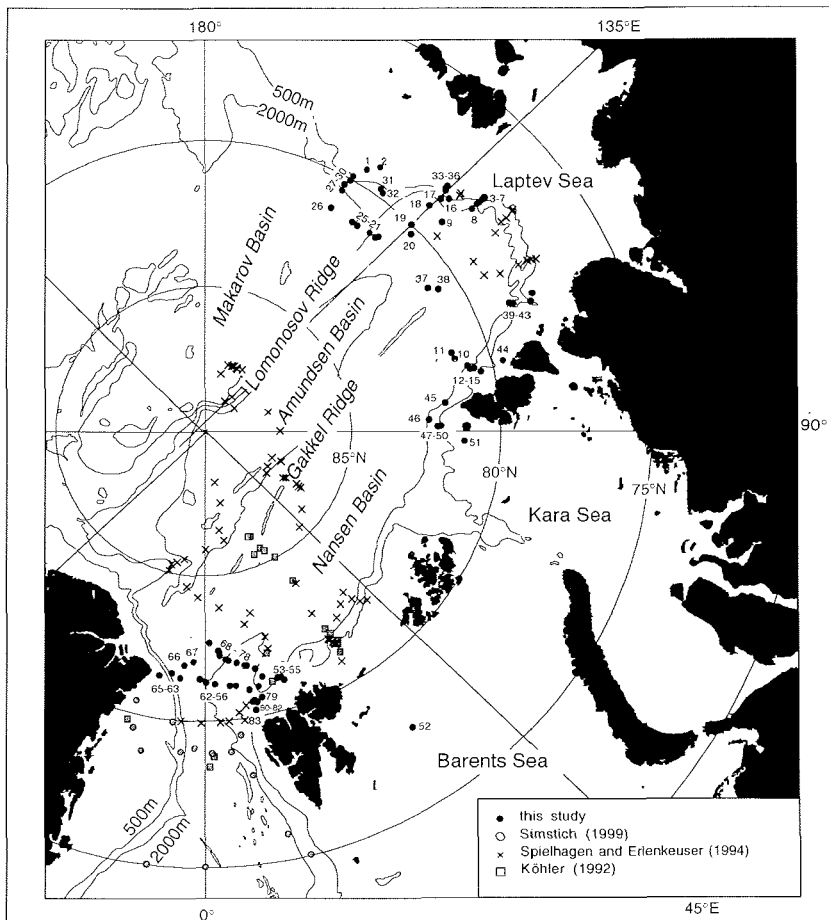


Fig. 4.1.: Geographic map of the Arctic Ocean and sample position. Data are listed in Table 4.1., except for previously published data.

The Arctic Ocean interior is covered by pack ice throughout the year, while the shelves are mostly ice free during summer (Kolatschek et al., 1996). Most of the sea ice is formed over the Laptev and Kara Sea (Walsh et al., 1985) and is transported by the Transpolar Drift across the Eurasian Basin to the western side of the Fram Strait (Fig. 4.2.). High freshwater discharge from the Siberian rivers and sea-ice melting during the summer months maintain low surface water salinities in the Arctic Ocean, ranging from 29 psu (salinity units on the ("Practical Salinity Scale 1978")) at the Laptev Sea continental margin to about

31.5 psu in the western Fram Strait. Freezing of sea water associated with brine release over the shelves forms the Arctic halocline, an intermediate density structure stratifying the Arctic Ocean (Aagaard et al., 1981). It is about 100-200 m thick, and separates the cold, fresh overlying Polar Mixed Layer from the Arctic intermediate water. The cold Polar water is carried out of the Arctic Ocean by the Transpolar Drift and the East Greenland Current through the western Fram Strait (Fig. 4.2.).

Relatively warm and saline Atlantic water ($T \sim 2.5\text{ }^{\circ}\text{C}$, $S > 34.9\text{ psu}$) enters the Arctic Ocean via the Fram Strait (West Spitsbergen Current, WSC) and the Barents Sea (Fig. 4.2.) forming the Atlantic Layer (Rudels et al., in press a). The two inflows converge east of the St. Anna Trough and continue in a cyclonic boundary current eastwards along the continental slope. A tight loop brings the Atlantic-derived water back towards the Fram Strait, following the Gakkel and Lomonosov ridges. The Atlantic Layer can be detected throughout the Arctic Ocean at 150-500 m water depth (Rudels et al., in press a, b). The underlying deep water is characterised by low temperatures ($< -0.5\text{ }^{\circ}\text{C}$) and high salinities ($> 34.9\text{ psu}$) (Anderson et al., 1994), but temperature-salinity characteristics vary for the different basins (Rudels et al., in press b).

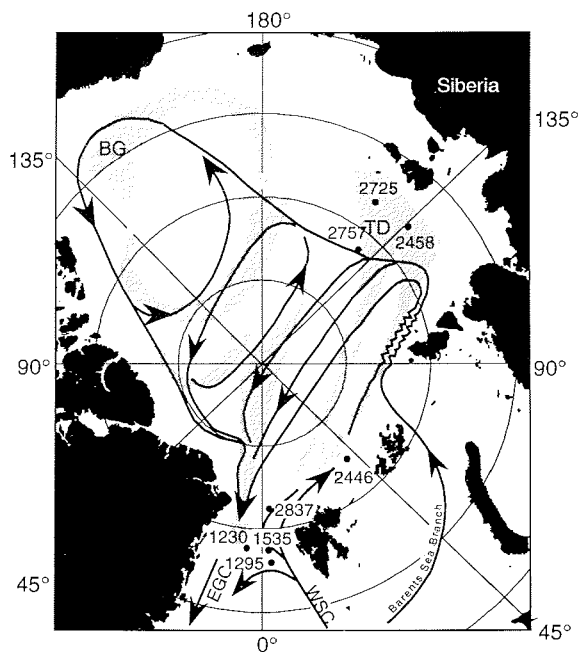


Fig. 4.2.: Hydrographic setting of the Arctic Ocean and positions of AMS ^{14}C dated surface sediments (see Table 4.4.). Black arrows provide a schematic view of Atlantic derived water masses after Rudels et al. (1994, in press b). Grey arrows denote the modern sea-ice drift paths. BG: Beaufort Gyre; TD: Transpolar Drift; EGC: East Greenland Current; WSC: West Spitsbergen Current.

4.4. SAMPLES AND METHODS

The samples used for this study were obtained during “Polarstern” expeditions ARK-XI/1 in August 1995 to the Laptev Sea continental margin (Rachor, 1997)

and ARK-XIII/2 in July 1997 to the western Barents Sea and the Fram Strait (Stein and Fahl, 1997). Stable isotope data of *N. pachyderma* (sin.) from sediment surfaces published by Köhler (1992), Spielhagen and Erlenkeuser (1994), and Simstich (1999), using the same size class and similar preparation methods, were added to extend our data set.

A vertically-stratified multinet of 63 μm mesh size was used for sampling of living planktic foraminifers in the upper water column. Continuously sampled depth intervals were usually 0-50-100-200-300-500 m (Table 4.1.). All catches were preserved in a 4% borax-buffered formalin sea-water solution and treated with bengal-rose-ethanol solution to stain "living" (protoplasma-containing) tests. Sediment surface samples were scraped off undisturbed box cores, taking the uppermost 0.5 cm of the sediment. Sediment samples were freeze-dried, wet-sieved through a 63 μm mesh, and split into several size classes. Stable isotope values of sediment surface samples from the Laptev Sea and Barents Sea continental margins with usually high amounts of coarse fraction ($>63 \mu\text{m}$) were not used for interpretation (see Table 4.1.). Here, high resolution seismic profiles (PARASOUND, 4 kHz) indicate current-related winnowing and mass movement deposits in the uppermost sedimentary sequences (H. P. Kleiber, pers. comm.) and thus redeposition of sediments is possible.

Planktic foraminifers (individuals $>125 \mu\text{m}$) were identified using the species concept of Kennett and Srinivasan (1983) and Hemleben et al. (1989) and counted for the 125-250 μm and $>250 \mu\text{m}$ size classes. Data are available from the PANGAEA data base of the Alfred Wegener Institute, Bremerhaven (<http://www.pangaea.de>). Specimens of *Neogloboquadrina pachyderma* (sinistral coiling) were rinsed in tap water, roasted in vacuo at 200 °C for 1 hour (for living individuals only to void protoplasma) and analyzed for oxygen and carbon isotopes using the automated Kiel-Device for sample- CO_2 preparation along with a Finnigan-MAT 251 isotope ratio mass spectrometer of the Leibniz-Laboratory of Kiel University. Due to the low foraminifer numbers in the plankton tows, only nonencrusted specimens of *N. pachyderma* (sin) could be measured in the 125-250 μm size class and only encrusted specimens in the $>250 \mu\text{m}$ size class. From the sediment surface samples, encrusted individuals of *N. pachyderma* (sin.) were measured in the 125-250 μm and $>250 \mu\text{m}$ size classes, while nonencrusted individuals were almost absent. According to the warm Atlantic water branches entering the Arctic Ocean in the WSC through the Fram Strait (see Fig. 4.2.), stations 2839 (no. 62) to 2853 (no. 70) (Table 4.1.) are assigned to the western Fram Strait, and the other stations to the eastern Fram Strait.

Water samples were collected at the same sites as the plankton tows. Oxygen isotopes were analysed at the "Institut für Umweltphysik" (UIP) Heidelberg and carbon isotopes at the Leibniz-Laboratory, respectively. Handling procedure for sea water $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_w$) were described in detail by Mensch et al. (subm.). $\delta^{13}\text{C}$ of DIC (dissolved inorganic carbon) ($\delta^{13}\text{C}_{\text{DIC}}$) was prepared either off-line (Erlenkeuser et al., 1999).

Table 4.1.: Station list and oxygen and carbon isotope compositions of *N. pachyderma* (sin.) from sediment surface samples. Stations which are not used for interpretation due to high amount of coarse fraction are underlined.

Number	Station (Box corer)	Latitude	Longitude	Water depth (m)	Coarse fraction (weighting %) (>63 μm)	<i>N. pachyderma</i> (sin.)				Net stations
						125-250 μm		>250 μm		
						$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	
Laptev Sea continental margin										
1	2723-4	79°27.5N	148°06.8E	224	3	3.27	0.46	-	-	
2	2724-4	79°08.9N	146°21.3E	100	2	3.58	0.29	-	-	
3	<u>2731-3</u>	77°35.9N	130°02.2E	90	54	3.06	-0.01	-	-	
4	<u>2732-4</u>	77°37.2N	130°02.5E	272	29	3.20	0.32	-	-	
5	2733-3	77°42.2N	130°02.4E	510	5	3.50	0.45	-	-	
6	<u>2734-3</u>	77°51.0N	130°03.0E	1106	44	3.29	0.49	-	-	36/021
7	2735-4	77°55.9N	130°02.6E	1719	7	3.41	0.47	-	-	36/022
8	2736-3	77°55.8N	130°02.5E	1695	2	4.12	0.49	-	-	36/023
9	2737-4	79°12.9N	131°28.9E	3155	3	3.22	0.56	3.26	0.62	36/024
10	2739-5	81°07.9N	106°01.7E	2787	2	3.19	0.85	3.31	0.84	36/025
11	2740-8	81°11.5N	107°35.1E	3210	6	2.86	0.87	2.87	0.97	
12	2742-3	80°48.3N	103°54.0E	1956	2	4.28	0.40	4.26	0.41	
13	<u>2743-7</u>	80°44.1N	103°11.7E	1060	61	3.37	0.79	3.44	1.00	36/031
14	2744-6	80°36.4N	103°03.2E	455	3	3.58	0.64	3.32	0.68	36/032
15	2745-7	80°24.9N	102°05.4E	255	8	3.86	0.48	-	-	36/033
16	<u>2747-8</u>	78°30.8N	133°49.3E	1995	69	3.38	0.53	-	-	
17	2748-2	78°41.9N	134°36.5E	2122	2	1.87	-0.70	2.03	-0.60	
18	2749-3	79°07.6N	135°06.8E	2783	3	2.84	0.19	2.35	0.07	36/044
19	2750-2	79°58.9N	135°00.1E	3358	3	2.15	-0.12	2.28	-0.05	
20	2751-2	80°14.3N	133°46.2E	3510	-	2.87	0.60	2.83	0.66	
	2752	80°55.6N	131°16.6E	3800	-	-	-	-	-	36/047
21	2755-5	81°03.3N	138°15.1E	2033	2	2.29	-0.05	2.20	-0.26	
22	2756-9	81°08.7N	138°38.9E	1793	1	3.21	0.60	3.17	0.61	
23	2757-7	81°09.6N	140°12.1E	1223	5	2.57	0.61	2.81	0.87	
24	2759-7	81°13.3N	143°27.0E	1610	3	2.92	0.83	2.83	0.95	
25	2760-5	81°13.6N	144°48.0E	2044	4	2.46	0.59	2.57	0.85	
26	2761-9	81°11.6N	150°27.2E	2587	6	2.37	0.94	2.09	1.08	
27	2762-4	80°29.5N	150°15.7E	1997	2	2.39	0.37	2.40	0.41	
28	2763-8	80°16.8N	150°27.4E	1588	1	2.46	0.17	2.32	-0.15	
29	2764-7	80°04.1N	149°48.6E	1001	10	2.83	0.54	2.24	0.34	
30	2765-6	79°52.8N	149°46.9E	557	5	2.82	0.25	2.81	0.32	
31	2767-6	79°44.4N	143°59.4E	557	3	3.39	0.46	3.17	0.54	
32	2768-3	79°49.0N	143°05.5E	984	3	2.44	-0.19	2.39	-0.42	
33	<u>2769-3</u>	78°23.0N	135°02.4E	984	12	1.76	-1.17	1.86	-0.53	
34	<u>2770-5</u>	78°21.0N	135°11.7E	531	14	3.13	0.27	-	-	
35	<u>2771-5</u>	78°19.6N	135°23.6E	214	63	2.75	0.02	-	-	
36	<u>2772-2</u>	78°15.2N	135°23.3E	104	33	2.38	-0.23	-	-	
37	2773-7	80°56.8N	122°38.7E	3561	9	2.53	0.72	2.36	0.87	
38	2774-2	80°40.9N	121°17.6E	3489	8	2.65	0.92	2.71	1.01	
39	<u>2775-4</u>	78°48.1N	113°00.1E	1600	24	3.45	0.57	3.66	0.70	
40	<u>2776-3</u>	78°45.6N	112°44.0E	1204	39	3.64	0.65	3.53	0.72	
41	<u>2777-3</u>	78°40.7E	112°39.6E	559	13	3.64	0.68	3.74	0.76	
42	2778-1	77°58.8N	113°03.5E	330	4	3.24	0.26	-	-	
43	2781-1	78°07.4N	111°55.0E	325	5	3.06	0.07	-	-	
44	2782-2	79°36.7N	103°21.1E	340	-	3.98	0.52	4.30	0.61	
45	<u>2784-2</u>	81°45.7N	96°35.9E	1656	35	3.56	0.55	3.28	0.51	
46	2785-4	82°20.3N	92°93.8E	2632	2	3.31	0.85	3.41	0.87	
47	<u>2787-6</u>	82°04.6N	91°00.6E	1096	78	3.71	0.88	3.61	0.91	
48	<u>2787-7</u>	82°04.5N	90°59.7E	1029	71	3.60	0.92	3.62	0.94	
49	<u>2788-4</u>	82°02.3N	90°59.1E	540	95	3.72	0.71	3.64	0.92	
50	<u>2789-5</u>	81°57.5N	91°06.0E	235	20	3.68	0.30	3.61	0.41	
51	<u>2791-5</u>	81°10.4N	87°30.2E	320	47	3.86	0.58	3.83	0.57	

Table 4.1. (continued): Station list and oxygen and carbon isotope compositions of *N. pachyderma* (sin.) from sediment surface samples. Stations which are not used for interpretation due to high amount of coarse fraction are underlined.

Number	Station (Box corer)	Latitude	Longitude	Water depth (m)	Coarse fraction (weighting % >63 μm)	<i>N. pachyderma</i> (sin.)				Net stations
						125-250 μm		>250 μm		
						$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	
Barents Sea										
52	2824-5	77°34.2N	34°38.6E	190	-	3.79	0.46	-	-	
Fram Strait										
53	<u>2830-7</u>	80°58.6N	17°30.5E	509	35	4.24	-0.06	4.57	0.14	
54	2831-7	81°05.6N	16°58.4E	934	-	2.83	0.22	-	-	44/058
55	<u>2832-12</u>	81°06.7N	16°13.1E	2065	20	3.33	0.49	3.53	0.57	
56	2833-5	81°58.3N	11°50.0E	1964	3	3.38	0.69	3.82	0.87	44/060
57	2834-6	80°54.9N	9°49.4E	1001	7	3.61	0.80	3.81	0.73	
58	2835-5	80°06.1N	7°04.0E	847	13	3.45	0.63	3.56	0.74	44/063
59	2836-6	81°07.9N	5°40.1E	657	12	3.38	0.49	3.60	0.75	44/064
60	2837-6	81°14.0N	2°25.1E	1028	3	3.26	0.43	-	-	
61	2838-9	81°17.7N	0°26.6E	2325	2	3.48	0.56	3.30	0.32	
62	2839-5	81°24.2N	0°58.3W	2926	2	3.57	0.72	3.63	0.81	
63	2840-4	81°25.3N	5°18.5E	3524	1	3.06	0.70	-	-	44/069
64	<u>2843-2</u>	81°34.0N	7°21.0W	2526	22	3.33	0.63	2.19	0.90	
	2844	81°34.9N	8°10.6W	1900						44/072
65	<u>2846-4</u>	81°35.2N	10°00.4W	521	72	3.26	0.57	3.76	0.64	44/074
66	2847-3	81°52.3N	4°32.3W	4130	1	3.05	0.85	-	-	44/076
67	2848-3	81°59.9N	2°25.8W	2600	5	3.35	0.77	3.50	0.89	44/077
68	2849-6	82°39.2N	1°27.9E	3238	15	3.24	0.74	3.22	0.83	44/079
69	2851-2	82°22.5N	3°36.9E	2927	3	3.66	0.80	3.64	0.95	
70	<u>2853-9</u>	82°19.1N	3°36.9E	2008	22	3.69	0.68	3.68	0.66	44/084
71	2854-2	82°12.0N	3°54.1E	1805	1	3.53	0.63	3.49	0.62	
72	2855-8	82°02.7N	5°17.3E	1455	1	3.39	0.49	3.63	0.68	
73	2856-7	81°59.3N	5°45.3E	961	6	3.42	0.53	3.48	0.67	
74	2857-10	81°54.1N	7°54.8E	855	2	3.60	0.72	4.10	1.11	44/089
75	2858-6	81°45.3N	9°39.9E	932	6	3.63	0.62	3.70	0.90	
76	2859-10	81°45.1N	10°11.4E	1180	6	3.76	0.76	3.67	0.86	44/091
77	2860-7	81°34.9N	11°51.1E	2032	2	3.94	0.66	3.80	0.87	
78	2861-11	81°16.4N	13°03.0E	2309	3	3.84	0.76	3.79	0.77	
79	2862-5	80°34.7N	11°47.3E	1042	9	3.24	0.42	3.04	0.29	44/094
80	2863-2	80°33.5N	10°17.9E	807	7	3.25	0.28	3.28	0.59	
81	2864-4	80°31.8N	10°22.1E	777	9	3.16	0.27	3.54	0.40	44/096
82	<u>2865-2</u>	80°29.7N	10°29.3E	822	16	3.17	0.28	2.88	0.13	
	2866	80°00.1N	10°52.3E	250	-	-	-	-	-	44/098
83	<u>2867-7</u>	80°11.9N	10°26.7E	517	42	4.53	0.22	3.13	1.01	44/099

Isotope values of carbonates are given in the conventional δ -notation (permille versus Vienna Pee Dee Belemnite, PDB). Isotope data of fossil *N. pachyderma* (sin.) are listed in Table 4.1., of living *N. pachyderma* (sin.) in Appendix 3.1. and 3.2. Measurement accuracy for planktic foraminifers is ± 0.08 ‰ for $\delta^{18}\text{O}$ and ± 0.05 ‰ for $\delta^{13}\text{C}$. Water isotope data are calibrated versus standard mean ocean water (SMOW) and have a precision better than 0.03 ‰ for $\delta^{18}\text{O}$ (Mensch et al., subm.). $\delta^{13}\text{C}_{\text{DIC}}$ refers to the PDB-scale, with accuracies of ± 0.1 ‰ for off-line preparation and better than ± 0.03 ‰ for automated processing.

4.5. STABLE ISOTOPES OF MODERN WATER

Due to the strong discharge from the Siberian rivers and summer sea-ice melting, the surface layer in the outer Laptev Sea and the western Fram Strait is characterized by low salinities of 29 psu and oxygen isotope values from -3 to -2 ‰. Both parameters continuously increase to deeper waters, but show a non-linearity, resulting from the river water component together with salt enrichment during sea ice formation (Bauch et al., 1997; Volkmann and Mensch, subm.; Mensch et al., subm.). Northeast of Severnaya Zemlya and in the eastern Fram Strait, $\delta^{18}\text{O}_w$ values show little vertical variation around 0 ‰ due to low influence of freshwater.

The carbon isotopes in Arctic Ocean water show a pronounced spatial pattern in the upper water column. Relatively low $\delta^{13}\text{C}_{\text{DIC}}$ values (0.5-1.0 ‰) in the outer Laptev Sea can be related to low $\delta^{13}\text{C}_{\text{DIC}}$ values of freshwater from the Lena River (Erlenkeuser et al., 1995) and to well-ventilated Arctic shelf waters (Bauch et al., in press). Higher $\delta^{13}\text{C}_{\text{DIC}}$ values (>1.0 ‰) in the Fram Strait might be attributed to a lower freshwater contribution and the larger distance to the shelf regions (Volkmann and Mensch, subm.). All $\delta^{13}\text{C}_{\text{DIC}}$ values are far off isotopic equilibrium with the modern atmosphere (Erlenkeuser et al., 1995; Bauch et al., in press) which is assumed to have a value of 2.5 ‰ (Emrich et al., 1970).

4.6. RESULTS

4.6.1. Distribution of living planktic foraminifers in the upper water column

In the outer Laptev Sea, northeast of Severnaya Zemlya, and in the western Fram Strait, the living planktic foraminifer fauna in the 125-250 μm size class is dominated by the polar species *N. pachyderma* (sin.), while the subpolar species *T. quinqueloba* is most abundant in the eastern Fram Strait and the western Barents Sea (Table 4.2.) (Volkmann, in press).

Table 4.2.: Relative abundances of the abundant planktic foraminifers in the water column and the sediment surface samples in the Arctic Ocean, listed for the 125-250 μm size class. "Exotic" species are listed in the text. Residual species consists of unidentified and broken individuals. Values in parentheses are the relative abundances of encrusted individuals related to the total amount of *N. pachyderma* (sin.)

Sampling area	Sample	Relative abundance (%)						
		<i>N. pachyderma</i>		<i>T. quinqueloba</i>	<i>G. glutinata</i>	<i>G. uvula</i>	"exotic" species	residual species
		(sinistral)	(dextral)					
Outer Laptev Sea	water column	78.09 (56)	7.56	9.78	0.86	0.46	0.17	3.16
	sediment	95.57 (99)	4.02	0.15	0.15	-	0.05	0.05
W'Fram Strait	water column	85.34 (13)	3.47	9.37	0.11	-	-	1.70
	sediment	93.78 (99)	4.52	1.49	0.04	-	-	0.16
E'Fram Strait	water column	38.12 (33)	1.74	58.65	0.22	0.14	-	1.01
	sediment	87.20 (100)	4.45	7.69	0.07	-	0.07	0.52
W'Barents Sea	water column	12.83 (17)	2.41	72.12	-	0.57	-	12.07
	sediment	94.11 (99)	2.94	2.94	-	-	-	-

Additional species are *N. pachyderma* (dex.) (8 %) and *Globigerina glutinata* (1 %). *Globigerinita uvula* and "exotic" species like *Globigerinella aequilateralis*, *Globigerina falconensis*, *Globigerina rubescens*, *Globigerinoides ruber*, and *Globoturborotalita tenella* compose less than 0.7 % of the total assemblages. All "exotic" tests were empty specimens were dead and found only in the outer Laptev Sea. The relatively high amount of non-polar and "exotic" species indicates the lateral transport with water masses of Atlantic origin (Carstens and Wefer, 1992; Bauch 1999; Volkmann, in press). In the >250 µm size class, *N. pachyderma* (sin.) amounts to 85-100 % (Table 4.3.).

Table 4.3.: Relative abundances of planktic foraminifers in the water column and the sediment surface samples in the Arctic Ocean, listed for the >250 µm size class. All specimens of *N. pachyderma* (sin.) show a thick secondary calcite crust.

Sampling area	Sample	Relative abundances (%)		
		<i>N. pachyderma</i>		<i>T. quinqueloba</i>
		(sinistral)	(dextral)	
Outer Laptev Sea	water column	95.6	3.4	-
	sediment	96.3	3.7	-
W'Fram Strait	water column	97.0	2.3	0.4
	sediment	96.8	3.1	0.1
E'Fram Strait	water column	99.0	0.9	0.5
	sediment	96.3	3.1	0.6

The absolute abundance of planktic foraminifers in the upper water column has minimum values in the outer Laptev Sea (<2 individuals/m³) and northeast of Severnaya Zemlya (<4 ind./m³). The mean average in the western Barents Sea and the western Fram Strait is 8 ind./m³ and in the eastern Fram Strait 11 ind./m³.

4.6.2. Distribution of planktic foraminifers in surface sediments

The surface sediments in the Arctic Ocean show highest test concentrations of planktic foraminifers in the 125-250 µm size class. Concentrations greater than 5000 individuals per gram dry sediment (ind./g) occur on the northwestern slope of the Yermak Plateau and on the southeastern Gakkel Ridge at water depths >3000 m. Towards the Siberian shelves and north of Svalbard concentrations decrease to less than 100 ind./g at water depths shallower than 1000 m.

The planktic foraminifer *N. pachyderma* (sin.) dominates the surface sediment assemblages in the 125-250 µm size class (94 %) (Table 4.2.). *T. quinqueloba* contributes less than 3 %. Only in the eastern Fram Strait, this species makes up 8 %. Here, *N. pachyderma* (sin.) comprises 87 %. *N. pachyderma* (dex.) shows a consistent abundance of 3-4 % in the investigated area. *G. glutinata* and "exotic" species like *G. ruber*, *G. rubescens*, *Orbulina universa*,

Turborotalita humilis, *G. aequilateralis*, and *Globigerinodes trilobus* reach less than 0.5 % of the total planktic foraminifer assemblage and are absent in the surface sediments of the Barents Sea. In the >250 μm size class, *N. pachyderma* (sin.) contributes >95 % to the planktic foraminifer assemblage. *N. pachyderma* (dex.) and *T. quinqueloba* reach 3-4 % and <1 %, respectively (Table 4.3.). Almost all individuals of *N. pachyderma* (sin.) in both size classes are encrusted.

4.6.3. Distribution of *N. pachyderma* (sin.) oxygen and carbon isotopes in Arctic Ocean surface sediments

Planktic foraminifers ideally calcify their shell in isotopic equilibrium with sea water, and their isotope composition reflects the ratio of the respective isotopes dissolved in the ambient sea water. However, metabolic and kinetic fractionation processes can affect the incorporation of stable isotopes into the foraminifer shell (Kohfeld, 1998), resulting in deviations from thermodynamic equilibrium (vital effect) (e.g., Wefer and Berger, 1991; Kohfeld 1998). Stable isotope measurements on living, nonencrusted *N. pachyderma* (sin.) (125-250 μm) in the outer Laptev Sea, northeast of Severnaya Zemlya, and the Fram Strait reveal a vital effect (absolute difference between the measured isotopic composition and the one expected for thermodynamic equilibrium) of 1.3 ‰ in $\delta^{18}\text{O}$ and 2.0 ‰ in $\delta^{13}\text{C}$, increasing, by absolute amount, under a permanent ice cover to 1.6 ‰ in $\delta^{18}\text{O}$ and 2.4 ‰ in $\delta^{13}\text{C}$ (Volkman and Mensch, subm.).

Because of the good correlation of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) in sediment surface samples between the 125-250 μm and >250 μm size class (Fig. 4.3.), the stable isotope composition is described in the following only for the widely used size class 125-250 μm .

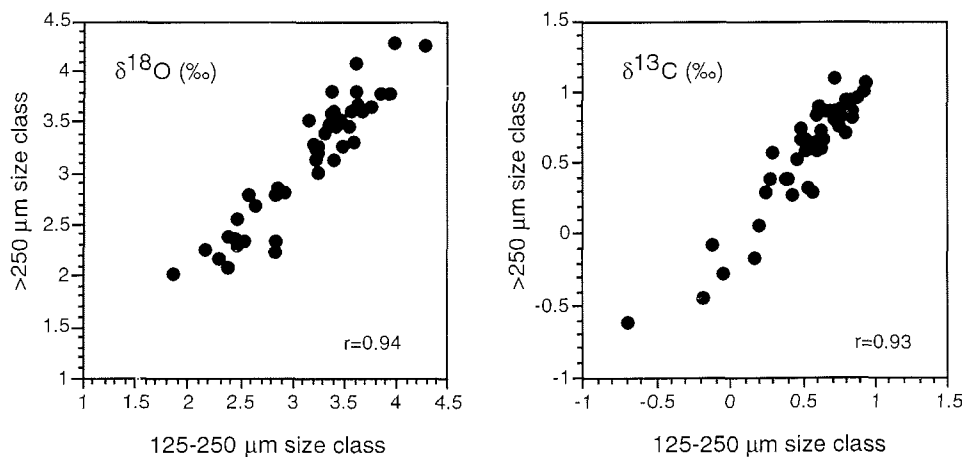


Fig. 4.3.: Stable isotope composition of *N. pachyderma* (sin.) from sediment surface samples in the 125-250 μm vs. >250 μm size class. Both oxygen and carbon isotope values show positive correlation. The correlation coefficient is given in the figure.

The lateral distribution pattern of $\delta^{18}\text{O}$ values shows a decrease from the Laptev Sea continental margin and along the Severnaya Zemlya continental margin ($>3.5\text{‰}$) to lighter values in the southeastern Amundsen Basin and Makarov Basin ($<2.5\text{‰}$) (Fig. 4.4.). In the Fram Strait, $\delta^{18}\text{O}$ values are generally $>2.5\text{‰}$ and reach highest values ($>3.5\text{‰}$) on the Yermak Plateau and the Barents Sea continental margin. A marked decrease is visible from the Nansen Basin ($<3\text{‰}$) to the Canada Basin ($<1.5\text{‰}$) in W-E stretching zones (Spielhagen and Erlenkeuser, 1994).

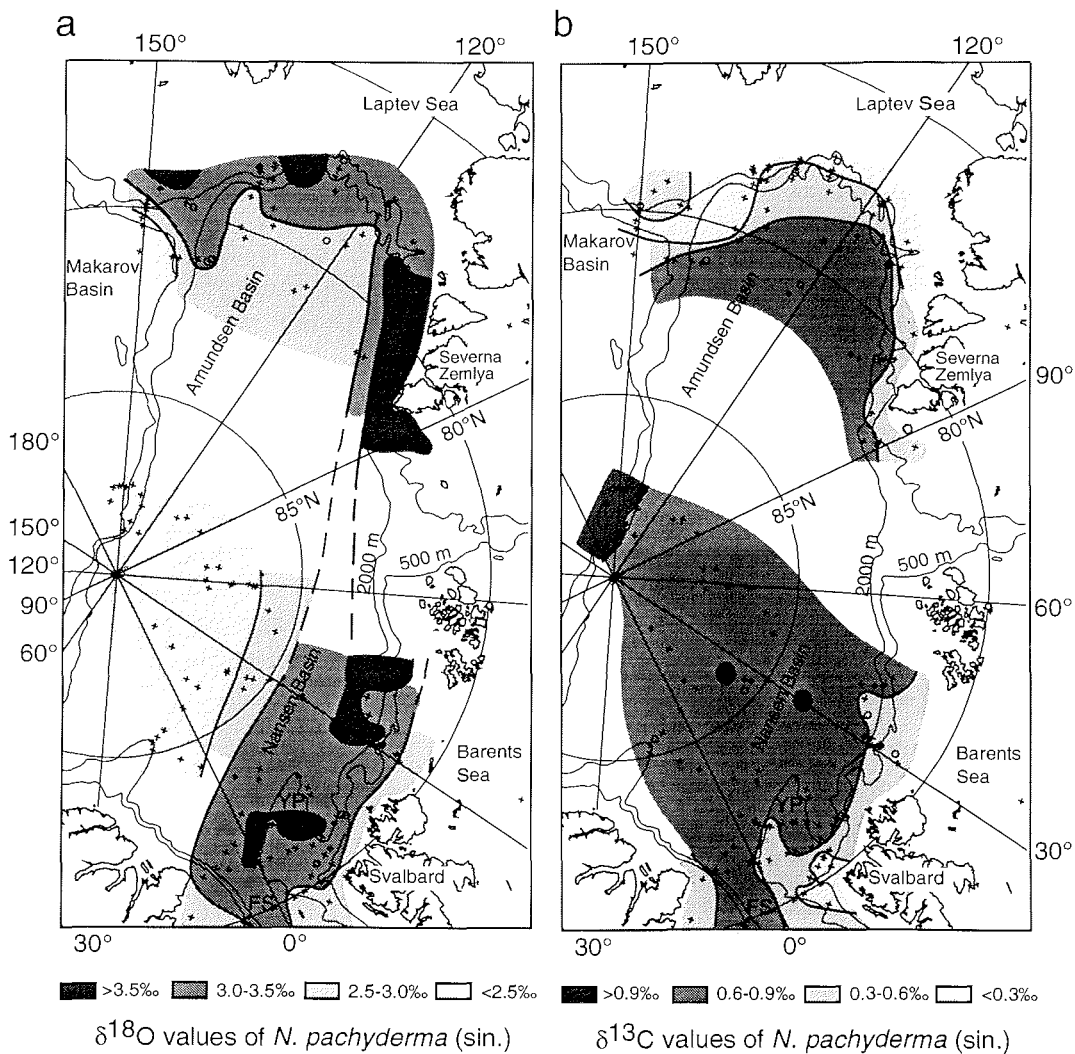


Fig. 4.4.: Lateral distribution pattern of stable (a) oxygen and (b) carbon isotope values from *N. pachyderma* (sin.) in sediment surface samples (crosses). Open circles mark outliers. YP: Yermak Plateau; FS: Fram Strait.

In contrast, the $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) in sediment surface samples show the opposite trend compared to oxygen isotopes, increasing from the Laptev Sea continental margin (<0.3 ‰) northwards (0.6-0.9 ‰) (Fig. 4.4.). Significantly lighter $\delta^{13}\text{C}$ values (-1.2 to 0.3 ‰) come from the northeastern Laptev Sea continental margin. In the Fram Strait, the $\delta^{13}\text{C}$ values show less variations and range between 0.3 and 0.9 ‰. High values are found on the northern Yermak Plateau and in the northeastern Fram Strait (0.6-0.9 ‰). On the southern Yermak Plateau and the Barents Sea shelf, $\delta^{13}\text{C}$ values decrease to 0.3 ‰. Highest $\delta^{13}\text{C}$ values (>0.9 ‰) come from the central Arctic Ocean (Spielhagen and Erlenkeuser, 1994).

In the eastern Fram Strait and north of Severnaya Zemlya the oxygen isotope values of *N. pachyderma* (sin.) from surface samples are generally lower than the equilibrium calcite values in the water column, calculated after O'Neil et al. (1969) and Shackleton (1974) (Fig. 4.5. and 4.6.). In the western Fram Strait and the outer Laptev Sea, $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) are in the range of equilibrium calcite of the uppermost water column and appear to reflect water column values at about 20-40 m water depth in the outer Laptev Sea and at about 40-80 m water depth in the western Fram Strait (Fig. 4.5. and 4.6.). The $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) from sediment surface samples match $\delta^{13}\text{C}_{\text{DIC}}$ values in the upper water column of the outer Laptev Sea and northeast of Severnaya Zemlya, while in the Fram Strait the fossil $\delta^{13}\text{C}$ values are 0.5-1.0 ‰ lighter than modern $\delta^{13}\text{C}_{\text{DIC}}$ (Fig. 4.6.).

Almost none of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of living *N. pachyderma* (sin.) are in equilibrium with the theoretical oxygen isotope values and are lower than equilibrium calcite values. At the Laptev Sea continental margin and northeast of Severnaya Zemlya, the vertical variation of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values is relatively high (Fig. 4.5.), while $\delta^{18}\text{O}$ values in the Fram Strait reflect the trends of equilibrium calcite values, and the vertical variation of $\delta^{13}\text{C}$ values is rather small (Fig. 4.6.).

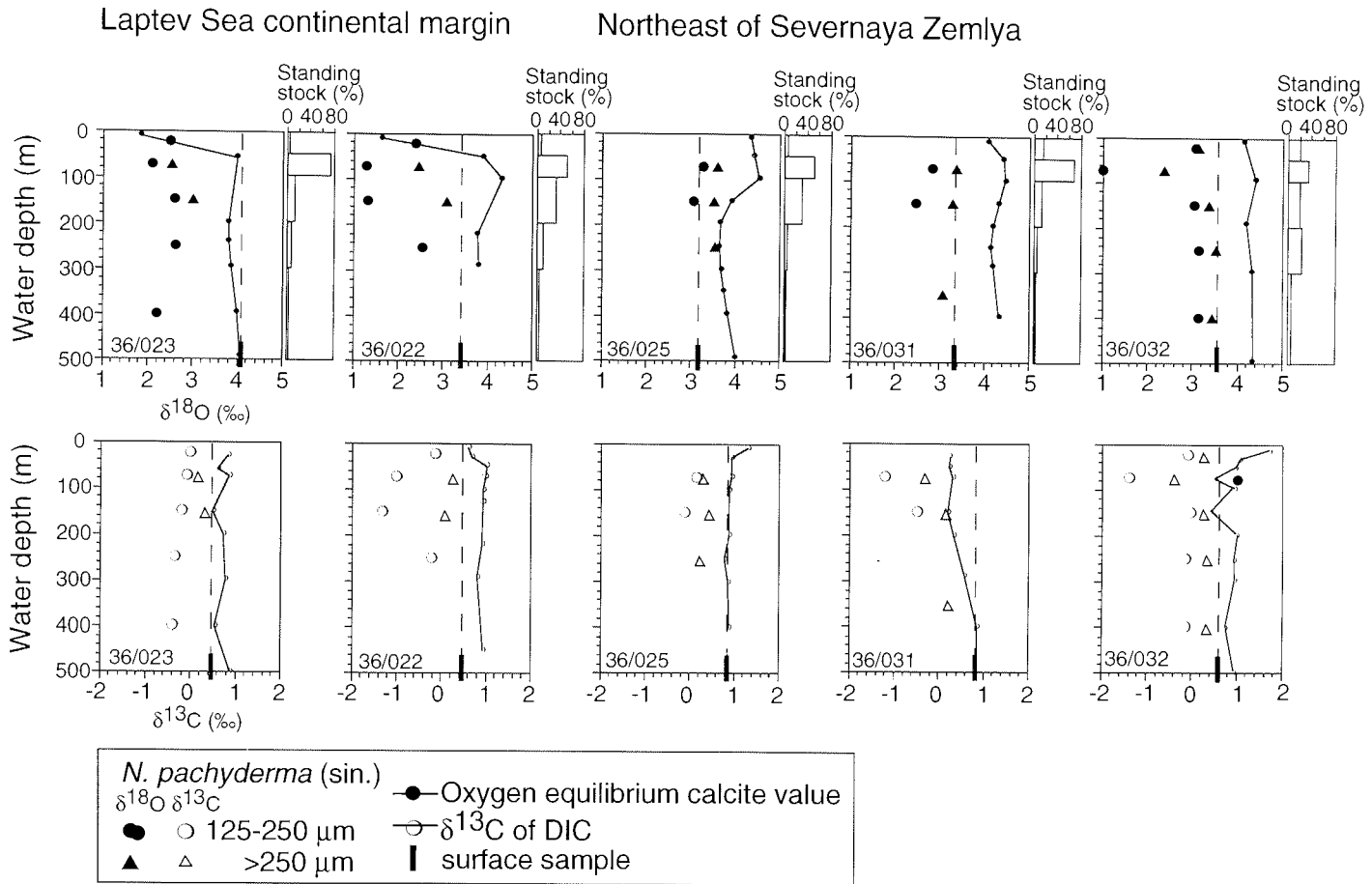


Fig. 4.5.: Stable oxygen and carbon isotope compositions of selected stations from living and fossil *N. pachyderma* (sin.) at the Laptev Sea continental margin and northeast of Severnaya Zemlya. Grey shaded bars mark the halocline waters. Oxygen equilibrium calcite values are calculated after O'Neil et al. (1969) and Shackleton (1974).

Fram Strait

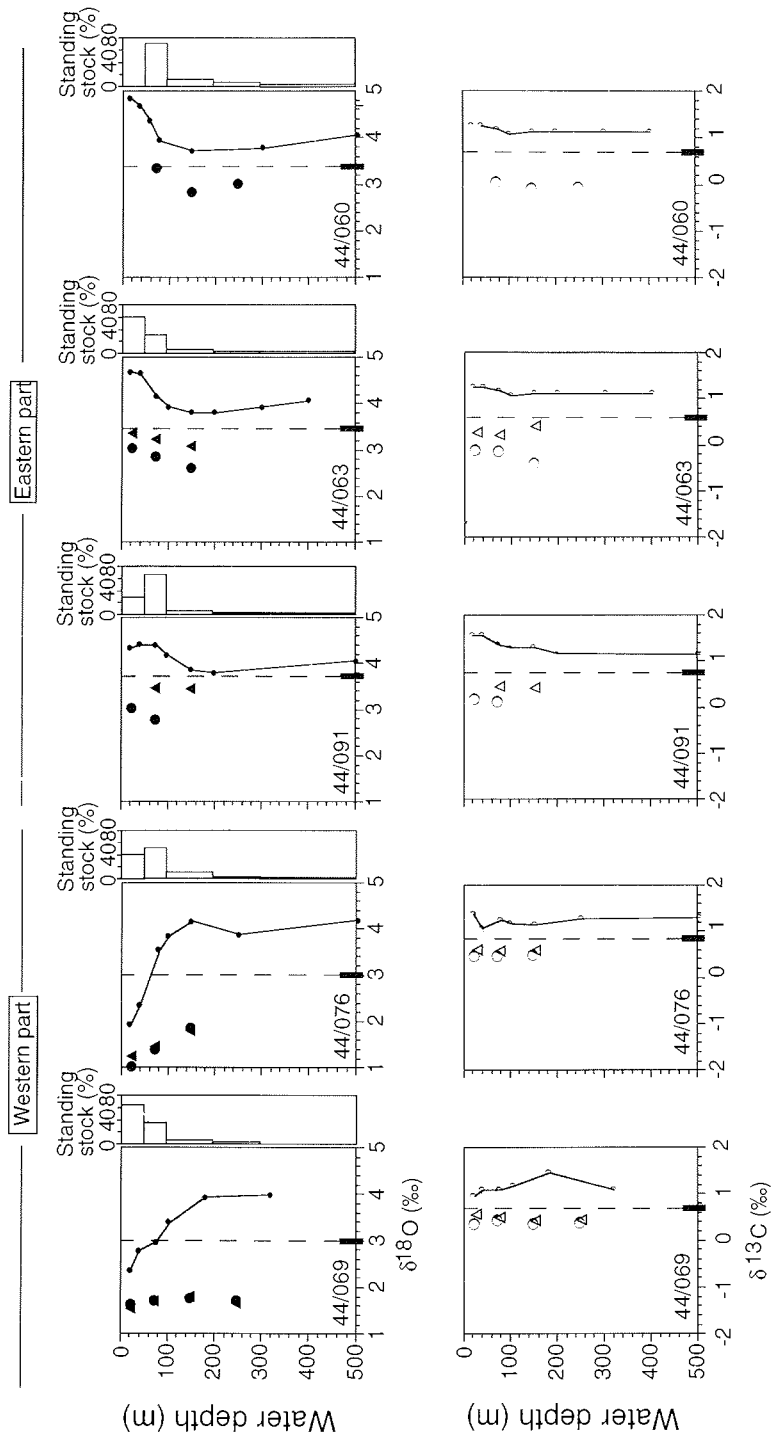


Fig. 4.6.: Stable oxygen and carbon isotope compositions of selected stations from living and fossil *N. pachyderma* (sin.) at the Fram Strait. Grey shaded bars mark the halocline waters. For explanation see Fig. 4.5.

4.7. DISCUSSION

4.7.1. Dissolution of planktic foraminifer tests

The sea-floor sediments in the Arctic Ocean consist chiefly of hemipelagic, fine-grained terrigenous material (Nørgaard-Pedersen, 1997) and the carbonate content is relatively low (<10 %) (Stein et al., 1994b). The planktic foraminiferal assemblages in the Arctic Ocean show significant enrichments of *N. pachyderma* (sin.) in sediment surface samples compared to multinet tows (Fig. 4.7.). This alteration to the dominance of the cold water species *N. pachyderma* (sin.) is predominantly caused by selective dissolution, preferably of thin-shelled species (e.g., Parker and Berger, 1971; Thunnell and Honjo, 1981). *G. ruber*, *T. quinqueloba*, and *G. glutinata* are delicate to dissolution, while the compact shell of *N. pachyderma* is more resistant (Vincent and Berger, 1981). While significant amounts of living *T. quinqueloba* were found in the eastern Arctic Ocean during various years (Carstens and Wefer, 1992; Carstens et al., 1997), *T. quinqueloba* is rare to absent in the >125 µm size fractions of the surface sediments due to carbonate dissolution.

Because all our samples are from water depths well above the lysocline in the eastern Arctic Ocean (>4000 m; Pagels, 1992), we assume that dissolution resulted from corrosive bottom waters released as brines during sea-ice formation on the Siberian shelves. From here, dense, CO₂-rich waters (Anderson et al., 1990) penetrate into the intermediate and deeper layers of the central basin (Rudels et al., 1994). Decay of organic matter during fall and winter can elevate the CO₂ content and the corrosivity of the upper waters which are afterwards transported downward by brines (Anderson et al., 1990; Steinsund and Hald, 1994; Rudels et al., in press a).

Dissolution of planktic foraminifers in shallow water was also suggested for late Quaternary sediments in the Arctic Ocean (Nørgaard-Pedersen, 1997). From comparison of living and fossil assemblages, changes in species composition and a minimum average loss of 80% due to dissolution and destruction by predators were described by Vilks (1975) for the Canadian Arctic. Reynolds-Sautter and Thunell (1989) showed significant enrichments of *N. pachyderma* (sin.) in surface sediments compared to sediment trap assemblages for the northeast Pacific. These sediment surface samples are from a depth below the lysocline and have undergone at least moderate dissolution. In contrast, low differences between living and fossil planktic foraminiferal assemblages were observed by Jensen (1998) for the Greenland-Norwegian Sea, where planktic foraminifers showed no or little dissolution (Vogt, 1986).

From these observations, it seems that the hydrography of regions with low annual variations (e.g., no freezing, no brine release in winter, no ice melting in summer) is better represented in fossil planktic foraminiferal assemblages than the hydrography of regions, where a pronounced seasonality supports winter-brine formation and corrosive bottom water. Accordingly, alteration of planktic foraminiferal assemblages due to dissolution leads to enrichments of thick-walled cold water species in Arctic Ocean sediments and an overestimation of a cold water environment, as deduced from the species composition.

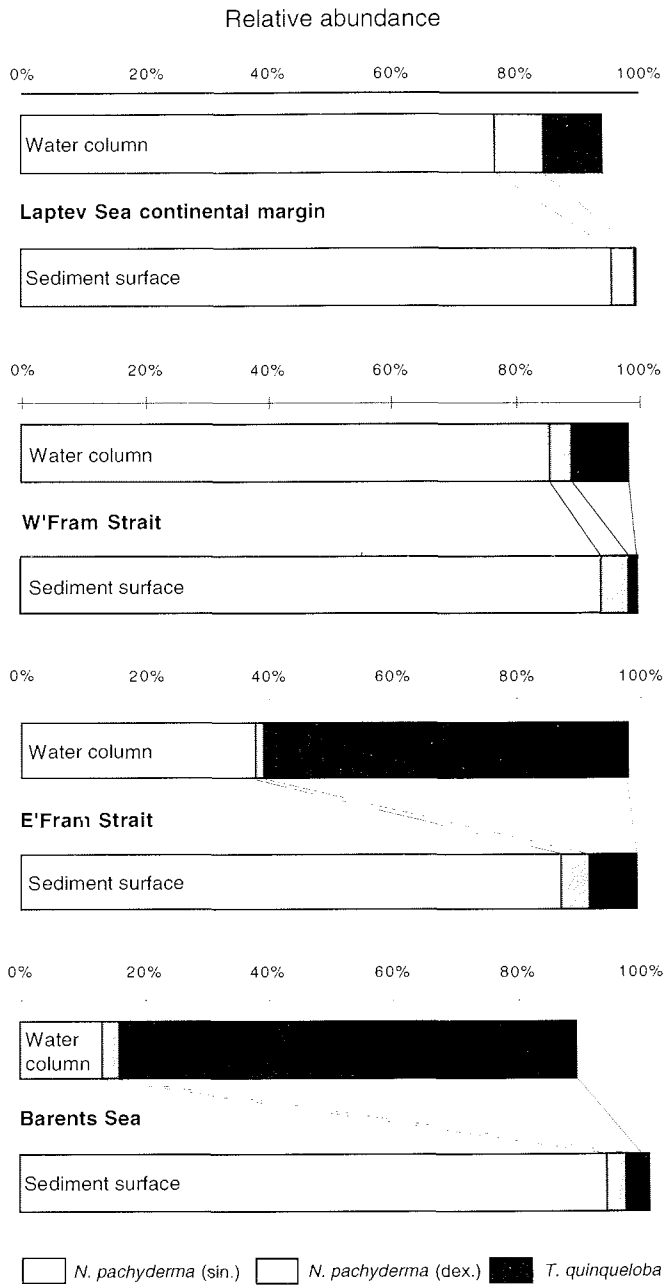


Fig. 4.7.: Comparison between the relative abundances of planktic foraminifers in the water column and in the sediment surface for different study areas in the Arctic Ocean. Abundances of other planktic foraminifers are listed in Table 4.2.

4.7.2. Planktic foraminifer distribution

The sediment surface planktic foraminiferal assemblages on the Laptev Sea continental margin and the Fram Strait reveal a monotonous distribution pattern with a dominance of *N. pachyderma* (sin.) in every size class (Tables 4.2. and 4.3.). Abundances of *T. quinqueloba* up to 8 % in the 125-250 μm size class in the eastern Fram Strait (Fig. 4.8.) can be attributed to the advection of warm Atlantic water and seasonally ice-free conditions. Despite selective dissolution discussed above, the planktic foraminiferal distribution pattern in the Fram Strait has implications for the paleoceanographic reconstruction of the distribution of cold Polar waters and warmer Atlantic waters and the position of the summer sea-ice margin. A localisation of the Polar and Arctic Fronts using planktic foraminiferal assemblages, as described for the Nordic Seas (Johannessen et al., 1994), is not possible in the Fram Strait, because here Polar waters are present directly adjacent to Atlantic waters.

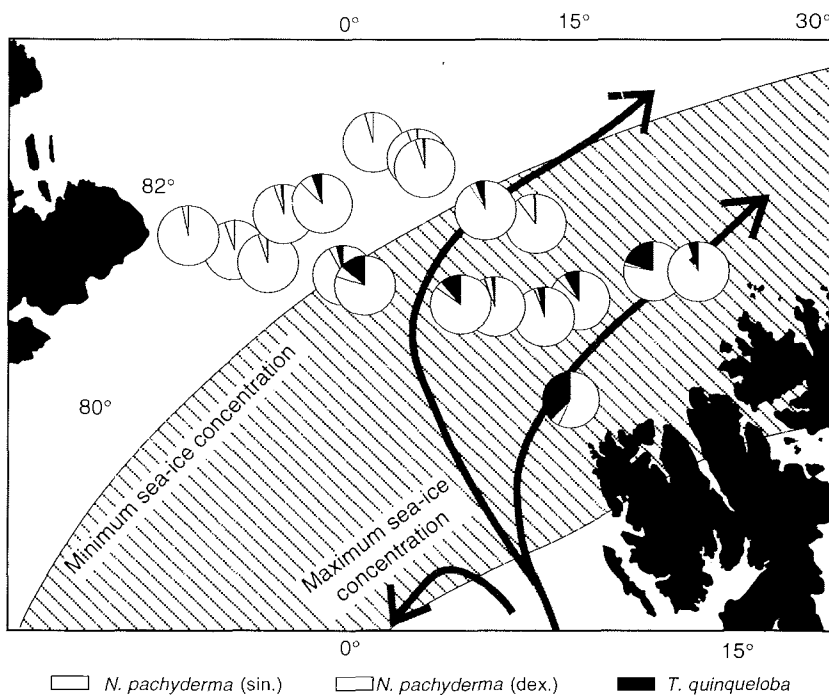


Fig. 4.8.: Relative abundances of planktic foraminifers in sediment surface samples of the Fram Strait. Sea-ice concentrations are after Romanov (1995). Grey arrows denote the Atlantic Water recirculation and inflow through the Fram Strait after Rudels et al. (in press b).

On the Laptev Sea continental margin, the planktic foraminifer assemblages in surface sediments show a consistent abundance of *N. pachyderma* (sin.) in both analysed size classes of about 96 %. *T. quinqueloba* amounts to 0.2 % in the 125-250 μm size class and is absent in the >250 μm size class. Because of the uniform distribution pattern, it is impossible to reconstruct water mass boundaries or to localize the paleo-sea ice margin.

4.7.3. Stable isotopes of planktic foraminifers

To realistically compare sediment surface and water column isotope data of planktic foraminifers, the surface sediments in the Arctic Ocean should represent late Holocene conditions. ^{14}C ages (Table 4.4.; sites are given in Fig. 4.2.) demonstrate that surface sediments are very young, although bioturbational mixing seems involved in most samples. Comparison of data from sediment surface samples with modern hydrographic conditions should be used carefully for calculations, where the seasonal ice cover and the freshwater discharge from the Siberian Rivers have to be taken into account. Both the ice cover and freshwater discharge into the Arctic Ocean show a strong annual variability (Parkinson, 1992; Aleksandrov and Kolatschek, 1997; Dmitrenko et al., 1999). Dissolution experiments of fossil *N. pachyderma* (sin.) indicate no influence of dissolution on the oxygen and carbon isotopes (Schiebel, 1991) and the isotope values are assumed to record environmental and physiological variations.

Table 4.4.: Core locations and results of Accelerator Mass Spectrometry (AMS) ^{14}C in the studied area of the Arctic Ocean. ^{14}C data were corrected for a reservoir effect of 400 years (Bard, 1988). * Real age probably lower due to mixture of the surface sediments.

Core	Latitude	Longitude	Sample depth (cm)	^{14}C -Ages (years BP)	Source
PS1230-1	78°51.3N	4°46.9W	surface	2125±75*	Spielhagen (unpubl. data)
PS1295-4	77°59.9N	2°28.1E	surface	560±60	Jones and Keigwin (1988)
PS1535-5	78°45.0N	1°46.5E	surface	140±20	Spielhagen (unpubl. data)
PS2446-4	82°23.8N	40°54.5E	6	700±40	Knies (1999)
PS2458-3	78°10.0N	133°23.7E	surface	modern	Spielhagen et al. (subm.)
PS2725	78°39.4N	144°07.9E	surface	modern	Stein and Fahl (in press)
PS2757-7	81°09.6N	140°12.1E	surface	600±30	Spielhagen (unpubl. data)
PS2837-5	81°14.0N	2°22.9E	10-11	135±25	Spielhagen (unpubl. data)

Oxygen isotopes

Almost all encrusted *N. pachyderma* (sin.) from sediment surface samples are enriched in ^{18}O if compared with nonencrusted living *N. pachyderma* (sin.) from multinet tows at the same locations (Table 4.5.), and the $\delta^{18}\text{O}$ vital effect of fossil *N. pachyderma* (sin.) of 0.6 ‰ (± 0.2 , $n=18$) is significant lower than for living individuals. Some single $\delta^{18}\text{O}$ values of living individuals resemble $\delta^{18}\text{O}$ values from sediment surface samples at the same position. However, depths of samples where values match those from the surface samples are variable from site to site and no clear relationship can be identified. Highest offsets between living and fossil individuals (-1.55 ± 0.4 ‰; -1.3 to -2.5 ‰ $\delta^{18}\text{O}$) exist for *N. pachyderma* (sin.) in samples affected by the low saline surface layer (salinity of ~ 30 psu) with vertical salinity differences of 4-5 psu in the upper 300 m on the Laptev Sea continental margin and in the western Fram Strait (Rudels et al., in press a, b). Here, $\delta^{18}\text{O}$ values of living individuals predominantly reflect the modern, low $\delta^{18}\text{O}_w$ values in the uppermost water column. Low offsets in $\delta^{18}\text{O}$ between fossil and living individuals of *N. pachyderma* (sin.) are found in the eastern Fram Strait and northeast of

Severnaya Zemlya, where a low saline surface layer is not developed or is less pronounced, and the observed vertical salinity differences are less than 2 psu.

Table 4.5.: Oxygen and carbon isotope composition of *N. pachyderma* (sin.) from sediment surface samples and the water column of the Arctic Ocean, and its isotopic differences. The $\delta^{18}\text{O}$ values of living individuals in the water column are averaged over the sampled depth intervals with emphasis on standing stock.

Station	<i>N. pachyderma</i> (sin.)					
	$\delta^{18}\text{O}$ (‰)			$\delta^{13}\text{C}$ (‰)		
	Water column	Sediment surface	Difference	Water column	Sediment surface	Difference
Outer Laptev Sea						
36/022	1.75	3.41	-1.7	-0.91	0.47	-1.4
36/023	2.53	4.12	-1.6	-0.01	0.49	-0.5
36/024	2.20	3.22	-1.0	-0.76	0.56	-1.3
NE of Severnaya Zemlya						
36/025	3.48	3.19	0.3	0.16	0.85	-0.7
36/031	3.07	3.37	-0.3	-0.98	0.79	-1.8
36/032	2.68	3.58	-0.9	-0.43	0.64	-1.1
W'Fram Strait						
44/069	1.96	3.06	-1.1	0.49	0.70	-0.2
44/076	1.61	3.05	-1.4	0.58	0.85	-0.3
44/077	1.20	3.35	-2.2	0.14	0.77	-0.6
44/084	1.83	3.69	-1.9	0.44	0.68	-0.2
E'Fram Strait						
44/060	3.50	3.38	0.1	0.13	0.69	-0.6
44/063	3.25	3.45	-0.2	-0.03	0.63	-0.7
44/091	3.16	3.76	-0.6	0.25	0.76	-0.5

In the Nansen Basin, $\delta^{18}\text{O}$ values of alive sampled *N. pachyderma* (sin.) match sediment surface data (Bauch et al., 1997). Compared to the outer Laptev Sea and the western Fram Strait, where highest offsets were calculated, surface water salinity is higher and the average depth of habitat lies deeper (Fig. 4.9.). In the polynya off NE-Greenland with large vertical gradients in temperature and salinity, no offset between living and fossil *N. pachyderma* (sin.) is found (Kohfeld et al., 1996). This open water feature appears regularly on the East Greenland shelf (Budéus and Schneider, 1995), and is thus well reflected in the isotopic composition of fossil individuals.

In contrast, the ice cover in the Arctic Ocean marginal seas (e.g., the Laptev Sea) shows a strong interannual variability (Parkinson, 1992). For example, the ice-edge position in summer 1995, when samples on the Laptev Sea continental margin were taken, was in an extreme northern position and far away from its average position during previous years (Aleksandrov and Kolatschek, 1997). Thus it is not surprising that the low $\delta^{18}\text{O}$ values of living specimens are strongly different from the surface sediment values. Even more, this finding may suggest that high offsets between living and fossil planktic foraminifers can be common in regions of strong interannual variations and/or high salinity gradients.

In general, the analysed living individuals in the 125-250 μm size class are nonencrusted. According to results from the Northeast Water Polynya (Kohfeld et al., 1996) and own data (Fig. 4.5. and 4.6.), a mean value of 0.3 ‰ should be subtracted from the offset. This value represents the oxygen isotope difference between nonencrusted and encrusted individuals (the value of own data was calculated from the difference between nonencrusted individuals from the 125-250 μm size class and encrusted individuals from the >250 μm size class). The remaining observed ^{18}O enrichment in the foraminifers from sediment samples can partly be explained by secondary calcification below 200 m water depth (Kohfeld et al., 1996). In deeper waters, salinity and $\delta^{18}\text{O}_w$ are higher than in the surface waters (Rudels et al., in press a, b; Volkman and Mensch, subm.) thus enriching the $\delta^{18}\text{O}_{\text{foram}}$ values. Also a lower precipitation rate, as assumed for later ontogenetic stages such as secondary calcification, tends to enrich ^{18}O and ^{13}C in the calcite shell (McConnaughey, 1989) if metabolic CO_2 contributes to chamber formation. The fact that almost all individuals of *N. pachyderma* (sin.) in sediment surface samples show a thick secondary calcite crust (Table 4.2.) supports the assumption that only encrusted individuals from deeper and isotopically heavier water depths are preserved (cf. Kohfeld, et al., 1996; Bauch et al., 1997; Simstich, 1999). Unfortunately, living planktic foraminifers were too rare below 300 m in the investigated area to obtain isotope data. When calculating the average isotope values of living individuals for each station, the lack of such information results in an overrepresentation of the upper water column. The resulting apparent difference between these values and those from the surface samples may thus to some extent be an artefact.

Relationship between $\delta^{18}\text{O}_{\text{foram}}$, depth habitat, and salinity

The high $\delta^{18}\text{O}$ offset between living and fossil *N. pachyderma* (sin.) are a result of hydrographic changes during the last centuries. The $\delta^{18}\text{O}$ values of living *N. pachyderma* (sin.) show a positive correlation to the average depth of habitat (Volkman and Mensch, subm.) (Fig. 4.9.). Under a permanent ice cover and at stations affected by cold Polar Water, *N. pachyderma* (sin.) dwells shallow at about 50 m water depth (Carstens and Wefer, 1992; Volkman, in press) and $\delta^{18}\text{O}$ values are about 1.5 ‰ (Fig. 4.9.a). At the ice margin and at stations affected by warm Atlantic Water, *N. pachyderma* (sin.) descends downward to about 100 m and its $\delta^{18}\text{O}$ values are >3 ‰. However, assuming the modern average depth of habitat also for the fossil individuals, $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) from sediment surface samples in the western Fram Strait are too heavy (Fig. 4.9.b) and might reflect a deeper habitat at about 100 m water depth. This apparent contradiction between the modern habitat and the isotopic evidence for a deeper habitat in the past might be resolved by oceanographic observations during the past decades. Zhang et al. (1998) and Rudels et al. (in press b) presented evidence for an ongoing freshening of surface waters in the western Fram Strait during the last decades. Therefore, isotope values of *N. pachyderma* (sin.) from surface sediments probably reflect a higher mean $\delta^{18}\text{O}$ value of more saline surface waters during the last few centuries rather than today's modern low saline and low $\delta^{18}\text{O}$ waters.

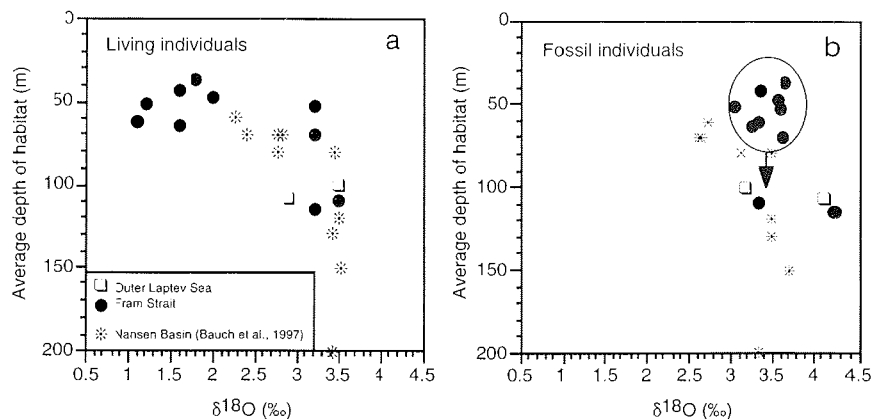


Fig. 4.9.: Average depth of habitat versus $\delta^{18}\text{O}$ values of *N. pachyderma* (a) from plankton tows (living individuals) and (b) from sediment surface samples in the Arctic Ocean. The difference between nonencrusted and encrusted individuals of 0.3‰ is added to the data. Western Nansen Basin data were obtained on encrusted individuals by Bauch et al. (1997). The $\delta^{18}\text{O}$ values of living individuals are averaged over the sampled depth intervals with emphasis on standing stock: $=\sum(\delta^{18}\text{O} \times \text{stand. stock})/\sum \text{stand. stock}$. Data set of fossil individuals is taken from the same locations as the living individuals and the modern depth habitat is assumed.

The isotope data from alive sampled planktic foraminifers are just a snapshot of Arctic water masses in the summers of 1995 and 1997, two of three years in the 1990s which were warmer than any other year for the past six centuries in the northern hemisphere (Mann et al., 1998). However, the sediment surface samples record an integrated value over several centuries (Table 4.4.) and may include possibly lower temperatures during the Little Ice Age (LIA, ~1400-1850 A. D.). Despite significant decadal-scale climatic variability of the LIA, it was a period of cold, dry conditions and increased atmospheric circulation (Kreutz et al., 1997). The water temperature had to be an unrealistic amount of $4\text{ }^{\circ}\text{C}$ lower than today (mean Arctic surface water temperatures are -1.5 to $-1.8\text{ }^{\circ}\text{C}$) to account for a difference of 1.2‰ $\delta^{18}\text{O}_{\text{foram}}$, assuming that a $1\text{ }^{\circ}\text{C}$ -decrease is associated with a 0.3‰ -decrease in $\delta^{18}\text{O}$ (O'Neil et al., 1969). If we assume a surface water warming similar to an atmospheric temperature warming of 1° to $3\text{ }^{\circ}\text{C}$, which was suggested in the Arctic locally for the past two centuries (Overpeck et al., 1997), this could explain a difference up to 0.9‰ . Anyway, one would also expect that the slower mixing processes in the ocean will result in a certain delay of the temperature increase relative to the atmosphere, therefore, temperature can not explain the $\delta^{18}\text{O}$ offset.

An alternative explanation for the high $\delta^{18}\text{O}_{\text{foram}}$ values could be higher salinities in the past. One can expect a lower river discharge from reduced precipitation in Northern Asia during the LIA had resulted in higher $\delta^{18}\text{O}$ values of the more saline surface waters. A salinity change of 1 psu is approximately equivalent to a change of 0.6‰ in $\delta^{18}\text{O}_{\text{foram}}$ (O'Neil et al., 1969). A salinity decrease of about 2 psu (and a corresponding $\delta^{18}\text{O}_w$ decrease) during the last centuries is a possible reason for the $\delta^{18}\text{O}$ offset between fossil and living planktic foraminifers. A weakening of the Arctic halocline due to lower

freshwater discharge results in stronger vertical mixing and larger ocean-ice heat flux (Prange and Gerdes, 1999). If this was the case during most of the time represented in the surface samples, the average depth of habitat of *N. pachyderma* (sin.) may have lain deeper than today (cf. Fig. 4.9.a) and the fossil $\delta^{18}\text{O}$ values reflect deeper water masses, caused by a weaker stratified water column. Going a step further, it can be speculated that a lower river water influx and therefore higher salinity of surface waters may even have decreased sea-ice formation. Under seasonally ice-free conditions, the past depth habitat of *N. pachyderma* (sin.) then may have been similar to the modern depth habitat around 100 m as described for living individuals (Volkman, in press). In summary, there is evidence that the oxygen isotope compositions of *N. pachyderma* (sin.) in the investigated area to some extent reflects the impact of natural climatic variabilities during the last 200-500 years or more.

In general, the lateral $\delta^{18}\text{O}$ distribution pattern of *N. pachyderma* (sin.) in sediment surface samples of the Arctic Ocean (Fig. 4.4., see also Spielhagen and Erlenkeuser, 1994) reflects the salinity of the average habitat depth. On the Laptev Sea continental margin, the seaward decrease in $\delta^{18}\text{O}$ values can be attributed to the shallow depth habitat in low saline waters, which *N. pachyderma* (sin.) prefers under the permanent ice cover (Carstens et al., 1997; Volkman, in press). In the southern, ice-free region on the Laptev Sea continental margin and northeast of Severnaya Zemlya, *N. pachyderma* (sin.) lives deeper in more saline waters resulting in isotopically heavier values. High $\delta^{18}\text{O}$ values ($>3.5\text{‰}$) of *N. pachyderma* (sin.) on the Yermak Plateau and the Barents Sea continental margin can be explained by the inflow of saline Atlantic water ($S>34.9$ psu). In the Fram Strait, the $\delta^{18}\text{O}$ values of living individuals strongly decrease from east to west according to the decreasing average depth of habitat (Volkman, in press). Due to slightly lower $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) in sediment surface samples in the west than in the east (Fig. 4.10.), we suggest a mean paleo-habitat of about 100 m water depth for the *N. pachyderma* (sin.) found in sediment surface samples of the Fram Strait.

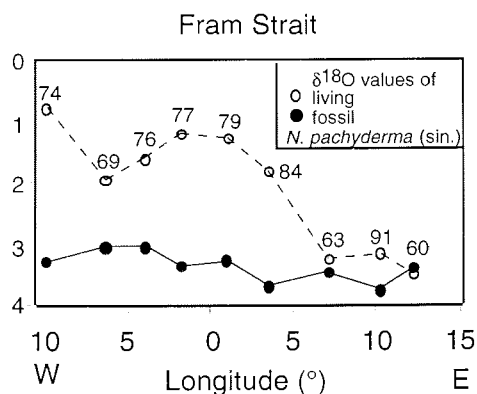


Fig. 4.10.: Stable oxygen isotope composition of living and fossil *N. pachyderma* (sin.) in the Fram Strait. Stations are arranged in a W-E transect, station numbers are given above the data points.

The maximum range of 0.7 ‰ of $\delta^{18}\text{O}$ values in surface samples between the western and the eastern part is then equivalent to a salinity difference of about 1.2 psu at this water depth. Indeed, the salinity difference between stations affected by Polar waters (33.5-34.0 psu) and stations affected by Atlantic waters (~34.9 psu) is in this range, which is in strong support of our calculations.

Carbon isotopes

Fossil *N. pachyderma* (sin.) in the 125-250 μm size class are generally enriched in ^{13}C if compared to living individuals from the same stations (Figs. 4.5. and 4.6.). While the offset is between 0.3-0.8 ‰ in $\delta^{13}\text{C}$ for stations in the Fram Strait, an offset >1 ‰ in $\delta^{13}\text{C}$ is predominant at the Laptev Sea continental margin and northeast of Severnaya Zemlya (Table 4.5.). Here, slightly negative $\delta^{13}\text{C}$ values were measured for living *N. pachyderma* (sin.), probably reflecting low $\delta^{13}\text{C}_{\text{DIC}}$ from the Lena river discharge (Erlenkeuser et al., 1995). The vital effect of fossil encrusted individuals of 1.4 ‰ (± 0.25 , $n=11$) in $\delta^{13}\text{C}$ is mainly caused by a decreased metabolic activity in later ontogenetic stages.

When discussing the reasons for the $\delta^{13}\text{C}$ offset between living and fossil *N. pachyderma* (sin.), the influence of anthropogenic CO_2 has to be taken into account. While the living individuals reflect the modern anthropogenically influenced conditions, the sediment surface samples include mainly older individuals from preindustrial time (Table 4.4.) and, as discussed above, it can even be assumed that they represent mainly preindustrial Holocene conditions (Beveridge and Shackleton, 1994; Bauch et al., in press). Increased concentration of atmospheric CO_2 produced by the combustion of fossil fuels and tropical deforestation has led to a reduction in ^{13}C in the atmosphere and subsequently in the oceanic reservoir (SUESS effect; Bacastow et al., 1996). The SUESS effect is estimated to be about -0.9 ‰ within the Arctic Ocean halocline of the southern Nansen Basin (Bauch et al., in press) about as high as in the NE Atlantic (Keir et al, 1998). About one third of the anthropogenic, ^{13}C -depleted CO_2 was taken up by the ocean (Siegenthaler and Sarmiento, 1993). A strong transport of carbon from the atmosphere, driven by extensive biological production on the broad continental shelves, has been calculated (Anderson et al. 1998; Olsson et al., 1999), and there is evidence that the Arctic shelf regions are relatively well-ventilated with respect to CO_2 (Bauch et al., in press).

At the Laptev Sea continental margin, the difference between $\delta^{13}\text{C}$ values of living *N. pachyderma* (sin.) and specimens from the sediment surface (-1.1 ‰) is considerably higher than in the Fram Strait (-0.3 ‰ in the west, -0.6 ‰ in the east) (Figs. 4.5. and 4.6.). This indicates that a large amount of anthropogenic CO_2 is entering the Arctic shelf areas through the well-ventilated Arctic shelf regions (Bauch et al., in press), while the low offset in the western Fram Strait demonstrates the larger distance to the shelf regions and worse ventilation. In the eastern Fram Strait, a slightly higher offset than in the west may be attributed to better ventilated Atlantic waters, entering the Arctic Ocean via the

West Spitsbergen Current from the Norwegian Sea, where this waters dominates the surface water and is be subject to air-sea exchange.

Lateral distribution of fossil $\delta^{13}\text{C}$ values

The lateral $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) in sediment surface samples shows a seaward increase (Fig. 4.4.) reflecting the isotopically light river outflow predominantly towards the north-east on the Laptev Sea continental margin. Higher $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) in the Eurasian Basin suggest better equilibrated halocline waters within the Transpolar Drift, formed on the Siberian shelves. However, all of the $\delta^{13}\text{C}_{\text{DIC}}$ values (0.7-1.7 ‰) found at the Laptev Sea continental margin waters and the western Fram Strait waters are far off the isotopic equilibrium with the atmosphere (Emrich et al., 1970). Low $\delta^{13}\text{C}$ values (<0.3 ‰) of *N. pachyderma* (sin.) in sediment surface samples northwest of Svalbard (Fig. 4.4.b) probably reflect higher water temperatures in the deeper average depth of habitat in this seasonally ice-free region (c.f., Volkman, in press). The $\delta^{13}\text{C}_{\text{foram}}$ values decrease with increasing temperature (Ortiz et al., 1996; Spero and Lea, 1996). Ortiz et al. (1996) assume that temperature is a stronger control mechanism than the influence of the metabolic rate.

On the other hand low $\delta^{13}\text{C}$ values might indicate low biological production and higher phosphate concentrations. However, high $\delta^{13}\text{C}_{\text{DIC}}$ values up to 1.9 ‰ (H. Erlenkeuser, unpubl. data) found in surface waters of the eastern Fram Strait are associated with very low phosphate concentrations (0.2 $\mu\text{mol/kg}$) (G. Kattner, unpubl. data) and suggest high biological consumption rather than air-sea exchange. The low $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) might be a local phenomenon, complicated by the complex water mass circulation. The distribution of $\delta^{13}\text{C}$ values suggests a possible source of isotopically light DIC from Svalbard in northwestern direction (see Fig. 4.4.b).

*Oxygen and carbon isotope relations of fossil *N. pachyderma* (sin.)*

In Figure 4.11. we have plotted the $\delta^{13}\text{C}$ values vs. $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) in Arctic Ocean surface sediments. Six separated isotope groups could be distinguished, which are predominantly determined by the species' depth habitat, ice coverage, the degree of river-water input, Atlantic waters, and air-sea exchange:

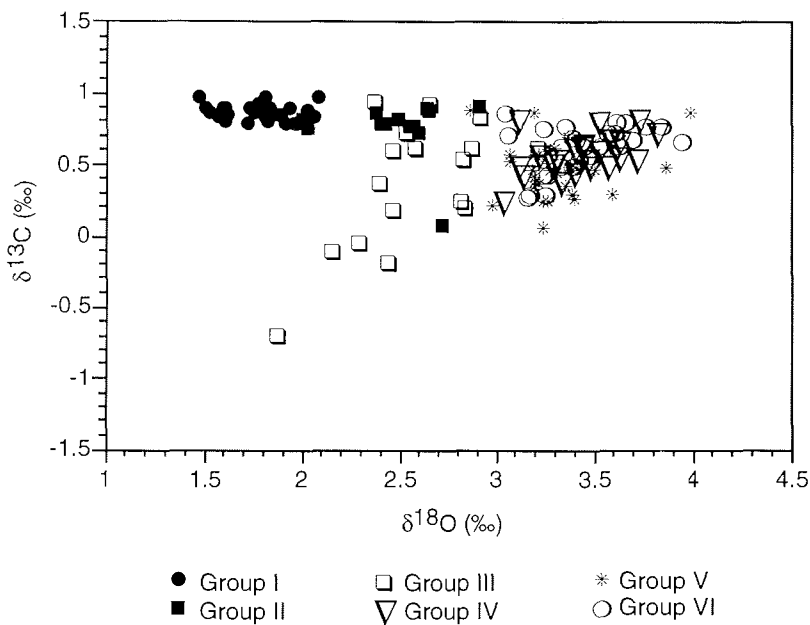


Fig. 4.11.: $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) in Arctic Ocean surface sediments. Data of Spielhagen and Erlenkeuser (1994) and Köhler (1992) are included. The different clusters separate values of a shallow depth habitat under permanent ice coverage (Groups I and II), river-water influenced values (Group III), and values of a depth habitat of 100 m water depth in seasonally ice-free regions (Groups IV, V, and VI).

Group I: This data set includes stable isotopes from the perennially ice-covered central Arctic Ocean and the Amerasian Basin. Low $\delta^{18}\text{O}$ values indicate a depth habitat of *N. pachyderma* (sin.) in shallow, low saline waters. Consistently high $\delta^{13}\text{C}$ values indicate relatively well equilibrated halocline water within the Transpolar Drift, formed on the Siberian shelves.

Group II: The perennially ice-covered central Arctic Ocean (Gakkel Ridge and Nansen Basin) is characterized by higher $\delta^{18}\text{O}_{\text{foram}}$ values than Group I from a similar shallow, but more saline depth habitat.

Group III: This perennially ice-covered facies north of the Lapetv Sea continental margin indicates a high freshwater signal from the Siberian rivers. A strong river-water influence and a shallow depth of habitat result in lowest $\delta^{13}\text{C}$ values and $\delta^{18}\text{O}$ values equivalent to the ice-covered facies (Groups I and II) above without any freshwater influence.

Group IV: At the seasonally ice-free Barents Sea and Svalbard continental margins, an average depth of habitat at about 100 m associated with higher salinity due to Atlantic water inflow results in higher $\delta^{18}\text{O}_{\text{foram}}$ values, but equal $\delta^{13}\text{C}_{\text{foram}}$ values as in Groups I and II due to a similar degree of air-sea exchange.

Group V: The seasonally ice-free region at the Laptev Sea continental margin is characterized by high $\delta^{18}\text{O}$ values resulting in first order from an average depth of habitat at about 100 m water depth. Lower $\delta^{13}\text{C}$ values are attributed to waters on the Arctic shelves, which are well-ventilated with respect to CO_2 and the ^{13}C -depleted river water component.

Group VI: The stable isotope signature in the Fram Strait is similar to that of Groups IV and V and results in first order from a depth habitat of 100 m as well. This is the case in Atlantic dominated waters in the eastern Fram Strait and also in the western Fram Strait, although living individuals here live shallower.

4.8. CONCLUSIONS AND FUTURE PERSPECTIVES

The results of this study reveal that planktic foraminifers allow good indicators for temperature, salinity, and productivity, but show that single proxies are of limited use for reliable reconstructions in the investigated area. Planktic foraminiferal assemblages combined with foraminiferal stable isotope compositions may give a more realistic link for paleoceanographic reconstructions in the northern high latitudes.

The planktic foraminiferal assemblages in surface sediments at the Laptev Sea continental margin and the Fram Strait are dominated by encrusted specimens of *N. pachyderma* (sin.). Other species show significant abundances (8 %) in the eastern Fram Strait. The hydrographic regime in the investigated area is well reflected in the living planktic foraminiferal assemblages, but the fossil assemblages are strongly influenced by selective dissolution, which can be attributed to corrosive, dense, CO_2 -rich shelf derived waters and leads to a relative enrichment in *N. pachyderma* (sin.). While amounts >5 % of fossil *Turborotalita quinqueloba* in the Fram Strait can be used to distinguish cold Polar waters and warmer Atlantic waters and to estimate the location of the summer sea-ice margin, the lack of *T. quinqueloba* in other Arctic areas may be caused by dissolution and can not be used to prove or disprove the influence of Atlantic waters in the past.

The $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) are a useful proxy for salinity reconstruction. Compared to $\delta^{18}\text{O}$ values of living *N. pachyderma* (sin.), $\delta^{18}\text{O}$ values from sediment surface samples are enriched in ^{18}O . Highest offsets are calculated at the Laptev Sea continental margin and the western Fram Strait. Here, the modern upper water column is characterized by cold Polar waters with salinities of ~ 30 psu. These low salinities are recorded in the shells of living individuals, while the fossil individuals apparently reflect higher salinities of deeper waters. A deeper habitat and lower calcification rates are suggested for encrusted *N. pachyderma* (sin.), which are predominantly preserved in deep-sea sediments. Though the upper sediments are of Late Holocene age, ^{14}C data reveal that several centuries are generally covered in the surface samples. A salinity decrease during the last centuries is also a possible cause for the $\delta^{18}\text{O}$ offset between living and fossil individuals. The $\delta^{18}\text{O}$ values of living and fossil individuals show that they did not precipitate their shell in isotopic equilibrium with the ambient sea water. The offset can be explained by

a species-specific vital effect for living individuals, but is difficult to validate for fossil specimens. However, the calculated vital effects of living individuals may reflect hydrographic conditions specific for every year and should be carefully used for paleoceanographic reconstructions (cf. Volkman and Mensch, *subm.*). For a better comparison of living and fossil individuals, isotopic analyses of sediment traps are necessary, which unfortunately are not available yet for the Arctic Ocean.

The carbon isotopes of *N. pachyderma* (sin.) are strongly controlled by the $\delta^{13}\text{C}_{\text{DIC}}$ values of the surrounding water masses where the foraminifers grew and by different precipitation rates during ontogeny. Low $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) in sediment surface samples reflect isotopically light river water. High offsets between living and fossil individuals at the Laptev Sea continental margin indicate an anthropogenic CO_2 uptake by ocean surface water. The distribution of $\delta^{13}\text{C}$ values in the Fram Strait shows a more complicated pattern, which needs further study, particularly including $\delta^{13}\text{C}_{\text{DIC}}$ values from the upper water column. The most probable determining factor for the relatively high $\delta^{13}\text{C}$ values might be the larger distance from the well-ventilated Siberian shelves and better equilibrated surface waters, although $\delta^{13}\text{C}_{\text{DIC}}$ values are still far off isotopic equilibrium. As for living individuals, there is a first order positive correlation between $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) from surface sediments and $\delta^{13}\text{C}_{\text{DIC}}$ values of surface water ($r=0.75$). This relationship suggests that carbon isotope data can be used to determine biological processes and, on a larger scale, the degree of air-sea exchange. We also suggest a decreased metabolic activity of encrusted individuals, which would result in a discrimination against the light isotopes. Although parts of the secondary calcite crust are certainly built below 100 m water depth (Kohfeld et al., 1996; Simstich, 1999), the $\delta^{13}\text{C}$ values of *N. pachyderma* (sin.) from surface sediments are a reliable proxy for $\delta^{13}\text{C}_{\text{DIC}}$ values in surface water masses.

5. FUTURE PERSPECTIVES

The planktic foraminiferal distribution and stable isotope data of this study are useful tools to reconstruct the paleoceanography in the northern high latitudes and the data set contributes to our understanding of planktic foraminifers in the northern polar regions, but also reveals relevant aspects for future work in this field. For a better interpretation of the fossil planktic foraminifer record, it is essential to improve the current knowledge of the biology and ecology of *N. pachyderma* (sin.) and *T. quinqueloba*, which are predominantly fossilized in subpolar and polar Quaternary sediments and are widely used for paleoceanographic reconstructions. The results of chapter 2 show that both species mostly have one depth maximum, which is located in two different water masses at some stations, usually the Polar Mixed Layer and the halocline due to the chosen sampling interval of 50 m. The hydrography is clearly reflected in the living assemblages. Therefore, closer plankton tow intervals of e.g., 20 m depth spacing, may be useful to record the water mass boundaries more clearly and to study the response of foraminifer assemblages to changes at the pycnocline.

Additionally, the vertical distribution of planktic foraminifers is often compared with the chlorophyll *a* concentrations to obtain information, whether or not the species adapt their habitat to the seasonally changing chlorophyll maximum. In chapter 2, I suggest to distinguish phytoplankton organisms on species level, because chlorophyll *a* concentrations do not provide information about the composition of plankton assemblages. Future work should integrate biological investigations on the distribution of diatoms and flagellates, which dominate the algal biomass in the Fram Strait and the outer Laptev Sea (Bauernfeind and Okolodkov, 1997, Okolodkov, 1997) and which seem to determine the abundance of *N. pachyderma* (sin.) (Volkman, in press).

Unfortunately, low planktic foraminifer abundances prevented the statistical analysis of a number of samples from the outer Laptev Sea. To improve the data base, future sampling of living planktic foraminifers should focus on catching of large amounts of tests at one station rather than many stations with low numbers. Each depth interval should include >300 specimens in the 125-250 μm size class, the minimum number used in statistical analyses of sediment surface samples (Pflaumann et al., 1996). When *N. pachyderma* (sin.) is dominating, Pflaumann et al. (1996) even suggest a counting limit of 2500 specimens to record also other species than *N. pachyderma* (sin.) out of the error of the standard deviation.

Higher numbers of foraminifers will also help with the stable oxygen and carbon isotope measurements. The shells of living nonencrusted *N. pachyderma* (sin.) in the investigated area are usually very thin and many tests are needed for accurate isotope measurements. In the Northeast Water Polynya, Kohfeld et al. (1996) determined a mass of <3 μg for nonencrusted individuals. They suggested that total masses of the foraminifer samples should be in the range of 40-180 μg . Accordingly, a number of 60 specimens could be necessary.

When larger numbers of foraminifers are available, the measurement of nonencrusted and encrusted individuals would be possible and the process of secondary calcification could be analyzed in more detail. A better knowledge

of the encrustation could help to better understand the species-specific vital effect and its decrease in value from shells in the water column to shells in the sediment surface. The stable isotope data in chapter 3 indicate that the vital effect of living individuals is different from region to region. However, up to now, only few studies exist about stable isotopes of living planktic foraminifers in the Arctic Ocean (Bauch et al., 1997, in press; Volkmann and Mensch, subm.). High vital effects have been calculated for the outer Laptev Sea (chapter 3), where river run-off and sea-ice production influence the water masses. To check, whether the influence of these parameters is a local phenomenon, comparable studies are necessary in regions with similar hydrographic conditions, e.g. in the Kara Sea, which is also characterized by freshwater discharge from the Siberian rivers (Aagaard and Carmack, 1989) and by seasonal ice coverage (Pavlov and Pfirman, 1995).

The oxygen isotope composition of planktic foraminifers depends on the sea-water temperature of calcification and water $\delta^{18}\text{O}$ (Emiliani, 1954). However, no obvious relationship seems to exist between foraminiferal $\delta^{18}\text{O}$ values and actual surface water temperature in the investigation area, while a positive correlation is given between $\delta^{18}\text{O}$ values of *N. pachyderma* (sin.) and salinity. For calculation of temperature or temperature variability in the high latitudes, Nürnberg (1995) used the magnesium content in the calcite shell of *N. pachyderma* (sin.), which might reflect even short-term climatic events and should be used in addition to isotope and faunal analyses. Further proxies such as cadmium/calcium (Cd/Ca) ratios in planktic foraminiferal calcite can also be used to reconstruct sea-surface temperature as well as paleoproductivity (Rickaby and Elderfield, 1999). In a next step, the carbon isotopes of living *N. pachyderma* (sin.) should be compared to carbonate chemistry of the ocean, because Spero et al. (1997) show evidence that the $\delta^{13}\text{C}$ signature of *Globigerina bulloides* strongly depends on the carbonate ion concentration $[\text{CO}_3^{2-}]$ of the ambient sea water. If we assume a similar response for *N. pachyderma* (sin.), this relationship can confound the standard interpretation of foraminiferal isotope data (Spero et al., 1997), because oceans during glacial periods had higher pH and $[\text{CO}_3^{2-}]$ than today (Sanyal et al., 1995).

Combined analysis of stable oxygen and carbon isotope values of *N. pachyderma* (sin.) from sediment surface samples reveals an environmental distribution pattern and can be used to estimate the paleo-habitat, salinity, ice-coverage, and degree of ventilation. However, the available data set should be extended to cover also the isotope facies (Fig. 4.12.), which were not sampled by Köhler (1992), Spielhagen and Erlenkeuser (1994), and in this study. In detail, group V and VI should be represented in more detail for a better understanding of the river-water influence on the foraminiferal isotope signal. This improvement may be useful for synoptic reconstructions of past environments similar to those described in this study. Stable isotope data of the different morphotypes of *N. pachyderma* (sin.) (Normalform and Kummerfom) from sediment surface samples (Appendix 5.1. and 5.2.) reveal a correlation coefficient of 0.93 for both oxygen and carbon isotopes. In cases of extremely low foraminifer contents in sedimentary sequences, both morphotypes can be used for isotope measurements in future.

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Appendix

Appendix 2.1.: Absolute and relative abundances of *N. pachyderma* and *T. quinqueloba* in the >250 μm size class as an integrated value in the upper 500 m of the water column in the Arctic Ocean. The faunal composition from samples with low numbers of foraminifers is only an approximate value and often not representative (*).

Cruise	Station	Count	>250 μm size class					
			<i>N. pachyderma</i> (sin.)		<i>T. quinqueloba</i>		<i>N. pachyderma</i> (dex.)	
			absolute	relative	absolute	relative	absolute	relative
			abundances	abundances	abundances	abundances	abundances	abundances
	(total)	(ind./m ³) 0-500 m	(%)	(ind./m ³) 0-500 m	(%)	(ind./m ³) 0-500 m	(%)	
ARK XII/1	22	14	0.10	85.2	0.00	0.0	0.02	14.8
	23	32	0.26	100.0	0.00	0.0	0.00	0.0
	24	22	0.18	100.0	0.00	0.0	0.00	0.0
	24a	13	0.10	100.0	0.00	0.0	0.00	0.0
	25	225	1.69	97.1	0.00	0.0	0.10	2.8
	27	149	1.17	99.0	0.00	0.0	0.01	0.3
	31	94	0.68	96.5	0.00	0.0	0.02	3.5
	32	201	1.46	88.8	0.00	0.0	0.06	3.1
	33	102	1.35	95.9	0.00	0.0	0.03	1.8
	40a	21	0.17	100.0	0.00	0.0	0.00	0.0
	45	7	0.05	50.0*	0.00	0.0	0.01	50.0*
	47	3	0.02	100.0	0.00	0.0	0.00	0.0
	60	12	0.09	95.8	0.00	0.0	0.01	4.2
	62	18	0.14	100.0	0.00	0.0	0.00	0.0
	64	5	0.04	100.0	0.00	0.0	0.00	0.0
	69	3	0.02	100.0	0.00	0.0	0.00	0.0
ARK XIII/2	39	4	0.06	100.0	0.00	0.0	0.00	0.0
	52	20	0.25	97.2	0.00	0.0	0.00	0.0
	58	13	0.10	100.0	0.00	0.0	0.00	0.0
	60	8	0.06	100.0	0.00	0.0	0.00	0.0
	63	32	0.26	100.0	0.00	0.0	0.00	0.0
	69	102	0.78	95.9	0.00	0.0	0.03	4.1
	74	341	1.91	98.1	0.03	0.8	0.06	1.0
	76	298	2.34	98.7	0.00	0.0	0.04	1.3
	77	137	1.05	97.7	0.00	0.0	0.02	0.5
	79	81	0.62	97.8	0.00	0.0	0.03	2.2
	84	56	0.45	100.0	0.00	0.0	0.00	0.0
	89	114	0.76	98.2	0.00	0.0	0.01	0.9
	91	66	0.50	99.4	0.00	0.0	0.01	0.5
	96	6	0.05	100.0	0.00	0.0	0.00	0.0
99	0	-	-	-	-	-	-	

Appendix 2.2.: Absolute abundances and standing stock (%) of living *N. pachyderma* (sin.) and *T. quinqueloba* in the 125-250 μm size class per sampled depth interval in the outer Laptev Sea.

		125-250 μm size class					
Station	Depth interval (m)	<i>N. pachyderma</i> (sin.)			<i>T. quinqueloba</i>		
		absolute abundance (ind./m ³)		relative abundance (%) standing stock	absolute abundance (ind./m ³)		relative abundance (%) standing stock
		lived	dead	lived	lived	dead	lived
outer Laptev Sea							
22	0-50	0.24	0.00	3.8	0.00	0.32	0.0
	50-100	3.20	1.52	50.5	0.00	0.56	0.0
	100-200	2.32	0.44	36.6	0.08	0.04	80.0
	200-300	0.52	0.72	8.2	0.00	0.08	0.0
	300-500	0.06	0.14	0.9	0.02	0.44	20.0
23	0-50	0.16	0.16	1.9	0.00	0.16	0.0
	50-100	6.16	0.00	73.2	0.72	0.88	94.7
	100-200	1.16	1.60	13.8	0.04	0.44	5.3
	200-300	0.72	0.92	8.6	0.00	0.00	0.0
	300-500	0.22	0.12	2.6	0.00	0.12	0.0
24	0-50	0.00	0.00	0.0	0.00	0.00	0.0
	50-100	2.88	0.24	75.4	0.08	0.08	33.3
	100-200	0.68	0.12	17.8	0.16	0.08	66.7
	200-300	0.24	1.40	6.3	0.00	0.48	0.0
	300-500	0.02	0.44	0.5	0.00	0.08	0.0
24a	0-50	0.00	0.24	0.0	0.00	0.16	0.0
	50-100	1.60	0.48	59.7	0.00	0.16	0.0
	100-200	0.68	0.48	25.4	0.00	0.04	0.0
	200-300	0.00	1.12	0.0	0.00	0.12	0.0
	300-500	0.40	0.48	14.9	0.04	0.26	100.0
25	0-50	2.40	0.08	12.2	0.32	0.72	25.8
	50-100	10.32	2.00	52.7	0.24	0.32	19.4
	100-200	6.08	0.80	31.0	0.68	0.28	54.8
	200-300	0.68	0.84	3.5	0.00	0.08	0.0
	300-500	0.12	0.56	0.6	0.00	0.20	0.0
27	0-100	2.16	0.04	32.7	0.40	0.00	38.5
	100-200	3.68	0.08	55.8	0.60	0.04	57.7
	200-300	0.56	0.12	8.5	0.04	0.00	3.8
	300-400	0.12	0.16	1.8	0.00	0.00	0.0
	400-500	0.08	0.04	1.2	0.00	0.00	0.0
31	0-50	2.08	0.16	18.2	0.00	0.64	0.0
	50-100	7.44	0.00	65.3	0.16	0.48	16.0
	100-200	1.52	0.12	13.3	0.52	0.00	52.0
	200-300	0.16	0.56	1.4	0.24	0.12	24.0
	300-400	0.12	0.76	1.1	0.08	0.32	8.0
	400-500	0.08	1.12	0.7	0.00	0.20	0.0
32	0-50	0.96	2.16	19.4	0.16	0.00	25.0
	50-100	1.68	0.16	33.9	0.08	0.00	12.5
	100-200	0.96	4.24	19.4	0.32	0.76	50.0
	200-300	1.12	4.80	22.6	0.00	0.60	0.0
	300-500	0.24	2.12	4.8	0.08	0.20	12.5

Appendix 2.2. (continued):

125-250 µm size class							
Station	Depth interval (m)	<i>N. pachyderma</i> (sin.)			<i>T. quinqueloba</i>		
		absolute abundance		relative abundance	absolute abundance		relative abundance
		(ind./m ³)		(%) standing stock	(ind./m ³)		(%) standing stock
		lived	dead	lived	lived	dead	lived
outer Laptev Sea							
33	0-50	1.20	0.00	6.5	0.00	0.00	0.0
	50-100	4.96	0.00	26.7	0.08	0.00	6.1
	100-150	5.20	0.16	28.0	0.72	0.16	55.1
	150-200	3.04	0.00	16.4	0.24	0.00	18.4
	200-245	4.18	0.62	22.5	0.27	0.09	20.4
40a	0-50	1.52	0.24	27.8	0.00	0.00	0.0
	50-100	2.24	1.76	41.0	0.00	0.00	0.0
	100-200	1.20	0.64	22.0	0.16	0.00	100.0
	200-300	0.36	1.04	6.6	0.00	0.00	0.0
	300-500	0.14	0.12	2.6	0.00	0.04	0.0
45	0-50	0.48	0.00	18.0	0.00	0.00	0.0
	50-100	1.44	0.00	54.1	0.08	0.00	33.3
	100-200	0.60	0.28	22.6	0.16	0.08	66.7
	200-300	0.08	0.16	3.0	0.00	0.00	0.0
	300-500	0.06	0.00	2.3	0.00	0.00	0.0
47	0-50	0.48	0.88	75.0	0.00	0.24	0.0
	50-100	0.16	1.36	25.0	0.00	0.08	0.0
	100-200	0.00	0.72	0.0	0.00	0.04	0.0
	200-300	0.00	0.20	0.0	0.00	0.04	0.0
	300-500	0.00	0.00	0.0	0.00	0.00	0.0
60	0-50	3.60	0.08	61.9	0.16	0.00	66.7
	50-100	1.36	0.08	23.4	0.08	0.00	33.3
	100-200	0.68	0.04	11.7	0.00	0.00	0.0
	200-300	0.12	0.16	2.1	0.00	0.00	0.0
	300-500	0.06	0.16	1.0	0.00	0.00	0.0
62	0-50	2.40	0.16	33.9	0.08	0.00	20.0
	50-100	2.80	0.00	39.5	0.32	0.00	80.0
	100-200	1.64	0.12	23.2	0.00	0.00	0.0
	200-300	0.20	0.04	2.8	0.00	0.00	0.0
	300-500	0.04	0.00	0.6	0.00	0.00	0.0
64	0-50	1.76	0.00	56.4	0.00	0.00	0.0
	50-100	1.04	0.08	33.3	0.00	0.00	0.0
	100-200	0.28	0.24	9.0	0.00	0.00	0.0
	200-300	no data					
	300-500	0.04	0.06	1.3	0.00	0.00	0.0
69	0-50	0.24	0.00	14.8	0.00	0.08	0.0
	50-100	0.88	0.00	54.3	0.00	0.00	0.0
	100-200	0.28	0.00	17.3	0.00	0.00	0.0
	200-300	0.16	0.00	9.9	0.00	0.00	0.0
	300-500	0.06	0.00	3.7	0.00	0.00	0.0

Appendix 2.3.: Absolute abundances and standing stock (%) of living *N. pachyderma* (sin.) and *T. quinqueloba* in the 125-250 μm size class per sampled depth interval in the Fram Strait and the Barents Sea.

Station	Depth interval (m)	125-250 μm size class					
		<i>N. pachyderma</i> (sin.)			<i>T. quinqueloba</i>		
		absolute abundance		relative abundance	absolute abundance		relative abundance
		(ind./m ³)		(%) standing stock	(ind./m ³)		(%) standing stock
	lived	dead	lived	lived	dead	lived	
Barents Sea							
39	0-50	no data					
	50-100	1.12	0.00	32.3	5.84	0.24	9.7
	100-150	1.36	0.08	39.2	12.72	0.24	21.2
	150-200	0.32	0.32	9.2	28.48	0.48	47.5
	200-290	0.67	0.00	19.3	12.89	0.40	21.5
52	0-50	0.00	0.00	0.0	0.00	0.00	0.0
	50-100	0.24	0.00	17.1	0.88	0.00	14.5
	100-150	0.48	0.08	34.3	2.40	0.00	39.5
	150-200	0.56	0.08	40.0	2.16	0.08	35.5
	200-300	0.12	0.04	8.6	0.64	0.04	10.5
Fram Strait							
58	0-50	1.20	0.72	16.6	0.96	0.56	6.2
	50-100	3.68	1.20	51.0	8.08	0.16	52.0
	100-200	1.28	1.12	17.7	5.56	0.20	35.8
	200-300	0.60	1.92	8.3	0.68	4.12	4.4
	300-500	0.46	0.96	6.4	0.26	1.84	1.7
60	0-50	0.00	0.00	0.0	0.00	0.00	0.0
	50-100	4.40	0.32	73.3	9.76	0.32	87.0
	100-200	1.00	0.36	16.7	1.16	0.08	10.3
	200-300	0.40	0.00	6.7	0.16	0.36	1.4
	300-500	0.20	0.08	3.3	0.14	0.14	1.2
63	0-50	8.88	0.32	60.9	4.56	0.32	32.9
	50-100	4.64	0.16	31.8	5.60	0.08	40.4
	100-200	0.84	0.68	5.8	2.96	0.68	21.4
	200-300	0.08	0.48	0.5	0.56	0.44	4.0
	300-500	0.14	0.16	1.0	0.18	0.52	1.3
69	0-50	30.72	0.24	62.6	1.76	0.00	55.7
	50-100	16.08	0.00	32.8	1.20	0.00	38.0
	100-200	1.68	0.28	3.4	0.16	0.04	5.1
	200-300	0.60	0.04	1.2	0.04	0.00	1.3
	300-500	no data					
74	0-50	22.64	0.00	38.2	1.04	0.00	28.3
	50-100	33.52	0.00	56.6	2.56	0.16	69.6
	100-200	2.72	0.00	4.6	0.08	0.00	2.2
	200-300	0.28	0.00	0.5	0.00	0.04	0.0
	300-500	0.08	0.02	0.1	0.00	0.02	0.0

Appendix 2.3. (continued):

Station	Depth interval (m)	125-250 µm size class					
		<i>N. pachyderma</i> (sin.)			<i>T. quinqueloba</i>		
		absolute abundance		relative abundance	absolute abundance		relative abundance
		(ind./m ³)		(%) standing stock	(ind./m ³)		(%) standing stock
	lived	dead	lived	lived	dead	lived	
Fram Strait							
76	0-50	14.80	0.24	39.6	0.72	0.16	35.3
	50-100	18.24	0.72	48.8	0.88	0.00	43.1
	100-200	4.08	0.56	10.9	0.44	0.00	21.6
	200-300	0.20	0.16	0.5	0.00	0.00	0.0
	300-500	0.02	0.04	0.1	0.00	0.06	0.0
77	0-50	26.00	0.40	49.7	1.28	0.08	44.4
	50-100	25.68	0.16	49.1	1.60	0.00	55.6
	100-200	0.48	0.08	0.9	0.00	0.00	0.0
	200-300	0.08	0.04	0.2	0.00	0.00	0.0
	300-500	0.04	0.02	0.1	0.00	0.00	0.0
79	0-50	24.16	0.08	67.9	0.88	0.00	50.0
	50-100	10.80	0.00	30.4	0.56	0.08	31.8
	100-200	0.36	0.12	1.0	0.24	0.16	13.6
	200-300	0.16	0.04	0.4	0.08	0.08	4.5
	300-500	0.08	0.06	0.2	0.00	0.00	0.0
84	0-50	22.56	0.56	82.3	0.72	0.00	75.0
	50-100	4.16	0.72	15.2	0.16	0.00	16.7
	100-200	0.52	0.28	1.9	0.08	0.00	8.3
	200-300	0.08	0.16	0.3	0.00	0.12	0.0
	300-500	0.08	0.06	0.3	0.00	0.00	0.0
89	0-50	82.80	0.40	51.8	5.12	0.32	50.4
	50-100	76.40	0.16	47.8	5.04	0.16	49.6
	100-200	no data					
	200-300	no data					
	300-500	no data					
91	0-50	6.24	0.16	27.2	1.20	0.00	17.8
	50-100	14.96	0.32	65.3	3.84	0.00	57.0
	100-200	1.44	1.84	6.3	1.56	0.24	23.1
	200-300	0.12	0.56	0.5	0.04	0.40	0.6
	300-500	0.14	0.24	0.6	0.10	0.14	1.5
96	0-50	0.48	0.08	16.8	3.04	0.24	21.1
	50-100	1.76	0.16	61.5	8.72	0.40	60.4
	100-200	0.48	0.16	16.8	2.12	0.20	14.7
	200-300	0.12	0.36	4.2	0.40	1.64	2.8
	300-500	0.02	0.22	0.7	0.16	0.92	1.1
99	0-50	0.00	0.00	0.0	0.32	0.08	1.5
	50-100	0.40	0.00	66.7	7.76	0.08	37.6
	100-200	0.20	0.00	33.3	10.76	0.52	52.1
	200-300	0.00	0.00	0.0	1.28	1.36	6.2
	300-500	0.00	0.00	0.0	0.54	2.94	2.6

Appendix 2.4.: Relative depth distribution of living *N. pachyderma* (sin) with a secondary calcite crust in the 125-250 μm size class. Standing stock: all individuals of living *N. pachyderma* (sin.); calc. ind.: the proportion of living individuals with a secondary calcite crust; calc. weight factor: (standing stock x calc. ind. x depth interval) / Σ (standing stock x calc. ind. x depth interval); average depth of habitat: Σ (standing stock x mean depth of depth interval) / 100.

Cruise	Station	Depth interval (m)	Standing stock (%)	Calc. ind. (%)	Calc. weight factor (%)
ARK XI/1	23	0-50	1.4	0	0
		50-100	55.8	6	6
		100-200	21.7	70	53
		200-300	13.0	33	15
		300-500	8.0	45	25
	25	0-50	9.2	40	3
		50-100	39.3	67	22
		100-200	44.8	84	61
		200-300	4.9	100	8
		300-500	1.8	100	6
	60	0-50	52.9	67	53
		50-100	20.0	41	12
		100-200	18.8	50	28
		200-300	3.5	0	0
		300-500	4.7	25	7
	62	0-50	26.5	47	12
		50-100	31.0	80	23
		100-200	36.3	73	50
		200-300	4.4	100	8
		300-500	1.8	100	7
ARK XIII/2	58	0-50	11.5	73	12
		50-100	35.1	54	28
		100-200	24.4	72	51
		200-300	11.5	0	0
		300-500	17.6	9	9
	63	0-50	55.4	11	19
		50-100	30.1	24	22
		100-200	10.9	43	28
		200-300	0.0	0	0
		300-500	3.6	71	31
	69	0-50	59.8	4	25
		50-100	31.3	6	20
		100-200	6.5	21	31
		200-300	2.3	47	24
		300-500	0.0	0	0
	76	0-50	35.5	8	7
		50-100	43.8	11	12
		100-200	19.6	79	78
		200-300	1.0	80	4
		300-500	0.2	0	0
84	0-50	79.5	4	29	
	50-100	14.8	10	14	
	100-200	4.0	57	46	
	200-300	0.6	100	11	
	300-500	1.1	0	0	
91	0-50	25.1	13	8	
	50-100	60.1	49	75	
	100-200	11.6	17	10	
	200-300	1.0	0	0	
	300-500	2.3	29	7	

Appendix 3.1.: Stable isotope composition of *N. pachyderma* (sin.) in the outer Laptev Sea and northeast of Severnaya Zemlya (ARK XI/1, 1995). Temperatures and salinities are averaged over the sampled depth intervals.

Station	Depth interval (m)	<i>N. pachyderma</i> (sin.)												pot. temperature (°C)	salinity	
		125-250 μm				>250 μm				Kummerform						
		Normalform		dead		living		dead		living		dead				
		$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)			
Outer Laptev Sea																
36/021	0-50														-1.06	31.93
	50-100														-1.60	33.95
	100-200	2.46	-0.27												-0.09	34.50
	200-300														1.51	34.82
	300-500	2.78	-0.07												1.24	34.86
36/022	0-50	2.38	-0.14												-1.33	31.96
	50-100	1.29	-1.00	1.96	-0.77	2.46	0.25								-1.78	33.87
	100-200	1.56	-1.04	2.15	-0.54	3.09	0.08			3.09	0.08				-0.98	34.32
	200-300	2.55	-0.20												1.76	34.85
	300-500														1.07	34.86
36/023	0-50	2.48	-0.01												-1.33	31.96
	50-100	2.11	-0.07			2.54	0.15								-1.78	33.87
	100-200	2.59	-0.18	2.87	0.18	2.99	0.31			2.72	0.39				-0.98	34.32
	200-300	2.63	-0.33	2.76	-0.20										1.76	34.85
	300-500	2.21	-0.39	1.64	-0.07										1.07	34.86
36/024	0-50														-1.60	31.47
	50-100	1.93	-0.83	1.61	-1.14	2.49	0.42								-1.71	33.69
	100-200	1.75	-1.00												0.34	34.55
	200-300														1.81	34.87
	300-500			2.38	-0.37										1.25	34.89
36/024a	0-50														-1.65	31.54
	50-100	2.03	0.26	2.58	0.26	2.51	0.56			2.51	0.56				-1.74	33.59
	100-200			2.58	0.26										0.30	34.53
	200-300			2.66	-0.03										1.79	34.87
	300-500	2.95	-0.11												1.20	34.88
36/025	0-50														-1.73	33.85
	50-100	3.26	0.16	2.60	0.07	3.59	0.27	3.20	0.33	3.71	0.20				-1.70	34.42
	100-200	3.06	-0.11			3.52	0.44								0.77	34.70
	200-300			2.75	0.09	3.56	0.23	3.48	0.25	3.56	0.23				2.45	34.92
	300-500			2.87	-0.16			3.31	0.75						1.64	34.91
36/031	0-50														-1.69	33.23
	50-100	2.84	-1.20			3.37	-0.36								-1.54	34.40
	100-200	2.45	-0.47			3.28	0.11								-0.37	34.67
	200-300			2.44	-0.69										0.54	34.79
	300-400			2.44	-0.69	3.09	0.20	2.77	-0.52	3.09	0.20				0.09	34.78
	400-500			3.09	-0.18					3.73	1.29				-0.14	34.79
36/032	0-50	3.05	-0.09	3.08	-0.14	3.12	0.26								-1.64	33.99
	50-100	1.00	-1.39			2.38	-0.41								-1.47	34.40
	100-200	3.04	-0.04	3.33	0.27	3.36	0.24	3.65	0.42	3.70	0.61	3.57	0.39		0.12	34.64
	200-300	3.13	-0.14	3.37	0.12	3.51	0.34	3.74	0.37	3.54	0.31	3.56	0.14		-0.09	34.71
	300-500	3.13	-0.14	3.36	0.08	3.45	0.33	3.19	0.36	3.44	0.18	3.49	0.37		-0.11	34.74
36/033	0-50														-1.51	33.92
	50-100					3.64	0.12			3.49	-0.18				-1.08	34.57
	100-150														-0.07	34.73
	150-200					3.31	0.40			3.31	0.40				-0.60	34.71
	200-245														-0.51	34.73
36/044	0-50														-1.66	31.65
	50-100														-1.73	33.67
	100-200	2.98	0.32												0.21	34.52
	200-300	2.58	-0.13												1.75	34.87
	300-500														1.17	34.88
36/047	0-50														-1.71	32.06
	50-100	2.3	0.36	2.05	0.28										-1.72	33.85
	100-200			1.90	-0.39										0.27	34.54
	200-300														1.68	34.86
	300-500														1.25	34.89

Appendix 3.2.: Stable isotope composition of *N. pachyderma* (sin.) and *T. quinqueloba* in the Fram Strait and Barents Sea (ARK XIII/2, 1997). Temperatures and salinities are averaged over the sampled depth intervals.

Station	Depth interval (m)	<i>N. pachyderma</i>						<i>T. quinqueloba</i>						potential temperature (°C)	salinity		
		125-250 µm			>250 µm			125-250 µm			dextral						
		sinistral		dead	living		living	sinistral		dead	dextral		living			dead	
		δ ¹⁸ O (‰)	δ ¹³ C (‰)	δ ¹⁸ O (‰)	δ ¹³ C (‰)	δ ¹⁸ O (‰)	δ ¹³ C (‰)	δ ¹⁸ O (‰)	δ ¹³ C (‰)	δ ¹⁸ O (‰)	δ ¹³ C (‰)	δ ¹⁸ O (‰)	δ ¹³ C (‰)			δ ¹⁸ O (‰)	δ ¹³ C (‰)
Barents Sea																	
44/039	0-50														2.62	34.77	
	50-100														2.13	35.01	
	100-150							2.47	-1.38			2.48	-1.47		1.67	34.98	
	150-200							2.63	-1.32			2.54	-1.36		1.33	34.97	
	200-290							2.52	-1.06			2.71	-1.07		0.97	34.95	
44/052	0-50														-1.77	34.06	
	50-100	2.93	-0.01									3.04	-0.09		-1.80	34.23	
	100-150	2.93	-0.01												-1.58	34.33	
	150-200	2.93	-0.01									3.44	0.20		0.43	34.59	
	200-300	2.93	-0.01									3.44	0.20		1.57	34.82	
Fram Strait																	
44/058	0-50	2.87	-0.40	3.07	0.13										0.17	34.03	
	50-100	2.95	-0.40	3.07	0.13			2.60	-1.65			2.64	-1.54		2.23	34.82	
	100-200	2.62	-0.35	2.74	0.00			2.30	-1.47			2.37	-1.40		2.34	34.91	
	200-300			2.87	-0.05					2.59	-1.38			2.55	-1.39	1.85	34.90
	300-500			2.81	-0.14					2.72	-1.01			2.60	-1.40	1.72	34.94
44/060	0-50														-1.32	33.77	
	50-100	3.36	0.06							3.07	-0.60				0.82	34.64	
	100-200	2.82	-0.07												2.39	34.90	
	200-300	3.00	-0.05												2.12	34.96	
44/063	0-50					3.36	0.26	3.54	0.18						-1.70	34.23	
	50-100	3.03	-0.10			3.24	0.22	3.51	0.04						-0.40	34.55	
	100-200	2.85	-0.14			3.08	0.40	3.25	-0.03						1.50	34.80	
	200-300	2.62	-0.40					2.95	-0.07						1.36	34.92	
44/064	0-50	3.10	-0.11												-1.78	34.22	
	50-100	2.74	-0.10												-0.54	34.50	
	100-200														2.01	34.89	
	200-300														1.93	34.94	
44/069	0-50	1.64	0.36			1.54	0.57								-1.56	32.65	
	50-100	1.70	0.44			1.70	0.50								-1.81	33.61	
	100-200	1.76	0.35			1.80	0.43								-1.78	34.11	
	200-300	1.71	0.39			1.65	0.43								-0.62	34.47	
44/072b	0-50	0.77	0.23			0.65	0.46								-1.22	32.15	
	50-100	1.42	0.37			1.38	0.54								-1.51	33.41	
	100-200					1.83	0.48								-0.78	34.37	
	200-300														0.38	34.80	
44/074	0-50														-0.97	32.04	
	50-100	0.82	0.30			1.16	0.39								-1.67	33.42	
	100-200														-0.80	34.33	
	200-300														0.64	34.79	
44/076	0-50	1.04	0.48			1.24	0.60	0.99	0.34						-1.54	32.31	
	50-100	1.40	0.48			1.45	0.55	1.32	0.40						-1.54	33.56	
	100-200	1.87	0.50			1.80	0.56	1.59	0.37						-0.45	34.43	
	200-300														1.26	34.84	
44/077	0-50	0.61	-0.07			1.22	-0.07								-1.75	33.65	
	50-100	1.12	0.15			1.45	0.45								-1.70	34.09	
	100-200														-1.04	34.36	
	200-300														1.15	34.77	
44/079	0-50	1.19	0.25			1.69	0.47	1.74	0.50						-1.74	33.38	
	50-100	1.48	0.39			1.90	0.54	2.04	0.46						-1.74	34.22	
	100-200					1.80	0.55								-0.48	34.50	
	200-300														1.33	34.86	
44/084	0-50	1.51	0.33			1.83	0.56	1.52	0.41						-1.67	33.40	
	50-100	1.68	0.43			2.17	0.59								-1.86	34.28	
	100-200	1.43	0.13												-0.58	34.47	
	200-300														1.62	34.87	
44/089	0-50	2.73	0.10			2.99	0.20								-1.60	33.97	
	50-100	2.71	-0.06			2.71	0.30								-0.33	34.45	
	100-200														1.60	34.82	
	200-300														1.83	34.93	
44/091	0-50	3.03	0.19												-1.73	33.95	
	50-100	2.78	0.13			3.46	0.46	2.84	0.07						-1.16	34.35	
	100-200					3.45	0.42	3.07	-0.03						1.21	34.75	
	200-300														1.82	34.91	
44/094	0-50					2.91	0.09	2.91	-0.10	2.15	0.18				0.64	33.70	
	50-100					2.91	0.09	2.90	-0.18	2.77	0.35				1.69	34.68	
	100-200					2.60	0.44	2.85	-0.24	2.90	0.30				2.09	34.88	
	200-300														1.46	34.93	
44/096	0-50							2.58	-0.66	2.49	0.43				-0.18	33.94	
	50-100							2.58	-0.66	2.49	0.43				1.50	34.74	
	100-200														2.25	34.91	
	200-300							2.01	-0.64	2.93	-0.06				2.02	34.94	
44/098	0-50														3.84	34.51	
	50-100							1.96	-1.14						3.12	34.82	
	100-150														3.46	34.99	
	150-200							2.31	-1.14			2.04	-1.39		3.07	34.99	
	200-254							2.57	-0.65			2.36	-1.07		2.68	35.00	
44/099	0-50														4.02	34.67	
	50-100							2.24	-1.16			2.01	-1.45		4.11	35.00	
	100-200							1.22	-1.65						3.25	34.99	
	200-300														2.71	35.00	
	300-500							1.90	-1.15	2.35	-1.26				1.77	34.97	

Station	z_p (m)	Nonencrusted δ_p		Depth interval (m)	Encrusted δ_t		Equilibrium calcite value		Model 1 with $M_s=0.5$		Model 2		Model 1 with $M_s=0.75$		Model 2			
		$\delta^{18}O$	$\delta^{13}C$		$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$ of DIC	δ_s		δ_s^G		δ_s		δ_s^G			
		(‰)	(‰)		(‰)	(‰)	(‰)	(‰)	$\delta^{18}O$	$\delta^{13}C$	M_s^G	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	M_s^G	$\delta^{18}O$	$\delta^{13}C$
									(‰)	(‰)		(‰)	(‰)	(‰)	(‰)		(‰)	(‰)
36/022	25	1.95	-0.60	z: 50-100	2.46	0.25	4.11	0.97	2.97	1.10	0.2	4.50	3.65	2.63	0.53	0.3	3.65	2.23
		1.95	-0.60	z: 100-200	3.09	0.08	4.04	0.92	4.23	0.76	0.5	4.23	0.76	3.47	0.31	0.75	3.47	0.31
36/023	25	2.4	-0.20	z: 50-100	2.54	0.15	3.82	0.72	2.68	0.50	0.2	3.10	1.55	2.59	0.27	0.3	2.87	0.97
		2.4	-0.20	z: 100-200	2.99	0.31	3.82	0.60	3.58	0.82	0.5	3.58	0.82	3.19	0.48	0.75	3.19	0.48
36/025	75	3.16	0.02	z: 100-200	3.52	0.44	4.04	0.90	3.88	0.86	0.5	3.88	0.86	3.64	0.58	0.75	3.64	0.58
		3.16	0.02	z: 200-300	3.56	0.23	3.66	0.88	3.96	0.44	0.5	3.96	0.44	3.69	0.30	0.75	3.69	0.30
36/032	25	2.55	-0.42	z: 50-100	2.38	-0.41	4.32	0.83	2.21	-0.4	0.2	1.70	-0.37	2.32	-0.41	0.3	1.98	-0.39
		2.55	-0.42	z: 100-200	3.36	0.24	4.29	0.79	4.17	0.90	0.5	4.17	0.90	3.63	0.46	0.75	3.63	0.46
		2.55	-0.42	z: 200-300	3.54	0.34	4.25	0.96	4.53	1.10	0.5	4.53	1.10	3.87	0.59	0.75	3.87	0.59
44/063	25	2.83	-0.21	z: 50-100	3.24	0.22	4.16	1.16	3.65	0.65	0.2	4.88	1.94	3.38	0.36	0.3	4.20	1.22
		2.83	-0.21	z: 100-200	3.08	0.40	3.85	1.09	3.33	1.01	0.5	3.33	1.01	3.16	0.60	0.75	3.16	0.60
44/091	25	2.91	0.16	z: 50-100	3.46	0.46	4.33	1.40	4.01	0.76	0.2	5.66	1.66	3.64	0.56	0.3	4.74	1.16
		2.91	0.16	z: 100-200	3.45	0.42	3.95	1.25	3.99	0.68	0.5	3.99	0.68	3.63	0.51	0.75	3.63	0.51
44/069	25	1.70	0.39	z: 50-100	1.70	0.50	2.96	1.12	1.70	0.61	0.2	1.70	0.94	1.70	0.54	0.3	1.70	0.76
		1.70	0.39	z: 100-200	1.80	0.43	3.66	1.31	1.90	0.47	0.5	1.90	0.47	1.83	0.44	0.75	1.83	0.44
44/076	25	1.44	0.49	z: 50-100	1.45	0.55	3.15	1.16	1.46	0.61	0.2	1.49	0.79	1.45	0.57	0.3	1.47	0.69
		1.44	0.49	z: 100-200	1.80	0.56	4.01	1.15	2.16	0.63	0.5	2.16	0.63	1.92	0.58	0.75	1.92	0.58

Appendix 3.3.: Stable isotope values of *N. pachyderma* (sin.) calculated for an abrupt calcification between 100-200 m (Model 1) and for a gradual calcification during downward migration (Model 2) after Simstich (1999).

Model 1: $\delta_s = (M_t \delta_t - M_p \delta_p) / M_s$, where δ_s is the average value of nonencrusted individuals, and δ_t the isotope value of encrusted individuals. M =relative mass of the foraminiferal shell.

Model 2: $\delta_s^G = (M_t \delta_t - M_p \delta_p) / M_s^G$ and $M_s^G = (z - z_p) M_s / \Delta z$, where Δz is the difference between the depth of nonencrusted z_p and encrusted z_t individuals.

The total mass M_t of the calcite test is expected to consist of the primary calcite M_p and the secondary calcite M_s , where $M_t = 1 = M_p + M_s$. Both models are calculated assuming a secondary calcite crust of 50 % (Arikawa, 1983), where $M_s = 0.5$ and of 75 % (Kohfeld et al., 1996), where $M_s = 0.75$. Equilibrium calcite values are averaged over the depth intervals of the nets.

Appendix 5.1.: Stable isotope composition of normalform and kummerform individuals of *N. pachyderma* (sin.) in the 125-250 μm size class from sediment surface samples at the Laptev Sea continental margin (ARK XI/1, 1995).

Station (Bcc corer)	Latitude	Longitude	<i>N. pachyderma</i> (sin.)				<i>T. quinqueloba</i>	
			Normalform		Kummerform		$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
			$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
Laptev Sea continental margin								
2723-4	79°27.5N	148°06.8E	3.27	0.46	3.29	0.42	-	-
2724-4	79°08.9N	146°21.3E	3.58	0.29	3.72	0.22	-	-
2731-3	77°35.9N	130°02.2E	3.06	-0.01	3.08	0.12	-	-
2732-4	77°37.2N	130°02.5E	3.20	0.32	-	-	-	-
2733-3	77°42.2N	130°02.4E	3.50	0.45	3.5	0.37	-	-
2734-3	77°51.0N	130°03.0E	3.29	0.49	3.36	0.44	-	-
2735-4	77°55.9N	130°02.6E	3.41	0.47	3.39	0.39	-	-
2736-3	77°55.8N	130°02.5E	4.12	0.49	3.92	0.47	-	-
2737-4	79°12.9N	131°28.9E	3.22	0.56	3.08	0.53	-	-
2739-5	81°07.9N	106°01.7E	3.19	0.85	3.06	0.75	-	-
2740-8	81°11.5N	107°35.1E	2.86	0.87	2.65	0.82	-	-
2742-3	80°48.3N	103°54.0E	4.28	0.40	4.35	0.53	-	-
2743-7	80°44.1N	103°11.7E	3.37	0.79	3.34	0.9	-	-
2744-6	80°36.4N	103°03.2E	3.58	0.64	3.5	0.62	-	-
2745-7	80°24.9N	102°05.4E	3.86	0.48	3.96	0.52	-	-
2747-8	78°30.8N	133°49.3E	3.38	0.53	3.27	0.37	-	-
2748-2	78°41.9N	134°36.5E	1.87	-0.70	1.92	-0.84	-	-
2749-3	79°07.6N	135°06.8E	2.84	0.19	2.65	0.16	-	-
2750-2	79°58.9N	135°00.1E	2.15	-0.12	1.95	-0.21	-	-
2751-2	80°14.3N	133°46.2E	2.87	0.60	2.32	0.7	-	-
2752	80°55.6N	131°16.6E	-	-	-	-	-	-
2755-5	81°03.3N	138°15.1E	2.29	-0.05	2.24	-0.15	-	-
2756-9	81°08.7N	138°38.9E	3.21	0.60	3.05	0.59	-	-
2757-7	81°09.6N	140°12.1E	2.57	0.61	2.74	0.87	-	-
2759-7	81°13.3N	143°27.0E	2.92	0.83	2.99	0.81	-	-
2760-5	81°13.6N	144°48.0E	2.46	0.59	2.58	0.76	-	-
2761-9	81°11.6N	150°27.2E	2.37	0.94	2.27	0.96	-	-
2762-4	80°29.5N	150°15.7E	2.39	0.37	2.48	0.43	-	-
2763-8	80°16.8N	150°27.4E	2.46	0.17	2.52	0.03	-	-
2764-7	80°04.1N	149°48.6E	2.83	0.54	2.34	0.5	-	-
2765-6	79°52.8N	149°46.9E	2.82	0.25	2.42	-0.01	-	-
2767-6	79°44.4N	143°59.4E	3.39	0.46	3.33	0.48	-	-
2768-3	79°49.0N	143°05.5E	2.44	-0.19	2.18	-0.35	-	-
2769-3	78°23.0N	135°02.4E	1.76	-1.17	2.44	-0.59	-	-
2770-5	78°21.0N	135°11.7E	3.13	0.27	3.14	0.25	-	-
2771-5	78°19.6N	135°23.6E	2.75	0.02	2.77	-0.27	-	-
2772-2	78°15.2N	135°23.3E	2.38	-0.23	-	-	-	-
2773-7	80°56.8N	122°38.7E	2.53	0.72	2.49	0.74	-	-
2774-2	80°40.9N	121°17.6E	2.65	0.92	2.59	0.91	-	-
2775-4	78°48.1N	113°00.1E	3.45	0.57	3.52	0.4	-	-
2776-3	78°45.6N	112°44.0E	3.64	0.65	3.32	0.61	-	-
2777-3	78°40.7E	112°39.6E	3.64	0.68	3.63	0.5	-	-
2778-1	77°58.8N	113°03.5E	3.24	0.26	3.09	0.18	-	-
2781-1	78°07.4N	111°55.0E	3.06	0.07	3.15	0.16	-	-
2782-2	79°36.7N	103°21.1E	3.98	0.52	4.03	0.61	-	-
2784-2	81°45.7N	96°35.9E	3.56	0.55	3.55	0.45	-	-
2785-4	82°20.3N	92°93.8E	3.31	0.85	3.29	0.85	-	-
2787-6	82°04.6N	91°00.6E	3.71	0.88	3.65	0.82	-	-
2787-7	82°04.5N	90°59.7E	3.60	0.92	3.69	0.82	-	-
2788-4	82°02.3N	90°59.1E	3.72	0.71	3.59	0.63	-	-
2789-5	81°57.5N	91°06.0E	3.68	0.30	3.61	0.02	-	-
2791-5	81°10.4N	87°30.2E	3.86	0.58	3.91	0.6	-	-

Appendix 5.2.: Stable isotope composition of normalform and kummerform individuals of *N. pachyderma* (sin.) and *T. quinqueloba* in the 125-250 µm size class from sediment surface samples in the Fram Strait and Barents Sea (ARK XIII/2, 1997).

Station (Boc corer)	Latitude	Longitude	<i>N. pachyderma</i> (sin.)				<i>T. quinqueloba</i>	
			Normalform		Kummerform		δ ¹⁸ O	δ ¹³ C
			δ ¹⁸ O	δ ¹³ C	δ ¹⁸ O	δ ¹³ C		
Barents Sea								
2824-5	77°34.2N	34°38.6E	3.79	0.46	-	-	-	-
Fram Strait								
2830-7	80°58.6N	17°30.5E	4.24	-0.06	4.58	-0.13	-	-
2831-7	81°05.6N	16°58.4E	2.83	0.22	-	-	2.61	-0.91
2832-12	81°06.7N	16°13.1E	3.33	0.49	3.67	0.68	-	-
2833-5	81°58.3N	11°50.0E	3.38	0.69	3.64	0.65	3.32	0.3
2834-6	80°54.9N	9°49.4E	3.61	0.80	3.76	0.65	-	-
2835-5	80°06.1N	7°04.0E	3.45	0.63	3.71	0.76	3.18	0.28
2836-6	81°07.9N	5°40.1E	3.38	0.49	3.89	0.58	2.91	-0.21
2837-6	81°14.0N	2°25.1E	3.26	0.43	-	-	-	-
2838-9	81°17.7N	0°26.6E	3.48	0.56	4.28	1.64	-	-
2839-5	81°24.2N	0°58.3W	3.57	0.72	3.48	0.85	3.23	0.47
2840-4	81°25.3N	5°18.5E	3.06	0.70	-	-	2.24	0.69
2843-2	81°34.0N	7°21.0W	3.33	0.63	2.61	0.80	-	-
2844	81°34.9N	8°10.6W	-	-	-	-	-	-
2846-4	81°35.2N	10°00.4W	3.26	0.57	3.30	0.74	2.65	0.5
2847-3	81°52.3N	4°32.3W	3.05	0.85	-	-	2.63	0.71
2848-3	81°59.9N	2°25.8W	3.35	0.77	3.67	0.92	3.13	0.41
2849-6	82°39.2N	1°27.9E	3.24	0.74	3.20	0.87	2.85	0.72
2851-2	82°22.5N	3°36.9E	3.66	0.80	3.65	0.79	-	-
2853-9	82°19.1N	3°36.9E	3.69	0.68	3.58	0.89	3.27	0.52
2854-2	82°12.0N	3°54.1E	3.53	0.63	3.41	0.75	-	-
2855-8	82°02.7N	5°17.3E	3.39	0.49	3.58	0.56	3.17	0.42
2856-7	81°59.3N	5°45.3E	3.42	0.53	3.39	0.64	-	-
2857-10	81°54.1N	7°54.8E	3.60	0.72	3.65	0.75	3.16	0.39
2858-6	81°45.3N	9°39.9E	3.63	0.62	3.67	0.81	-	-
2859-10	81°45.1N	10°11.4E	3.76	0.76	3.71	0.76	3.42	0.55
2860-7	81°34.9N	11°51.1E	3.94	0.66	3.84	0.84	-	-
2861-11	81°16.4N	13°03.0E	3.84	0.76	3.74	0.81	-	-
2862-5	80°34.7N	11°47.3E	3.24	0.42	2.70	0.51	-	-
2863-2	80°33.5N	10°17.9E	3.25	0.28	3.43	0.52	-	-
2864-4	80°31.8N	10°22.1E	3.16	0.27	3.66	0.81	-	-
2865-2	80°29.7N	10°29.3E	3.17	0.28	3.45	-0.20	-	-
2866	80°00.1N	10°52.3E	-	-	-	-	-	-
2867-7	80°11.9N	10°26.7E	4.53	0.22	4.71	0.34	-	-

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