Stockholm University

Bachelor Thesis

Degree Project in Marine Geology 15 hp

Quaternary Foraminifera biostratigraphy and lithologic variations in sediment from the Alpha Ridge, Arctic Ocean

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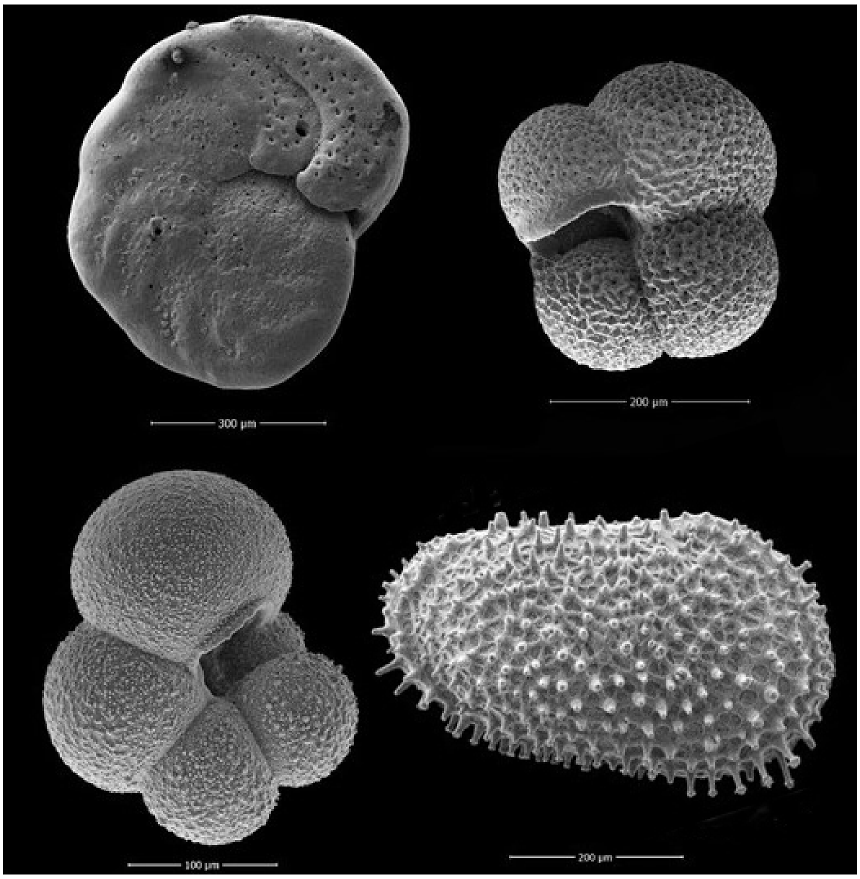

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ABSTRACT

The biostratigraphy and lithostratigraphy of a 7,49-meter-long sediment core from the Alpha Ridge in the Central Arctic Ocean was investigated in an attempt to connect depositional patterns with Quaternary Marine Isotope stages, and derive an age model for the core. Radiocarbon isotope dating of two samples using planktonic foraminifera *Neogloboquadrina pachyderma*, was performed to constrain the age model interpretations together with biostratigraphic markers of *Bulimina aculeata*, which correspond to MIS 5.1 and *Turborotalita egelida*, MIS 11. The results of this study are compared with results from better investigated cores from the Lomonsov Ridge.

1.INTRODUCTION

The rapid climate changes promoted by human activities are today an important topic among citizen, researchers and politicians. The global heating created by greenhouse gas emission is a big issue and the Arctic is a very sensitive part of the global climate system (Polyak et al., 2013). Continued warming could provoke melting of the sea ice and glaciers and accelerate the reduction in the summer sea ice cover (Cronin et al., 2014). If this continues, then it could lead to several impacts like sea level rise and flooding of communities, methane emission from frozen sediments, which would rapidly increase the greenhouse gas concentration of the atmosphere (Tan et al., 2015) and changes in the ocean surface circulation. Although we know that the sea ice is rapidly decreasing today, we still don't know how much and why it changed in the geologic past. Specifically, over glacial cycles in the Quaternary (Polyak et al., 2010).

Paleoclimate researchers try to look at sediment to determine how the climate has looked in the past (Polyak et al., 2013). Changes in assemblages of microfossils, especially foraminifera, and lithological properties, both reflect changes in past climate. Glacial periods are reflected by an absence of microfossils (heavy ice conditions) and lots of Ice Rafted Debris (IRD) (coarse grained sediments), while interglacial periods have finer grained sediments, microfossils and are bioturbated. Although the lithology of Arctic Ocean sediments is known, and how to identify glacial and interglacial types of sediments (Jakobsson et al., 2013), it is very difficult to determine ages of Arctic Ocean sediments due to the rare and sporadic occurrence of microfossils. For example, a lack of microfossils, like foraminifera in the ACEX (IODP 302) record close to the North pole, was problematic for deriving a continuous age model (Backman et al., 2006).

1.1 AIMS

The aim of this project is to integrate biostratigraphic (foraminifera occurrences) and lithostratigraphic data to identify and characterize Quaternary glacial cycles in a sediment core from the Alpha Ridge, and construct a core chronology. By identifying foraminifera bearing intervals, interpreting past climate states and dating of sediments becomes possible. This is required to develop an integrated Quaternary history of cryospheric changes in the Central Arctic Ocean.

1.2. HYPOTHESIS

Abundance patterns of microfossils (like foraminifera) and lithologic variations in ice rafted debris (IRD), like quartz and other smaller rock fragments, reflect changes to the cryosphere on glacial-interglacial timescales. More microfossils in certain intervals connect to interglacial periods and more IRD rich sediment indicate colder glacial periods. Two species of foraminifera are useful for stratigraphic markers, *B. aculeata* for MIS 5.1 and *T. egelida* for MIS 11 (Cronin et al., 2014). Downcore patterns in these proxies can be correlated with the global Marine Isotope Stages (MIS) (Lisiecki and Raymo, 2005) and used to develop a Quaternary age model.

2.BACKGROUND

2.1 QUATERNARY

In the field of geology, geological time is divided into blocks of variable length under the following hierarchy: -Eons, Eras, Periods, Epochs and Ages. This allows workers to more easily refer to a particular phase of Earth's history rather than always saying the time in years. The Quaternary is the present Period in which we live, reaching back from 0 - 2.58 Ma (Millions of years ago). The Quaternary is the Period in which extensive glaciation in the Northern Hemisphere took place with major changes in climate and oceanography. Marine Isotope Stages (MIS), based on the ratio of oxygen-18 ($\delta^{18}O$) to oxygen-16 isotopes ($\delta^{16}O$) in benthic (bottom living) foraminifera, provides another way dividing up Quaternary time, with each stage corresponding to a different glacial phase: interglacial (odd MIS number) and glacial (even MIS number) cycles. For example, MIS 1 is the present interglacial cycle going back 14 kyr. In MIS 2, 14-29 kyr was the Last Glacial Maximum part of the last glacial period. During the Quaternary, there was a transition from smaller, 41 kyr less intense glacial cycles, to 100-kyr more intense glacial cycles. This event, called the Mid-Pleistocene transition, occurred around 1 Ma (Fig 1) (Lisiecki and Raymo, 2005). This system of naming glacial stages is used in the following report.

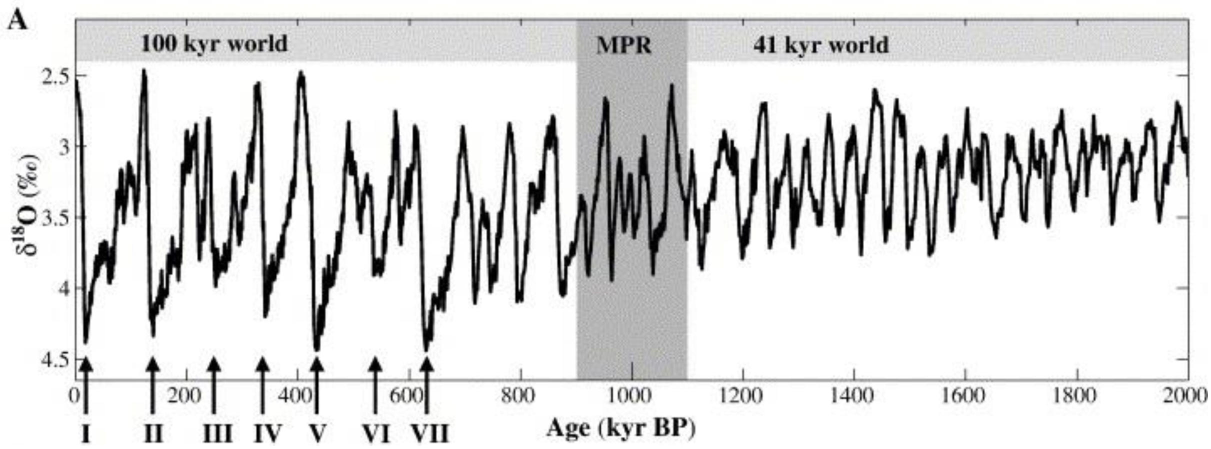


Figure 1. Marine isotope stages (MIS) shown in this figure. Glacial cycles 100 kyr from present back to 1 Ma, before the Mid-Pleistocene transition (MPR), the glacial cycles were 41 kyr. The Latin numbering arrows shows the last big seven glaciations with 100 kyr cycling since the MRP (Schulz et al., 2006).

2.2 LOCATION AND OCEANIC SETTINGS OF THE SEDIMENT SAMPLES

The sediment core AO16-9-PC1 was taken on the Alpha Ridge (Fig. 2) at 2212-meter water depth in the Central Arctic Ocean (Johansson et al., 2016). The location of the core is beneath the Beaufort Gyre (Fig. 3), which carries a lot of sediment entrained in sea ice and icebergs from the Canadian and Greenland coasts.

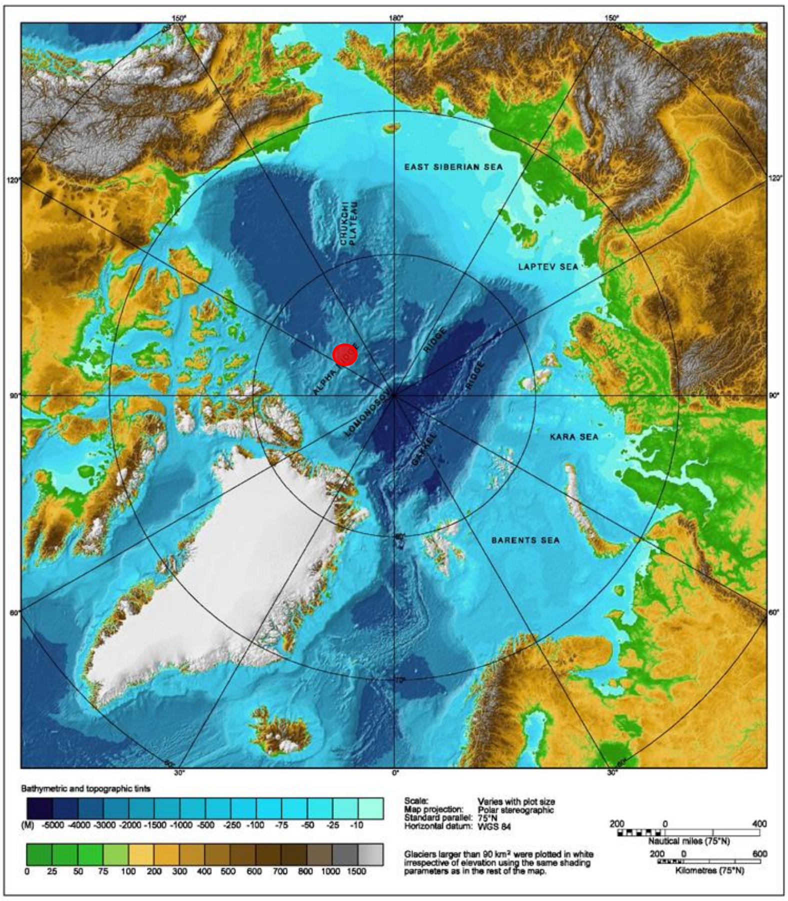
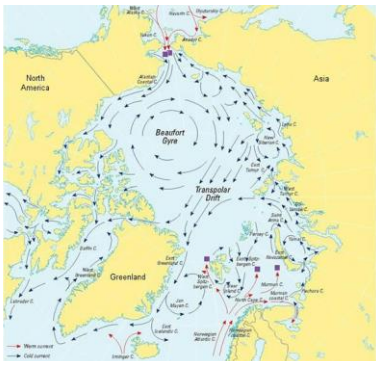


Figure 2. A bathymetric map over the Arctic and the red dot showing where the sediment core was drilled (*http://oceanexplorer.noaa.gov/explorations/02arctic/background/plan/media/arctic_bath_600.jpg*).

Figure 3. The Ocean surface circulation in the Arctic, with the circular Beaufort Gyre and the Transpolar drift, exchanging Arctic deep waters to Atlantic surface waters (*https://nsidc.org/sites/nsidc.org/files/images//beaufort_gyre.jpg*).



In the Arctic Ocean, four water masses exist (Fig.4), the Polar surface waters (0-50 m), the Atlantic layer (200-1000 m), the Arctic Intermediate water and the Arctic deep water (Cronin et al., 2014), which the AO16-9-PC1 samples are taken from. The western Arctic is more isolated from the Atlantic surface and intermediate waters, and more heavily influenced by Pacific surface waters. It's yet not truly known to what degree planktic foraminifera are transported by ocean currents or are local inhabitants in the Arctic Ocean (Polyak et al., 2013).

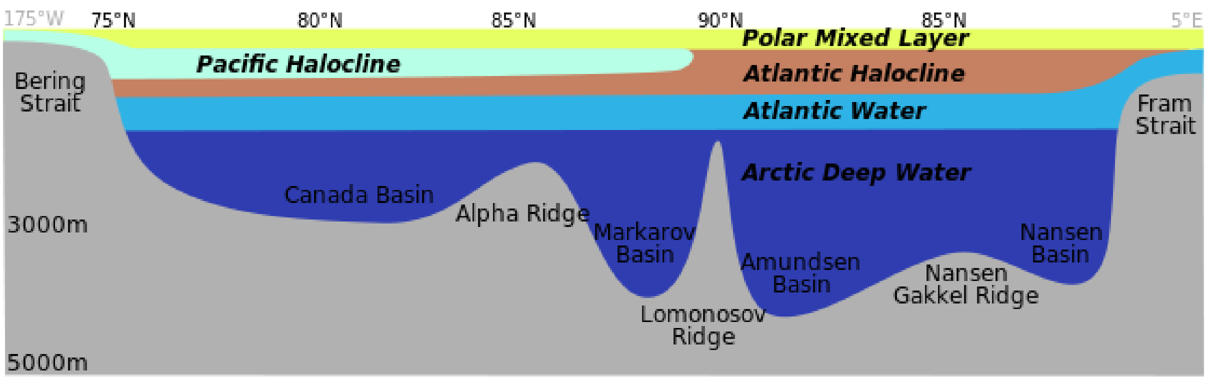


Figure 4. A cross section through the Arctic Ocean showing the different depths and water masses (*https://upload.wikimedia.org/wikipedia/commons/thumb/c/c1/BrnBld_BeringToFram.svg/650px-BrnBld_BeringToFram.svg.png*).

2.3 LITHO-, BIOSTRATIGRAPHY AND DATING

Stratigraphy is a term that describes the order of sedimentary layers and their relationship to the geologic time scale. Examples of methods used for dating are radiometric dating, which gives an absolute age, paleomagnetic dating and cyclostratigraphy based on $\delta^{18}O$ curves or Milankovitch periods. Radiocarbon dating is a tool used for determining precise ages of younger sediments consisting of organic carbon, like the shells of calcareous microfossils in ocean sediments. The half-life is 5568 years, then the 50 % of the decayed carbon-14 (C^{14}) is left in the sample and only 10 half-lives can be measured before almost all C^{14} have decayed, which correspond to an age of 50-60 thousand years. Therefore, a limit of 50-60 thousand years can be radiocarbon dated. The general sedimentation rate in the Central Arctic Ocean is only 1-2 cm/kyr (Backman et al., 2004). Therefore, only sediments from a depth around 0-50 or 100 cm can be used for radiocarbon dating. Lithostratigraphy is based on the lithological properties in the sediment, like changes in colors in the bedding, appearance of bioturbation, and grain sizes in different layers with graded or distinct boundaries. Biostratigraphy is based on fossils, in this case microfossils, mostly foraminifera. In the Arctic, glacial versus interglacial sediments can be identified with coarser grained sediments and absence of microfossils due to heavy ice conditions representing glacial conditions and abundances of microfossils with finer grained sediment and bioturbation indicating interglacial conditions.

2.4 SEDIMENT PARTICLES

Foraminifera, the most common type of microfossils in sediments, are ocean living calcareous ($CaCO_3$) microorganisms, widespread through the entire World's Oceans. There are basically two different types of foraminifers: benthic foraminifera, seafloor living, and planktonic, floating around in the water column. Foraminifera are commonly used as a biostratigraphic indicator in geological time. It's also used for radiocarbon dating, to get a precise age for the sediment, oxygen isotope measurements to investigate global ice volume distribution and with Mg/Ca, used for paleo-thermometric measurements.

Ice rafted debris (IRD) are sediment and rock fragments, transported from the continents by icebergs or sea ice and accumulate in the deep ocean's sediments. Normally, lack of greater sediment particles, especially continental minerals like quartz, are missing in the deeper oceans. IRD in sediments is an indicator of glacial and deglacial paleoenvironments (Polyak et al., 2013).

3. METHODS

The Arctic Ocean 2016 expedition took place August 8th to September 20th from Longyearbyen, Svalbard, with the main purpose of mapping the seafloor, paleoceanography, paleoclimatology and other geological research. This excursion was in collaboration between the Swedish Polar Research Secretariat and the Geological Survey of Canada. The research vessel being used for this excursion was the icebreaker *Oden*, owned by the Swedish Maritime Administration (Gårdfelt et al., 2016).

The sediment core AO16-9-PC1, is a 7,49 meters long piston core, taken at the Alpha Ridge in the Central Arctic Ocean at 85° 57.34'N, 148° 19.55'W at a water depth of 2212 meter (Fig. 5) (Johansson et al., 2016).

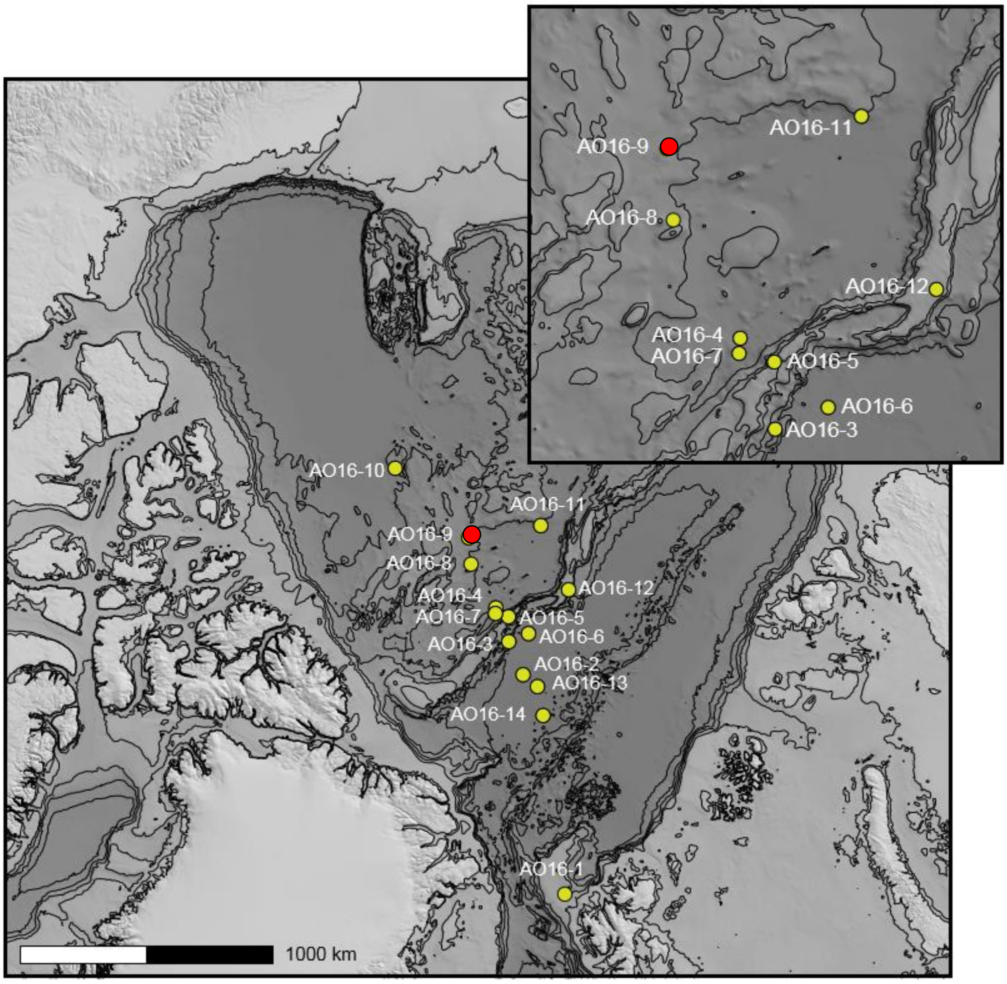


Figure 5. A map over the Arctic Ocean with location over sediment coring sites. AO16-9-PC1, red dot, is the core being investigated for this report (Johansson et al., 2016).

3.1 BULK DENSITY MEASURMENTS

High resolution Bulk density measurements are a useful tool for estimating changes in sediment grain size. Coarser sediments tend to have a lower porosity, and therefore a higher bulk density, while fine-grained sediments have a higher porosity (Cronin et al., 2014).

The bulk density data for the core AO16-9-PC1, was measured onboard the research vessel *Oden* with the Geotek Multi Sensor Core Logger from Stockholm University. The different densities along the core were taken with gamma rays measurements. Calibration was made for the bulk density with an already known density for a piece of aluminum mixed with water (Johansson et al., 2016).

3.2 SAMPLE PREPARATION

The 7,49-meter piston core AO16-9-PC1, was sampled every 20 cm of each section with 2-cm thick plastic tubes (40 samples total). The samples were taken shipboard and stored frozen. They were removed from the freezer and preserved in the fridge before working with them. The tubes were washed very carefully through a 63 µm wet sieve with pressured distilled water to remove pieces smaller than 63 µm, and put into an oven at 50^{o}C for several hours for drying. Once the samples were dried, they were weighed using a Sartorius MCI Analytic AC 210P scale and put into small labeled glass vials. Before looking at the samples in the microscope, they were dry sieved once again so only particles between 125 µm and 500 µm where investigated. This made it easier finding foraminifers and estimate abundances of mineral particles versus foraminifers and other calcareous and siliceous pieces. When all samples were looked at, an additional 7 other samples from various depths with lower or higher peaks in the Bulk density were washed with a sieve and analyzed.

3.3 OPTICAL ANALYSES

The samples with particles between 125 µm and 500 µm where examined using a Leica M205 C microscope, and the estimated relative abundance of foraminifers versus mineral particles were recorded in an excel document, along with comments on abundances of other minerals and biogenic components. Abundances were recorded on a scale of 1-5 for foraminifers in general, planktonic foraminifers and benthic foraminifers (Fig. 6). Microfossils were also identified to a species and subspecies level (if possible) by looking at several books describing foraminifera species.

1	Barren	None
2	Rare	<5%
3	Few	5-10%
4	Common	10-20%
5	Abundant	>20%

Figure 6. Number 1 meaning barren, that the sample has been looked at but no foraminifers found; 2, rare with less than 5% foraminifers; 3, Few between 5-10%; 4, Common with 10-20 %, enough for sea ice proxy method; and 5, more than 20%, abundant and enough foraminifers for radiocarbon dating.

3.4 RADIOCARBON ISOTOPE DATING

Radiocarbon dating required at least 4 mg of calcareous particles. To obtain this weight, 700-800 species of the planktonic foraminifera *Neogloboquadrina Pachyderma* (Fig. 5), were picked from samples AO16-9-PC1-1, 20-22 cm and AO16-9-PC1-2, 100-102 cm, which contains an abundance of that species and is located at the upper 20 cm and 66 cm of the sediment and were likely not too old for radiocarbon dating. Many of the specimens contained pyrite crystallization inside the empty spaces, and those pyrite crystals were washed away before the procedure. The sample AO16-9-PC1-1, 20–22 cm (Depth 0,2-0,22 m) weighed 7.123 mg and AO16-9-PC1-2, 100-102 cm (Depth 0,66-0,68 m) weighed 6.952 mg (Fig. 7).

Figure 7. *Neogloboquadrina pachyderma* collected, weighted and ready to be sent for radiocarbon isotope dating.

3.5 SCANNING ELECTRON MICROSCOPY (SEM)

For the SEM, different species of foraminifera and other particles were picked from samples AO16-9-PC1-1, 20-22 cm (Depth 0,2-0,22 m); AO16-9-PC1-2, 48-50 cm (Depth 0,74-0,76 m); AO16-9PC1-3, 8-10 cm (Depth 1,87-1,89 m); AO16-9PC1-3, 80-82 cm (Depth 2,59-2,61 m); AO16-9PC1-3, 100-102 cm (Depth 2,79-2,81 m) and AO16-9PC1-6, 0-2 cm (Depth 6,29-6,31 m) to determine test and wall structure and aid species identification. This is, especially useful for planktonic foraminifera, where small differences in wall texture determine taxonomic species and genera. SEMing, also an excellent way of assessing the state of preservation and corrosion of shells from pore water.

Representative species found along the core were picked out and put on a carbon tape, coated with gold using an Agar sputter coater to get better resolution in the SEM (Leica Microsystems, 2013). The concept with SEM is that microscopically solid materials can be shown in detail, because of electron beam that allows very high resolution imaging, to see the crystal structure, morphology and chemical composition (Swapp, 2017).

4. RESULTS

4.1 CORE DESCRIPTION

The core consists of decimeter thick layers of dark grayish coffee brown and lighter yellowish caramel brown colors, which have more distinct boundaries in section 1 and 2 (Fig.8a). In the other sections, the colors appear a bit lighter (Fig.8b), except from the bottom on section 6 which starts to get darker again. The boundaries are more faded and the thickness of the different layers varies from 5 cm to decimeter thick until section 5, there the layers become a more regular 5 cm thick. Some bioturbation, especially in the later core sections.

Grain sizes vary from sandy silt in the lighter layers to the darker layers of silty clay, sometimes with more pinkish streaks. The end of section 3 is mostly olive brown clay mud. After section 3, the silty sand disappears, and its only silty clay or clay mud.

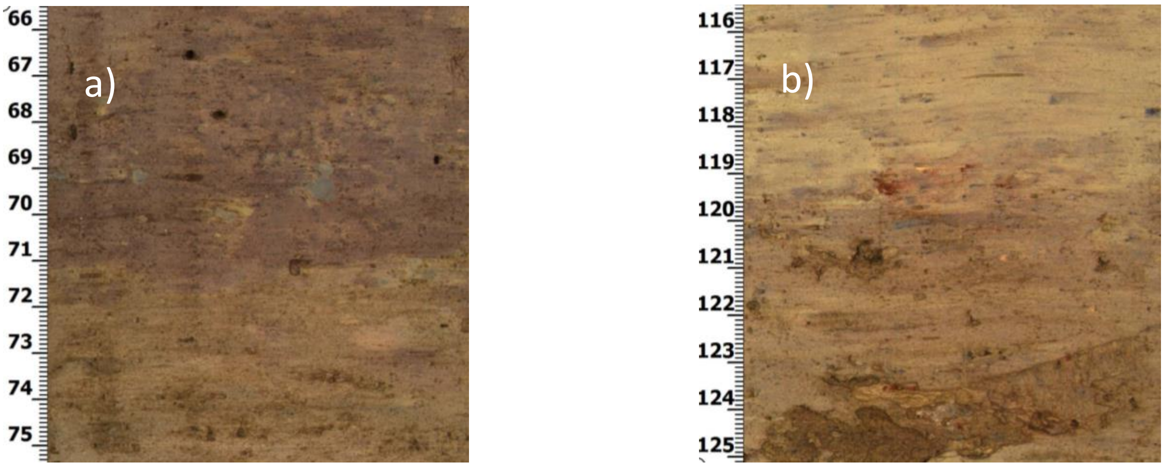


Figure 8. a) Showing a piece of section 2, 66-75 cm. The distinct boundary from the darker to lighter color. Also, some clasts are visible in the darker sediment. **b)** A piece from section 3, 116-125 cm, showing even more lighter color and more faded boundaries to the darker. Bioturbation in the lower part.

4.2 MICROFOSSILS FOUND AND THEIR NATURAL HABITAT

In the optical microscope analyses, some samples were full of microfossils in forms of planktonic and benthic foraminifera, sponge spicules, ostracods, pteropods, mollusc shells, shell fragments and other calcareous particles (Fig.9).

Planktonic foraminifera	**Benthic Foraminifera**	**Other microfossils**
		Sponge Spicule
Neogloboquadrina pachyderma	Cibicidoides wuellerstorffi	Ostracod
Turborotalita quinqueloba	Quinqueloculina	Pteropod
Turborotalita egelida	Pyrgo	Shells
Cf. globoquadrina	Oridorsalis umbonatus	Other unknown calcareous particles
	Elphidium	
	Bulimina aculeata	
	S. concava?	
	Recturigerina strata?	
	Epistominella exigua?	
	Agglutinated	
	Other unknown elongated (Fig.9.1)	
	 **Figure 9.1.** Unknown benthic foraminifera in the samples from core AO16-9-PC1.	

Figure 9. A table showing all species of microfossil found in the samples from AO19-9-PC1.

Planktonic foraminifera

Neogloboquadrina pachyderma (Fig.10) is the most abundant planktonic foraminifera found in the Arctic sediments and therefore used for radiocarbon dating. *N. pachyderma* in general lives in colder water but do exist in warmer waters. There are two types of *N. pachyderma*, sinistral and dextral variants. The sinistral variant likes colder water and have even been found living in sea ice. The dextral variant lives in oceans with sea surface water densities above 25.5 kg/m^3 (Hibrecht, H; 1996). Both variants, especially the sinistral one (Eynaud, 2011) were abundant in the Arctic core, until about 3-4 meters below the seafloor (mbsf) where all the other microfossils disappeared except for agglutinated benthic foraminifera. Some *N. pachyderma* even existed in depths with high IRD contents, like quartz sand, but only as few or very rare. 1-2 pieces of *N. pachyderma* were found in the 3.68 mbsf sample, but it's doubtful that they existed there, or still have been preserved because no other microfossils exist in that sample, not even agglutinated foraminifera which are the only ones occurring after that depth. That sample could therefore have been contaminated.

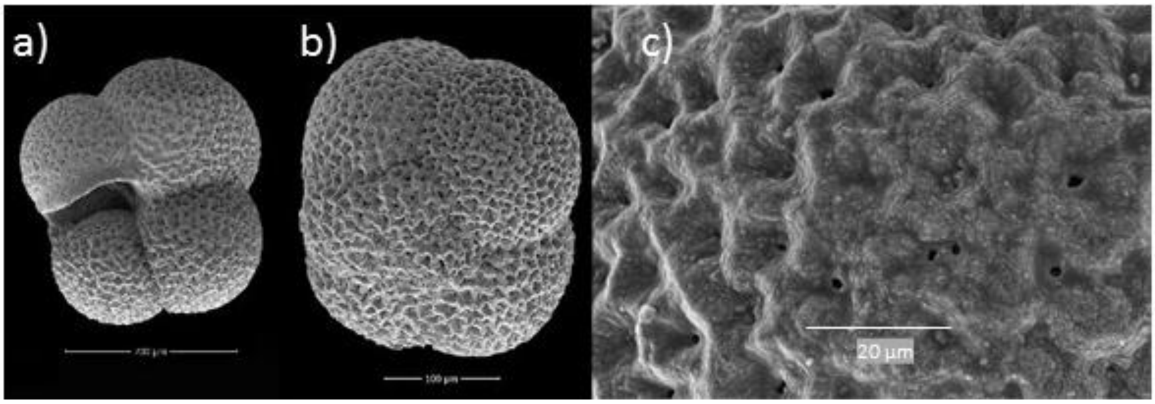


Figure 10. a) A four chambered *Neogloboquadrina pachyderma* from sample AO16-9-PC1-1, 20-22 cm, umbilical view. **b)** *N. pachyderma* spirul view. **c)** *N. pachyderma* zoom in to see the cancellate wall texture.

Turborotalita quinqueloba (Fig.11) is the second most common planktonic specimen in Arctic Ocean sediments. It is abundant in high latitudes with colder water and don't like it too salty, maximum of 35 psu (Hibrecht, 1996). It was hard to distinguish planktonic foraminifera in general and especially *T. quinqueloba* from *T. egelida*. For sure it's present in the top layers of the core, and very abundant (dominantly over the *N. pachyderma*, which were only a few specimens at that depth) at 2.39 mbsf together with *T. egelida*.

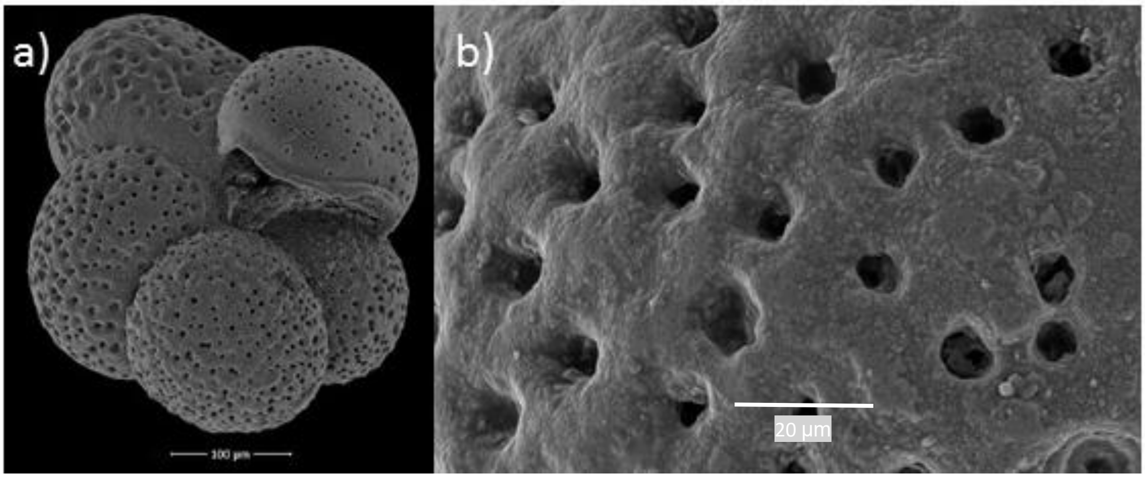


Figure 11. Almost clavate *Turborotalita quinqueloba* from sample AO16-9-PC1-1, 20-22 cm. **a)** umbilical view. **b)** zoom in on the walls.

Turborotalita egelida (Fig.12), planktonic foraminifera, thought to only exist in the sediments in the Arctic Ocean from the warmer interglacial period MIS 11, when summer sea surface temperatures were 8-10 C^{o} with a probability of high surface productivity (Cronin et al., 2014). *T. egelida* were identified abundantly at 2.39 mbsf together with *T. quinqueloba*.

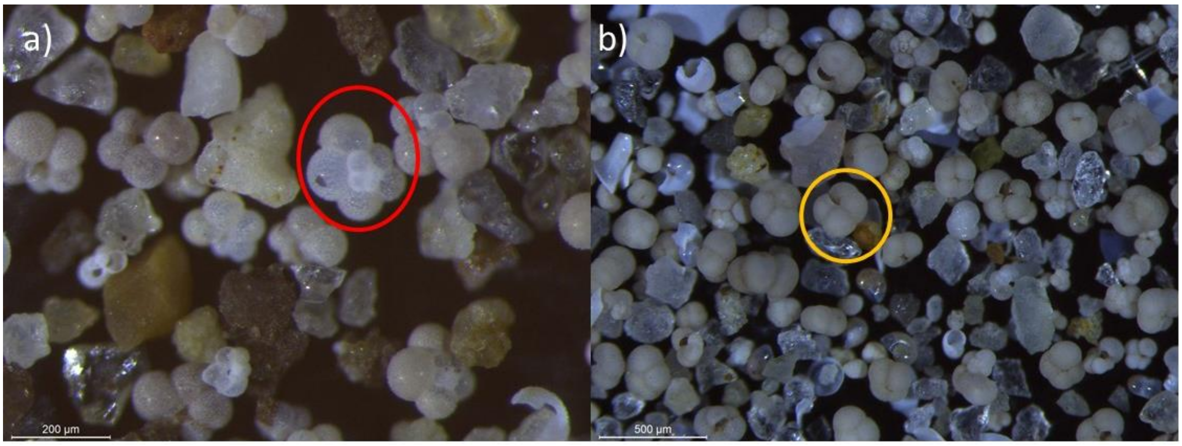


Figure 12. A comparison of a sample with abundances of *T. egelida* and another sample of abundances of *N. pachyderma*. **a)** *Turborotalita egelida* from sample AO16-9-PC1-3, 60-62cm. **b)** *Neogloboquadrina pachyderma* from sample AO16-9-PC1-1, 20-22 cm.

Benthic foraminifera

Cibicidoides wuellerstorffi (Fig.13a) is one of the most abundant benthic foraminifera in this core. This species is found worldwide (WoRMS, 2010) and known to live even under ice covered conditions (Polyak et al., 2013). It appears in most samples where calcareous benthic foraminifera were found, also rare or few in samples with high contents of IRD.

Quinqueloculina (Fig.13b), a world-wide species, with several subspecies. Suspecting that the *Quinqueloculina* subspecies found in the Arctic sediments are *Quinqueloculina arctica*.

Pyrgo (Fig.13c) is a worldwide species, but the subspecies is unknown, and in the samples, it appears a bit deeper in the sediment, but is very common were it exists. Even a few could be found in one sample dominated by >90% quartz sand and other IRD.

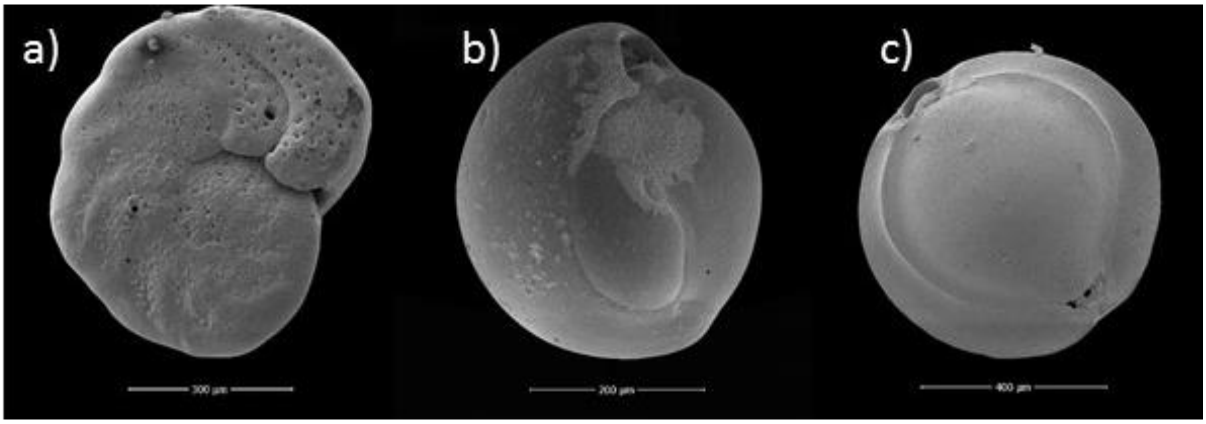


Figure 13. Benthic foraminifera. **a)** *Cibicidoides wuellerstorffi,* umbilical view, from sample AO16-9-PC1-1, 20-22 cm. **b)** *Quinqueloculina* umbilical view, from sample AO16-9-PC1-1, 20-22 cm. **c)** *Pyrgo*, umbilical view, from sample AO16-9-PC1-3, 80-82 cm.

Bulimina aculeata (Fig.14), is known to be most abundant in MIS 5.1 in the Arctic Ocean, and therefore is a common biostratigraphic marker for the MIS 5.1 interglacial (Cronin et al., 2014). *Bulimina aculeata* is found very abundantly in the 63 µm – 150 µm particles, only in a depth of 1.26 mbsf, and at least one sample in 2.39 mbsf.

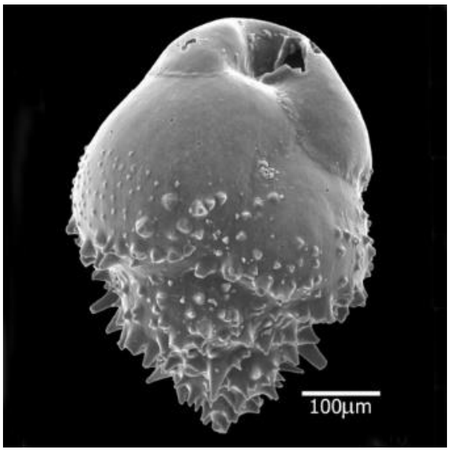


Figure 14. *Bulimina aculeata* from sample AO16-9-PC2, 100-102 cm.

Other microfossils

Sponge spicules (Fig.15a), have a siliceous skeleton. *Ostracodes* (Fig.15b), small crustacean, live in the upper seafloor sediments and are omnivores. *Pteropods* (Fig.15c), are free swimming pelagic snails. Their shells are easily dissolved and thus are sensitive to ocean acidification because the shell is made of aragonite.

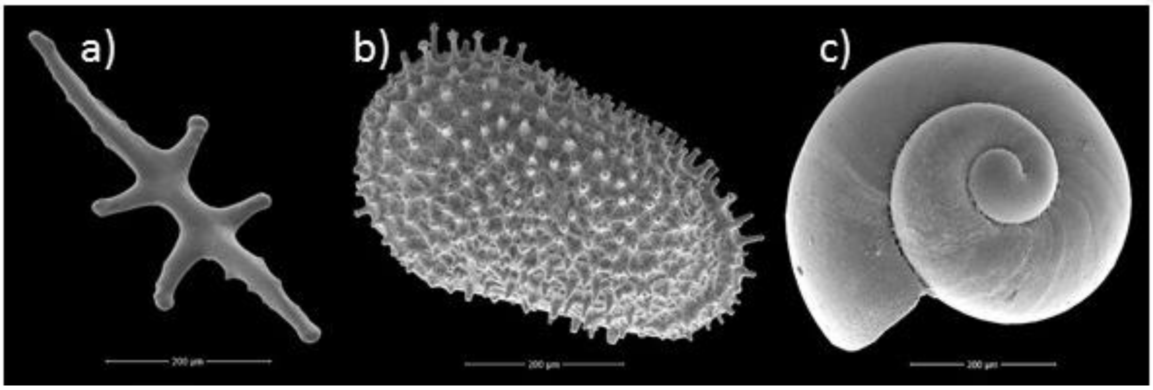


Figure 15. Calcareous microfossils from sample AO16-9-PC1-1, 20-22 cm **a)** Sponge Spicule. **b)** Ostracod. **c)** Pteropod.

Agglutinated benthic foraminifera (Fig.16) have test or shells consisting of sedimentary particles, often incorporating small yellow/orange crystals in a shape of unknown benthic foraminifera. The increase in abundances in agglutinated benthic foraminifera starts to appear within the older and deeper sediments about 3-4 mbsf. It appears around the same time as the calcareous species disappear (Fig.17).

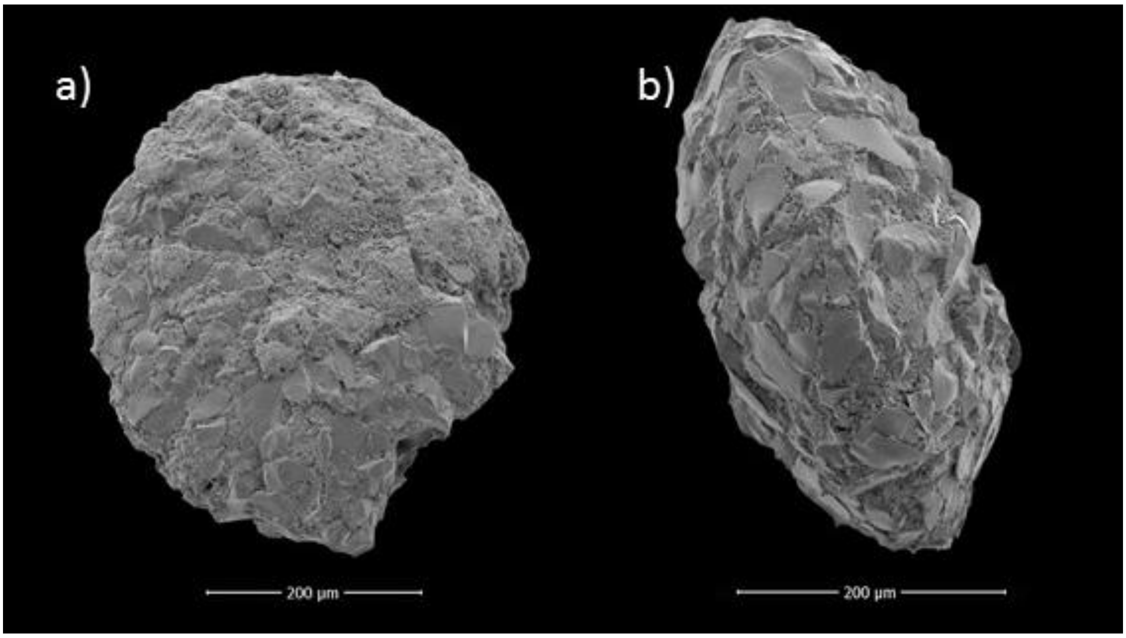


Figure 16. Agglutinated benthic foraminifera abundant in the deeper parts of the sediments. **a)** Unknown view, from sample AO16-9-PC1-3, 100-102 cm. **b)** Edge view, from sample AO16-9-PC1-6, 0-2 cm.

The occurrences of the different species of microfossils found together with benthic and planktonic foraminifera abundances, were presented on a diagram (Fig.17) with the purpose to get an overview over the microfossils at certain depths.

Planktonic- versus benthic foraminifera abundances in depth and different occurences of different species of microfossils at AO16-9-PC1

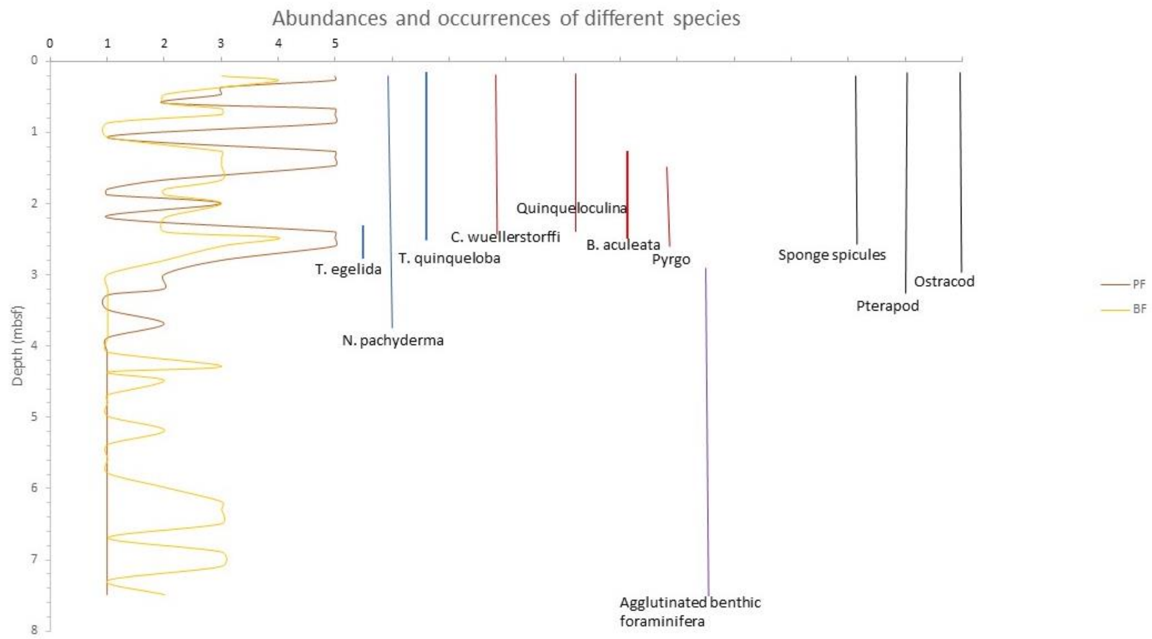


Figure 17. This diagram shows the abundances of benthic versus planktonic foraminifera. The dark red is planktonic foraminifera (PF) and the yellow is benthic foraminifera (BF). In the foraminifera abundances: 1 = barren, 2 = rare, 3 = few, 4 = common and 5 = abundant. To the right are just different species of microfossils, occurring at different depths.

4.3 SEDIMENTATION RATE BASED ON RADIOCARBON ISOTOPE DATING

The results of radiocarbon isotope dating on *Neogloboquadrina pachyderma* from sample AO16-9-PC1-1, 20-22 cm and AO16-9-PC1-2, 40-42 cm depth were used to calculate a linear sedimentation rate of 3.2 cm/kyr (Fig. 17). It is not known whether the top sediments are modern, as some sediment may have been lost. Therefore the sedimentation rate between the seafloor and the first samples (0.8 cm/kyr) is uncertain.

Lab Number	Sample	Depth (mbsf)	Middle age (cal yr. BP)	Calibrated Age (cal. Yr BP) (Min)	Calibrated Age (cal. Yr BP) (Max)	Sed rate (cm/kyr)
462439	AO16_9_PC1_1_20_22	0,2	26145	25770	26520	0,803
462438	AO16_9_PC1_2_40_42	0,66	40175	38915	41435	3,2

Table 1. Table of radiocarbon isotope dating to determine the age of certain intervals in the sediment. The first sedimentation rate is calculated from 0,2 mbsf to the top, and got an average result of 0,803 cm/kyr. The other average sedimentation rate is an average between 0,2 meter to 0,66 meter and is 3,2 cm/kyr.

5. DISCUSSION

5.1 AGE MODEL 1

Correlating core lithology and microfossil abundances to marine Isotope stages. Low bulk density intervals above 3 mbsf coincide with higher abundances in foraminifera, and are recognized as interglacial/interstadial periods. The MIS interpretations are based on comparing the bulk density data and foraminifera abundances with the global $\delta^{18}O$ isotope record (Lisiecki and Raymo, 2005) (Fig. 18). It's easier to correlate the MIS when the glacial cycles are large and very long (100 kyr) instead of 41 kyr. The core photography shows the darker interglacial cycles and lighter glaciations. By looking at the core lithology, where the darker and lighter layers get more compact at around 4,5-5 mbsf, the initial interpretation is that the Mid-Pleistocene transition occurs around this level. However, the bulk density and foraminifera data doesn't clearly capture this transition, because of dissolution in the older Quaternary sediments (starting from 3 mbsf), making the biostratigraphic studies more difficult and the density data gets smoother.

Polar regions like Arctic have less carbonate productivity than other subtropical or tropical areas and tend to have corrosive bottom waters, which partly explains the dissolution (Eynaud, 2011). However, the Central Arctic Ocean in general, is affected by strong dissolution around MIS 13 – MIS 17 for unknown reasons (Cronin et al., 2014). Across much of the Arctic, including the Lomonsov Ridge, Alpha Ridge, the Northwind Ridge the Morris Jesup Rise north of Greenland, the calcareous-agglutinated transition appears during MIS 7-8 according to Cronin et al., (2008).

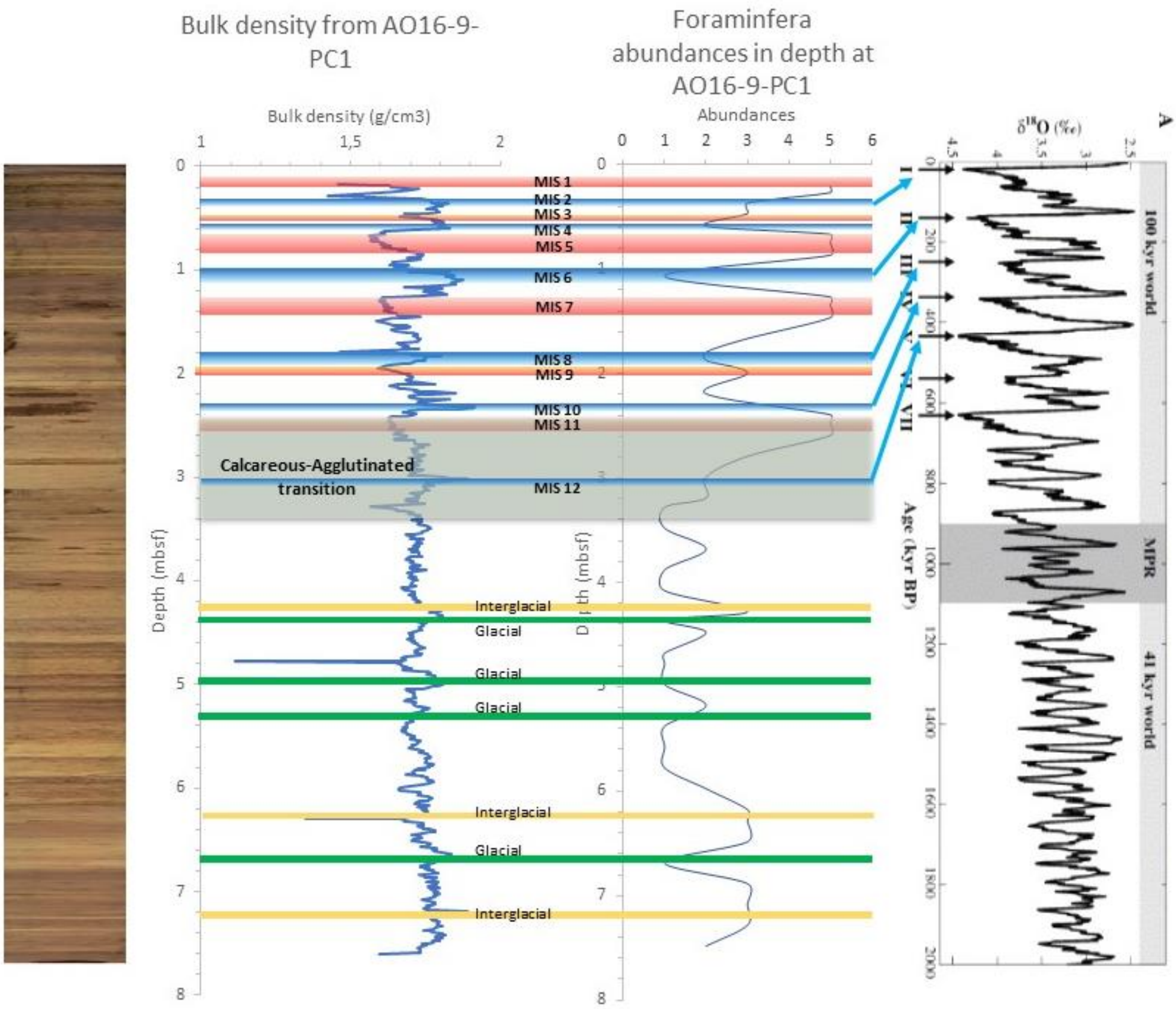


Figure 18. Showing the core photography side by side to bulk density data and foraminifera abundances. In the foraminifera abundances 1 = barren, 2 = rare, 3 = few, 4 = common and 5 = abundant. The red and orange shows lows in bulk density and higher abundances of foraminifera, that might correspond to interglacials MIS 1, MIS 3, MIS 5, MIS 7, MIS 9 and MIS 11. The blue shows higher bulk density data together with absence of microfossils, which might correlate to glacial periods MIS 2, MIS 4, MIS 6, MIS 8, MIS 10 and MIS 12. The global $\delta^{18}O$ record is shown to illustrate the intense 100 kyr glaciations. The Calcareous-Agglutinated transition describes where agglutinated foraminifera starts appearing and where calcareous microfossils disappear. Green and yellow lines are probably unknown glacial and interglacial periods based on the greater peaks in bulk density and foraminifera abundances data. Age model 1 below is based on the interpretation shown in this figure..

In the first proposed age model, highest abundances of microfossils occur between 0,2 – 3 mbsf, (MIS 1 – MIS 11), except for *Pyrgo*, that only appears between 1,3 - 3 mbsf, (MIS 7 – MIS 11), and agglutinated foraminifera before MIS 11 (Figs. 17, 18). However, one broken sample of agglutinated foraminifera maybe was found at MIS 9.

Based on the MIS assignments in Fig. 18, an age-depth model (Age model 1) was constructed (Fig.19). The average sedimention rate is calculated to be 0,6 cm/kyr by calculating from 0,2 mbsf corresponding to MIS 2 to 2,47, where MIS 11 starts (Lisiecki and Raymo, 2005). According to this sedimentation rate, the Mid-Pleistocene transition should start at around 5,4 mbsf and the 41 kyr glaciation cycles could be captured in the foraminifera abundances data if dissolution wasn't present, even though the sampling interval is 20 cm/sample. A major problem with this age model is that it assigns MIS 5 to a radiocarbon dated interval that is only 41 ka old (Tab. 1).

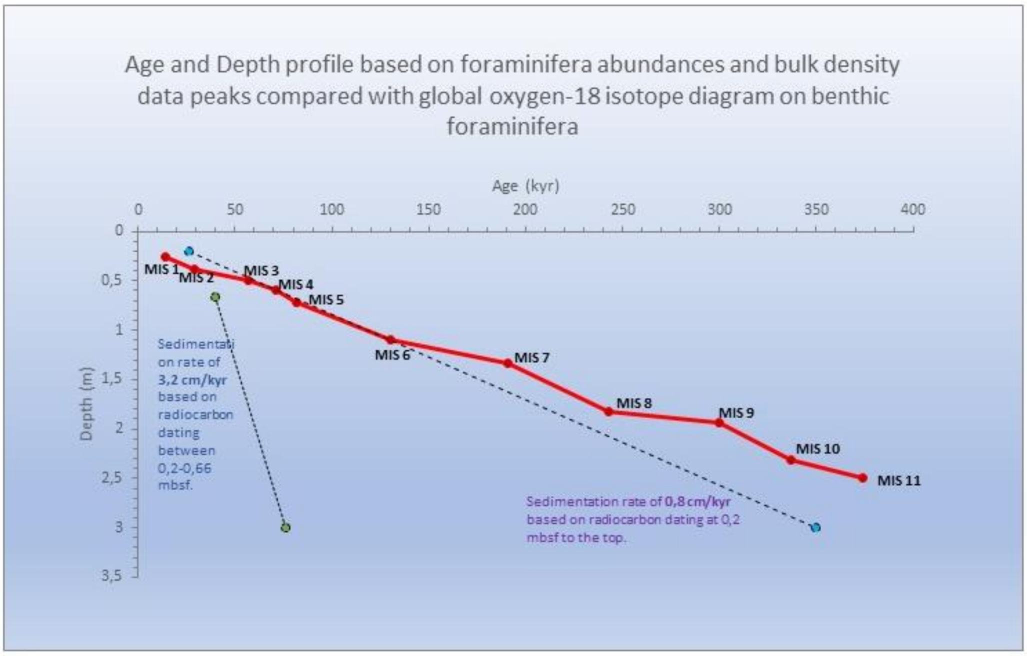


Figure 19. Age model 1, showing the different interglacial-, glacial cycles recognized from the diagram patterns with already known age for the different Marine Isotope stages (MIS), and the two sedimentation rates based on radiocarbon isotope dating and how their trend line would look like if it continued to 3 mbsf.

5.2 AGE MODEL 2

Age model 2 is constructed using only the radiocarbon dates, and 2 proposed biostratigraphic markers. One proposed biostratigraphic marker is *Bulimina aculeata*, commonly associated with MIS 5 (Cronin et al., 2014). In this core, it occurs abundantly in the sample AO16-9-PC1-2, 100-102 cm, 1.26 mbsf corresponding to MIS 7 in age model 1 (Fig. 18).

Turbotalita egelida, is believed to be a biostratigraphic marker for MIS 11(Cronin et al., 2014). Here, *T. egelida* were found in sample AO16-9-PC1-3, 60–62 cm, 2.39 mbsf (Fig. 17). First, we thought we found *T. egelida* in the top samples, which was wrong (H. Coxall and T. Cronin – pers. communication) because the morphological and wall texture differences between *T. egelida* and *Turborotalita quinqueloba* are not well documented (H. Coxall – pers. communication). Because of this, we use the occurrence of *T. egelida* at 2.39 mbsf as a marker for MIS11

From this information, a second age-depth model was created using the 2 radiocarbons dates, and the 2 biostratigraphic datums (Fig. 20). In this age model, the foraminifera abundances peaks don't capture all interglacials between MIS 5 and MIS 11 as there is only 1 foram peak and 2 interglacials (MIS 7 and 9) (Fig. 20).

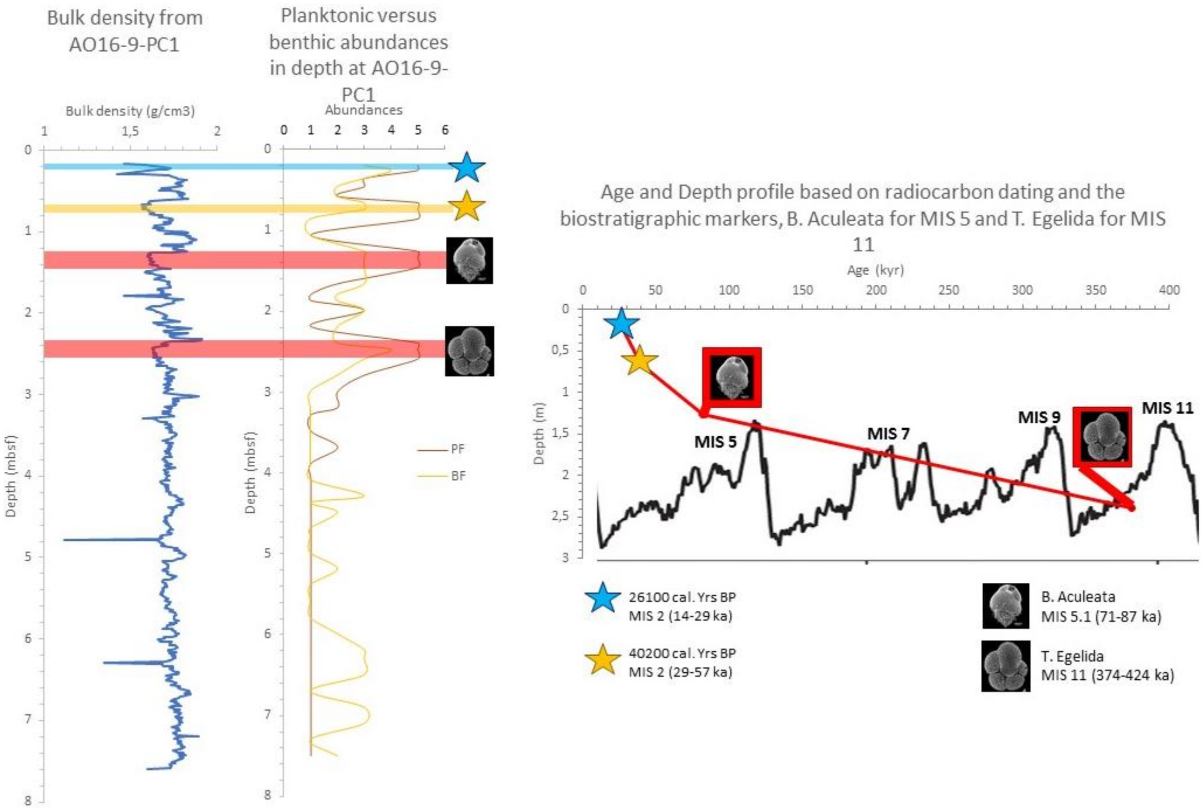


Figure 20. Age model 2. Bulk density and foraminifera diagram side by side with the age model, which is based on radiocarbon isotope dating and biostratigraphic markers of *B. aculeata* corresponding to MIS 5.1 and *T. egelida* corresponding to MIS 11. The age model also has oxygen-18 isotope data.

5.3 SEDIMENTATION RATES FROM THE AGE MODELS

Radiocarbon dates provide the most reliable age estimates for the sediments. They indicate that the average sedimentation rate from the seafloor to 0,2 mbsf is 0.6 cm/kyr, and then increases to 3.2 cm/kyr between 0.2 and 0.66 mbsf (Tab. 1). Extrapolating this higher sedimentation rate would place the Mid-Pleistocene transition at a depth of 28,8 mbsf, which seems too deep for this core. However, given the large changes in grain size seen above 2.39 mbsf (inferred from bulk density variations) the assumption of a linear sedimentation rate does not seem correct.

The biggest problem with age model 1, is the contradiction between the radiocarbon date at 0.66 mbsf (41 ka) (Tab. 1) and the placement of MIS 5 at this interval (Fig. 18). Age model 2 did not consider how the peaks of the bulk density and foraminifera abundances correlated to the global δ^{18}O isotope record (Lisiecki and Raymo, 2005). Linear sedimentation rates are only drawn from the radiocarbon isotope dating's and biostratigraphic markers (*B. aculeata* and *T. egelida*) (Fig.20). The sedimentation rate is therefore very fast in the top and gets extremely slow after MIS 5. However, in this age model, foraminifera abundance data does not capture both interglacials (MIS 7, and 9) between MIS 5 and MIS 11. This may be because of the 20 cm sampling resolution. because MIS 11 occurs at the same location in age model 1 and 2, the long-term sedimentation rate is the same for each age model (0,6 cm/kyr).

5.4 COMPARISION WITH DATA FROM THE LOMONSOV RIDGE

The mean sedimentation rate from the ACEX borehole, at the Lomonsov Ridge, is 1-2 cm/kyr for the past million years, confirmed with radiocarbon isotope dating of the top 25 cm of the core (Cronin et al., 2008). The remainder of the age model was made by identifying variations of interglacial and glacial cycles, that were connected to the Milankovitch orbital cycles. Although, there are uncertainties in the age modeling, due to lack of microfossils, bad overlaps deeper in the sediments and poor magnetic inclinations because of the high latitude (O'Regan et al., 2008). MIS 1-6 had a very detailed chronology, and MIS 6-21 based on cyclostratigraphy. A total sedimentation rate, based on top sedimentation rate and cyclostratigraphy in older sediments, is 1.3 cm/kyr for the Quaternary on the Lomonsov Ridge (Cronin et al., 2008).

Based on foraminifera abundance patterns, sedimentation rates on the Lomonsov Ridge, differs a lot from those found on the Alpha Ridge. Agglutinated foraminifera start to appear abundantly at 6 mbsf from ACEX (MIS 9), and are most abundant below 3 mbsf in AO16-9-PC1. Both age models indicate that this is before MIS 11. The single agglutinated fragment found at around 2 mbsf in AO16-9-PC1 may mark the end of the agglutinated-calcareous transition found at MIS 9 in the ACEX record (Cronin et al., 2008). In MIS 9 from the Lomonsov Ridge, there is also a trend of more abundant benthic foraminifera than in planktonic ones, which is not the case for the core from the Alpha Ridge, which consistently has more planktonic foraminifera. Overall sedimentation rates are lower in AO16-9-PC1 than at ACEX, although both records seem to have higher sediment rates in the upper few meters, where longer intervals of coarse grained material are found.

Lomonsov Ridge samples also have few calcareous planktonic and benthic foraminifera between MIS 1 – 9 and none after MIS 9. The AO16-9-PC1 core has much higher abundances, and more diverse assemblage than ACEX. For example, neither *B. aculeata* or *T. egelida* were found at ACEX, so a direct comparison of these proposed biostratigraphic markers is not possible. The Mid-Pleistocene transition can be seen by low agglutinated foraminifera abundances between MIS 22-24 and MIS 12-20 and low sediment bulk density or decreasing density from ACEX a pattern that is not clear in existing samples form AO16-9-PC1.

5.3 UNCERTANTIES

One of the challenges in this study relates to difficulties in assuming proportions of foraminifera versus minerals and problems identifying agglutinated forams, and how to determine whether some of these agglutinated tests were broken or whole. Exact species identification of foraminifera is very tricky. Below 3 mbsf, it seems like the foraminifera and other microfossils have dissolved, as shown by SEM imaging. The bulk density data is also more even and both coarse IRD and microfossils are absent - except some agglutinated foraminifera that were present. This makes it difficult to identify and correlate lithology changes with glacial and interglacial stages. Although age model 2 is consistent with both radiocarbon dates and biostratigraphic markers proposed in the literature (Cronin et al., 2014), it is hard to see how MIS 7 and MIS 9 can fit between MIS 5 and MIS 11 in the stratigraphy.

5.4 FURTHER STUDIES

In future studies of this and other Arctic cores, more radiocarbon isotope dating could be applied, to better define Holocene and deglacial sedimentation rates. Increased sampling resolution from (< 20 cm/sample) to be very sure to capture all glacial and interglacial periods, especially if the last age model is the correct one. Paleomagnetic measurements could also be applied to provide additional age control. Further studies of proposed biostratigraphic markers, like *B. aculeata* and *T. egelida*, in other close by coring sites, to really investigate if *T. egelida* existed and are abundant in more than MIS 11 and if *B. aculeata* exists more abundantly in other intervals. *T. egelida* is also well-known to be difficult to identify from *T. quinqueloba*. *Pyrgo* were also absent until 1.3 mbsf and then became very abundant in the samples where it was found until 3 mbsf. It could become a new biostratigraphic marker, if further studies were done on other cores to confirm its occurrences.

6. CONCLUSIONS

Calcareous planktonic and benthic foraminifera are relatively abundant in the upper 3 m of a 7.49 sediment core (AO16-9-PC1) from the Alpha Ridge. Below 3 mbsf, dissolution of calcareous microfossils starts occurring and agglutinated benthic foraminifera starts appearing. This pattern is recognized across the Arctic Ocean and is called the calcareous-agglutinated transition. This caused the bulk density data and foraminifera abundances to get smoother and harder to distinguish the glacial and interglacial intervals after that depth.

A preliminary correlation between these abundances, lithologic changes and interglacial periods (MIS 1-11) were made for the upper 3 mbsf (Age model 1). However, this was not supported by radiocarbon dates and the identification of 2 biostratigraphic markers *(B. Aculeata – MIS 5.1 and T. Egelida – MIS11*). As a result, a second age model based on 2 radiocarbon dates and these markers was constructed (Age model 2). In this age model, the foraminifera abundances do not capture interglacials MIS 7 and 9. So neither age model is completely satisfactory.

The age and depth models are therefore doubtful even if the first one coincides better with the global $\delta^{18}O$ isotope record (Lisiecki and Raymo, 2005) and the second have 4 age-depth points supported by direct measurements or published literature.

Further resolution requires more radiocarbon isotope dating, paleomagnetic measurements and a more detailed look into biostratigraphic markers *Bulimina aculeata* and *Turborotalita egelida* in this core or others from the same area. After further studies, determinations of where the Mid-Pleistocene transition occur could be more precisely discussed, if it corresponds to both age models' sedimentation rate of 0,6 cm/kyr, then it could possible start at 5,4 mbsf.

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