

Foraminiferal assemblage changes over the last 15,000 years on the Mackenzie-Beaufort Sea Slope and Amundsen Gulf, Canada: Implications for past sea ice conditions

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[1] Two cores, one from the Beaufort Sea Slope at 1000 m water depth (core 750) and one from the Amundsen Gulf at 426 m (core 124), were collected to help determine paleo-ice cover in the Holocene and late glacial of this area. Site 750 is particularly sensitive to changes in paleo-ice cover because it rests beneath the present ice margin of the permanent Arctic ice pack. Core 124 was sampled just in front of the former glacier that moved out into the Amundsen Gulf and started to recede about 13 ka B.P. Both cores have a strong occurrence of calcareous foraminifera in the upper few centimeters, but these disappear throughout most of the Holocene, suggesting more open water in that time period than present. In the sediments representing the end of the last glacial period (dated at ~11,500–14,000 calibrated years B.P. (cal B.P.)) a calcareous fauna with an abundant planktic foraminiferal fauna suggests a return to almost permanent ice cover, much like the central Arctic today. Together with the foraminifera there was also abundant ice-rafted debris (IRD) in both cores between 12,000 cal B.P. and ~14,000 cal B.P., but those units are of different ages between cores, suggesting different events. The IRD in both cores appears to have the same magnetic and chemical signals, but their origins cannot be determined exactly until clay mineralogy is completed. There is abundant organic debris in both cores below the IRD units: the organics in core 750 are very diffuse and not visually identifiable, but the organic material in core 124 is clearly identifiable with terrestrial root fragments; these are ¹⁴C dated at over 37,000 years B.P. This is a marine unit as it also has glacial front foraminifera in the sediment with the organic debris that must have been originating from subglacial streams. The seismic and multibeam data both indicate glaciers did not cross the core 124 site.

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1. Introduction

[2] Paleoceanography in the Beaufort Sea part of the Canadian Arctic has not been carried out since the late 1960s and early 1970s when the first sustained effort was made to sample the Beaufort Shelf and Slope as well as many of the Arctic channels [Vilks, 1969, 1989; Iqbal, 1973]. Some early work was done in the deep sea Arctic as part of the United States T-3 ice island project and ice stations LOREX, FRAM and CESAR (summarized in the work by Scott and Vilks [1991]) however the deep sea areas have extremely slow sedimentation rates (1 cm/10,000 years [Scott et al., 1989a]). These areas cannot provide the high-resolution records required to determine what conditions were in the last few centuries or decades in relation to the projected global warming. The initiation of two large international projects (CASES{Canadian Arctic Shelf Ex-

change Study} and ArcticNet) led by Canadian scientists aboard several research vessels, most notably the dedicated, scientifically outfitted icebreaker, *CCGS Amundsen*, has begun to fill the 30 year gap in knowledge. The data presented here are the first to present extended radiocarbon dated sequences from the Beaufort Slope and Amundsen Gulf that provide records of the end of the last glaciation (locations are in Figures 1 and 2). The corresponding surface foraminiferal distribution data [Scott et al., 2008a] and several papers by previous workers provide the means to interpret changing foraminiferal assemblages at the two core sites at intervals that span the Holocene and into the end of the last glaciation.

[3] Present-day water properties are extremely variable on the Beaufort Shelf with ice cover in the winter, opening in June–July and freezing over in October/November. The perennial sea ice margin fluctuates more or less at the core 750 site (Figure 1) but it has been changing rapidly within the short time since 2004 so that the summer margin is now farther out judging from recent satellite photos. Toward the end of June and the beginning of August 2004 all the sea ice disappeared off the Beaufort Shelf and also out of Amundsen Gulf to the position of line 100 (Figure 1). However, ice in the Gulf started forming as soon as the 24 h daylight was fading. The year 2006 was the first year in the CASES time

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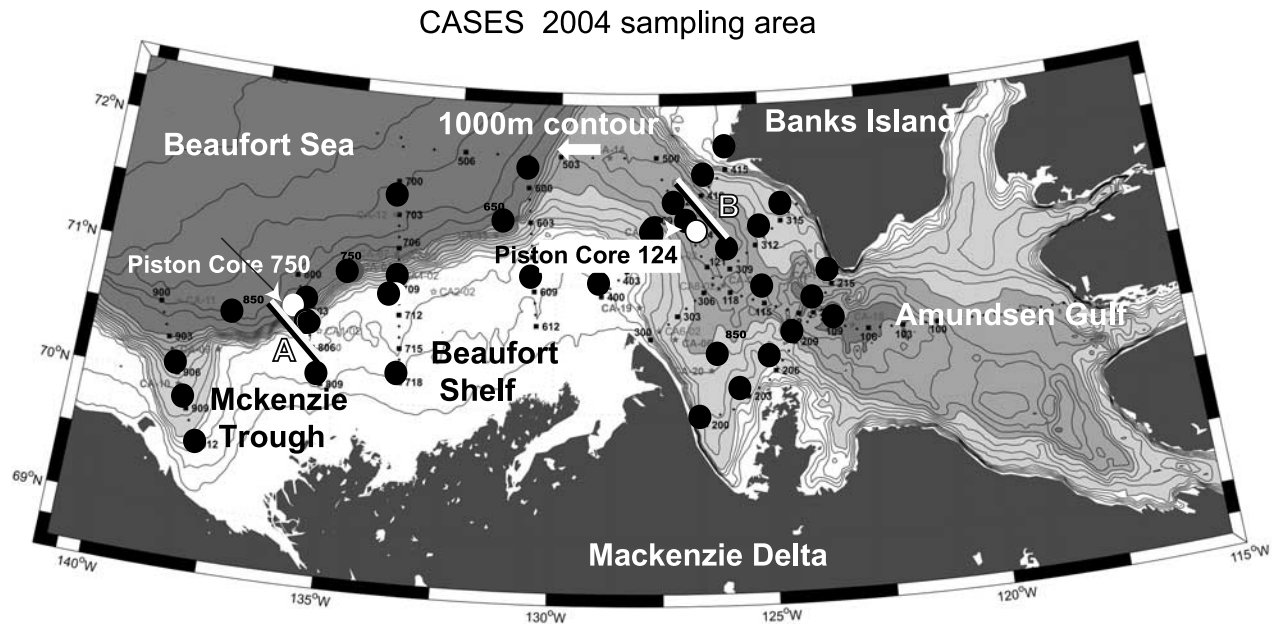


Figure 1. Areal map of the CASES field area with depth and station locations. Black circles are box core locations. Line A corresponds to the seismic line for core 750; line B corresponds to the seismic line for core 124 (both are shown in Figure 2). White arrow below “1000 m contour” has the arrow point on the actual 1000 m contour (after *Scott et al.* [2008b], with permission from Aboriginal Issues Press).

frame (since 2002) that M’Clure Strait (the major opening of the NW Passage) was ice free. It does not appear [*Iqbal*, 1973] that it was open even in 1970 when the Arctic ice pack was at least 50 km farther out than in 2004.

[4] The salinities are highly variable depending on wind direction, which can blow the Mackenzie River plume from the river either east or west although the dominant seems to be to the east. In the winter the salinity and temperature are uniformly higher and colder respectively. In our measurements taken coincidentally with the benthic sampling, the thermocline and halocline were usually about 20–30 m below the surface and transmissometer readings were much higher on the shelf. Salinities above the halocline were often below 30‰ and temperatures varied from 2 to 10°C while below the halocline salinities were uniformly 34.5‰ and temperature was –2°C. This is probably the case as well throughout most of the Holocene but probably much less when the area was perennially ice covered during glacial and early postglacial times.

[5] In the Amundsen Gulf, where there is less influence from the river, salinities are generally higher and suspended particles are much less of a factor.

2. Previous Work

[6] *Cushman* [1948] and *Loeblich and Tappan* [1953] established the taxonomy for many of the species discussed by later authors. *Phleger* [1952] was the first to examine the surficial distributions of Arctic shelf foraminiferal species. His work showed that many of the species that presently live on Canadian Arctic shelves are noncalcareous because

of the lowered salinities and extreme cold water. Several studies followed *Phleger’s* work into the Arctic Archipelago [*Carsola*, 1952; *Iqbal*, 1973; *Marlowe and Vilks*, 1963; *Vilks*, 1969, 1976]. However, *Vilks* [1989] provided the first comprehensive investigation of Beaufort Shelf benthic foraminifera resulting from the circum Americas cruise of the *CCGS Hudson* in 1969–1970 which sampled many of the same stations as were sampled again in 2004 [*Scott et al.*, 2008a]. *Green* [1960] and *Lagoe* [1977, 1979] established much of what we know about the deep water Arctic species from data collected from the T-3 ice island occupied by an international group of scientists for several years [*Clark et al.*, 1980]. These studies were added to by examination of material from the ice stations in the central Arctic (LOREX, FRAM, CESAR, and other sites [*Markussen et al.*, 1985; *Scott and Vilks*, 1991; *Bergsten*, 1994; *Wollenburg and Kuhnt*, 2000]). *Osterman et al.* [1999] repeated some of the surface stations of previous studies and added new ones in the western Arctic. *Polyak et al.* [2002, 2004] examined recent material from the Siberian Shelf, which provided a useful comparison to the Beaufort Shelf. *Scott et al.* [1989a] provided the first detailed paleoclimatic and stratigraphic record from the central Arctic from the collection of cores from the Alpha Ridge but these cores only provide a broad framework with a low resolution of 10,000 years per centimeter. Other paleoceanographic work from other parts of the Arctic will also be discussed [*Jennings et al.*, 2002; *Poore et al.*, 1994; *Wollenburg and Kuhnt*, 2000; *Wollenburg et al.*, 2001, 2004].

[7] In terms of techniques for detecting presence/absence of sea ice several recent papers have used various microfossil

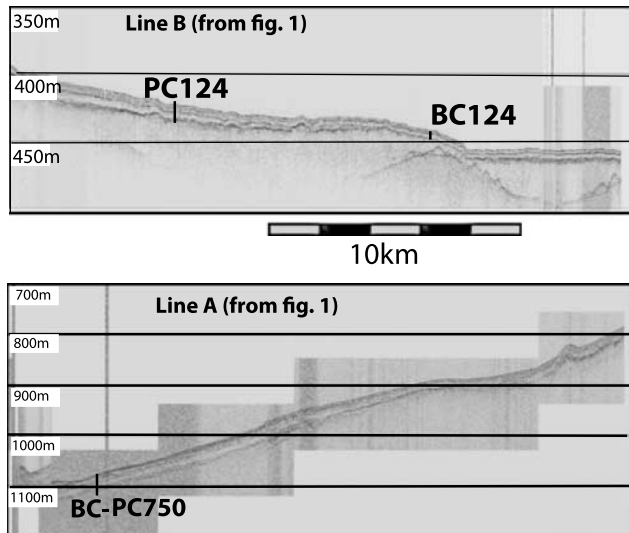


Figure 2. Seismic profiles of core sites 750 and 124. A 3.5 kHz subbottom profiler was used for profiling. Image provided and enhanced during Leg 8, CASES, June 2004 by Jason Bartlett, Canadian Hydrographic Service. BC 124 is also shown for comparison; it is in a different water depth and setting which turned out not to be comparable with the PC 124 site.

proxies for paleo-ice conditions, in particular *Wollenburg and Kuhnt* [2000] and *Wollenburg et al.* [2001, 2004], discuss how seasonal versus perennial ice can be detected using foraminiferal proxies which are similar to what is used in this paper. In those papers they suggest that when calcareous species decrease in the sediments, it indicates higher productivity. The increased organic matter from the surface productivity introduced to the seafloor destabilizes the carbonate tests because the increased biological degradation of the organic matter reduces the sediment pH levels. Other proxies have also been used such as chlorophycean algae from river runoff (i.e., less sea ice if there is much runoff [*Matthiessen et al.*, 2000]), multiproxy data from a thermokarst lake on Richards Island in the Beaufort Sea using a series of proxies (pollen, dinoflagellates, foraminifera, thecamoebians and geochemistry [*Solomon et al.*, 2000]), and in the eastern Arctic using dinoflagellates for paleo-sea ice conditions (some dinoflagellates do better with sea ice than others [*Mudie et al.*, 2005]). Perhaps most closely tied to this paper is one by *Mudie et al.* [2006] which looked at a multiproxy record of cores from Jones Sound in the eastern Arctic also to examine the ice history. In present work planktic/benthic foraminiferal ratios (higher ratio means less sea ice), presence/absence of calcareous material (presence of more carbonate means more sea ice) and abundance of tintinnids (unicellular ciliates that live in the surface water and prefer brackish water, little or no sea ice) are used as ice cover proxies. In an accompanying paper A. Rochon et al. (Multi-proxy record of Holocene climatic changes in the eastern Canadian Arctic: Preliminary results,

paper presented at Annual Scientific Meeting, ArcticNet, Banff, AB, Canada, 2005) discuss the palynology of these cores.

3. Methods

3.1. Collection of Cores

[8] Piston cores were collected using a Benthos[®] piston corer with a 9 m barrel and core liner inside diameter of 96 mm. We did not obtain cores longer than 7 m but that was sufficient to capture the Holocene/glacial boundary in these cases. Box cores were collected coincidentally with the piston cores except in the case of PC 124 where the box core was collected in June 2004 and the piston core was not collected until August 2004 (Table 1). This resulted in those two cores not being collected in the same position as can be observed in Figure 2 and Table 1.

3.2. Foraminiferal Preparations

[9] The methods described here are particularly important in Arctic foraminiferal studies because of different size fractions used by various authors and particular sediment treatments. Accompanying box cores were also collected at each core site to assure that the true surface was recovered; positions, core lengths, core type, water depth and date collected are contained in Table 1.

[10] Ten cm³ samples taken at 10 cm intervals were sieved through 63 μm sieves to retain the larger foraminifera. Forty five μm sieves were used to retain the smaller size fraction which allowed information from the smaller fraction that had been previously overlooked to be included in the reconstructions. Another technique used was keeping the samples in liquid suspension since many of the smaller and fragile species are extremely difficult to examine when dried. In samples that contained large numbers of specimens, a wet splitter was used to divide the sample into equal aliquots of 300–500 specimens [*Scott and Hermelin*, 1993].

[11] Komokiacea, rare in the surface material and usually observed in organic rich sediments [*Scott et al.*, 2008c], were found pyritized in box core 750 (Figure 3). These specimens are thought to be preserved in organic-rich environments causing reducing conditions leading to pyritization of the tests (Figure 3).

3.3. X-Ray Photography

[12] X rays were taken on the Dalhousie X-ray unit using mammography film with 5–20 s exposure depending on sediment density. Some of these are reproduced here in digital form (Figures 7 and 8).

3.4. Sedimentological Analyses

[13] Sediment analyses were carried out at ISMER on piston cores 124 and 750 at 10 cm intervals (Figure 4). Prior to grain size analyses, the samples were added to a Calgon electrolytic solution (sodium hexametaphosphate) and rotated for about 3 h using an in-house rotator. The samples were then sieved over the instrument (2 mm) and disaggregated in an ultrasonic bath for 90 s prior to their analysis. Disaggregated samples were then analyzed with a Beckman-

Table 1. Positions, Dates, Water Depths, and Core Type Collected for Cores Discussed in This Paper

Date	Core Type	Latitude	Longitude	WD ^a	Core Length
9 Jul 2004	BC 750	71.20°N	134.08°W	1087 m	30 cm
9 Jul 2004	PC 750	71.20°N	134.06°W	1087 m	586 cm
28 Jul 2004	BC 124	71.23°N	126.43°W	442 m	38 cm
8 Aug 2004	PC 124	71.24°N	126.46°W	426 m	750 cm

^aWD, water depth.

Coulter LS-13320 (0.04–2000 μm) laser sizer. The results of three runs were averaged. The average continuous disaggregated particle size distribution output was then processed using the Gradistat software for sediment parameters [Blott and Pye, 2001].

3.5. Geochemical and Isotopic Analyses

[14] Bulk sediment was dried, ground and analyzed for its total carbon (C_{tot}) and nitrogen (N_{tot}) content using a Carlo-Erba elemental analyzer, whereas the inorganic carbon content was determined on aliquots using a UIC coulometer at the GEOTOP research center. The organic carbon content (C_{org}) was obtained by calculating the difference between C_{tot} and C_{inorg} . In addition, aliquots were acidified twice with HCl to dissolve the carbonates, and then washed, dried and loaded on the carousel of a Carlo-Erba elemental analyzer in line with a Micromass IsoPrime mass spectrometer at the GEOTOP research center, and then run for ^{13}C content. The isotopic data are reported in δ values (‰) with reference to VPDB [Coplen, 1995] following the usual corrections [e.g., Craig, 1957].

3.6. Magnetic Properties

[15] Low-field volumetric magnetic susceptibility (k) was measured on u channel samples (rigid u-shaped plastic liners with a square 2-cm cross section and a length of 1.5 m) using the magnetic susceptibility track at the University of Florida [Thomas et al., 2003] at 1 cm intervals on cores 750 and 124 (Figure 5). Low-field volumetric magnetic susceptibility primarily reflects changes in the concentration of ferrimagnetic minerals such as magnetite, but is also influenced by large magnetite grains [e.g., Stoner et al., 1996; Stoner and St-Onge, 2007]. In addition, an anhysteretic remanent magnetization (ARM) was produced using a 100 mT peak alternating field and a 50 μT direct current biasing field and subsequently measured at the University of Florida, using a 2 G Enterprises Model 755 cryogenic magnetometer, at 1 cm intervals. However, the width at half height of the response function of the magnetometer pickup coils is ~ 4.5 cm [Weeks et al., 1993], so that smoothing occurs. Edge effects caused by this smoothing at core breaks were cut from the final data. ARM is primarily responding to changes in the concentration of ferrimagnetic minerals, but is also strongly grain-size-dependent, being particularly influenced by magnetite grain sizes < 10 μm [e.g., Stoner et al., 1996; Stoner and St-Onge, 2007].

3.7. Chronological Control in the Cores

[16] In the box core 750 we were fortunate to have some short-term dating provided by ^{210}Pb dating from D. Amiel and K. Cochran (personal communication, 2004) (Figure 6). These data indicate that the upper 13 cm accumulated in the

last 100 years on the basis of the decay rate of ^{210}Pb that indicates all the ^{210}Pb isotopes were disintegrated at 13 cm (5 half lives of ^{210}Pb) in box core 750 although the Cs signal extended to the same level which would suggest an age of AD1960 (the “bomb” signal) which means the 13 cm level could actually be younger than 100 years. The 100 year level in core 117 is less well defined because the ^{210}Pb is dispersed unevenly downcore by bioturbation, but the lack of ^{137}Cs below the 5 cm level indicates that level to be at least 50 years old (the “bomb” signal), suggesting a slower sedimentation rate than the core 750 site.

[17] For longer time scales we used radiocarbon dating with calcareous foraminifera as the source for the carbon-14. The dates were calibrated with CALIB 5.0.2 [Stuiver et al., 2005] online calibration software [Hughen et al., 2004] data set and assuming an δR value of 410 ± 50 years (corresponding to a reservoir age of $860 \text{ years} \pm 45 \text{ years}$). This δR value was estimated with the rounded average of the 5 dates obtained on preindustrial mollusc shells collected alive close to the Amundsen Gulf [McNeely et al., 2006]. The first and last ages represent the 2σ cal age range, whereas the ages in parentheses are the average age

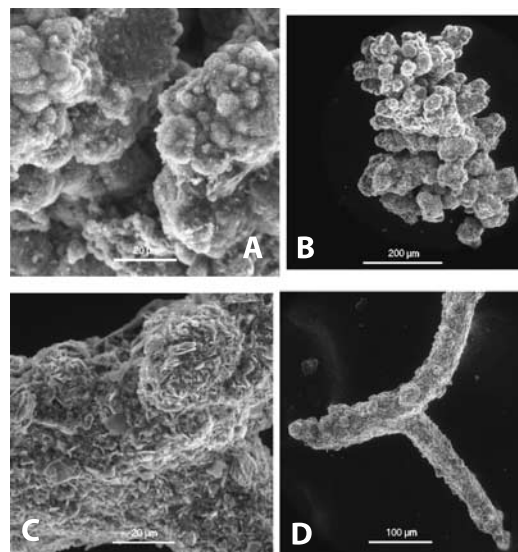


Figure 3. (a, b) *Cerebrum c.f. coralliformis* Schröder et al. [1989]. Figure 3a is blowup of wall structure; Figure 3b is view of whole specimen. These are pyritized, so it is difficult to know what we do not see. (c, d) *Rhizammina algaeformis* Brady [1879]. Figure 3c is close-up of test structure; Figure 3d is whole specimen. Scale bars are all in microns. Although it does not show in the SEM photos these specimens were pyrite-covered black specimens.

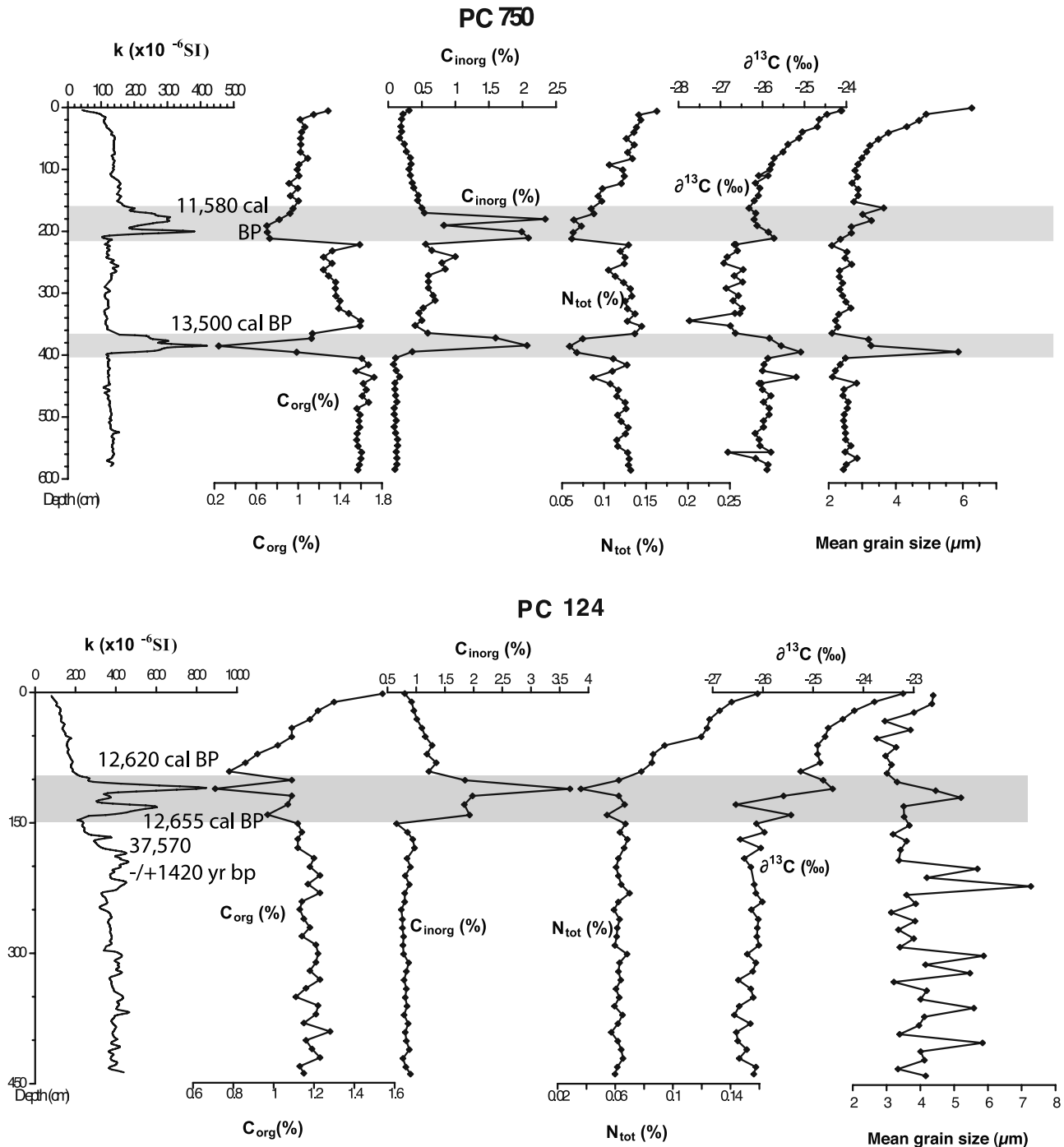


Figure 4. Low-field volumetric magnetic susceptibility (k), mean grain size, percent organic and inorganic carbon, N (nitrogen percent), $\delta^{13}C$, and sediment sorting of piston cores 750 and 124 [after Scott et al., 2008b]. The shaded areas highlight zones of poorly sorted coarser sediments that are the IRD zones discussed in this paper (see text for details); examples of the IRD are in Figure 7 X rays. Carbon-14 dates are indicated at the appropriate intervals.

(Table 2). Foraminifera were mixed which means both planktics and benthics were combined to obtain dates.

[18] The sedimentology (Figures 4 and 5) for these two cores suggest that the upper IRD unit in 750 is coincident

with both the IRD units in core 124 however the dates for the IRD of core 124 fit between the IRD units of core 750 suggesting other sources for the IRD units in core 750.

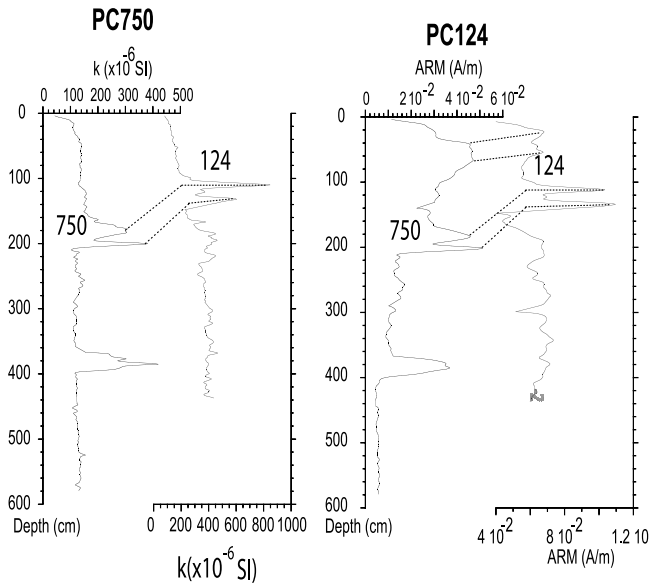


Figure 5. Comparison of (left) low-field volumetric magnetic susceptibility (k) and (right) anhysteretic remanent magnetization (ARM) of cores 750 and 124. Dotted lines indicate correlative features (after Scott *et al.* [2008b], with permission from Aboriginal Issues Press).

However, until the clay mineralogy is completed for both cores it is difficult to determine the provenance for these units.

4. Results

4.1. Sediment Properties for Cores in This Study

4.1.1. Piston and Box Core 750

[19] These cores were near the middle point of the slope between the Mackenzie Trough and the Amundsen Gulf (Figures 1, 2, 7, 8, 9, and 10). Sedimentation rates on the slope are relatively high: $^{210}\text{Pb}/^{137}\text{Cs}$ indicates 10–15 cm of sedimentation in the last 100 years, including core 750 in 1000 m of water (Figure 6). X rays and photographs of the piston and box core 750 show varying lithology and color changes, especially in the upper 30 cm and in the zone of IRD at 140 cm and 380 cm core depth (Figures 7 and 8). Increased inputs of coarser sediments are indicated by magnetic susceptibility and grain size measurements at the base and upper part of the IRD zone. In these two intervals, higher values of magnetic susceptibility are mirrored by an increase in the average grain size and by higher sorting values, indicating inputs of poorly sorted and coarser sediments such as IRD. Indeed, the discrete intervals of IRD observed on the X rays at 180 and 200 cm are also observed in the continuous magnetic susceptibility profile and reflect its two-peak structure. Similarly, the higher magnetic susceptibility, grain size and sorting values around 380 cm also match the first appearance of IRD on the X rays. The box core indicates that probably the top 3 cm was lost off the top of the piston core. Two radiocarbon dates were obtained for PC 750 (Table 1): one at 180 cm (11,297 calibrated years B.P. (cal B.P.)) and one at 380 cm (13,286 cal B.P.). The $^{210}\text{Pb}/^{137}\text{Cs}$ data suggest a very rapid sedimentation rate in

the last 100 years (15 cm/100 years) versus the time period from 100 years to 12,000 cal B.P. (1 cm/100 years). The seismic profile (Figure 2) does not suggest any slump but this was relatively low-resolution 3.5 kHz data. Between 12,000 and 14,000 cal B.P. the sedimentation rate is 12 cm/100 years, comparable with the upper 15 cm, probably as a result of the addition of IRD in that time frame. In the sediments below the IRD there are few microfossils but there are relatively high amounts of organic material that appear to be terrestrially derived and degraded badly. It is impossible to obtain a reliable age for these sediments because we do not know how much is reworked material from a much older time period (i.e., relict permafrost from when the shelf was exposed).

4.1.2. Piston and Box Core 124

[20] The box and piston cores were collected on different legs of the CASES Beaufort Shelf mission and when the locations were examined closely several months later the two cores were clearly not in the same location (Figure 2). For this reason the box core is not discussed farther here but will be in a combined set of box cores examined from the entire Amundsen Gulf (line 100 (Figure 1)) as part of an upcoming M.Sc. thesis. For the piston core 124 an example of the X rays are included to compare with core 750 (Figure 8). Ice-rafted debris are again present between 80 and 190 cm with unstructured sediment above that, similar to core 750 (below the upper 15 cm) and with one date at 120–130 cm of 12,376 cal B.P. (Table 2); this is from the upper IRD unit; there was insufficient material for dating below that level. Additionally the magnetic susceptibility and ARM profiles of both cores can easily be correlated (Figures 4 and 5) in the IRD zones, with the two-peak structure observed in core 750 also found in core 124. Below these two coincident peaks, the correlation is unclear and likely reflects the very different nature of the sediment below the IRD in core 124. Below that zone sediment is much richer in organic matter that is definably terrestrial with root fragments and some sand. There are some foraminifera (both calcareous and agglutinated) in these sediments suggesting the organics are being deposited in a glacial marine environment. The likely origin of the organics at the base of Core 124 is from preglacial tundra up stream from the glacier that entered the Gulf. The old ^{14}C date (>37,000 years B.P.) and a very negative ^{13}C value confirm this. The organics in this core are much more definitive in the sense that they can be easily distinguished as terrestrial plant fragments and since this site is very close to the terminus of the glacier that was in Amundsen Gulf (Figure 12) it would appear that this glacier was depositing freshwater permafrost peat to the core 124 site that was just seaward of the glacier during the last glacial period.

4.2. Paleomagnetism and Other Physical Properties

[21] These data proved to be very interesting because for both core 750 and core 124 (Figures 4 and 5), the physical properties matched up very well with the IRD, suggesting even without chronological control that these units had the same source. However, the upper IRD unit in core 124 was older than the corresponding one in core 750. This suggests a lag in the movement of the material around the

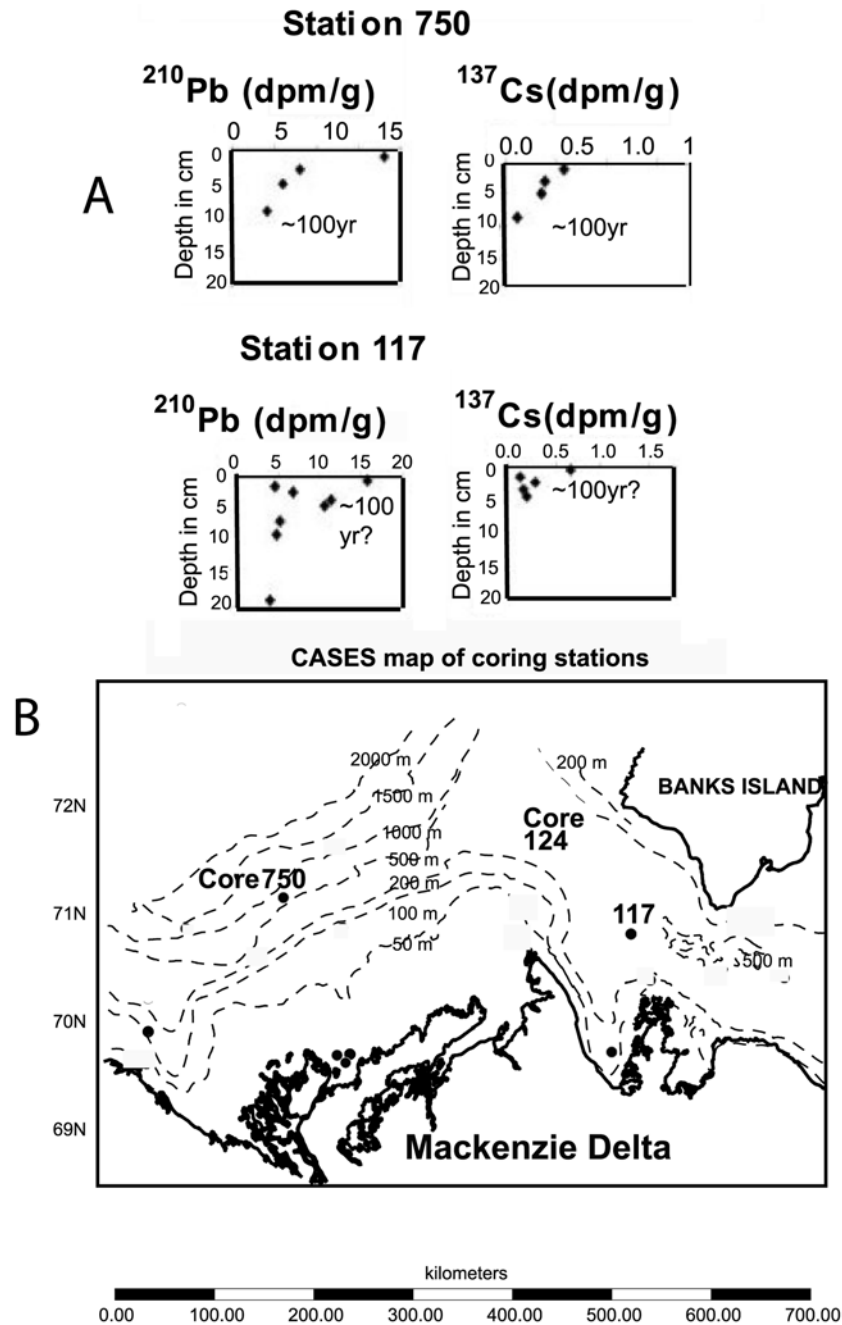


Figure 6. (a) The ^{210}Pb and ^{137}Cs profiles for core 750 and core 117 (position of core 124 also shown in the Amundsen Gulf). (b) Map of Beaufort Shelf with stations where ^{210}Pb and ^{137}Cs profiles were done. Although core 124 was away from core 117 most of the Gulf had low sedimentation rates in deeper water. Dates are courtesy from Amiel and Cochrane (personal communication, 2004).

edge of the Beaufort Shelf to the 750 site. The spikes in magnetic susceptibility were particularly convincing but all the parameters (ARM anhysteretic remanent magnetization, IRM isothermal remanent magnetization, SIRM-saturated isothermic remanent magnetization, and grain size) were conclusive as well as to the common origin of the IRD peaks. One set of values that stands out is the relatively high C_{inorg} values in the sediments for all IRD units but

low C_{org} in both cores. The mean grain size is generally larger for the IRD units but these units of course are poorly sorted.

4.3. Chronology

4.3.1. Box Core 750

[22] As mentioned above the box core provided the only short-term ^{210}Pb estimates (less than 100 years) and indi-

Table 2. Radiocarbon Dates^a

Core	Depth (cm)	Material	Conventional Age (years B.P.)	Calibrated Age (cal B.P.)	Lab Number
750	179–180	Forams (mixed)	10,865 ± 30	11,297 (11,580) 11,865	UGAMS-27757
750	381	Forams (mixed)	12,450 ± 90	13,286 (13,500) 13,715	BETA-206657
124	121–132	Forams (mixed)	11,500 ± 90	12,376 (12,620) 12,867	UGAMS 1756, 1757
124	131–132	Forams (mixed)	11,560 ± 90	12,390 (12,655) 12,917	UGAMS-01757
124	182–183	Organics-terrestrial peat	37,570 ± 1,420	No correction; older than limit, $\delta^{13}\text{C} = -25.9\text{‰}$	UGAMS-02319

^aThe two conventional ages were calibrated with the CALIB5.0.2 [Stuiver *et al.*, 2005] online calibration software using the *Hughen et al.* [2004] data set and assuming a ΔR value of 410 ± 50 years (corresponding to a reservoir age of 860 ± 45 years). This ΔR value was estimated with the rounded average of the five dates obtained on preindustrial mollusc shells collected alive close to the Amundsen Gulf [McNeely *et al.*, 2006]. The first and last ages represent the 2σ calibrated age range, whereas the ages in parentheses are the average ages. Forams (mixed) means both planktics and benthics combined to obtain a date. Lab number abbreviations: UGAMS, University of Georgia AMS dating lab; BETA, BETA analytical.

cated that approximately the upper 13 cm of site 750 was deposited in the last 100 years (Figure 6).

4.3.2. Piston Core 750

[23] The radiocarbon dates in the piston core suggested sedimentation rates prior to 100 years B.P. were much lower: the upper most radiocarbon date was in the upper IRD unit of core 750 where calcareous foraminifera first became abundant; this date was at a core depth of 180 cm with an age of 11,297 (11,580–11,865) cal B.P. (Table 1). Extrapolating from the box core this would indicate that below the 15 cm level in core 750 the sedimentation rate was 15 cm/1000 years from 100 years B.P. to 11,500 cal B.P. and 100 cm/1000 years between 11,500 and 13,500 cal B.P., an order of magnitude higher in the IRD units.

4.3.3. Piston Core 124

[24] This core had no ^{210}Pb dating but there were two radiocarbon dates. The youngest one was at 123 cm (12,620 cal B.P.) and the other was at 132 cm (12,655 cal B.P.); this provides sedimentation rates of 10 cm/1000 years for the

upper 120 cm and 10 cm/100 years for the lower section. Additionally some organic sediment that appeared to be terrestrial peat material was dated from the 182–183 cm level; this date was $37,570 \pm 1420$ with a $\delta^{13}\text{C}$ of -25.9‰ , which suggests terrestrial organics. These are certainly from tundra, probably well to the south of this core location, eroded by the glacier and transported here by subglacial meltwater. In extreme cases this could deliver freshwater tundra debris to as far as the Beaufort Sea Basin. This age reveals nothing about the age of deposition for the sediment it is in but it does show that there was significant subglacial transport of material over long distances during the last glacial: the freshwater tundra would not have formed in the Gulf itself so it would have come from the nearest land which is either on the edges of the present gulf (not likely because the glacier was coming from the south) or from the head of the gulf some 100 km to the south. The box core for this site was collected at a different time on a subsequent CASES leg (see Table 1) and unfortunately was collected at

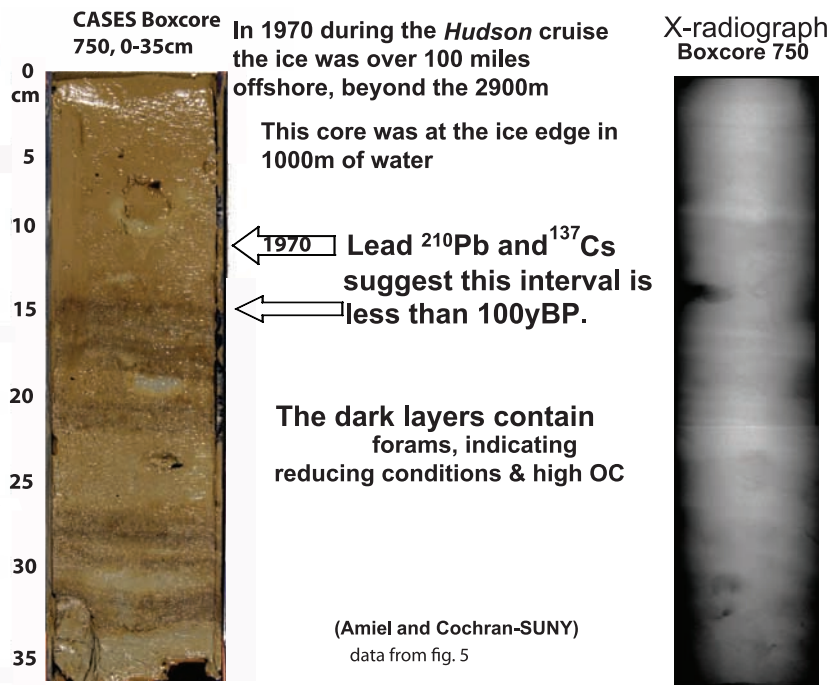


Figure 7. Photo and X ray of box core 750; note banding present in both X ray and photo.

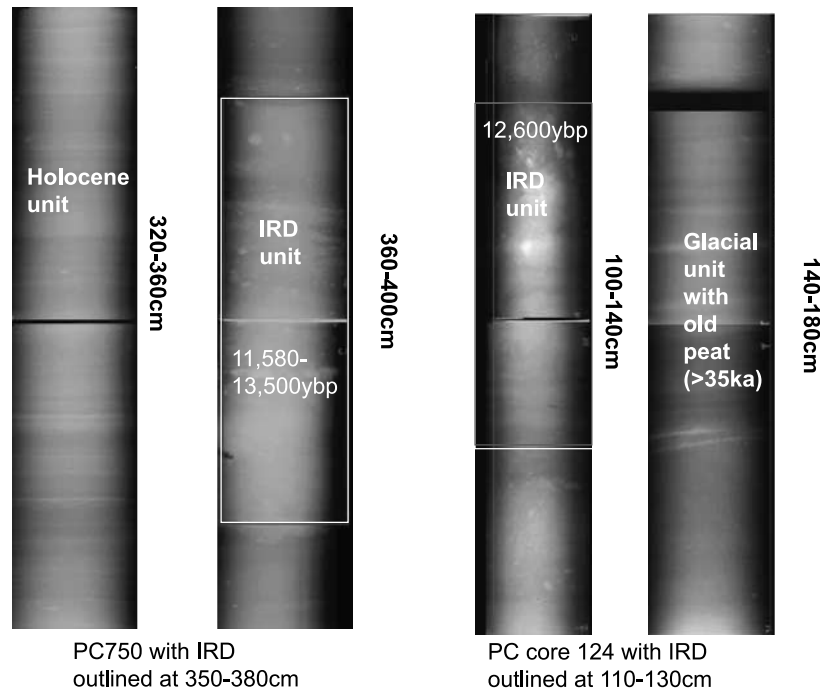


Figure 8. X rays of PC 750 and 124 noting some examples of the intervals of ice-rafted sediments (350–380 cm in 750 and 140–180 cm in 124). The extent of the IRD zones can be observed more fully in Figure 4, where mean grain size peaks are shown [after Scott *et al.*, 2008b].

a different location and depth and hence not matched to the upper part of the piston core 124.

4.4. Foraminifera

[25] Figure 1 shows the locations of all the box core stations (foraminiferal data for surface studies by Scott *et al.* [2008a, 2008c]) with the two piston core sites highlighted. Total numbers of individuals and percentages were determined for both the $>63 \mu\text{m}$ and the $45\text{--}63 \mu\text{m}$ size fractions which show there were high abundances in both fractions but almost always different dominant species between them, illustrating once again why the small fractions must be examined, especially for some of the deep-sea calcareous forms. Shaded areas on cores in Figures 9, 10, and 11 correspond to foraminiferal assemblages that suggest more permanent sea ice cover. *Trochammina* spp. are grouped together in the graphs but they are separated in supplementary data tables. Actual numerical data for each species throughout all cores are contained in Data Sets S1–S3.¹

4.4.1. Box Core 750

[26] Figure 9 illustrates most common species versus depth in core for the both the total and the smaller size fractions. Total numbers are high in the upper 3 cm ($>5000/10 \text{ cm}^3$) consisting mainly of the smaller size fraction (*B. arctica*, *Trochammina* spp.). For the larger size fraction the abundant species in the top 1 cm include *Stetsonia arctica*, *Buliminella hensoni* and planktic foraminifera as well as some *Oridorsalis umbonatus* and *Trochammina* spp. Tin-

nids have their highest abundance at the top of the box core and are comparatively rare throughout the rest of the BC 750 and PC 750. The foraminifera decrease markedly below 3 cm, with most common being *Trochammina* spp. and the small calcareous species *Bolivina arctica* to the 14 cm mark. From 14 to 31 cm there are again large numbers ($500\text{--}2500/10 \text{ cm}^3$) but here the komokiaceans *Rhizammina algaeformis* and *Cerebrum c.f. coralliformis* [Schröder *et al.*, 1989] (Figure 3, not on graph) are most abundant. These komokiacean forms have rarely been recorded in the Arctic and almost never as fossils anywhere: here they are pyritized because of the reducing conditions caused by what appears to be a large flux of organic material between 13 and 31 cm (Figure 7). Komokiacea are a relatively newly described group of foraminifera, which have largely organic, not agglutinated tests, which rarely preserve in the sediments [Tendal and Hessler, 1977]. In the lower 3 cm of the box core these species decrease and a more typical deep sea Arctic species, *Cribrostomoides subglobosa*, becomes prominent. It is important to note that most species do not have equal numbers in both size fractions (e.g., *B. hensoni* has very few specimens larger than $63 \mu\text{m}$) and these species are some of the dominants.

[27] Planktics are relatively abundant in the surface and surprisingly comprise a significant % of specimens in the small fraction: the fraction below $150 \mu\text{m}$ is rarely examined for planktics. One other rare occurrence in the surface 2 cm was *Oridorsalis umbonatus* (this is the only occurrence at this site except the 150 cm level in the PC). Percentage data for all species versus depth are in Data Set S1.

¹Auxiliary materials are available at <ftp://ftp.agu.org/apend/pa/2007pa001575>.

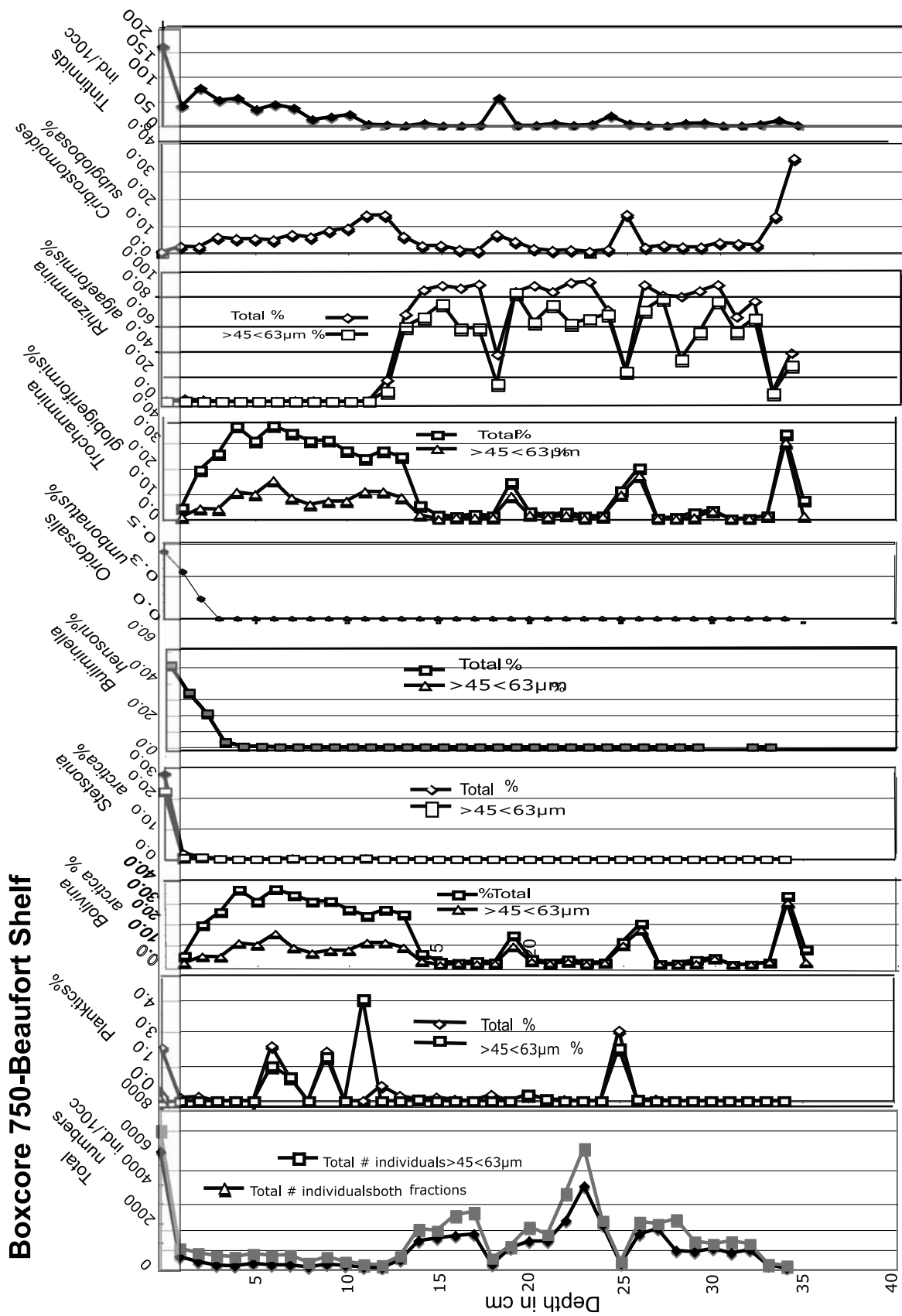


Figure 9

4.4.2. Piston Core 750

[28] The box core indicates that the only upper 5 cm were bypassed by the piston core, which is actually quite remarkable given the conditions during collection, and it means that it is relatively straightforward to match common horizons for the PC and BC. For the size fractions >45 and 63 μm (Figure 10 and Data Set S2) it is easy to note that the upper 5 cm is absent; the 5 cm mark in the box core is almost identical to the piston core surface. At the 30 cm mark the fauna from the bottom of the box core is dominated by *Cribrostomoides subglobosa* and this species continues in relatively low numbers until 70 cm. Abruptly at 150 cm a calcareous fauna, first dominated by *Oridorsalis umbonatus*, *S. arctica* and planktics (150–200 cm), is replaced below by *Islandiella* from 200 cm to 400 cm in varying numbers. Planktics remain high throughout this interval. *Stetsonia* decreases at 200 cm but returns in high percentages at 380 cm. Below 400 cm the fauna is mostly *Trochammina* spp. but in very low numbers and virtually all foraminifera disappear below 450 cm.

[29] The 45–63 μm assemblages are similar to the >63 μm fraction, especially in the upper 30 cm where *R. algaeformis* dominates both size fractions. However, the only prominent calcareous species in the upper 150 cm is *Bolivina arctica*, which occurs rarely in the larger size fraction. In the 120–380 m section the most common smaller size species are *Buliminella hensoni*, *B. arctica*, and *S. arctica* together with high numbers of *Trochammina* spp. Tintinnids in this core are missing in the upper part (only present in the BC) but are present at 90–100 cm and then again at 100–220 cm.

4.4.3. Piston Core 124

[30] Since very little appears to have been lost from the piston core at this site, the box core is not discussed in this paper (in addition to the fact that the BC was taken in a very different location (see Figure 2)). The top of the core has an agglutinated fauna with low numbers (mostly *Saccammina difflugiformis* and *Trochammina* spp.) and a large % of *B. arctica* (45–63 μm only) as well as the highest number of tintinnids in this core. At 5 cm there is an abundant fauna dominated by the deep sea calcareous species *Stetsonia arctica* and *B. hensoni* (45–63 μm only) (Figure 11 and Data Set S3). The 45–63 μm fraction contains the greatest numbers and percentages of specimens (often over 50% of the fauna, and the species are typically the deep sea benthics (*S. arctica*, *B. hensoni*, and large numbers of the *Trochammina* spp.)).

[31] Planktic foraminifera, *Islandiella teretis*, and some *Trochammina* spp. dominate the larger >63 μm fraction (Figure 11 and Data Set S3). At 10 cm the fauna contains lower numbers again dominated by *Trochammina* spp. but including calcareous species in lower numbers. This fauna persists to the 100 cm level where agglutinated species almost disappear to be replaced by a series of calcareous species (*S. arctica*, *I. teretis*, planktics, *Buliminella hensoni*, and *Fursenkoina fusiformis*). Below 180 cm the numbers

drop sharply but with the same species, which are well preserved, indicating higher sedimentation rates but no change in oceanography.

[32] Tintinnids are most common in the upper 10 cm but decrease markedly below that level. Percentage data for all species are included in Data Set S3.

5. Discussion and Implications

5.1. Comparison With Other Foraminiferal Core Data in the Beaufort Sea

[33] *Vilks and Joice* [1976] examined the >63 μm fraction in many cores from the Beaufort Sea shelf which was helpful to some extent however they looked at much larger samples and dried their material; since they used weight after sieving and drying it is not possible to really compare absolute numbers of specimens/wt. to a number from a volume of sediment. However, we can make a few relative comparisons of species found and P/B ratios. They examined samples from a relatively wide sampling interval of 25 cm and used 5 cm lengths of core sample; given the low sedimentation rates in the Arctic, a 5 cm section could mean as much as a 1000 year interval. Their core 359, which was in 2031 m of water, contained a relatively high number of benthic and planktic foraminifera in the surface (355 benthics, 327 planktics) with *Islandiella islandica*, *I. teretis* and *Stetsonia horvathi* (= *arctica*) as dominants at 0 cm; this P/B ratio is similar to present permanent ice-covered areas and is similar to the central Arctic [*Scott et al.*, 1989a] at a similar water depth, especially considering the volumes used. They also observed *Oridorsalis* (= *Eponides tener* in their table) in a large percentage (16%) at the surface, which shows Atlantic influence here just as observed by *Scott and Vilks* [1991] for the eastern Arctic. This is in contrast with *Lagoe's* [1977] results where he saw virtually nothing in the deeper parts (>2000 m) of the Beaufort Sea in his surface samples. The *Vilks/Joice* core 359 was over 10 m in length but below the surface they only observed over 100 planktics in a few samples. However, between 3 and 4 m core depth, there were large numbers of planktics (300–400) suggesting that dissolution was not taking place in those intervals. If the deep-sea sites of *Vilks and Joice* had sedimentation rates similar to the central Arctic, all calcareous foraminifera would have disappeared in the Pliocene at about 1–1.5 m but since that was not the case we can assume sedimentation rates in the Beaufort Sea are much higher than the Central Arctic. In the CESAR sites [*Scott et al.*, 1989a] the Pliocene had only rare agglutinated species which could have been lost in processing by *Vilks and Joice*. What makes *Lagoe's* [1977] data (samples from the 1960s) very interesting is that he found very few foraminifera in any of his Beaufort Sea deep water samples where *Vilks and Joice* did find some in their cores taken several years after T-3; this may relate to timing of calcareous species at the surface of core 750 which only occur in

Figure 9. Percentage distribution of selected species for the >45 < 63 μm fraction and total percents in box core 750 versus depth in centimeters. Shaded area (0–3 cm) corresponds to the section where more permanent sea ice is suggested to have been present (after *Scott et al.* [2008b]), with permission from Aboriginal Issues Press).

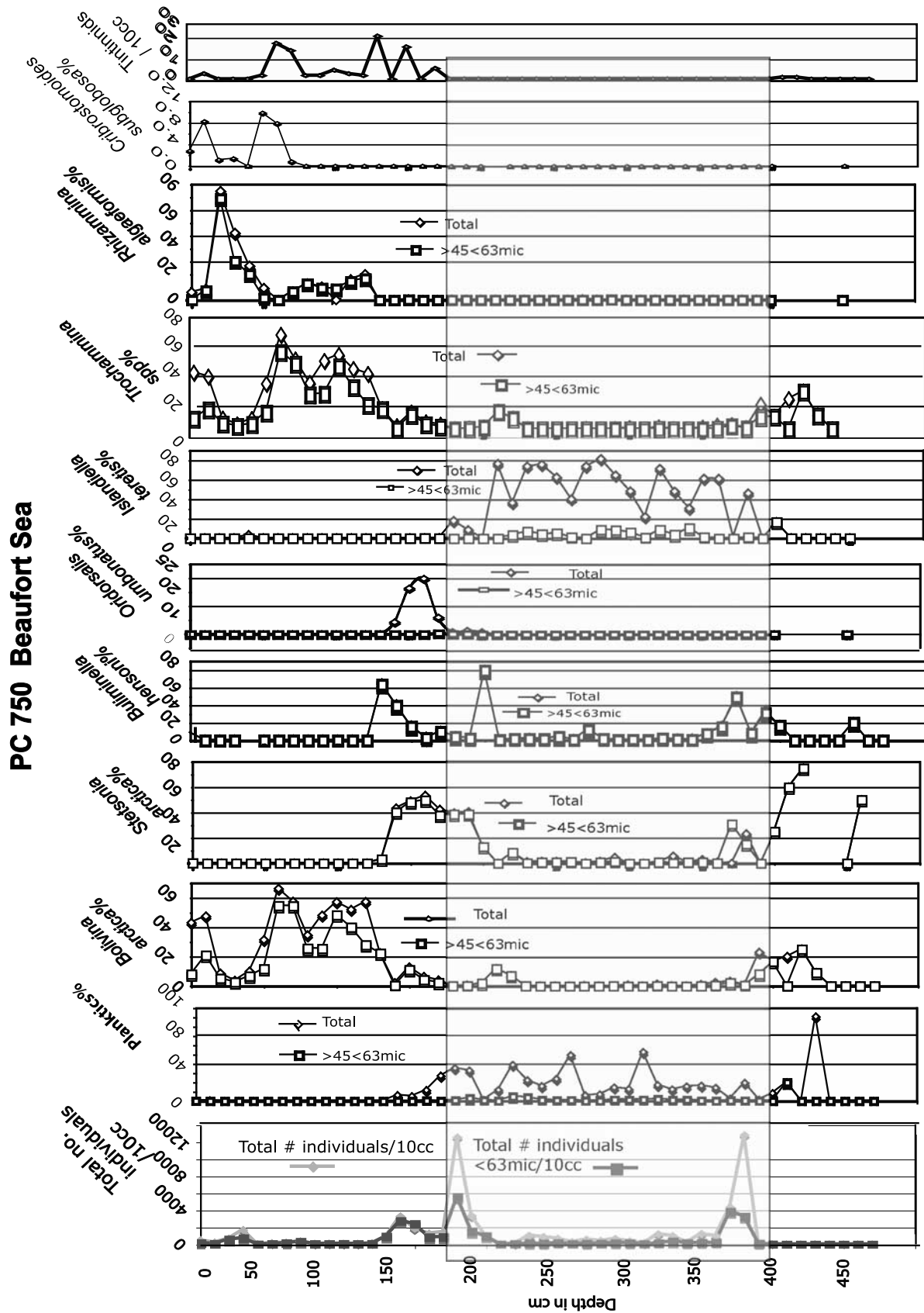


Figure 10

the upper 2 cm which post date Lagoe's and the Vilks/Joice samples. The almost barren intervals in core 750 below the surface (excluding the Komokiacea zones) might be in the time frame of Lagoe's samples taken in the early 1960s as part of the T-3 ice island expedition. To make a true comparison of these areas more cores from the deeper water part of the Beaufort Sea are required, especially since it seems that Lagoe's samples in particular may have been taken before the calcareous fauna in the surface of BC 750.

5.2. Previous Sea Ice Records From the Arctic

[34] Paleo-sea ice cover is one of the main objectives of this project to enable us to extend the short historical record using the past as a possible key to future ice conditions. There have been several methods employed by others to detect the presence of perennial sea ice, some of which will be used in conjunction with the present investigation [Ledu *et al.*, 2008]. However, in one of the more elegant studies of paleo-ice cover, Fisher *et al.* [2006] obtained Holocene sea ice reconstructions on the basis of bowhead whale remains [Dyke *et al.*, 1996; Dyke and Saville, 2001], dinoflagellate cysts in cores [de Vernal *et al.*, 2005a, 2005b] and oxygen stable isotopes in planktic foraminifera [Hillaire-Marcel *et al.*, 2004] together with ice cores from the islands in the Canadian Arctic Archipelago. These data were used to determine that there was less sea ice between 9,000 and 10,000 cal B.P. and 5000 cal B.P. when whales from the eastern and western Arctic could commingle. Greenland ice core and isotope records show that these early Holocene values have not been reached since then. However, just in the last summer season (ArcticNet legs, September and October 2006), ships were able to navigate to places not reached in many years. Mudie *et al.* [2005] used palynological techniques and transfer functions to suggest substantial climate shifts in the last 6000 years in the eastern Arctic, specifically on Devon Island and in the North Water polyna of Baffin Bay. They report large oscillations of 2–4°C cooler to 6°C warmer for SST, with sea ice cover ranging from 2 months longer to 4 months less cover than in the period 6500–2600 years B.P. than present conditions. It was also suggested these changes might have caused major life style changes for the Paleolithic societies. These cycles are suggested to last 50–100 years for the warming and 300 years to replace the colder water, i.e., very rapid even by human standards and within the scale of the present global warming scenario, i.e., warming in a 50–100 year time frame. The difference is that these occurred before any significant anthropogenic influence such as the massive CO₂ increase observed in the last 100 years.

[35] As part of the CASES studies Schell *et al.* [2008a] looked at box cores from the Amundsen Gulf (stations 403, 415) and in these shorter records it appears, on the basis of foraminiferal assemblages, that ice may have been thicker and/or more extensive in this area in the last 100 years than in the previous few 100 years; this also reflected in the upper part of the piston core 124 which lies close to line 400

(Figure 1). However, below the surface core 124 has a record similar to core 750, i.e., less sea ice than present.

[36] The opening of the Arctic channels has had profound influence on the east coast of Canada. The Inner Labrador Current developed about 5000 years B.P. [Scott *et al.*, 1984, 1989b]; this introduced colder, lower-salinity Arctic surface water to the southeastern Canadian continental shelves and caused as much as a 10°C lowering of water temperature together with lowered salinity with effects from Baffin Bay to the northern Nova Scotian shelf.

[37] The last small variation in the last few years reflected in the upper 2 cm of box core 750 is suggestive of just how rapid this change can be. It is also interesting to consider that if the Arctic Archipelago channels open up even more, the cold water flow will increase to the south, and with it, a transfer of more cold water which could cause more cooling southward, at least on the east coast of North America. The feedback mechanisms here are certainly not well understood; although warming was observed in the Arctic in the early Holocene, the most dramatic warming on the east coast of Canada came in the mid-Holocene [Scott *et al.*, 1984, 1989b; McCarthy *et al.*, 1995] followed by the cooling that coincided with the introduction of cold Arctic surface water after 5000 years B.P. If the preliminary microfossil data from box core 750 are interpreted correctly then it suggests slight cooling in the last 20–30 years, at least in that one location. This is in contrast with polynas or open water leads observed in Amundsen Sound and other locations in the last few years (observations from CASES and D. Barber, Univ. Manitoba; websites listed in the acknowledgments).

5.3. Foraminiferal Evidence for Sea Ice Changes From the Present Study

[38] In 1970, when the Beaufort Slope was last sampled extensively for sediments and microfossil studies, the sea ice was much farther offshore (as indicated by a core taken in 3000 m of water which is at least 50 km farther into the Beaufort Sea than our core at 1000 m water depth). However, it would appear that since that time there has been more sea ice, which allowed the development of a strong Arctic calcareous fauna, observed in only the top 2 cm of the 750 box core. This includes the Atlantic deep water species, *Oridorsalis umbonatus*, which only occurs again in the upper IRD unit which is almost 12,000 years earlier than present. The presence of more calcareous species indicates more sea ice (= less surface productivity) as shown in several Arctic studies [e.g., Wollenburg *et al.*, 2001]. Also in core 124 there is a strong calcareous foraminiferal presence in the upper 10 cm and also tintinnids but this fauna disappears and reappears at 100–150 cm to coincide with the first appearance of IRD. The present fauna contains planktics and *Islandiella teretis* followed by the addition of smaller Arctic species deeper in the core; the tintinnids suggest either high SPM and/or lower salinity but they do not reoccur below the surface level. Below 150 cm

Figure 10. Distribution of selected species for the >45 < 63 μm fraction and total percents of piston core 750 versus depth in centimeters. Shaded area (180–400 cm) corresponds to the section where more permanent sea ice is suggested to have been present.

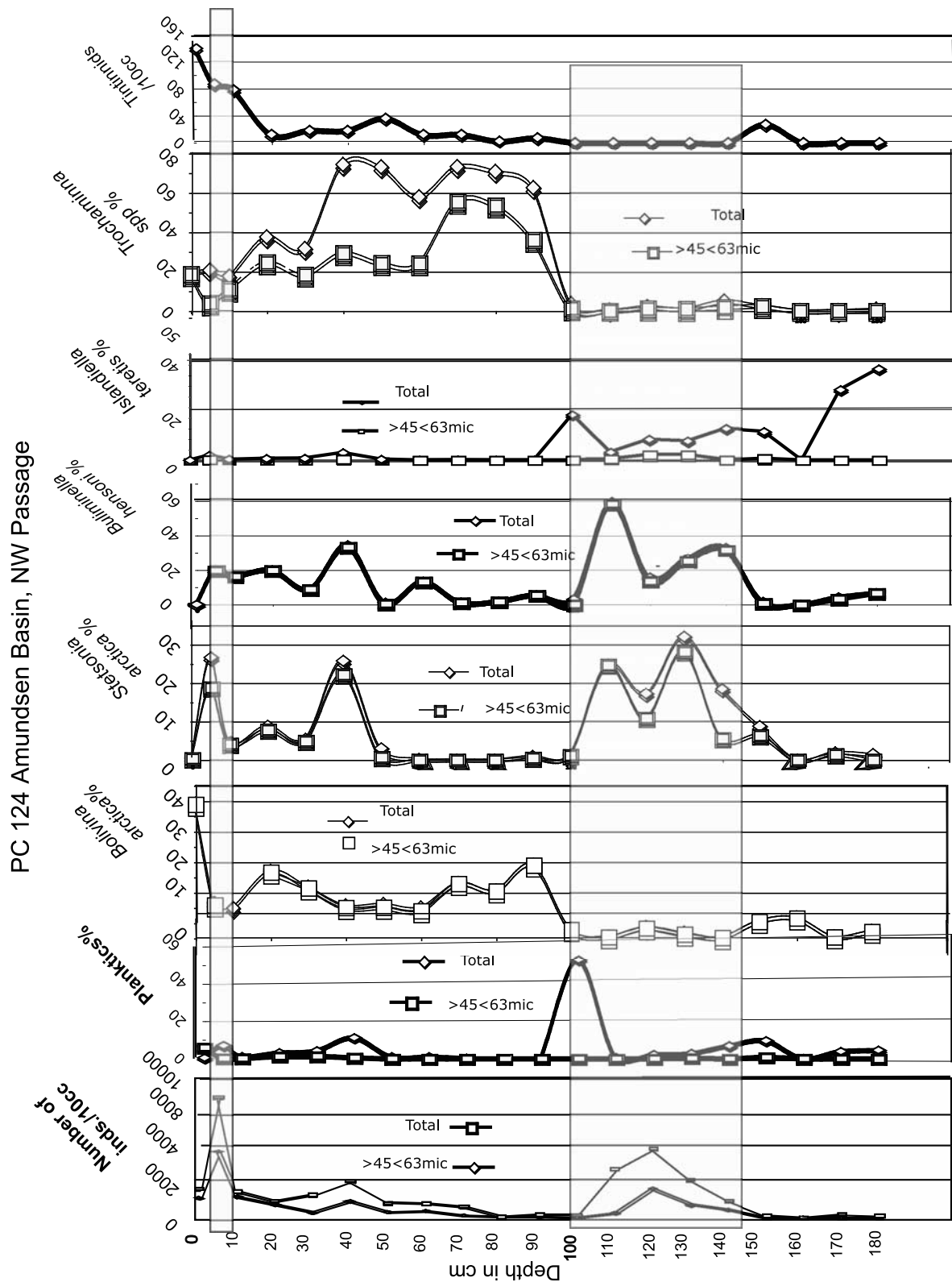


Figure 11. Distribution of selected species for the >45 < 63 μm fraction and total percents in piston core 124 versus depth in centimeters. Shaded areas (5–10 cm and 100–145 cm) correspond to the sections where more permanent sea ice is suggested to have been present. There are no specimens of *O. umbonatus* in this core or in the surface samples from the Amundsen Gulf [Scott et al., 2008a]. After Scott et al. [2008b].

the fauna becomes sparse but is well preserved (*I. teretis* and a few planktics). These are contained in the sediments below the IRD, which contain abundant terrestrial organics (dated as last glacial age). Although this is a low-abundance fauna, it does resemble other ice margin faunas in Quaternary marine sediments from the last glaciation off eastern Canada [e.g., Scott *et al.*, 1984].

[39] It would be tempting to say that diagenetic problems occurred below 5 cm, however, in cores 750 and 124, some of the calcareous species do extend into that zone, most notably *B. arctica* and *B. hensoni*. Additionally the *R. algaeformis* and *Cerebrum* sp. in core 750 do not exist anywhere else; this combination of the Komokiacean species has never been observed anywhere in a fossil state. Although Komokiacea are reported to be from oligotrophic environments [Schröder *et al.*, 1989, and references therein] Komokiacea have been found living on the Beaufort Shelf which is organic rich sediment sometimes with methane [Scott *et al.*, 2008a]. They were very large and occurred only in benthic dredges and did not occur in the smaller foraminiferal samples. The pyrite that is present, which allows the preservation, is most likely the result of relatively high organic matter input causing the reducing conditions favorable for pyrite formation, which is not common to deep-sea sediments where these species are generally found. This is suggestive of much more open water which allowed addition of more organic matter to the bottom sediments (thus decreasing the pH of the sediments by causing reducing conditions resulting from abundant labile organic matter) prior to 2004 sampling. This is similar to the present in Baffin Bay where below 500 m there are also no calcareous species living in modern sediments; although the fauna has different species from box core 750, *Rhizammina algaeformis* is a major component of the Baffin Bay surface fauna. In a piston core from Baffin Bay, collected as a site survey core for ODP Leg 105, turbidite layers were found in glacial units with abundant *R. algaeformis* in layers resting on top of the turbidites and this reoccurred several times in the last glacial [Scott *et al.*, 1989c].

[40] The 1970 sampling indicated that no calcareous species were present [Vilks and Joice, 1976]. ²¹⁰Pb data (with ¹³⁷Cs control) in box core 750 suggest that the organic layer occurred around 100 years ago but with a lower sedimentation rate in the uppermost 3 cm and a period of very high sedimentation just below ~15–25 cm in the box core. This rapid sedimentation rate was not present below the 25 cm depth or above the IRD in 750. This middle unit, which is the longest time unit in core 750, contained a largely low number fauna of *Cribratomoides subglobosa*, *Trochammina* spp. and *Bolivina arctica* suggestive of highly seasonal ice cover which has been suggested by several papers cited here as indicating more seasonally open conditions. The photograph of the box core (Figure 7) shows brown banding suggesting higher organic contents in the interval with the abundant agglutinated fauna.

[41] The record from PC 124 is different in a number of ways from PC/BC 750. First of all the Holocene record down to the IRD is 50 cm less than that for 750 suggesting a slower sedimentation rate at this site. Tintinnids persist

much farther downcore in 750 than in 124 suggesting more freshwater input for the surface waters throughout the Holocene at the 750 site. The Komokiacean zone is not present in core 124; the water is of course not as deep at this site as it is for the 750 site however there might have been komokiaceans here but not preserved without the presence of a high organic section. Below the upper few centimeters the two cores have similar faunas above the IRD zones. There are a few more calcareous species in the corresponding unit of core 124 suggesting a more oceanic fauna (the deep water Arctic species such as *S. arctica* and *B. hensoni* plus a presence of planktics). However, the site lacks the species *Oridorsalis umbonatus* (a deep sea Atlantic water indicator) and suggests no Atlantic water is penetrating into the Amundsen Gulf. This species also was not observed in the Beaufort Shelf surface samples above 250 m water depth [Scott *et al.*, 2008a, 2008c] and its first appearance in the Arctic Ocean was 250,000 years ago as shown in the CESAR cores [Scott *et al.*, 1989a]. Coincidentally at the time when *O. umbonatus* first entered the Arctic basin *B. arctica* started to decline (in the >63 μm fraction at least) suggesting the Atlantic species replaced the native Arctic species. Hence although the core 124 site is in much shallower water it retains a more Arctic oceanic fauna than the deeper core 750 site. This reflects the Amundsen Gulf isolation from Beaufort Shelf processes (i.e., high organic input, freshwater fluxes) throughout most of the last 12,000 years as well as from the deeper Atlantic water that appears at site 750. In the last few (10s) of years tintinnids indicate more freshwater even in the Gulf; this however had little influence on the benthic fauna. In the IRD zones of both cores agglutinated species decrease to trace amounts while calcareous species have significant increases in both size fractions, largely the same species except for deep water Atlantic species. In summation these data suggest more sea ice in the Amundsen Gulf throughout most of the Holocene than was present on the edge of the Beaufort Shelf at the core 750 location. This would suggest that the increased sea ice enhanced the preservation of calcium carbonate in bottom sediments at site 124 for longer time than at the slope site 750.

5.4. Conditions During and Before the Last Glacial

[42] Wollenburg and Kuhnt [2000] looked at living faunas in reference to primary production. They found highest numbers of living foraminifera associated with high-productivity zones, which generally occurred in seasonally ice-free areas. They also noted that preservation of calcareous foraminifera in the high-productivity zones was poor compared with perennial ice areas, a factor also noted by Scott and Vilks [1991] and Schröder-Adams *et al.* [1990] in areas close to this one. This corresponds with an interpretation of more persistent sea ice in the Amundsen Gulf during the Holocene than at the shelf edge of the Beaufort Shelf (core 750). In two related papers, Wollenburg *et al.* [2001, 2004] looked at paleoproductivity in cores from the same area examined previously by them. They were able to see reduced productivities during glacial periods when areas now only seasonally ice covered, were covered perennially. They examined the 24,000 years B.P. interval and the

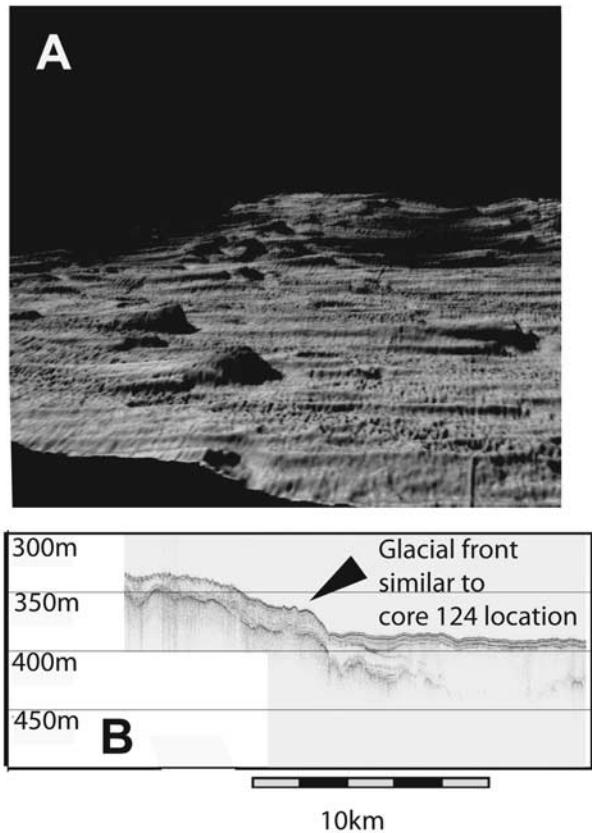


Figure 12. Multibeam and seismic images across the area of the PC 124 site showing the general morphology of the glacial front associated with this area, which is slightly upslope and away from the former ice front. The drumlin-like features are approximately 10 km long and up to 60 m high, all inland from the glacial front. The seismic line is from along line 100 near station 124, and drumlin-like features are from farther east in the Amundsen Gulf. The drumlin pattern is similar to those on Banks Island [Stokes *et al.*, 2006].

145,000 years B.P. intervals respectively. Although our cores do not appear to penetrate even to the 24 ka B.P. glacial, they certainly do penetrate into the upper part of last glacial period and, at both sites, there appears to be good preservation of calcareous species where there were ice-rafted sediments. This suggests overall lower productivity in the IRD unit where there would have been much more sea ice and abundant icebergs. There are no icebergs presently in the western Canadian Arctic so this had to be a time when the Wisconsin glacial was ending and the glacier, presumably in Amundsen Sound, was decaying and shedding icebergs into the ocean. The paleomagnetic signals suggest that the IRD in both cores may have the same source presumably from Amundsen Gulf since there were no glaciers on the Beaufort Shelf. However, the timing appears to be outside the error bars to place them at the same time. The two IRD units in core 124 are tightly grouped at around 12,000 cal B.P. while the core 750 IRD units occur above and below those times. This would

suggest a different source and studies are now under way to using clay mineralogy to determine the provenance of the different units.

[43] There are few foraminifera in core 750 below the IRD in what is thought to be end of the last glacial. Is that because of high sedimentation rates along the margin? We cannot determine that without age control but sea level would have been sufficiently low to allow grounded sea ice. The grounded ice could have scraped and eroded organic-rich permafrost, present on the Beaufort Shelf, placing it in suspension to produce the highly organic sediments that characterize the unit below the IRD of core 750. The organic particles in core 750, below the IRD unit, have a $\delta^{13}\text{C}$ value (-25 – -26‰), similar to the value from the ^{14}C dated material below the IRD unit in core 124. However, the organics in the glacial sediments of core 124 below the IRD are of a fundamentally different type than those from core 750. They are more refractory and possibly less prone to promoting low pH in the sediments as the more labile organics coming off the Beaufort Shelf may have been and hence there is good preservation of a low-number calcareous fauna.

[44] From the preliminary data in core 124, the organic matter below the IRD unit appears to be much more abundant (1.2–1.3% as opposed to less than 1% in the upper part of 124) and the organics are identifiable as terrestrial plant fragments. At site 750 where the organics are not readily identifiable as to source, but the organic carbon percent is slightly higher (see Figure 4) than that at site 124 (1.5%). Preliminary examination of site 124 organics suggests the glacier, whose terminus was not far from the core location (Figure 12), might have been bringing relict permafrost fragments from terrestrial sites on land, possibly from the closest land, which would have been to the southeast over 150 km away. The date at 182 cm of 37,570 years B.P. and the low $\Delta^{13}\text{C}$ value (-25‰) suggest a terrestrial origin of permafrost or tundra from the last interglacial that was delivered to this site by subglacial flow to the position of core 124. Although counting of foraminifera stopped at 182 cm this sequence continued for another 3 m downcore. Certainly the glacier was grounded very near here judging from the drumlin-like features just southeast of the channel from site 124 (Figure 12).

[45] There are four other core studies in the western Arctic, Poore *et al.* [1994], Polyak *et al.* [2004], Andrews and Dunhill [2004] and Schell *et al.* [2008b]. Poore *et al.* [1994] examined cores from the Northwind Ridge into the Canada Basin. That study examined piston cores in water depths of 945–3500 m so it barely overlaps with our deepest station. In the core at 950 m they see some foraminifera but since they examined only the fraction $>150\ \mu\text{m}$ they did not see most of the dominant species. However, in another study, Poore *et al.* [1999] examined cores from close to the Siberian Shelf in the western Beaufort Sea. They obtained oxygen stable isotope values from a period over the last 14 ka but most interesting were some very low δO^{18} values at around 11 ka which was suggested to be from the “Agassiz” flood event which was suggested to come from the Mackenzie River. Poore *et al.* [1999], Polyak *et al.* [2004] and Andrews and Dunhill

[2004] obtained stable isotope values that cross the last interglacial/glacial boundary. At that boundary (with dates similar to the IRD dates in cores 750 and 124) *Polyak et al.* [2004] suggest meltwater signals with low positive to slightly negative values for δO^{18} (-0.5 – 2.0%) obtained from abundant calcareous foraminiferal species (both planktics and benthic). Andrews and Dunhill suggest that their low stable isotope values (which are higher than the Russian ones (δO^{18} , $+2.5\%$)) may be related to the Agassiz flood event which they also suggest might have come from the Mackenzie River. Their site is on the Alaskan slope (500 m WD), which is very close to our site 750 in both the proximity and in the ages of our IRD units. Stable isotope data show little evidence of a substantial surface meltwater event during the IRD peaks 750 (δO^{18} $+1.0\%$ in only one narrow horizon [*Scott et al.*, 2007]). Recently obtained δO^{18} stable isotope values from planktic foraminifera in the 11,000–11,500 cal B.P. time range from a core from the Mackenzie Trough [*Schell et al.*, 2008b] indicate values higher than any planktic values measured so far at any age in this area: $+2.70$ – 3.48% for *Neoquadrina pachyderma* with $\delta^{13}\text{C}$ values of $+0.43$ – 1.21% . On the basis of those data, which are the closest to the Mackenzie River, we would suggest that there was permanent sea ice here at the time of the Agassiz event. If there was meltwater associated with the Agassiz event then it must have been originating from Russian rivers on the Siberian shelf at that time, not the Mackenzie River.

5.5. Discussion and Implications of Results From the Data in This Paper

[46] Tintinnids indicate some freshwater input as well as high amounts of suspended particulates (SPM) [*Scott et al.*, 1995]: their presence generally precludes significant permanent ice cover since ice cover usually means little runoff or freshwater in the water column. This is most obvious in samples from the Mackenzie Trough where the freshwater plume is strongest in the Holocene [*Schell et al.*, 2004, 2008b]. The presence of abundant agglutinated species suggests high productivity in the surface waters and less sea ice as discussed above. Conversely if there is significant freshwater input there are fewer planktic foraminifera. However, the highest number of tintinnids is found in the surface samples of both core 124 and 750 together with large numbers of planktics. It has been shown in several studies mentioned above that if the P/B ratio is close to 1:1 there is probably permanent ice. None of the intervals in these cores suggested perennial ice cover except the IRD zones in the late Wisconsinan of both cores 124 and 750, unlike the Central Arctic where a P/B ratio of between 1:1 and 1:4 is the normal condition throughout the Quaternary [*Scott et al.*, 1989a]. In the surface samples of both cores and the slope stations at 1000 m (703a, 750, 850), planktics ranged from 20 to 25% except in station 850 which is on the edge of the Mackenzie Trough [*Scott et al.*, 2008a]. At station 850 planktics were only 11% and there were abundant tintinnids, reflecting the influence of the Mackenzie River. These faunas suggest that although there was more ice, it was not perennial ice. The closest condition to perennial ice cover presently is in the Amundsen Gulf.

There, mostly in the center, planktics ranged from 16 to 50% in surface samples, especially on line 100, which runs down the center of the Gulf [*Schell et al.*, 2008b] (Figure 1). As in core 750, the planktics and calcareous species disappear but unlike core 750 they reappear a few centimeters below the surface above the IRD unit. The Mackenzie plume appears to have little influence in the Amundsen Gulf and there are few other rivers that flow into the Gulf so there are relatively few freshwater (or sediment) sources for this area [*Moss*, 2006; *Schell et al.*, 2008a].

[47] *Jennings et al.* [2002] observe significant variability in Arctic sea ice from the East Greenland Shelf using some of the same proxies we have used in this paper, the presence of IRD, isotopes, foraminiferal assemblages, but also use the presence of ice-rafted carbonate. Changes in the spacing of IRD events coincide with cooling periods with more carbonate and calcareous foraminifera where some foraminifera suggest cooling as they increase while others suggest more meltwater and a decrease in isotopic values; preliminary work with stable isotopes [*Scott et al.*, 2007] suggest no evidence of meltwater with uniformly heavy isotopic values, especially in the benthic species.

[48] The presence of Komokiacea, although the first report from the western Arctic, is not particularly surprising since they are found in deep waters around the world including the Antarctic [e.g., *Tendal and Hessler*, 1977; *Schröder et al.*, 1989; *Goody*, 1999; *Goody et al.*, 1994, 2004]. The significant factor was the overwhelming abundance of these taxa preserved in the subsurface sediments resulting from pyritization of the tests. We know of no other reported occurrence of the high numbers in fossil assemblages comparable to those observed here (>4000 individuals/ 10 cm^3 combined >45 – $63\ \mu\text{m}$ and the $>63\ \mu\text{m}$). *Goody et al.* [2004] found typical abundances of usually less than $1000/10\text{ cm}^3$ in both modern and core samples. Their presence and the corresponding pyrite in box core 750 is almost a certain indication of a brief influx of organic material: this appears to commence at the 13 cm depth in the box core which ^{210}Pb data suggest is within the last 100 years. However, the sedimentation rate appears to decrease dramatically below 30 cm down to the IRD zone (140 cm). It is not clear at this point whether there is a sediment bypass between 12,000 years B.P. and the last 100 years or just dramatically reduced sedimentation rates but the foraminiferal fauna is significantly reduced in both benthics (only a few *Trochammina* spp.) and a calcareous Arctic species (*Bolivina arctica*) with no planktics. The seismic record does not suggest any slumping so we would suggest slow sedimentation with less sea ice coverage than at present as indicated by the abundance of calcareous foraminifera in the surface sediments. However, there is certainly no sediment bypass or possibility of slumping at the core 124 site and the sedimentation rate is even less than at the slope site.

5.6. Early Glacial Movement in the High Arctic

[49] Many of the features observed on Banks Island and other nearby Arctic islands appear very similar to the drumlin-like features in the Amundsen Gulf (Figure 12).

Stokes et al. [2006] suggest a large ice stream in Amundsen Gulf on the basis of the patterns from drumlins on Banks Island but we present the first direct evidence and timing of these ice stream events as well as the actual termination of the ice stream almost to the edge of the Gulf (Figures 2 and 12). The multibeam images of the seafloor exactly match in morphology to the images of *Stokes et al.* [2005, 2006] on land but these are under water in the Gulf. The difference is that we can see exactly where the ice terminated in the Gulf, data not available to *Stokes et al.* [2005, 2006].

[50] The IRD and its dating suggest some early movement of glacial ice and ice bergs in high Arctic, comparable to some data from much farther south [e.g., *Stea et al.*, 1994]. This would mean some earlier warming here than in other Arctic areas such as the Hudson Bay where thick glacial ice remained much later. *Stokes et al.* [2005, 2006] discuss ice streams coming to the upper Amundsen Gulf around 9000–11,000 cal B.P. but these are dates from land-based glaciers. *Stokes et al.* [2005] suggest ice streams coming out of M'Clure Strait at older ages but these dates are based on correlations with IRD from Fram Strait in the eastern Arctic. The IRD unit of core 124 (12,376 cal B.P.) predates those dates and suggests movement in the Gulf much earlier than suggested for nearby land-based glaciers.

6. Summary

[51] Some of the important points are summarized below as we see them.

[52] 1. New data presented here and by *Scott et al.* [2008a, 2008c] illustrate the importance of the small (45–63 μm) fraction of the benthic foraminiferal population; without looking at these data many sections would have been almost barren.

[53] 2. A combined use of benthic and planktic foraminifera together with tintinnids provides us with a means to detect freshwater influence and sea ice cover as well as overall paleoceanographic conditions.

[54] 3. Data from other studies as well as this one suggest that high-productivity zones can be linked to lower sea ice cover, which result in higher organic flux to the seafloor, which increases the solubility of carbonate at the seafloor.

[55] 4. Data here suggest slightly more sea ice in the last 20–30 years than in at least the previous 10,000 years at the slope site (1000 m) with a large increase in calcareous species.

[56] 5. More sea ice also seems to appear just before present in the Amundsen Gulf as determined by fluctuations of tintinnids/planktics, agglutinated benthic species and increased presence of calcareous species below the upper few centimeters. This matches the record of *Schell et al.* [2008a] from other cores in the Amundsen Gulf and Beaufort Shelf.

[57] 6. The reduced presence of sea ice in the Holocene of the Beaufort Sea is reinforced by the absence of calcareous

material in the surface material of both *Vilks and Joice* [1976] and *Lagoe* [1977].

[58] 7. The opening up of the Arctic channels inferred by core records from Jones Sound does not match with any event we see in the Beaufort Sea cores which makes the obtaining of long records from M'Clure Strait all that more urgent to help determine the connection between the open Arctic Ocean and events recorded in the eastern Arctic.

[59] 8. The IRD correlations suggested by the sedimentology and magnetic measurements indicate that IRD from the two cores may be from the same source, but the two dates close to 12,500 cal B.P. in the units from core 124 indicate that these IRD units may not be coincident with those in core 750. However, this cannot be proven without clay mineralogy as has been done by *Darby* [2003] from Arctic sea ice. Nonetheless, both cores suggest earlier movement than land-based dates from previous work.

[60] 9. Studies in the Arctic Ocean to the west [*Andrews and Dunhill*, 2004; *Polyak et al.*, 2004; *Poore et al.*, 1999] suggest an Agassiz flood at \sim 11,000 cal B.P. coming from the Mackenzie River: new oxygen stable isotope data from the Mackenzie Trough dated at 11,000–11,500 cal B.P. suggest higher than present salinities, not lower, precluding any large amount of freshwater coming from the Mackenzie which is supported by the data in core 750.

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