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Arctic Ocean glacial/interglacial regimes over the Late Quaternary

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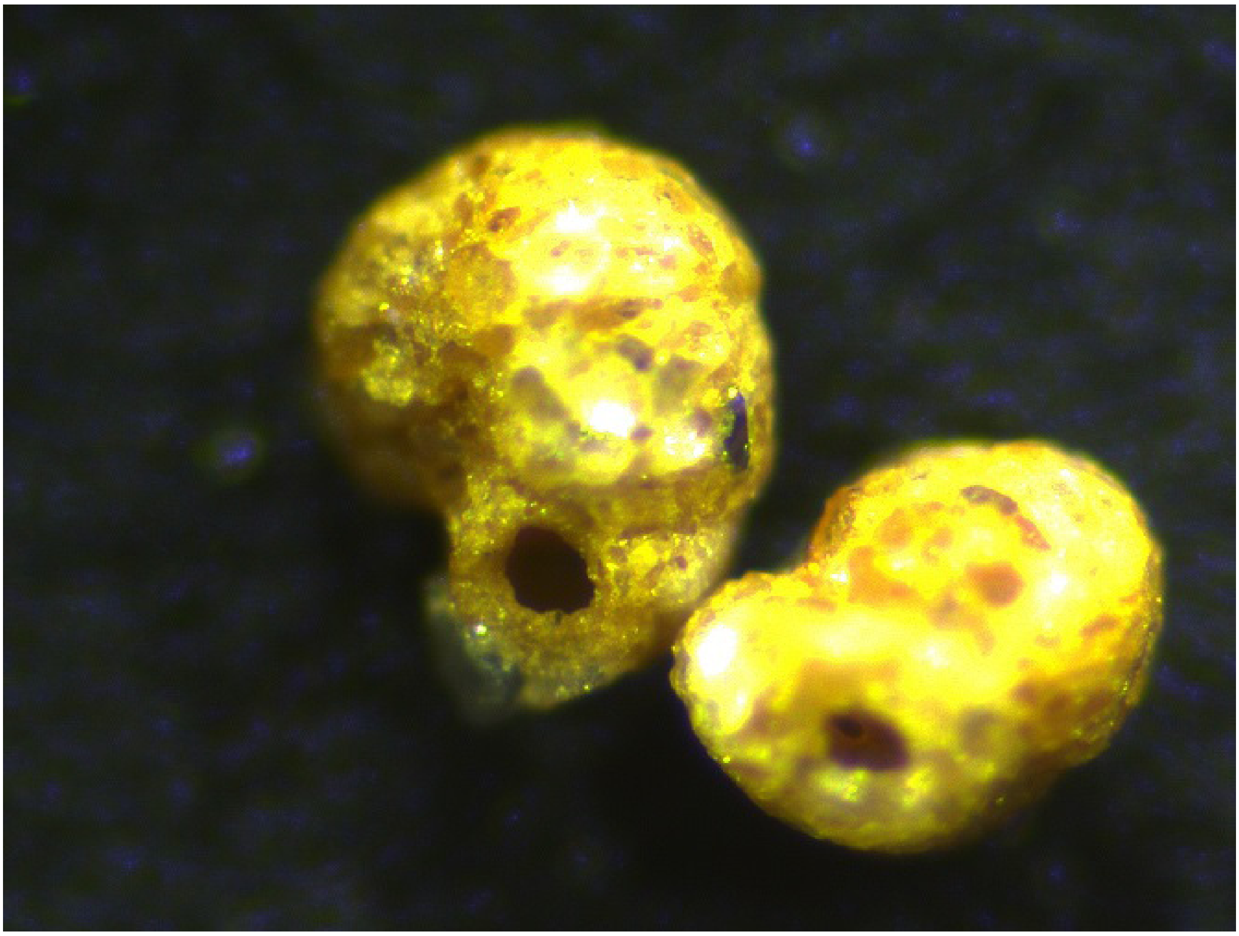

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Arctic Ocean glacial/interglacial regimes over the Late Quaternary

Do agglutinated benthic foraminifera assemblages in the Arctic Ocean reflect changes in food availability or water chemistry on glacial/interglacial time scales?

ABSTRACT:

Agglutinated foraminifera are thought to be more resistant to environmental changes in comparison to calcareous species. However, the use of agglutinated foraminifera as a paleoclimatic proxy has been given little scientific attention in the past, although they have proven to help deciphering Arctic Ocean glacial history. The absence of calcareous foraminifera down core is a notable feature in several collected sediment cores from different parts of the Arctic Ocean. Does the absence of calcareous species reflect calcium carbonate corrosive pore water chemistry or a change in the ecology?

Previous research on Arctic Ocean sediment cores reveals a cyclic nature in the sedimentation. That is to say, glacial periods that are recognized by accumulation of coarse grained terrestrial material, and interglacial periods proven to be rich in calcareous foraminifera and agglutinated foraminifera. In this study a new sediment core from the southern Lomonosov ridge is analyzed for micropaleontogical studies. As a result, abundances in agglutinated foraminifera had allowed to qualitatively estimate the age of the core and to reconstruct the late Quaternary glacial history over this specific part of the Arctic Ocean.

Key words: Agglutinated benthic foraminifera; Arctic Ocean; Lomonosov Ridge; Paleoclimate; Sea ice;

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1.0 INTRODUCTION:

Previous studies from Arctic Ocean sediment cores reveal a cyclic sedimentological nature of the sub bottom strata that follow multi-millennial climate fluctuations (Polyak and Jakobsson, 2011). These key observations show that warmer periods in Earth´ history (interglacials/interstadials) are characterized by sediment abundant in calcareous planktonic and benthic foraminifera and agglutinated benthic foraminifera, while colder periods (glacials/stadials) are recognized in the sedimentary archive by accumulation of coarse grained terrestrial material (O´Regan et al., 2008). Another recognizable feature in Arctic Ocean sediments are post depositional dissolution patterns of calcareous microfossil tests due to corrosive pore waters, leaving more resistant tests of organic cemented agglutinated foraminifera behind (Cronin et al., 2008). Do the absences of calcareous species down core only reflect the pore water chemistry or a change in the ecology as well?

During the summer of 2014, the two leg research expedition SWERUS-C3, an international cooperation between Sweden, Russia and US focused to collect information about the interactions between; the cryosphere, climate and carbon. The cryosphere in this case meaning, sea ice and locked up subsea and costal permafrost. During SWERUS-C3 Leg 2 expedition (Jakobsson and Koshurnikov, 2014) the gravity core 29-GC1 was recovered from the southern part of the underwater mountain chain, the Lomonosov ridge, at 824 meters below current sea level (Figure 1).

The location of the core is significant because; it corresponds to the minimum sea ice edge extent today. Furthermore, geophysical bathymetric maps made with multibeam echo sounder and chirp sonar images in the area reveal proof of ice grounding events on this part of the Lomonosov ridge. Therefore, the development of an age model for Core 29-GC1 is needed to allow the investigation of the glacial history of this part of the Arctic Ocean. This information over the geological past is important for future climate projections and improvement of climate models.

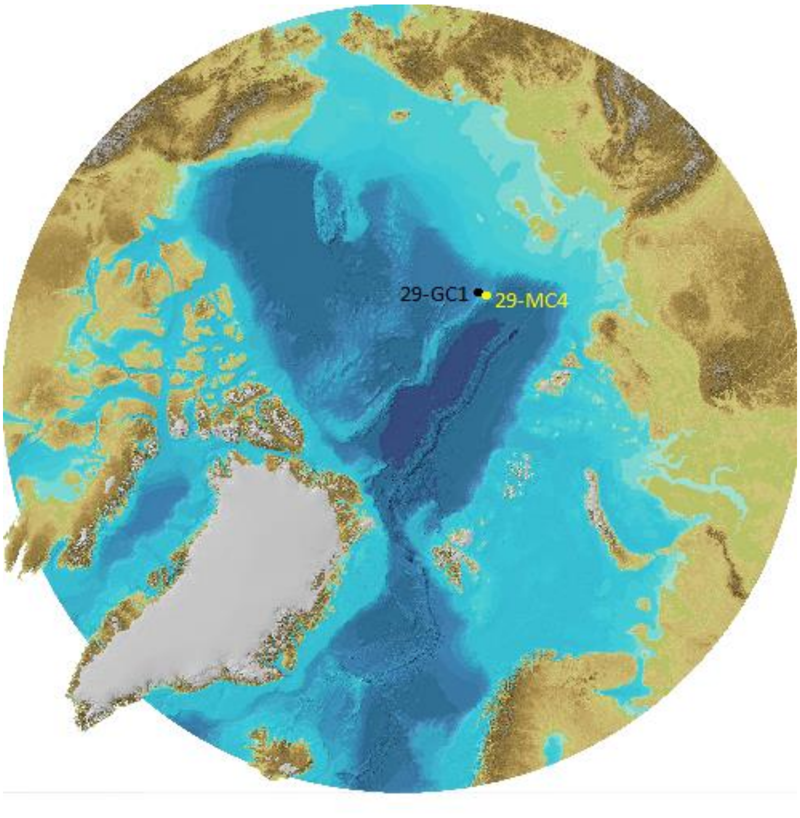


Figure 1 Map of the Arctic Ocean displaying the coring locations for gravity core 29-GC1 and multicore 29-MC4 on the southern Lomonosov ridge. (*The International Bathymetric Chart of the Arctic Ocean (IBCAO)* version 3.0 Jakobsson et al. 2012)

1.1 Aim of study:

The aim of this study is to develop a late Quaternary glacial/interglacial history of the southern Lomonosov ridge area in the Arctic Ocean. To accomplish this the relative abundance of calcareous and agglutinated foraminifera was recorded in a new sediment core collected from the Arctic Ocean during the summer 2014, and an age model was developed, using both new radiocarbon dates and the agglutinated foraminifera abundance records.

The hypothesis to test is: “during warm periods (interglacials), agglutinated foraminifera are abundant, due to the lack of sea ice cover. During colder periods (glacials/deglacials), coarse grained terrestrial material and ice rafted debris accumulates instead”. This is predicted by the increased primary production in interglacials due to the lack of a thick sea ice cover allowing light to penetrate the waters, resulting in increased flux of organic material to the sea floor, and thus larger numbers of benthic organisms that are dependent on surface derived food. However, colder periods reflect on the difficulties of primary production and organic flux to the sea floor due to the ice covered ocean. In this study, agglutinated foraminifera abundances is the proxy used to test this hypothesis due to the lack of calcareous species down core.

2.0 BACKGROUND

2.1 Arctic Ocean sea ice

Since 1979 satellites orbiting the Earth have recorded the advance and retreat of the Arctic Ocean sea ice. The data collected by the satellites shows an overall decline in Arctic sea ice extent over time (Lindsey, 2014). Sea ice, simply layers of frozen sea water, grows in the Arctic Ocean during the Northern hemisphere´s winter months and reaches its peak extent usually in the month of March. In 2015 however, the peak extent of the sea ice was reached already on February 25 according to the National snow and ice data center (2015). The minimum extent of the sea ice is usually reached in the month of September after intense melting off the ice during the Northern hemisphere´s summer months. This year’s maximum extent on February 25 was the lowest maximum extent ever recorded by the satellites since the start of the recordings in the late 70´s (NSIDC 2015).

Changes in weather patterns and natural variability patterns such as the Arctic oscillation are known factors to contribute to changes in the extent of the Arctic sea ice over time. However, the increased melting patterns cannot be explained by only natural causes (Polyak et al., 2010). The increased melting of Arctic sea ice is being coupled to natural variability cycles and increased emissions of greenhouse gases, resulting in a rise in the average global temperature (Lindsey, 2014).

The increased average global temperature is resulting in longer Arctic sea ice melt seasons. The melt season of the sea ice starts earlier and the start of new sea ice formation is beginning later. This pattern is resulting in fewer amounts of the thick multi-year ice, that have survived one or more melt seasons, and more amounts of the annual ice that is weaker and thinner (Polyak et al., 2010). This change in the Arctic sea ice melt pattern is strongly affecting the Earth’s albedo. The thinner annual ice is not as reflective as the thicker multi-year ice, as the dark ocean surface is reflect through the thin ice sheets. The annual ice is very flat, this resulting in melt ponds that extend over big areas above the ice, also contributing to the lowering of the albedo. The albedo of sea ice can reach a reflectivity of 80% when it is fresh and covered in snow. During the melt season the albedo drops to around 50% and could be even lower in areas of flat annual ice with melt ponds. The dark surface of the ocean only reaches an albedo effect of about 10% (Polyak et al., 2010). The change in the Arctic Ocean sea ice melting pattern is allowing the Arctic Ocean to absorb more of the incoming solar energy and then further contributing to the increased sea ice melting (Vinas, 2014). According to climate models made by NASA, a sea ice free Arctic during the Northern hemispheres summer months might be expected this century (Vinas, 2014) and according to models made by other authors an ice free Arctic might be expected at 2040 or even earlier (Polyak et al., 2010).

2.2 Previous work:

In the past there have been difficulties and limitations in the process of gathering information about the Arctic Ocean´s geological history. Before the use of heavy ice breakers there were constraints in the process of collecting sediment cores and mapping of the ocean floor due to the partly ice covered ocean. Due to the concern over the rapid decrease in the Arctic Ocean sea ice during the past few years, the advance in the field followed quickly. Coring and mapping expeditions such as ACEX, HOTRAX, LOMROG and most recently the SWERUS expedition have all contributed to collecting important pieces of information from the sedimentary archive. Through geophysical mapping made with multibeam echo sounders and chirp sonar images, a larger context can be made then from just recovered sediment cores. The multibeam images can reveal glacial features and erosion patterns and the chirp sonar can image the sedimentary layers below. These tools are important and valuable assets for the interpretation of the geological history and the related climate changes through time (Polyak and Jakobsson, 2011).

The geological archive in turn holds information about the past sea ice conditions and dynamics (Polyak and Jakobsson, 2011). The extent and distribution of sea ice is recorded in the sediments, preserved on the sea floor. The distribution of floating sea ice is affecting the deposition of marine sediments through physical, chemical and biological processes (Polyak et al., 2010). The long term perspective of the Arctic Ocean history is important to understand in the mean of understanding the present day retreat of the ice, and also future conditions (Polyak and Jakobsson, 2011). The ocean sediments provide the most extensive and complete record of glacial history in the Arctic Ocean (Polyak et al., 2010).

Previous work made by Polyak and Jakobsson in 2011 shows that Arctic Ocean sediments reveal a cyclic nature of altering layers. In general these layers are corresponding to interglacial, deglacial and full glacial environments. Interglacial layers are recognized by the abundance in microfossils. Deglacial layers are dominated by coarse grained terrestrial material and ice rafted debris. Full glacial layers are often finer grained and may have been deposited by melt water (Polyak and Jakobsson, 2011). It is although hard to know if sediment is ice berg derived or sea ice derived, it is important to distinguish between the two to understand the full context. Sea ice deposited sediments are generally finer grained, icebergs can deposit grains of any size, even large boulders (Polyak et al., 2010 and O´Regan et.al 2008). Both sea ice derived and ice berg derived sediments can have similar appearances in the geological record, both of these higher ice conditions suppress Arctic Ocean biota (Polyak and Jakobsson, 2011).

Preservation of foraminifera in Arctic Ocean sediments are influenced by primary causes such as the distribution of sea ice and flux of organic material to the ocean floor, and by secondary causes such as long term pore water dissolution after burial. Previous work made by Cronin et al. in 2008 shows that abundance of agglutinated foraminifera are corresponding to interglacial and deglacial periods in Earth´s history, and that the disappearance of calcareous species down core might be related to the pore water chemistry. Similar observations are made in this study; the lack of calcareous species brings the agglutinated foraminifera into focus.

2.3 Agglutinated benthic foraminifera:

Agglutinated benthic foraminifera (ABF), the term agglutinated refers to the organism's tests that are built from foreign particles glued together with a variety of cement (Figure 2). The selection of foreign particles to be included in the tests of ABF's are reckoned to be random in some cases, but also to be chosen for its specific gravity, shape or size (Hemleben et al., 1990).

Figure 2 Microphotograph of various agglutinated benthic foraminifera tests built mainly out of grains of quartz.

In 1988 Schröder stated that agglutinated species often have been ignored from studies of recent benthic fauna. The author also mentioned that "the disappearance of various species below the sediment surface has been interpreted as an indication that no agglutinated forms are preserved in the fossil record". Schröder (1988) investigates this statement further and finds it not to be true. ABF are known to be affected by several modification factors after burial, such as compressional effects, geochemical processes and decalcification. Species with fragile tests are reckoned not to survive the fossilization process. Species with more resistant tests will therefore be the most dominant in the fossil record. But this in turn may indicate that the record lacks species that would be most indicative of the past paleoenvironment (Schröder, 1988). The first foraminifera to appear in the geological record were primitive ABF with secreted organic cement, this occurred during the early Cambrian period. As Schröder (1988) noted, many of the modern groups of ABF that are observed today are also preserved as fossils in the geological record (Shröder, 1988 Hemleben et al., 1990).

The ability of ABF to secrete biomineralized calcite cement did not evolve until the base of the geological period of Carboniferous. ABF are a widely distributed group of marine meiofauna that are represented as a diverse and abundant group in nearly all marine ecosystems. They are known to be tolerant to environmental extremes and are known to be able to survive where the more advanced calcareous test bearing foraminifera cannot (Hemleben et al., 1990).

Fossil foraminifera have become essential tools in paleontology and biostratigraphy and in the reconstruction of paleo-ocean environments. Radiocarbon dating and isotope analysis of calcareous tests have become standard procedures in many studies to reconstruct age models and ocean paleotemperatures. However, in large parts of the ocean, calcareous tests dissolve as they sink below the carbonate compensation depth or get dissolved by too calcium carbonate corrosive pore waters. In these cases, ABF with organic cement may be preserved. Although, ABF are not immune to dissolution or destruction, this depending on the species texture, morphology and maybe most dominantly, type of cement (Cronin et al., 2008).

In sediment samples where ABF are preserved, they can act as climate variability indicators. Even though they are more tolerant to environmental changes compared to the more evolutionary evolved calcareous species, they still depend on the primary production in the surface water and the flux of organic matter to the sea floor to survive (Hemleben et al., 1990). It is known by evidence that surface sediments with dominant abundance of ABF accumulate in seasonally ice free environments with high organic-flux to the sea floor and well oxygenated bottoms waters (Cronin et al., 2008). The glacial/interglacial shifts on the Arctic Ocean sea ice may therefore be reconstructed with the aid from sediment samples containing agglutinated benthic foraminifera.

3.0 MATERIALS AND METHODS:

3.1 Sampling sites:

The gravity core 29-GC1 and the multicore 29-MC4 were collected with a gravity corer and a multicoring device on board the research vessel ice breaker Oden during the SWERUS-C3 Leg 2 expedition, August-October 2014 (Jakobsson and Koshurnikov, 2014). The gravity core was collected at Latitude 81.299356 Longitude 141.782550, and the multicore at Latitude 81.1342771 Longitude 141.775463, both on the southern part of the Lomonosov ridge off the coast of Russia and the Siberian shelf (Figure 1). The gravity core was retrieved at 824 meters below current sea level. The core recovery was 78% having a total of 4.67 meter of sediments divided in four sections of 1.5 m. On board the research vessel, 60 samples (10cc) were collected from the four sections with either 8 cm or 3 cm spacing between each sample, out of these 60 samples, 13 had 3 cm spacing.

Core 29-GC1 appears red/brown in color with some sandy patches in section 3 and 4.In section four at 75 cm a centimeter wide crumbly terracotta red layer was observed and two thinner layers with the same appearance. The aggregated crumbly lumps of possibly clay did not disintegrate when washed trough a 63µm sieve. In section four at 122-167 cm a distinct gray layer is observed and displayed in Figure 3 (Gemery, 2014).

Figure 3 Photograph of core 29-GC1 with a centimeter scale bar on the far left and the four divided sample sections (Gemery, 2014).

3.2 Sample preparation and microfossil counting:

Fifteen of the samples were washed on board through a 63µm sieve using ship water and a final deionized water rinse and their fine fraction (<63µm) was washed away. These washed samples were weighed for the first time at Stockholm University and therefore these samples have a greater source of error due to sample handling.

Core 29-GC1 was brought back to Stockholm University together with the samples collected. The 45 remaining samples from core 29-GC1 were freeze dried for 72 hours in a Scanvac Coolsafe 55-4 freeze dryer at -55˚C. The dry bulk weight was recorded for all samples after freeze drying. All samples were then washed through a 63µm sieve with deionized water. The remaining coarse fraction was dried in the oven at 50˚C for at least five hours before the samples were weighed again and stored in glass vials. While sieving, the fine fraction was saved in plastic bags inside 1L beakers. After settling for at least 5 days, the excess water was siphoned off and the fine fraction was dried at 50°C in the oven. Finally, the weights from the fine fraction were recorded and the samples were stored in the plastic bags.

All 60 sand sized (>63µm) sediment samples were studied with a stereo microscope. Large samples were split using a micro splitter to allow a faster counting of microfossils on a picking tray. Many samples were not split at all and studied as whole samples. Others were split up to five times, and in this case the foraminifera counting were up-scaled. Foraminifera were counted on a picking tray strewn with sediment. Individuals were recorded as either agglutinated benthic foraminifera, calcareous benthic foraminifera or planktonic foraminifera. Individuals of all three microfossil groups were included in the counting process. These were not distinguished at species level. Only whole specimens were counted, fragments and broken specimens were excluded from the counting process. The illustrations (Figure 2 and Figure 4) were taken with a digital camera from Leica Microsystems DFC 295 together with the Leica Application Suite (LAS) version 3.6.0.

In order to further explore the controls on agglutinated foraminifera occurrence, ten whole specimens of agglutinated benthic foraminifera (ABF) were picked from a 250µm sieve from core 29-GC1, section 2, 135-137 cm. The composition of their tests cement was investigated by studying their reaction with a 10 % diluted hydrochloric acid (HCl). The acid was dripped onto the specimens with a pipette. If the cement had a calcium carbonate composition, then it should have started to dissolve under the influence of the HCl. However, the acid did not visually affect the tests with fizz or bubbles, this may in turn indicate a cement of another chemical origin.

3.3 Pore water analysis:

Pore water chemical analysis of core 29-GC1 and core 29-MC4 was conducted onboard IB Oden by Clint Miller (2014), the alkalinity value of both cores collected was recorded. Alkalinity refers to the ability of an aqueous solution to naturalize an acid. Sea water is slightly alkaline, but more acidic at depth. The carbonate buffering system help prevents larges fluctuations and allows the values to stay within a limited range. Cold water can dissolve more carbon dioxide than warm water, thus dense cold deep waters becomes more acidic. Organisms that build their shell out of calcium carbonate will dissolve below the carbonate compensation depth to buffer the system (Trujillo and Thurman, 2014).

The alkalinity values of the pore water in the cores collected are of interest for this study because no calcareous microfossil tests were observed below 14 cmbsf except for two specimens at 52 cm. This absence of calcareous species might reflect corrosive pore water chemistry.

3.4 Age model:

The age model was built using two tools: (1) absolute radiocarbon dating on foraminifera, which occur at a few horizons (2) and the down -core distribution of agglutinated foraminifera which provides a microfossil stratigraphy.

Core 29-GC1 had enough bulk sediment organic material (>5 mg of C) for radiocarbon dating at only the topmost sample (section 1, 0-2 cm). Therefore, radiocarbon analysis was conducted on calcareous material from multicore 29-MC4. Multicore 29-MC4 was recovered close to the location of 29-GC1 (Figure 1) and it contained enough calcareous microfossils to get three radiocarbon ages. The radiocarbon analyses were conducted by the Beta Analytic radiocarbon dating laboratory (London, UK). The material that was sent for dating comprised monospecific samples of the tests of the polar planktonic foraminifera species *Neogloboquadrina pachyderma* (Figure 4). From the intervals 0-1 cm, 4-5 cm and 6-7 cm, 10.756 mg, 9.388 mg and 9.239 mg of calcium carbonate tests were collected respectively. The tests were picked with a thin brush from the picking tray that was strewed with the sediment sample. The weights of the calcium carbonate tests were recorded on a microbalance and stored in glass vials before shipped off to the UK.

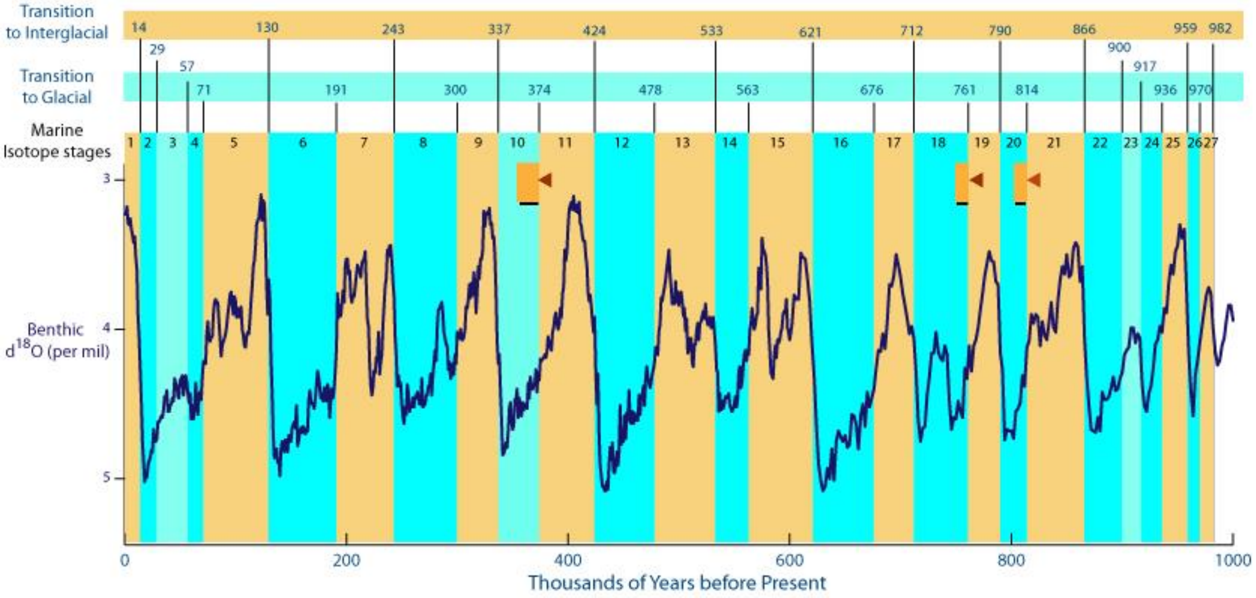
Figure 4 Microphotograph of the polar planktonic foraminifera specie *Neogloboquadrina pachyderma* used to obtain the radiocarbon dates in this study.

As described above, calcareous fossils were only present in the top most 7 cm of multicore 29-MC4. Therefore, another approach was used to complete the age model. This was attained trough the abundances of agglutinated benthic foraminifera. Presence of agglutinated foraminifera in the samples was interpreted as climatic indicators of interglacial periods (Cronin et al., 2008). The glacial/interglacial periods were given an age range based on the established marine isotope stages (MIS) reference system for recognizing Pleistocene glacial cycles as record by oxygen isotopes in benthic foraminifera. For this we refer to LR04 benthic stack developed by Lisiecki and Raymo (2005) (Figure 5).

The MIS represent altering warm and cold periods (interglacials/glacials) in Earth’s history. The paleotemperatures for these periods are derived from oxygen isotope analysis of marine microfossils. The test-building organisms incorporate the oxygen isotopes O^{18} and O^{16} present in the seawater when building their shells. The ratio of these two isotopes varies depending on the prevailing water temperature and ice volume. During glacials, the shells are rich in O^{18} since the O^{16} is locked up in glacial ice. This is explained by the fact that the lighter isotope O^{16} evaporates more readily and falls as precipitation, during colder periods as snow, which will accumulate to form glaciers.

We are currently living in an interglacial period, the Holocene, equivalent to MIS1. Odd numbers are represented in the MIS benthic stack as interglacial periods, and even number as glacial periods. The different periods have been given an age range in the stack, which is found to correlate to terrestrial evidence of glacial/interglacial periods (Rundic et al., 2013). MIS6 is believed to have been a major full glacial period with extremely large ice sheets and ice shelves and may be the source of ice grounding events (Jakobsson et al., 2010) MIS5 was the latest major interglacial period before the present Holocene (MIS1). MIS5 is divided into sub stages, were *b* and *d* are colder sub stages and *a*,*c* and *e* are warmer sub stages. MIS3 was a warmer period in between two glacials, but MIS3 is reckoned not to have been as warm as MIS5 and MIS1.

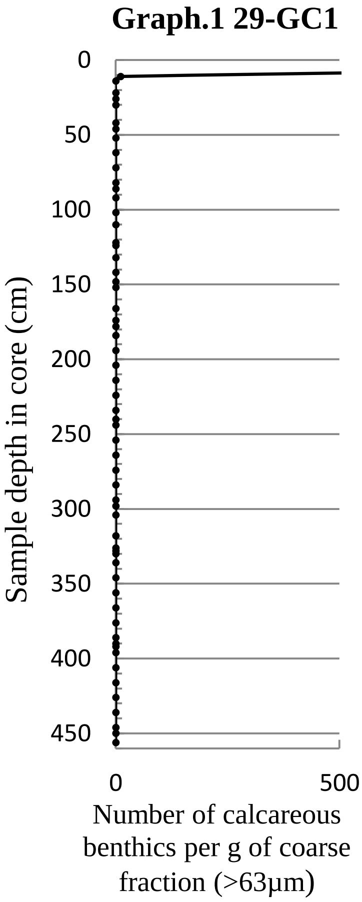
Figure 5 The marine isotope stages, LR04 benthic stack, made by Lisiecki and Raymo (2005).

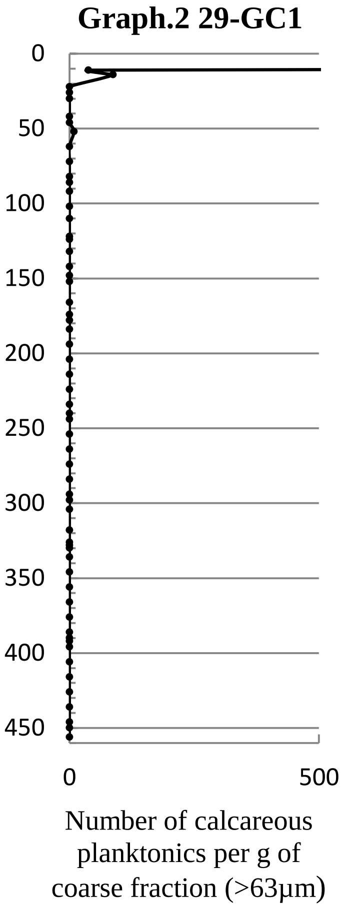


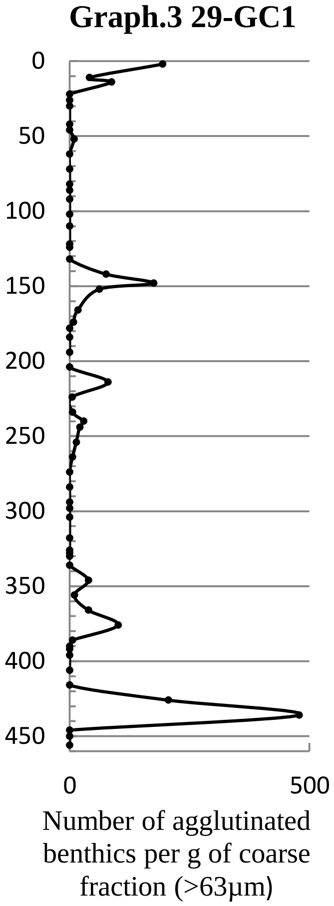
4.0 RESULTS:

4.1 Microfossil distribution:

Calcareous benthic foraminifera were only abundant in sample section 1, 0-2 cm. In sample section 1, 9-11 centimeters the calcareous benthic foraminifera were rare. After this section all other samples were barren of calcareous benthic species (Graph 1). Calcareous planktonic tests were very abundant in sample section 1, 0-2 cm and abundant down to 14 cmbsf. Only 2 specimens were found below this core depth, both at 52 cmbsf (Graph 2). Agglutinated benthic foraminifera were found to be more abundant down core than in the top layer. The peak in abundance in between 426-436 cmbsf proven to be agglutinated tube shaped foraminifera. This peak is protruding above the gray layer that has tentatively been assigned an age of MIS6. The peak in agglutinated foraminifera above the MIS6 layer might represent the marine isotope sub stage MIS5e (Graph 3).



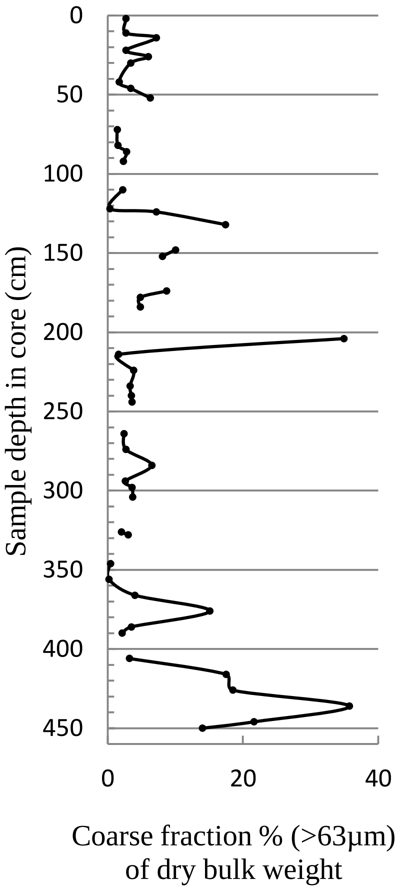




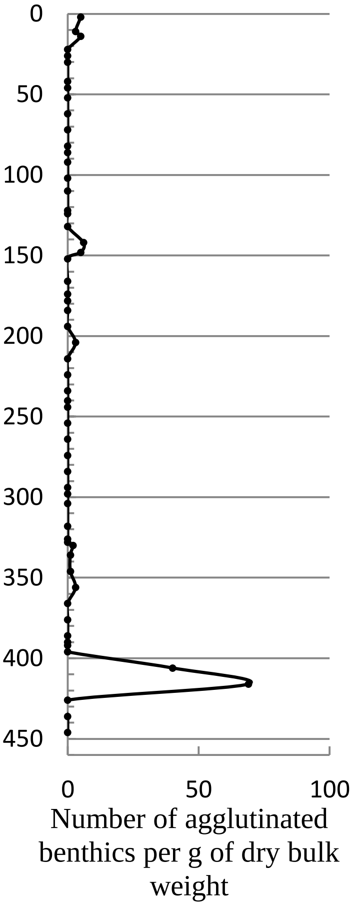
4.2 Coarse fraction and bulk weight:

The dry bulk weights and the coarse fraction weights (>63µm) were recorded in nearly all samples. The coarse fraction weight percentage may vary between samples. This due to reasons such as higher or lower amounts of coarse grained material, such as ice rafted debris or large specimens of foraminifera. In this study, sample section 4, 80-82 cm and sample section 4, 50-52 cm both contained larger clasts, the largest ones observed were both approximately 8 mm in diameter. These clasts were visually much larger than all other clasts in the samples. Sample section 4, 50-52 cm also contained agglutinated foraminifera. Sample section 4, 110-112 cm and 120-122 cm both contained high numbers of agglutinated tube shaped foraminifera and the coarse fraction percentage for sample section 4, 120-122 cm reached almost 35%. Graph 4 displays the coarse fraction (>63µm) percentage of the dry bulk weight. A few data points are missing in the graph, these come from the ship processed samples where the fine fraction was washed away. The recorded number of agglutinated benthic foraminifera standardized to one gram of dry bulk weight is displayed in Graph 5.

Graph.4 29-GC1



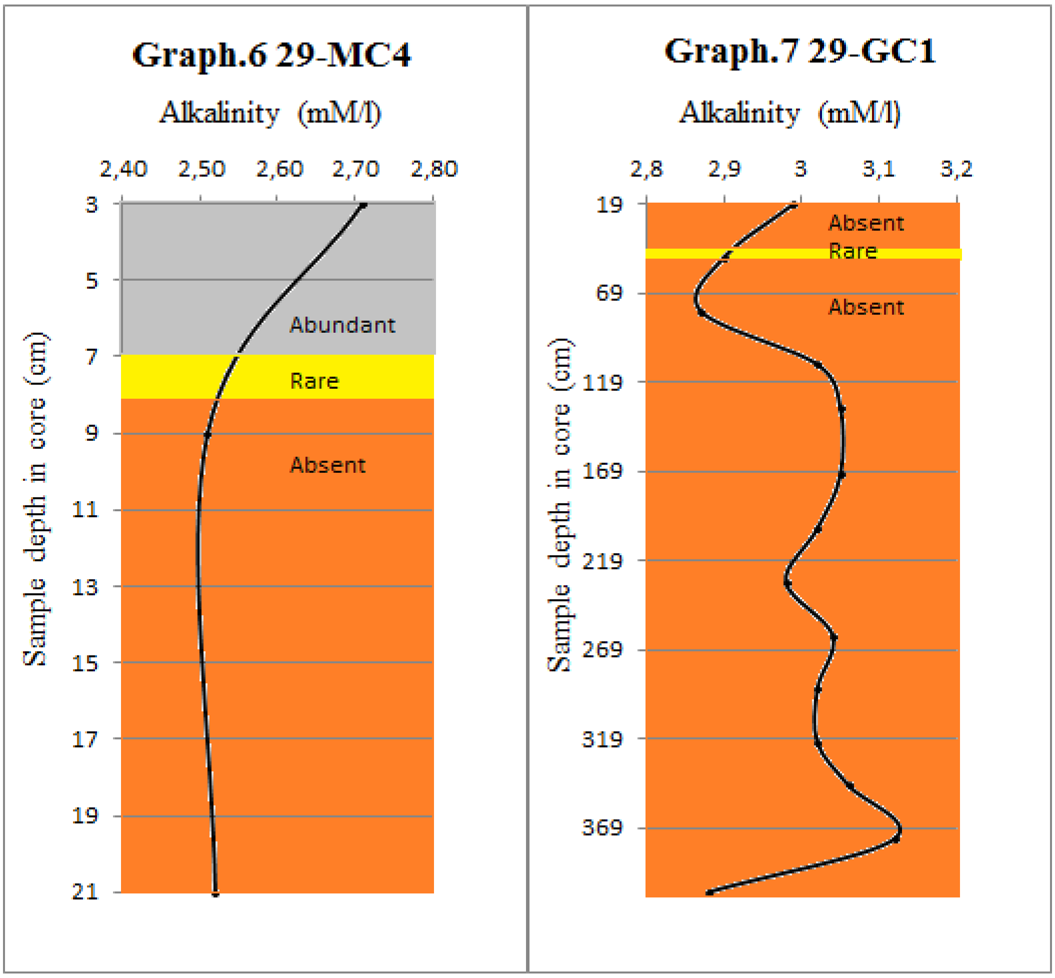
Graph.5 29-GC1



4.3 Pore water

In multicore 29-MC4 the alkalinity value peaks at 3 cmbsf reaching 2,71 mM/L and then drops to 2,51 mM/L at 9 cmbsf. Below 8 cmbsf no calcareous tests were found in the multicore and this may indicate a pore water chemistry that is corrosive to calcium carbonate (Graph 6). In gravity core 29-GC1, calcareous foraminifera were observed to be abundant down to 14 cmbsf, below this depth only 2 specimens of calcareous planktonic foraminifera were found at 52 cmbsf and below this depth all the samples were barren of calcareous tests. In the pore water analysis conducted the alkalinity is slightly higher down core and the lowest value obtained is 2,87 mM/L at 79 cmbsf (Graph 7).

Graph 6&7 Alkalinity values in core 29-MC4 and core 29-GC1.



4.4 Radiocarbon absolute dating:

Table.1 Radiocarbon dates based on *N.pahcyderma*.

Sample source	Sample Weight (mg)	δ ^{13}C (‰)	Radiocarbon Age (BP)
29-MC4, 0-1 cm	10.756	-0.5	1080 ± 30
29-MC4, 4-5 cm	9.388	-0.9	2440 ± 30
29-MC4, 6-7 cm	9.239	+0.2	2700 ± 30

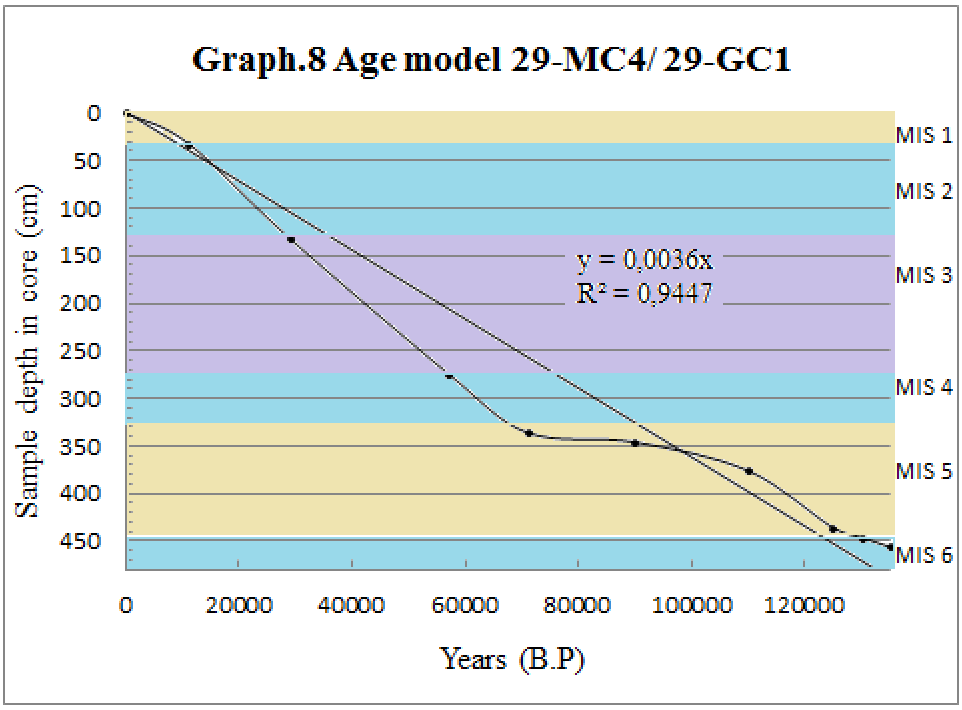
The radiocarbon age is corrected for the isotopic fractionation between the stable isotopes ^{13}C and ^{12}C (Table 1). The radiocarbon age is also automatically adjusted for the global marine reservoir effect (R) by the Beta Analytic radiocarbon dating laboratory (London, UK). The R varies through time and it is adjusted depending on the age of the carbonate sample based on the MARINE13 ^{14}C curve (Stuvier et al., 2014). This is due to the fact that it takes several hundred years for the carbon dioxide in the atmosphere today to be equilibrated throughout the ocean water column. Furthermore, the ^{14}C exchange will depend on the mixing capabilities of the water column. The modern R is approximately 400 years, but this can vary even for closely related geographical locations. The radiocarbon age obtained also needs to be corrected for the local marine reservoir effect (ΔR). The ΔR is depending on the complexities in the ocean circulation. The local marine reservoir effect in the Arctic Ocean is not yet entirely known. In this study a value of 300 years was used.

The calibrated age was computed by using the CALIB radiocarbon calibration program Calib 7.1 and the database MARINE13 (Stuvier.et al 2014). Prior to the calibration the radiocarbon age was adjusted for ΔR using the local Arctic Ocean value of 300 years (Table 2).

Table 2 Calibrated median ages and age ranges from Calib 7.1 (Stuvier.et al 2014).

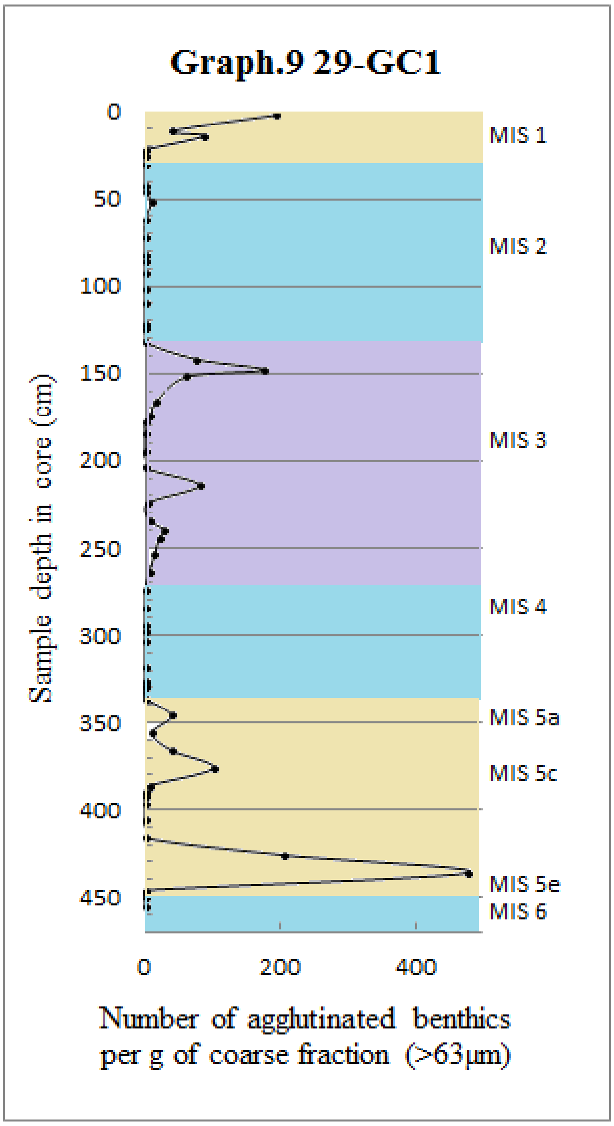
Sample source	Calibrated median age (B.P)	Calibrated age range (1σ) (B.P)	Calibrated age range (2σ) (B.P)
29-MC4, 0-1 cm	428	396-472	326-486
29-MC4, 4-5 cm	1731	1687-1784	1621-1880
29-MC4, 6-7 cm	2033	1985-2084	1936-2125

4.5 Age model:



Graph 8 Age model based on absolute radiocarbon dates and agglutinated foraminifera assemblages.

Based on the calibrated radiocarbon median age (Table 2) a linear sedimentation rate of an approximate average value of 2.9 cm/kyr was assumed for all of the Holocene. Since no calcareous biostratigraphic markers were found down core, the age model after the Holocene is based on the peaks of the counted ABF assemblages. Based on the hypothesis presented in this study, the accumulation of ABF is assumed to correspond to interglacial periods. The first data point in the age model (Graph 8) represents a quantitative age obtained from the three radiocarbon ages in the collected multicore 29-MC4 (Table 2). The rest of the data points are based qualitatively on the agglutinated foraminifera counting in the collected gravity core 29-GC1 (Graph 9). The peaks in the accumulation of the agglutinated foraminifera were given an age range from the LR04 Benthic stack made by Lisiecki and Raymo (2005) (Figure 5). Based on the model presented, the sedimentation rate after the Holocene is approximately 5 cm/kyr until the beginning of MIS5. During the MIS5 the sedimentation rate is slower, reaching an average rate of 1.8 cm/kyr. The assumption has been made that there has been no break in the sedimentation and that no MIS stages are missing (Graph 8&9).



Graph 9 Marine isotope stages applied to the number of agglutinated foraminifera per gram of coarse fraction (>63µm).

5.0 DISCUSSION:

The foraminifera distribution in core 29-GC1 consists of sections abundant in ABF in certain layers down core, and only calcareous species in the top most centimeters. Perhaps the main factor that is reckoned to control the distribution of ABF is food availability, depending on primary production in the surface waters and the flux of organic material to the ocean floor. The possibility to find food for benthic foraminifera is higher during interglacial periods when the sea ice cover is lacking and benthic species can thrive. The primary productivity and food availability will be low when the surface of the ocean is covered in ice, or when a lot of drifting ice restrains the presence of Arctic Ocean biota (Polyak and Jakobsson, 2011). The agglutinated species do give an indication about ice free waters above, but this could occur in deglacial periods as well as a full interglacial period. One sample in this study contained a large clast (8 mm) of ice rafted debris together with abundant agglutinated species, indicating deposition during a deglacial period. The agglutinated foraminifera are known to be more tolerant to environmental extremes and environmental changes than the more evolutionary advanced calcareous species (Hemleben et al., 1990). However, it is hard to conclude if previous environmental conditions have been totally unfavorable for calcareous species.

Agglutinated species ability to resist destruction and dissolution during burial after death controls the vertical distribution of agglutinated foraminifera in ocean sediment (Schröder, 1988). Where pore water chemistry dissolves calcium carbonate, agglutinated species with calcitic cement will be destroyed. Species test texture and morphology also controls the vertical distribution and more residual fauna will be dominant in the geological record. The indication of organic cement instead of calcite cement in all of the ABF tested with HCL in this study agrees with the theory of corrosive pore water chemistry in parts of the Arctic Ocean (Cronin et al., 2008 Kender and Kaminski, 2013). Organic material is often permineralized and preserved as silica during the state of early diagenesis (Hemleben et al., 1990). Kender and Kaminski (2013) argue that sections of well-preserved and diverse agglutinated specimens coincide with elevated concentrations of biogenic silica in the sediments pore water. The authors also states the opposite, that sections with low preservation and abundance of ABF is related to lower concentrations of biogenic silica in the observed pore water. In the Arctic Ocean coring expedition (ACEX) record, described by O´Regan et al. (2008) pore water geochemical profiles shows a peak in alkalinity at 4 mbsf reaching 2,7 to 3,0 mM before dropping to less than 2,5 mM at 15 mbsf. In the ACEX record zones barren of calcareous tests and zones with only few and poorly preserved specimens were observed down core, the authors presents the possibility of pore water dissolution of calcareous tests (O´Regan et al., 2008). The observation regarding alkalinity values is similar to the observations made in this study.

Certain limitations arises when working with agglutinated foraminifera, quantitative measurements such as radiocarbon dates, cannot be conducted due to the restricted amount of organic material in the agglutinated tests. The agglutinated fauna can however act as indicators of warmer periods and give certain guidelines in the work performed. Work conducted by Cronin et al. (2008) shows results similar to the observations made in this study. The result gained from ACEX core 4C recoverd from the central Lomonosov ridge shows only abundant numbers in calcareous microfossils in the uppermost sediment interval. Agglutinated foraminifera down core are occurring sporadically but often in large numbers. These intermittent intervals are thought to be connected to interglacial and deglacial periods (Cronin et al., 2008).

Sections down core containing ABF were in this study used as indicators of interglacial periods in the geological record. The ability to use ABF as indicative markers for warmer periods in Earth´s history was helpful for the development of the age model in this study, in the way that sedimentation rates became more realistic. If the sedimentation rate were to be based only on the radiocarbon age, a linear sedimentation rate had to be assumed for all sections past the Holocene. The age model does however contain certain weaknesses; it is hard to estimate a correct sedimentation rate from the abundance of agglutinated foraminifera. As mentioned earlier, the preserved agglutinated species might reflect on deglacial as well as full interglacial periods.

The assumption that there has been no break in the sedimentation and that the end of MIS6 is reached at the base of 29-GC1 is based on the peaks of the agglutinated assemblages and the correlation between core 29-GC1 and two cores collected by the Polarstern cruise in 1995 (core PS-2757 and PS-2760). The physical properties of these three cores have been correlated and all three cores display the distinct gray layer that has tentatively been assigned an age of MIS6 (Jakobsson et al., *manuscript in preparation*).

5.1 CONCLUSIONS:

Although little scientific effort over the past has been given to the species of agglutinated benthic foraminifera, their significance in this study cannot be ignored. In the absence of calcareous tests, the agglutinated foraminifera are the major clues to the deciphering of the Arctic Oceans glacial history. The conclusion that abundance in agglutinated foraminifera reflects food availability and, thus, that they cannot thrive underneath large ice sheets, makes them important stratigraphic markers in the geological record. The agglutinated species can in this way act as climatic indicators for warmer periods in Earth´s history.

Directions for future studies would be to refine and develop paleoenvironmental proxies based on agglutinated benthic foraminifera as biostratigraphic markers.

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