Paleo–sea ice conditions of the Amundsen Gulf, Canadian Arctic Archipelago: Implications from the foraminiferal record of the last 200 years

Trecia M. Schell,[1] Tamara J. Moss,[1] David B. Scott,[1] and Andre Rochon[2]

Received 6 March 2007; revised 11 July 2007; accepted 28 September 2007; published 26 March 2008.

[1] Four boxcores were collected as part of the Canadian Arctic Exchange Shelf Study (CASES) in the Amundsen Gulf at water depths of 59 m to 600 m. Data from these cores help to develop a record of changes in the oceanographic history of the area over the last 200 years, with particular reference to the indication of paleo–sea ice formation, a key element of the Arctic ecosystem. The four sites cover a range of water depths and environments to provide a basis for comparison. The benthic foraminifera of sites CA-06 (253 m water depth) and CA-18 (600 m water depth) show an increase in Arctic Surface Water associated agglutinated foraminifera over the last ~100 years (uppermost 8 to 16 cm). These are indicating a decrease in sea ice cover and in cold saline Arctic Bottom Water influence; these are similar to Canadian Arctic Archipelago postglacial faunas. This contrasts with abundant planktic foraminifera at the same stations, suggesting strong, oceanic Arctic surface influence (little freshwater) in the central Gulf. The foraminifera of sites 403B (59 m water depth) and 415B (56 m water depth), at the outermost edges of Amundsen Gulf, indicate that the present-day location of the winter flaw lead has been in place for at least the last 100 years, with foraminiferal faunas similar to those of the Beaufort Shelf. Additionally, station 415 is on an earlier Holocene shoreline that is covered with cobbles.

Citation: Schell, T. M., T. J. Moss, D. B. Scott, and A. Rochon (2008), Paleo–sea ice conditions of the Amundsen Gulf, Canadian Arctic Archipelago: Implications from the foraminiferal record of the last 200 years, *J. Geophys. Res.*, *113*, C03S02, doi:10.1029/2007JC004202.

1. Introduction

[2] The ecological impacts of climate warming are a popular topic of study in today's scientific community. Previous reports by the Intergovernmental Panel on Climate Change [*Intergovernmental Panel on Climate Change*, 2001] predicted that doubling of carbon dioxide in the atmosphere would result in global average temperatures to increase by 1.5°C to 4.5°C, and perhaps up to 11°C [*Adam*, 2006]. The Canadian Arctic is suggested to be particularly sensitive to the warming and is demonstrating dramatic changes to its climate, which are evident in changes to the permafrost and sea ice cover. These changes can affect the well-being of species which depend on particular ecological processes and conditions that have been typical of this Arctic region. Changes in the Arctic climate can also affect the coastal Inuit communities of this region, whose traditional way of life is dependent on what is now a threatened Arctic environment. The Inuvialuit of Banks Island find it increasingly dangerous to hunt on the sea ice [*Ashford and Castleden*, 2001]. The extreme climactic conditions present many practical challenges to conduct research of the Arctic region. The fundamental question has always been how much of this change is ''natural'' versus anthropogenic The collection and analysis of historical as well as prehistoric changes (as defined by fossil assemblages of microfossils in these cores) in Arctic oceanography and sedimentation data is a valuable means of beginning to shape a more long-term (over 1000 years) scientific understanding of Arctic natural history and in this case sea ice cover.

[3] Over the course of a year (September 2003 to August 2004) the Canadian Arctic Shelf Exchange Study (CASES) operated the Canadian Coast Guard ship, NGCC *Amundsen* in the Western Canadian Arctic. The research activities of CASES involved the collection of a multitude of scientific data from the Beaufort Shelf ecosystem. The focus was to determine the impacts of climate warming on the biological and physical processes of the Beaufort Shelf, and to apply these conclusions on a global scale (CASES 2004). The data from our study in Amundsen Gulf, as a part of the Beaufort Shelf ecosystem, will extend this knowledge to the last few centuries.

1.1. Environmental Setting

[4] Amundsen Gulf is a 400-km-long, ~200-km-wide embayment or marine trough between Banks Island and

[1]Centre for Environmental and Marine Geology, Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, Canada.

[2]Institut des Sciences de la Mer de Rimouski, Université du Québec à Rimouski, Rimouski, Quebec, Canada.

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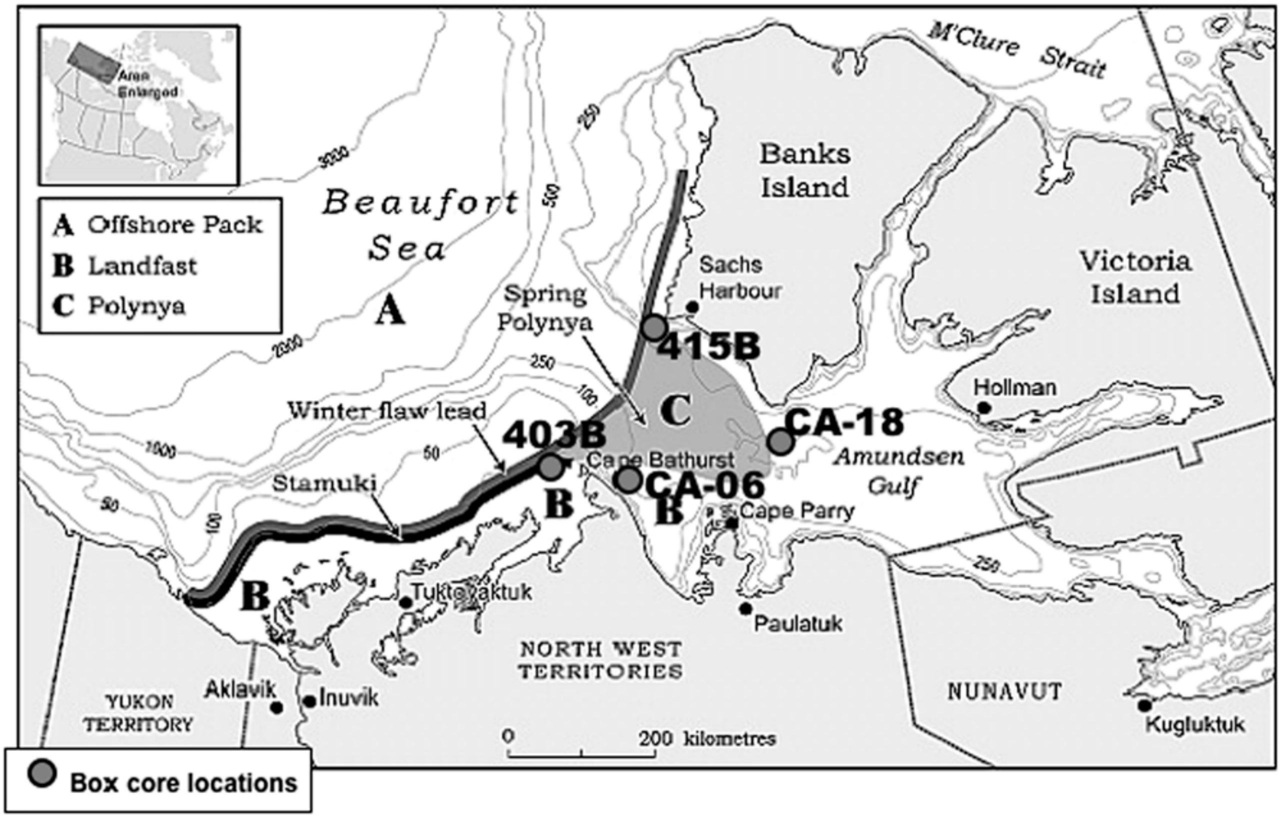

Figure 1. Location map of the 4 core sites in relation to the three sea ice regimes (a) offshore pack ice, (b) landfast ice, and (c) polynya location in the Amundsen Gulf region (modified from *Barber and Hanesiak* [2004]).

Victoria Island on the eastern side, and the Arctic mainland coast at the western shore. Amundsen Gulf is the one part of the westernmost end of the Northwest Passage, and connects the Dolphin and Union Straits, and also the Prince of Wales Strait with the Beaufort Sea, and the Arctic Ocean.

[5] The history of sea ice and glacial ice in the Amundsen Gulf area are both important factors in determining the long-term (millennial-decadal) exchange of surface waters between the Arctic Ocean, the Beaufort Sea and the Northwest Passage during the late Quaternary period. During the Last Glacial Maximum (LGM) this area was under the influence of the Laurentide and Innutian Ice Sheets, and with deglaciation several major ice streams or conduits formed including the Mackenzie River to the west (Laurentide IS), the Amundsen Gulf Ice Stream in the middle (Laurentide IS, and possibly bounded by the Innutian IS), and the easternmost M'Clure Strait–Viscount-Melville Sound (Innutian IS) [*Stokes et al.*, 2006]. In Amundsen Gulf, seafloor imagery and LandSat imagery [*Blasco et al.*, 2005; *Stokes et al.*, 2006] show the subglacial bed form evidence for several major paleo-ice streams, and their retreat. They suggest that by 11,000 calibrated years before present (cal BP) the glacial retreat was occurring, and by 10,000 calBP Amundsen Gulf was ice free (indicated by the presence and dating of the Colville Moraine, and other deposits). Thin ice stagnated, and melted in situ [*Sharpe*, 1988], possibly the cause of the deep '600 m hole' in Amundsen Gulf. These glacial outwash, or ice stream events, are similar in timing to the micropaleontological evidence from a longitudinal transect of piston cores from the Mackenzie Trough (T. M. Schell et al., submitted manuscript, 2008).

[6] Other interest in the paleoceanographic history of the Canadian Arctic Archipelago (CAA) is focused on the recent decrease in sea ice and the possibility that the Northwest Passage from Lancaster Sound to the Amundsen Gulf and Beaufort Sea may become ice-free in summer [i.e., *Lange et al.*, 1999]. Historical oceanographic measurements over the past ~50 years show that the annual temperature in

Table 1. Location of Boxcore From CASES 2003–2004 (Amundsen)

Station Number	CASES Sample Number	Latitude	Longitude	Water Depth	Sampling Device	Sample Type	Length (cm)
CA-06	2003-CA06A	70°35.489′N	127°13.568′W	253 m	boxcore	Push core	35.5
CA-18	2003-CA18A	70°39.003′N	123°04.824′W	600 m	boxcore	Push core	34.5
403B	2004-804-403B	71°06.777′N	128°18.303′W	59 m	boxcore	Push core	29.0
415B	2004-804-415B	71°54.455′N	125°52.092′W	56 m	boxcore	Push core	22.0

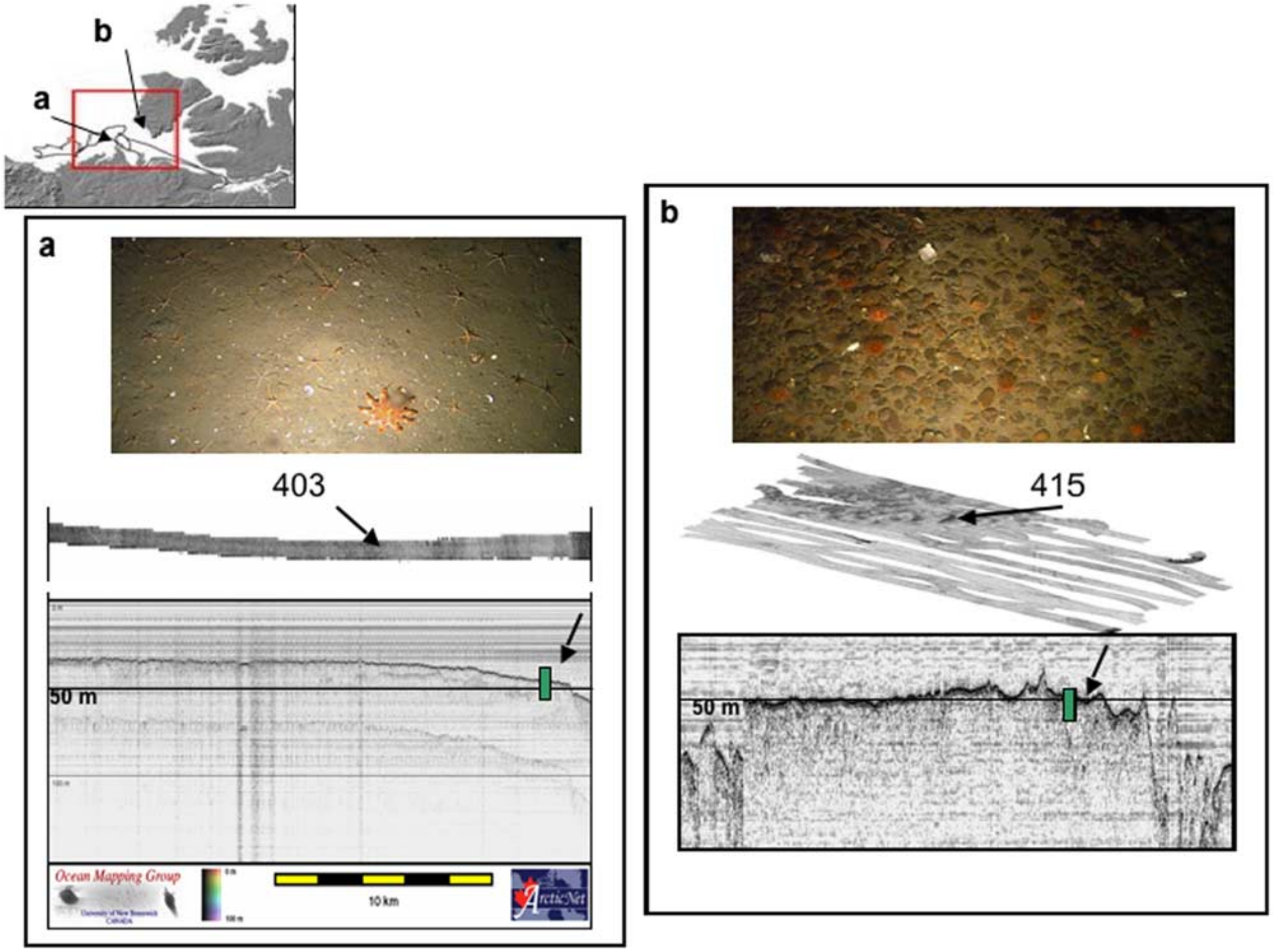

Figure 2. Seafloor images, seafloor surface backscatter images and seismic sub bottom profiles from site (a) 403B and (b) 415B.

the western Canadian Arctic has increased by ∼0.6°–1.2°C [*Overpeck et al.*, 1997] and there has been an 8% reduction in sea ice extent since 1978 [*Couture and Bancroft*, 2003]. These historical values are presently used to initialize and constrain global circulation models (GCMs) to predict future climate change in the Canadian Arctic. The results suggest that by 2070, there will be a 2° to 4°C increase in SST between Baffin Bay and the Central Arctic Ocean [*MacKenzie*, 2003]. The historical records, however, are too short to allow realistic evaluation of the GCM estimates. The palynological records from North Water Polynya (NOW) and Coburg Polynya show quasi-cyclical changes of 2° to 4°C at intervals of 1000–1500 years for the past 8000 years [*Levac et al.*, 2001; *Mudie et al.*, 2006], and archaeological evidence shows major century-scale changes in hunting modes of paleo-Inuit peoples that may reflect climate changes during the past 4000 years [*Savelle and Dyke*, 2002; *Mudie et al.*, 2005; *Fisher et al.*, 2006].

1.2. Sea Ice Cover

[7] In the winter, sea ice along the continental margin of the Beaufort Sea consists of offshore polar pack ice, shore fast ice, and first year ice that forms between the offshore and inshore zones [*Barber and Hanesiak*, 2004]. The offshore pack ice is mobile annually and multiyear in regions beyond the extent of the maximum landfast ice (Figure 1a). Landfast sea ice forms annually within the coastal margins over the continental shelves (Figure 1b). A flaw lead polynya system is usually located on the shelf break between the Amundsen Gulf and Beaufort Sea. The Cape Bathurst Polynya complex consists of series of leads and a latent heat polynya within the Amundsen Gulf (Figure 1c). Summer ice in the Beaufort Sea varies from season to season. Normally in April, a polynya develops at the entrance of Amundsen Gulf and expands toward the west. In August, the open water in a normal year may extend 180 to 300 km off the Canadian coast. However, it did not extend that far in the 2004 season. The average time of freezeups in the Beaufort Sea is the second week of October [*Barber and Hanesiak*, 2004].

1.3. Scope

[8] The scope of this work is to provide paleoecological data that aids in reconstructing the most recent (last 100 years) history of sea ice cover using (where possible) ^{210}Pb decay rates in concert with the foraminiferal and other microorganisms preserved in the boxcore sediments.

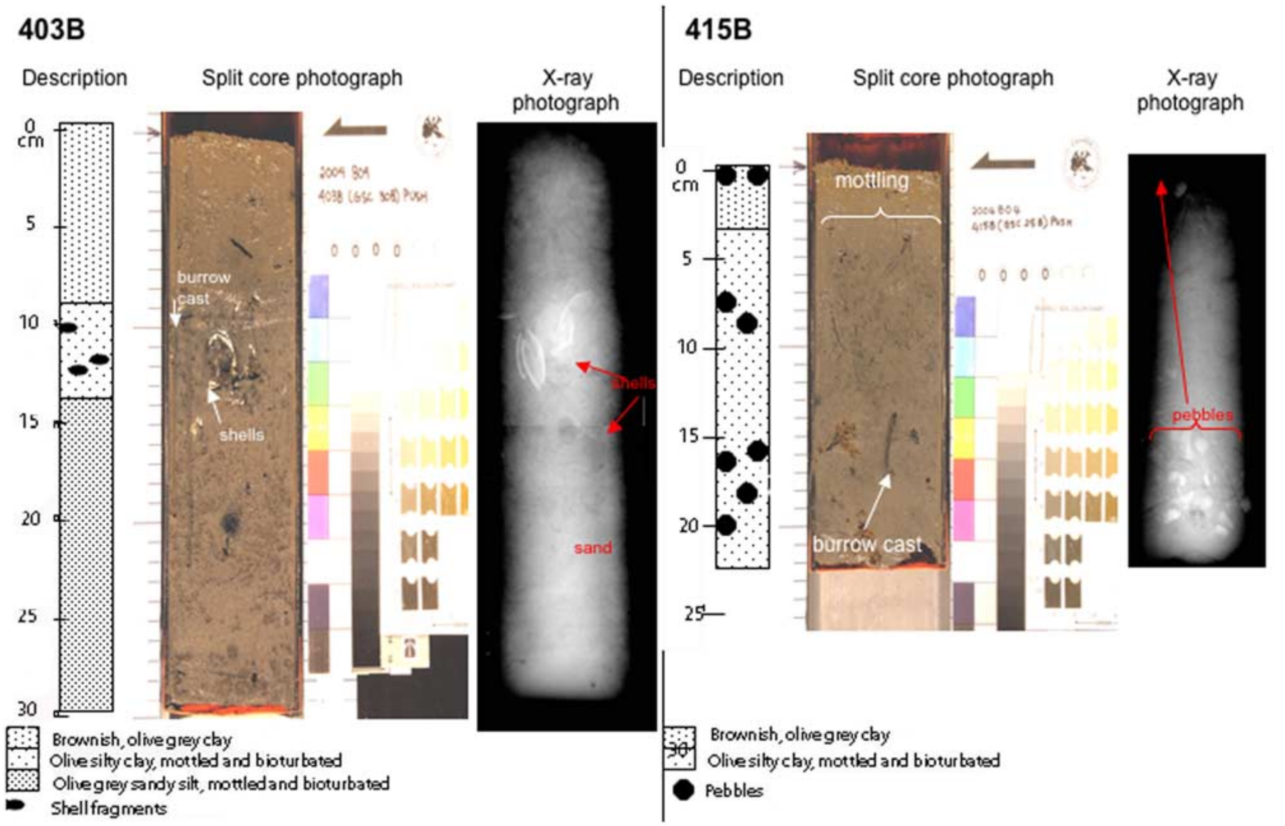

Figure 3. Sediment descriptions, core photographs and x-ray images from boxcore 403B (a) and 415B (b) (modified from *Moss* [2006]).

1.4. Previous Work

[9] An effective way of obtaining data on Arctic paleoceanography is the use of biogenic sediments, such as foraminifera, to indicate water mass boundaries and specific Arctic environments [*Schell et al.*, 2004; *Scott et al.*, 2006, 2008; *Mudie et al.*, 2005, 2006]. Oceanographic factors such as salinity, temperature, oxygen concentration, turbidity and carbonate dissolution, are influential to the distribution of foraminifera. *Overpeck et al.* [1997] used lake records, tree rings, glaciers, and some marine sediments to reconstruct the last 400 years of Arctic climate change. They were able to capture the "little ice age" as well as the subsequent warming. Also in that paper it is suggested that the last 50 years may be enhanced by anthropogenically produced greenhouse gases.

[10] Many studies of Arctic foraminifera have been carried out over the past ~150 years [*Parker and Jones*, 1865; *Cushman*, 1948; *Loeblich and Tappan*, 1953; *Phleger*, 1952, Plates 13 and 14; *Anderson*, 1963, Figures 1–13; *Marlowe and Vilks*, 1963]. *Vilks* [1964, 1969, Plates 1–3, 1976] explored the areas of the inter-island seas of Queen Elizabeth Island. *Iqbal* [1973] explored the M'Clure Strait and found assemblages to be influenced by the proximity of the Arctic Ocean and occurred in numbers 10 times higher on the continental shelf than in M'Clure Strait proper. Calcareous foraminifera are abundant in deep-sea, high-salinity Arctic waters while agglutinated (non-calcareous species) are often dominant on the Arctic and subarctic shelf and shallow seas [*Lagoe*, 1977; *Vilks*, 1989; *Schröder-Adams et al.*, 1990; *Scott et al.*, 2006, 2008]. *Scott and Vilks* [1991] found a diverse assemblage of agglutinated species at depths of 800 to 1,000 m in surface samples near the Fram Strait which corresponded to a seasonally ice free area. Several studies since then have also observed this [*Wollenburg et al.*, 2000, 2001, 2004].

[11] *Vilks* [1989] found low diversity in the calcareous species in the sediments of the Amundsen Gulf where the bottom water was within the warm and saline Intermediate Atlantic layer. *Islandiella teretis* (*Cassidulina laevigata*) was the dominant species in this area. *I. teretis* and E. ex dominated an increase in diversity toward the Princes of Wales Strait and Viscount Melville Sound. *clavatum*. This area is shallower and within the Arctic Surface Waters (ASW), which is cold and more saline. The shallow water agglutinated species *Spiroplectimma biformis* [*Vilks*, 1989; *Madsen and Knudsen*, 1994] along with *Textularia earlandi* marks the ASW [*Ishman and Foley*, 1996] and indicate a glaciomarine habitat [*Korsun and Hald*, 2000]. Shallow water environments with warmer water inflow from the Arctic Intermediate Water (AIW) are delineated by *Cassidulina reniforme* [*Ishman and Foley*, 1996].

[12] Calcareous faunas, because of the shallower and seasonally warmer water that prevents calcium carbonate dissolution, dominate the sandier and slightly shallower sediments of the Arctic Ocean continental shelf. The dominant agglutinated species are *Trochammina nana* and *Saccamina sphaerica*. The dominant calcareous species

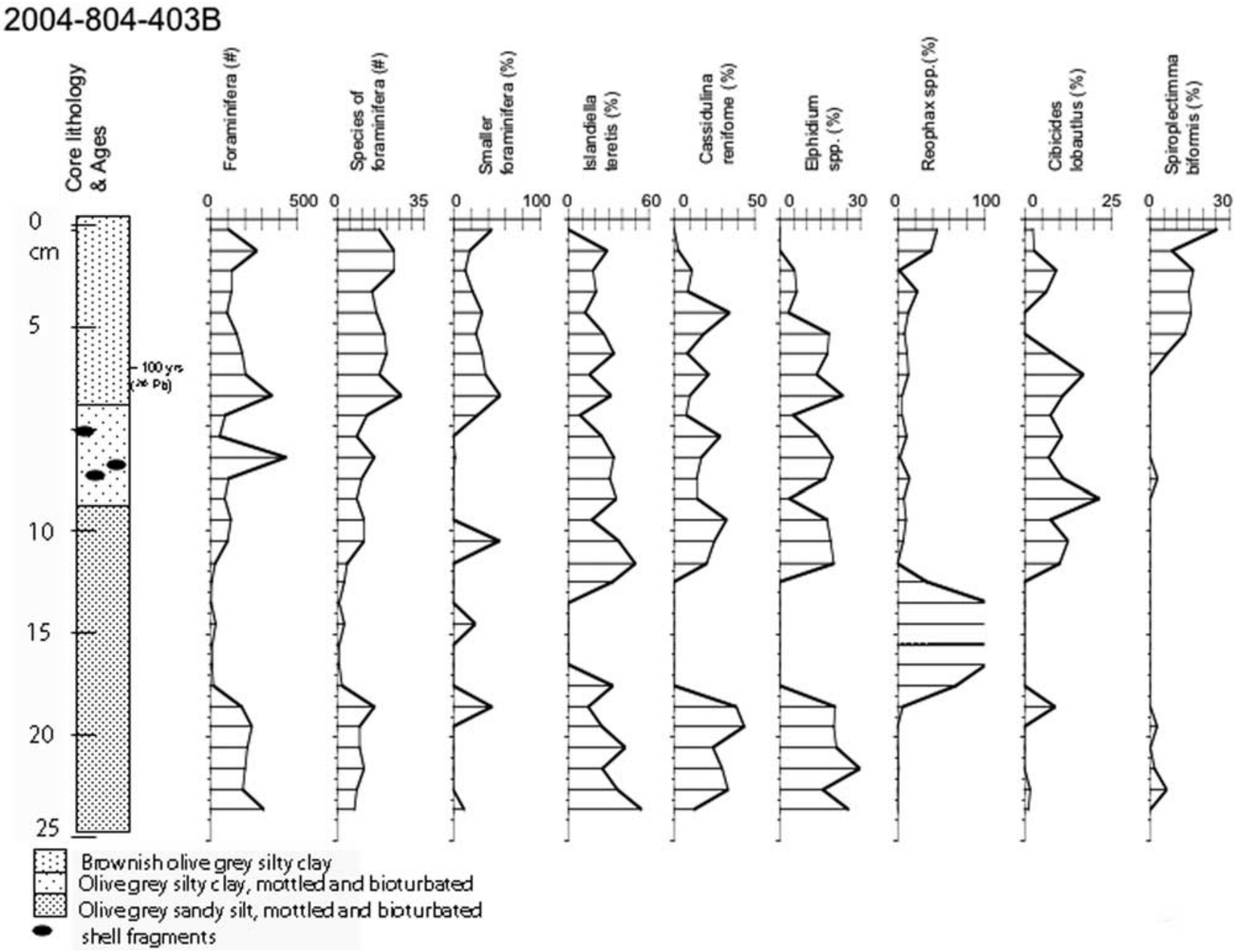

Figure 4. Core lithology, and the major foraminiferal fauna associations for core 403B (modified from *Moss* [2006]).

include *Islandiella teretis, I. norcrossi*, and *Cibicides lobatulus* [*Vilks*, 1989].

2. Materials and Methods

2.1. Fieldwork

[13] At the beginning of the CASES Overwintering Expedition aboard the *NGCC Amundsen* in September of 2003, 2 boxcores were collected in Amundsen Gulf and several more boxcore sites were added in 2004 (Figure 1 and Table 1). Suitable core sites with sufficient, relatively undisturbed sediment were chosen with the aid of seafloor surveying using Multibeam sonar, and a subbottom profiler (3.5 kHz). In 2004, in situ pictures of the seafloor were taken with a Benthos camera system (Figure 2).

[14] Upon collection, all materials were sealed, refrigerated at 4°C and stored on board until demobilization. The cores were then split, described, photographed and subsampled for various proxies (dinoflagellates, diatoms, foraminifera, and paleomagnetism) at the Bedford Institute of Oceanography's core laboratory facility. For the foraminiferal samples, 5–10 cm^3 of sediment were collected at 1 cm intervals in the boxcore. X-ray photographs of the archived core halves were taken by C. Younger (Dalhousie University), with fine-grained mammography films. These sediment cores are archived in the National Core Repository, at GSC-Atlantic.

2.2. Foraminifera Sample Processing and Analyses

[15] The sediment samples were gently rinsed with distilled water through 63 and 45 μm mesh sieves. The separated size fractions were placed into small capped plastic containers with distilled water (and ~5 mL of buffered formalin are added to top up the containers). Once counted, the samples were preserved in small glass vials held in solution containing equal amounts of distilled water and 10% ethanol (for preservation). For longer-term archiving of the counted samples ~1 mL of buffered formalin was added (for additional preservation).

[16] For statistical purposes, at least 300 specimens were counted per sample per size fraction (where found present) with a 20–40x Wild binocular light microscope. For exceedingly abundant samples, the samples were wet split following the method of *Scott and Hermelin* [1993] to obtain a manageable sample. Relative abundances are used to compare cores and only the species with relative abun-

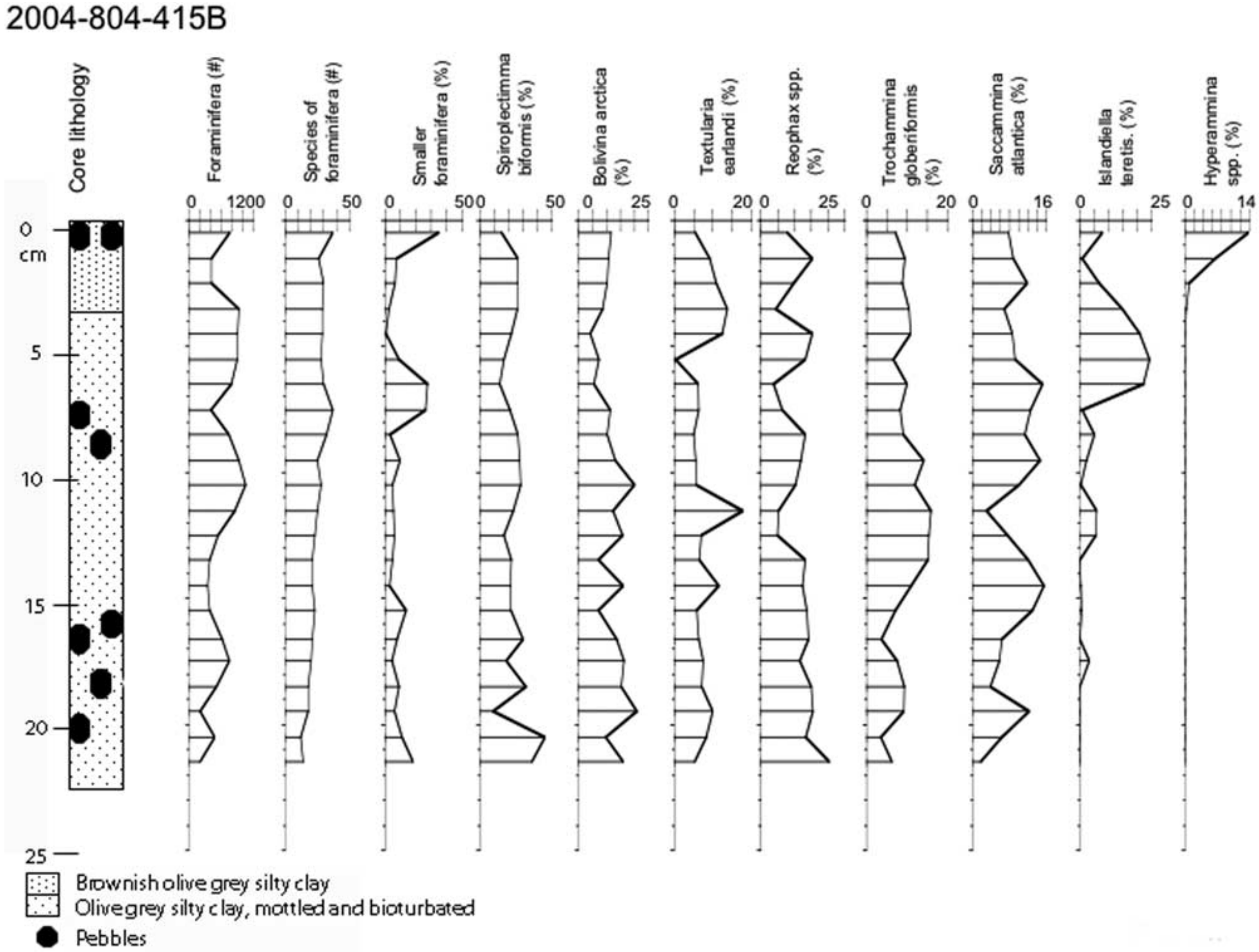

Figure 5. Core lithology, and the major foraminiferal fauna associations for core 415B (modified from *Moss* [2006]).

dance >10% were selected to simplify the abundance plots. The smaller size fraction of 45 to 63 μm has not commonly been examined in any other works from the Arctic but in this paper and others of *Scott et al.* [2008], it has become recognized as a very important part of the faunal assemblage: at times, over 80% of the sample is of the smaller size fraction and different species compositions.

3. Results and Discussion

3.1. Foraminiferal and Sedimentological Results

[17] The 29-cm-long boxcore from station 403B (56 m) was collected on the western shore of the mouth of Amundsen Gulf on the eastern fringe of the Beaufort Shelf (Figure 1). Sediments from boxcore 403B consist of an olive grey sandy mud from 29 cm to 15 cm, and a silty mud from 15 cm to 0 cm (Figure 3). The uppermost 8 cm of sediment is a slightly brownish olive grey silty mud. From 28 cm to 18 cm large burrow casts occur in the sandier portion that also contains some mud lenses. Several shells and shell fragments occur between 15.5 cm to 5 cm. These features are visible in the x-ray photographs (Figure 3). ^{210}Pb dates from a nearby site (station 406) but in deeper water (179 m) suggests a sedimentation rate of 10 cm in the last 100 years based on both Cs and ^{210}Pb decay rates; these two isotopes go to background at 10 cm (D. Amiel and K. Cochran, SUNY, personal communication, 2004).

[18] The sediments of boxcore 403B contain an average of 300 foraminifera (and 15 species, largely calcareous) per sample from 29 cm to 22 cm. Followed by a barren zone (less than 25 individuals, and 2 species, largely agglutinated) between 22 cm to 17 cm (Figure 4). From 15 cm to 0 cm the average is 100 to 200 foraminifera (and 10 to 15 species, mostly calcareous) per sample (Figure 4) with a peak in abundance at 12 cm (400 individuals). *Islandiella teretis* (30–50%), *Cassidulina reniforme* (40–50%), and *Elphidium* spp. (~30%) are the dominant species except between 24 cm to 18 cm where *Reophax* spp. range from 40 to 60% (Figure 4). *Cibicides lobatulus* is present in minor amounts (5 to 25%). From 7 cm to 0 cm the agglutinated species *Spiroplectimma biformis* (15 to 30%) appears along with *Reophax* spp. (~20%), while the numbers of calcareous species decline.

[19] The 22-cm-long boxcore from station 415B (59 m) was collected on the eastern shore of the mouth of Amundsen Gulf near the shores of Banks Island (Figure 1). The sediments of boxcore 415B consist of olive gray muddy clay with several intervals of coal pebbles (21 cm, 19–

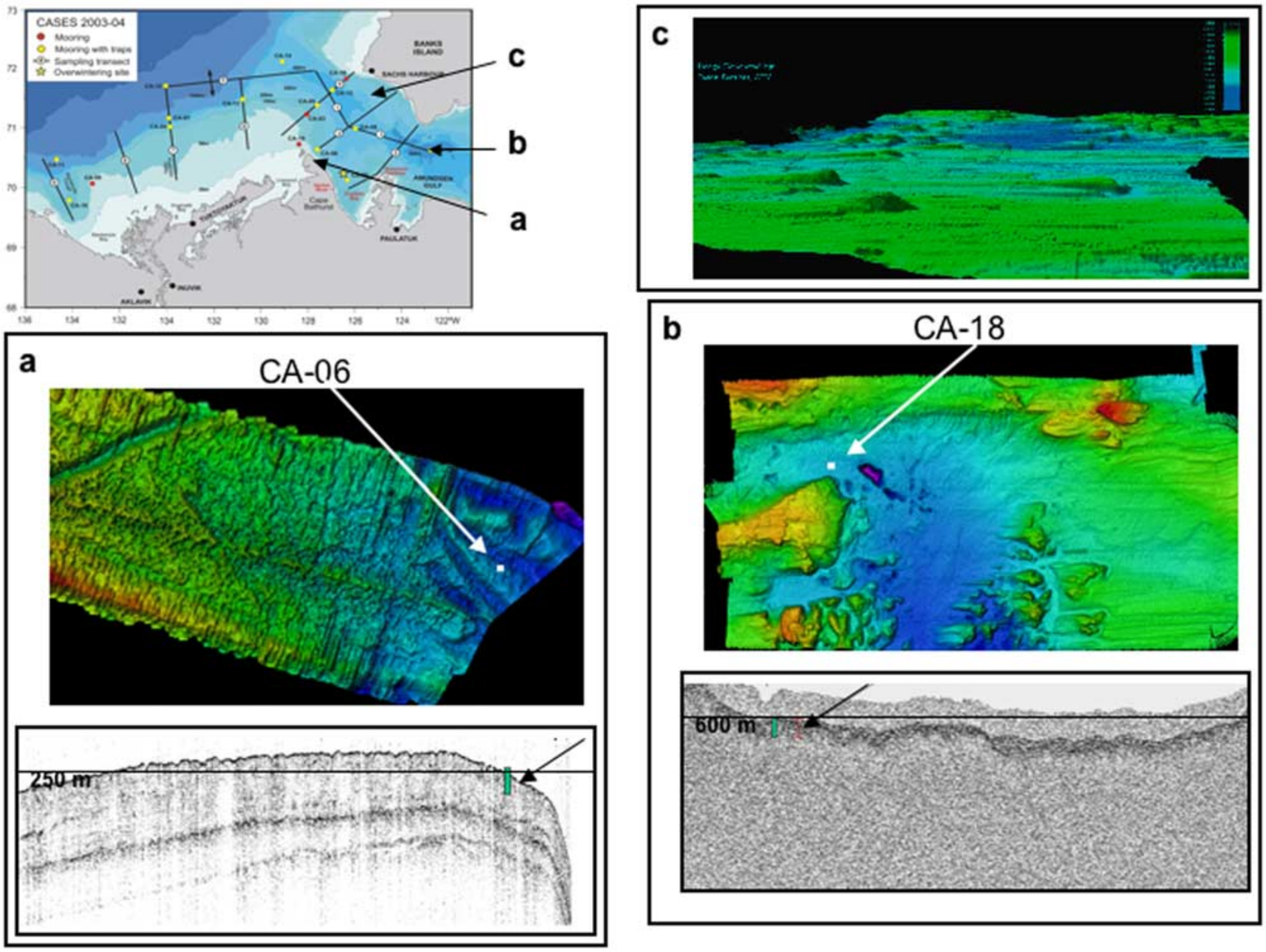

Figure 6. Swath bathymetry seafloor images of (c) the Amundsen Gulf, with additional seismic subbottom profiles in the vicinity of sites (a) CA-06 and (b) CA-18.

15 cm, and 11–6 cm, and 0 cm; Figure 3). The uppermost 5 cm of sediment are a slightly browner olive grey mud. Shells and burrow casts are found between 17.5 cm to 13.5 cm, and the sediments are bioturbated (or mottled) from 29 cm to 4.5 cm (Figure 3). Because the surface of this core appeared to be a relict shoreline no dating was done on it.

[20] The sediments of boxcore 415B contain dominantly agglutinated foraminifera (70–80%) and, averages between 400 to 800 individuals and 30 to 40 species per sample (Figure 5). The major species are *Spiroplectammina biformis* (20 to 30%), *Bolivina arctica* (15 to 20%), and *Reophax* spp. (10 to 20%). Minor species include *Textularia earlandi* (5 to 15%), *Saccammina atlantica* (8 to 16%) and *Trochammina globigeriniformis* (8 to 14%). *Islandiella teretis* ranges from 5 to 20%, from 17 cm to 0 cm, and *Hyperammina* spp. appears in the uppermost 3 cm up to 14%.

[21] The boxcore from site CA-06 was collected in 253 m of water along the western shore of the Amundsen Gulf, near Cape Bathurst (Figures 1 and 6). At this depth, the core is located at the ~200 m interface between the overlying cold, less saline Arctic Surface Waters, and the lower colder, saline Arctic Intermediate Waters. The sediments of boxcore CA-06 consist of an olive grey mud from 35 cm to 7 cm, and from 7 cm to 0 cm it is a brownish red silty mud (Figure 7). The x-ray photographs show evidence of bioturbation from 35 cm to 0 cm, and the average TOC is 9%. ^{210}Pb and Cesium dating on nearby core with a similar water depth (boxcore 309, 397 m water depth) provides a less definitive sedimentation rate because it appears that the Cs and Pb isotopes are mixed equally down to about 10 cm suggesting a slow sed-rate with bioturbation; the same appears to be the case at other the deep water sites in the Gulf (stations 117, 101, 206 (D. Amiel and K. Cochran, SUNY, personal communication, 2004)).

[22] The sediments of boxcore CA-06 contain an extremely high number of total foraminifera ranging from 8000 to 3000 individuals per 10 cm^3 sample below 11.5 cm, to 1000 to 2000 foraminifera from 11.5 cm to 0 cm (Figure 8). A ^{210}PB date of 100 years at 16 cm, with factor of 10 margin of error (D. Amiel and K. Cochran, SUNY, personal communication, 2004) provides some chronology unlike the other deep water cores. Calcareous foraminifera are dominant (80 to 100% of the fauna) up to 11.5 cm, with a transition until 7.5 cm, and after 7.5 cm to 0 cm agglutinated foraminifera dominate (almost 100%). *Tintinnopsis rioplatensis* (a brackish water cilate, or tintinnid) is most common in two intervals 34.5 cm until 29.5 cm, and 6 cm until 0 cm. Tintinnids are associated with river waters,

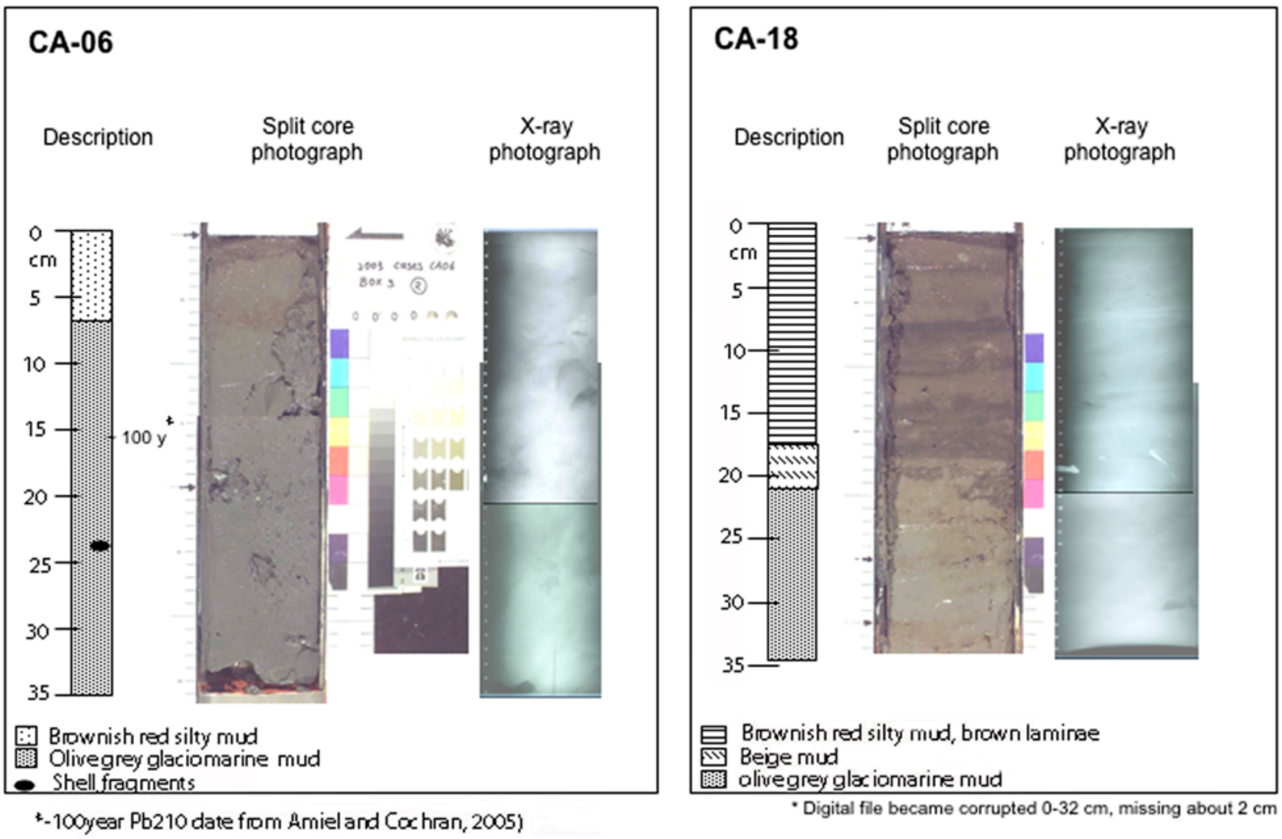

Figure 7. Sediment descriptions, ^{210}Pb date, core photographs, and x-ray images for boxcores CA-06 and CA-18.

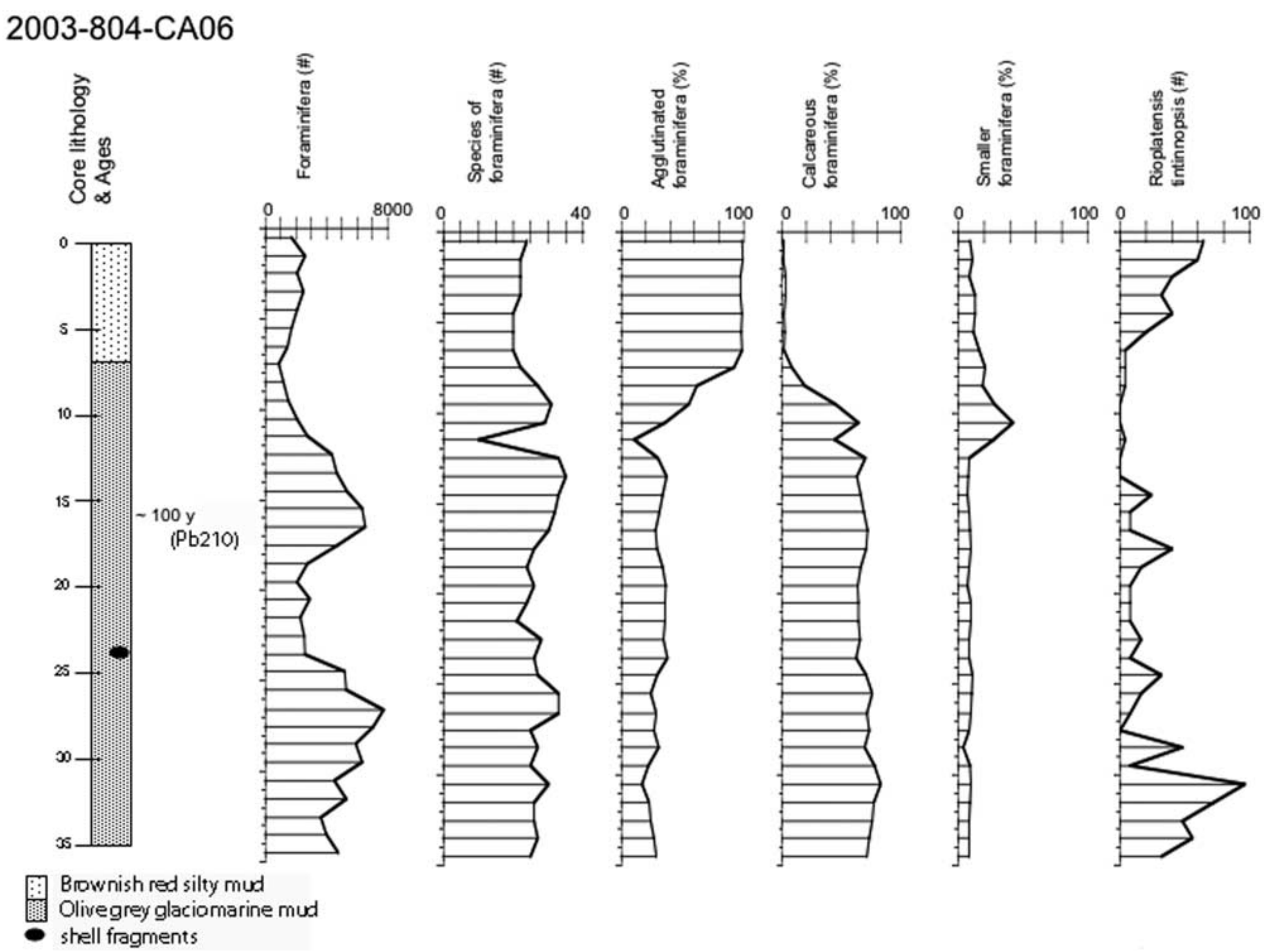

Figure 8. Core lithology, date, and major foraminifera trends in boxcore CA-06.

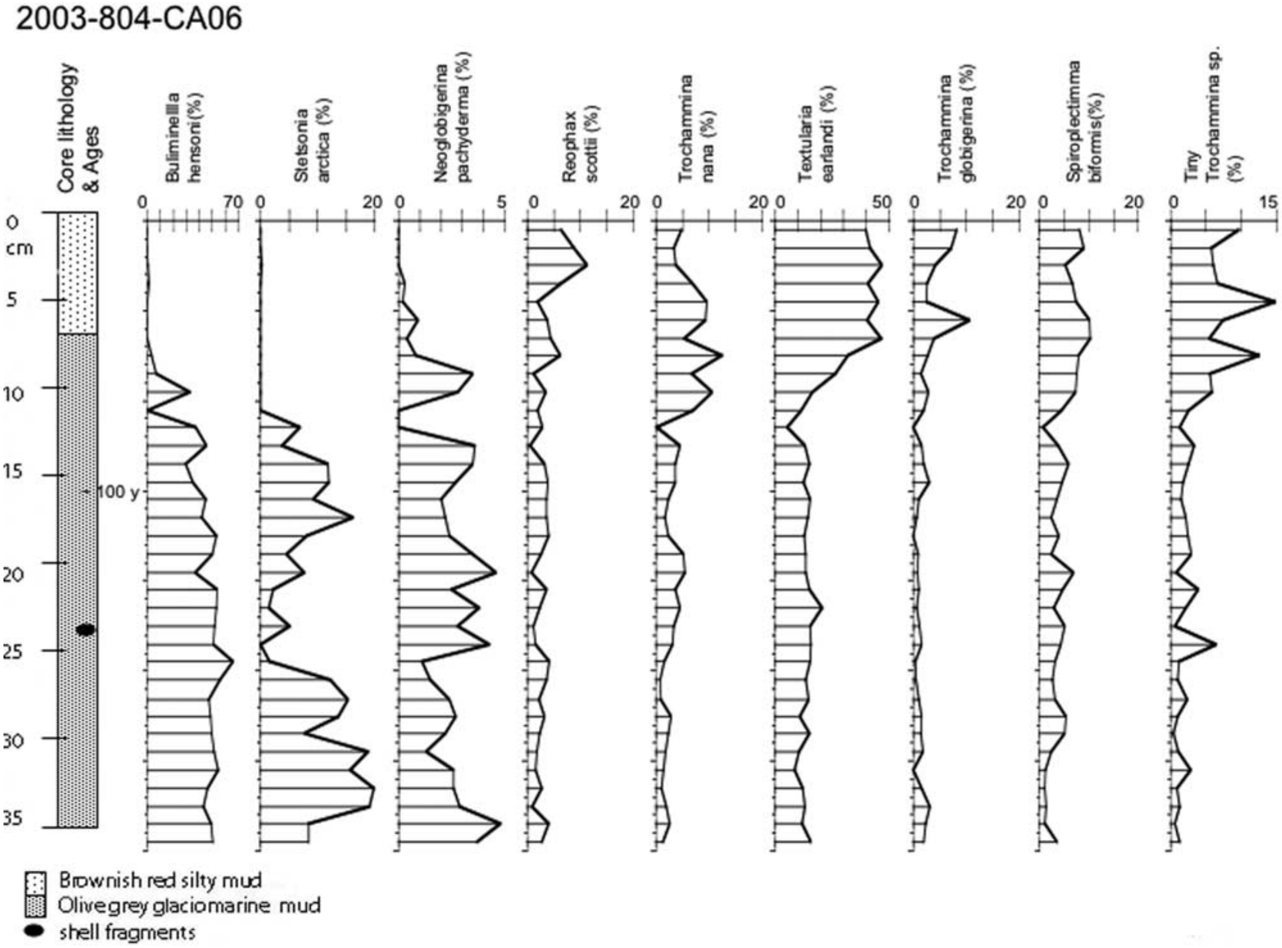

Figure 9. Core lithology and major foraminifera species found in boxcore CA-06.

and are an indicator of freshwater flux. The two endemic Arctic Bottom Water benthic calcareous species *Buliminella hensoni* (∼50%), and *Stestonia arctic* (∼20–10%), and *Neoglobigerina pachyderma* (the only planktic calcareous species) have minor presence (up to 5%) from 34.5 cm until 11.5 cm (Figure 9) with minor amounts of agglutinated species (less than 5 to 10%). Above 11.5 cm, the number of smaller foraminifera increases from 10 to 40%, and the dominant foraminifera are the agglutinated species common to Arctic Surface Waters, *Textularia earlandi* (20–50%), tiny *Trochammina* sp. (10–15%), *Spiroplectimma biformis* (∼10%), *T. globigeriniformis* (∼10%), and *T. nana* (∼10%). Together with this minor amounts of *N. pachyderma* (∼4 to 1%) are decreasing.

[24] The boxcore from site CA-18 in 600 m was collected from the middle of Amundsen Gulf, at water depths associated with the Arctic Intermediate waters (Figure 1) and also area of effluent from the Prince of Wales Sound, which connects to M'Clure Strait. The sediments of this core consist of an olive grey mud from 34 cm to 21 cm, then a light brown mud from 21 cm to 17 cm, and from 17 cm to 0 cm it is a brownish-red mud with dark brown laminae (Figure 7). The x-ray photographs show evidence of bioturbation from 34 cm to 17 cm, and from 17 cm to 0 cm it is laminated.

[25] The sediments of boxcore CA-18 contain a much lower number of foraminifera ranging from 600 to 200 individuals per 10 cm^3 sample from 34.5 cm until 8.5 cm, and ∼100 individuals from 8.5 cm until 0 cm (Figure 10). The number of tintinnids found follows the same trend (5–30 below 8.5 cm; and 5–15% above 8.5 cm). Unfortunately, we do not have any ages associated with this core. This core is almost 100% agglutinated foraminifera, and is 50 to 70% the smaller foraminifera from 34.5 cm until 8.5 cm. In this lower interval, the Arctic Surface Water species *Textularia earlandi* (35 to 20%), tiny *Trochammina* sp. (35 to 25%), *Trochammina globigeriniformis* (15 to 25%), *Saccamina difflugiformis* (∼10%), and *Trochammina nana* (∼25%) are most dominant (Figure 11). The Arctic Bottom Water calcareous species *B. hensoni* is present, but most abundant from 33 cm until 27.5 cm (∼20%), followed by the calcareous planktic *N. pachyderma* from 27.5 cm to 21.5 cm (25–10%) (Figure 12). *Islandiella teretis* (∼7%), *Cribrostomoides jeffersyi* (∼10%), *Saccamina atlantica* (∼7%), *Trochammina nana* (∼15%) and *Trochammina nitida* (∼5%) are present in minor amounts. Above 8.5 cm, *T. earlandi* (∼20%), *Trochammina globigeriniformis* (∼10–25%), *Trochammina pseudoinflata* (∼5–25%), *S. difflugiformis* (∼5–20%), *Trochammina quadriloba* (∼5–15%), and *Reophax nodulosa* (∼2–14%). *Hyperammina* sp. fragments (∼12%) are present in minor amounts.

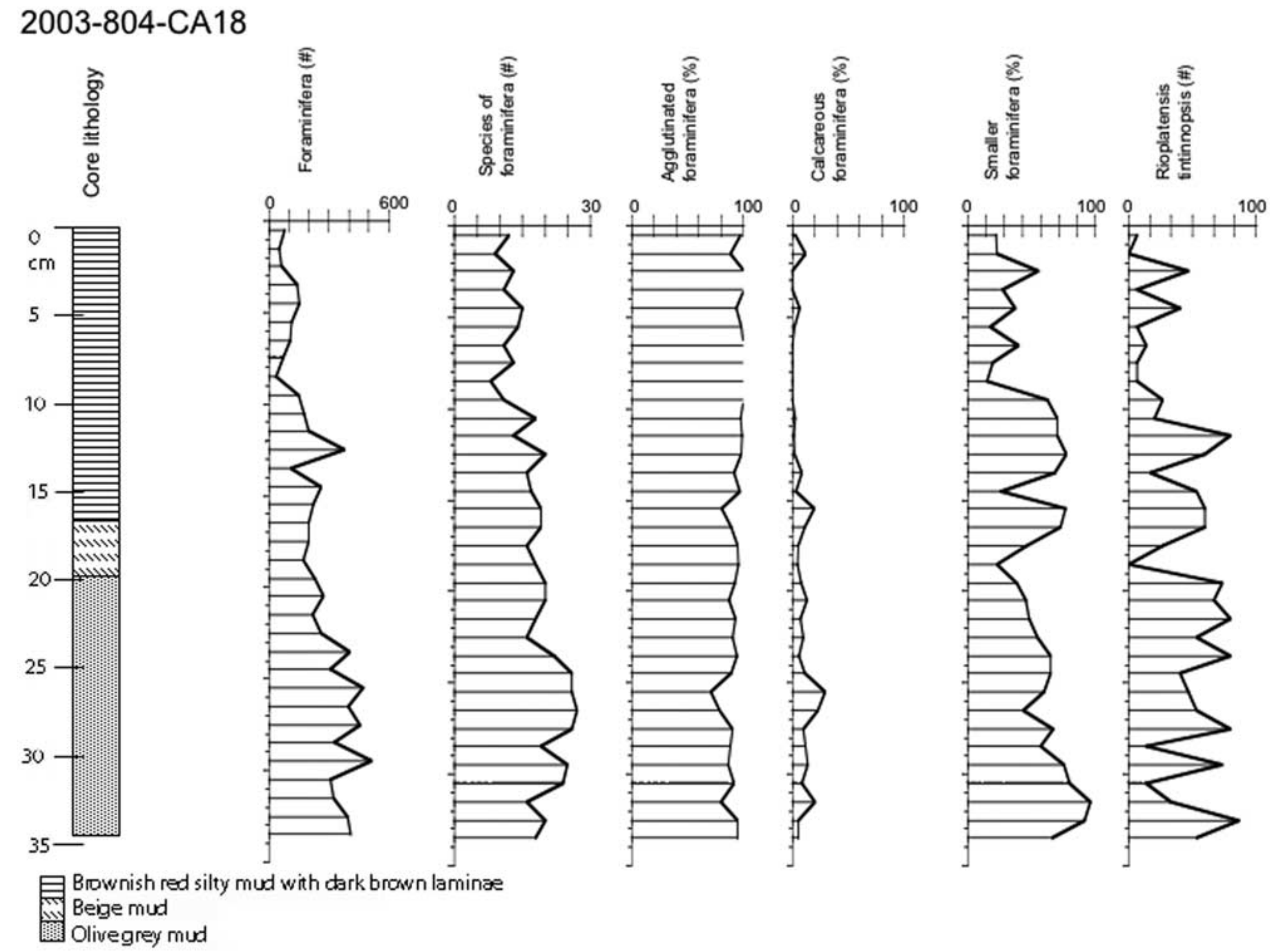

Figure 10. Core lithology and major foraminifera trends in boxcore CA-18.

3.2. Paleoecological Interpretations

[26] Site 403B is located in an area of overlap between the Beaufort Shelf and Amundsen Gulf, and is in the present-day location of the edge of the winter flaw lead (Figure 1). The smaller grain size, and bioturbation from 29 cm to 5 cm may indicate deepening environment at site 403B under a high sedimentation rate. As conditions become increasingly quiescent sediments in suspension may deposit faster but, the endobenthic faunas may not be able to accommodate the rate of aggradation (hence the disappearance of burrows and shells). The dominance of the calcareous foraminifera *Elphidium* spp., an inner Beaufort Shelf species and *Islandiella teretis* an outer Beaufort Shelf species [*Vilks*, 1989; *Scott et al.*, 2006, 2008] indicates the strong influence of the far-reaching Mackenzie River plume from 29 cm to 7 cm. From above 7 cm, agglutinated faunas common to postglacial conditions are found (*S. biformis* and *Reophax* spp.), and both species indicate an increasing influence of the Arctic Surface Water, postglacial conditions and increasing open water conditions; the ^{210}Pb dates from a nearby site (station 406) suggest this may be as recent as the last 100 years.

[27] Boxcore 415B near the Banks Island shore and located in the leading edge of the winter flaw lead. It also contains abundant burrowing and shell traces in muddier sediments than 403B. But site 415B also contains abundant, rounded coal pebbles from the nearby onshore exposed beach cliff deposits (the Smoking Hills). This site is dominated by the agglutinated foraminifera common to Arctic Surface Waters, or postglacial deposits (*S. biformis*, *T. globigeriniformis*, *T. earlandi* and *R. arctica*). Also a significant presence of *Bolivina arctica* (∼20%) occurs, a calcareous species that is not common in the present-day Arctic waters but it was during Pleistocene [*Scott and Vilks*, 1991]. In the uppermost 8 cm, a significant occurrence of *Islandiella teretis* (∼25%), is present a common outer Beaufort Shelf calcareous species, that is also common to warm, saline Arctic Intermediate waters [*Vilks*, 1989]. This core may have captured a relict or Pleistocene nearshore environment, owing to the presence of *B. arctica* and the rounded pebbles. Site 415B could be in an area of extremely low sedimentation, or active erosion such that the older deposits are covered by little sediment. Unfortunately no age dating material was obtained from this core.

[28] Site CA-06 is located on the western side of Amundsen Gulf, near Cape Bathurst and is proximal to the coast and several river sources from the Tuktoyaktuk Peninsula and Franklin Bay (Figure 1 [*Stokes et al.*, 2006, Figure 1]). The rivers' influence is apparent in the overall numbers of tintinnids and types of foraminifera present. This site is

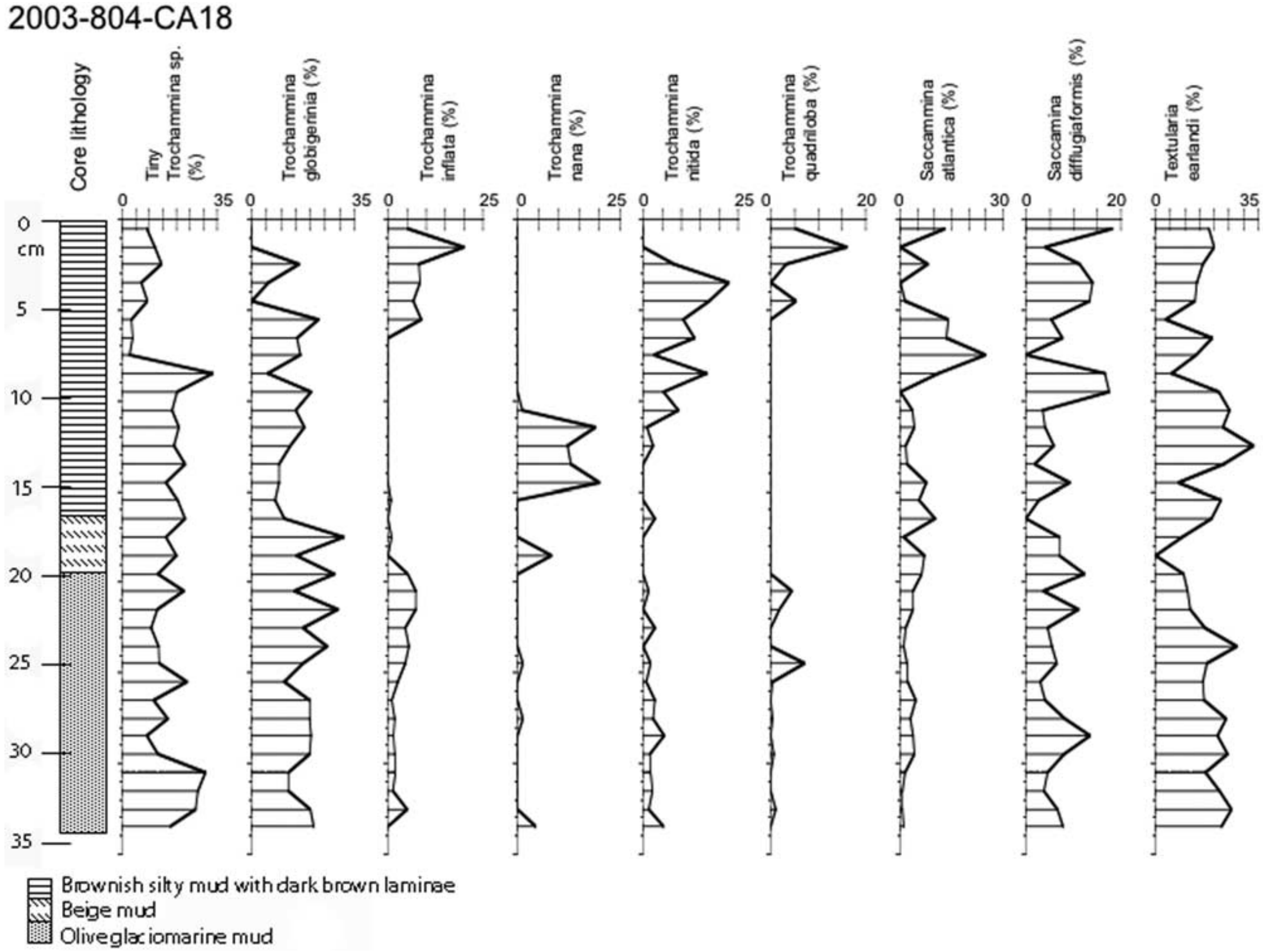

Figure 11. Core lithology, and major foraminifera species found in boxcore CA-18.

located in a region of land-fast ice formation, and is ice-covered except in the summer season. The ^{210}Pb date at 16 cm (and decreasing sediment bulk density) indicates that within the last 100 years there has been an increasing rate of sedimentation to the site. Also in the last ~100 years, the decline of the calcareous deep Arctic water foraminifera and conversely the increasing numbers of agglutinated ASW associated foraminifera and tintinnids indicates less saline (less sea ice) and more open seasonal waters.

[29] Site CA-18 is located in the middle and deepest area of Amundsen Gulf. Biologists refer to this area as "the hole," and increased biological activity has often been associated with this area such as whale feeding. This site contains an almost exclusively agglutinated fauna associated with the Arctic Surface water assemblages, particularly above 10 cm [*Vilks*, 1989; *Blasco et al.* 2005; *Scott et al.*, 2006, 2008]. Below 10 cm, a significant percentage (~20 to 25%) of deep Arctic Water calcareous foraminifera is also present despite the water depth. This bias in the faunal types may be due to preservational potential as observed in other parts of the Arctic below high-productivity areas [e.g., *Wollenburg and Kuhnt*, 2000; *Wollenburg et al.*, 2001, 2004]. In the lower unit it may reflect more sea ice at the time of deposition which limits productivity and therefore enhances carbonate preservation.

3.3. Contrasts Between the Sites

[30] These four sites represent four very different benthic/pelagic environments within the Amundsen Gulf. Site 403 represents the eastern edge of the Beaufort Shelf with high sedimentation rates and a mixture of calcareous and agglutinated foraminiferan species, but with low overall abundance. It is also the only core with significant amounts of mollusc shells and is similar to most areas on the inner Beaufort Shelf [*Scott et al.*, 2008]. Site 415 is also in shallow water but on the opposite side of the Gulf, and is located on what appears to be an old shoreline. This core has mostly agglutinated species except in the upper 5 cm where there are significant amounts of *Islandiella teretis*. Seismic subbottom profiles would indicate that deposition here was probably not continuous. The presence of a shoreline also suggests a much different sea level history between sites 403 and 415. Site 403 is situated on the edge of a delta which almost certainly is experiencing accelerated subsidence due sediment loading, while site 415 is in an essentially non-depositional environment and situated on a relict terrain (i.e., an old shoreline).

[31] Sites CA-06 and CA-18 are located in similar environments, although CA-18 is in much deeper water. The sediments of core CA-18 have a sharp lithologic boundary at 18 cm below which more planktic foraminifera and deep water calcareous benthic foraminifera occur. The sediments

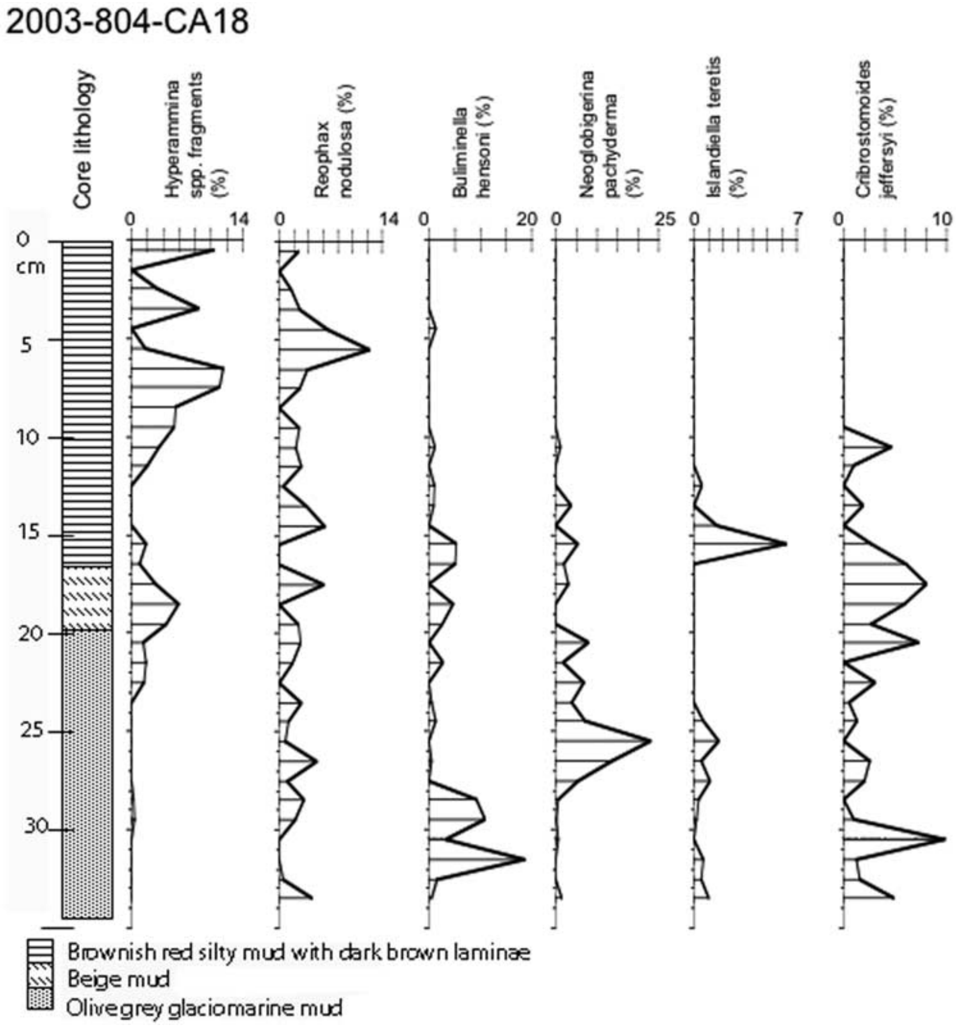

Figure 12. Core lithology, and major foraminifera species found in boxcore CA-18.

of core CA-06 have a less distinct litho-boundary in at 7 cm, but a have a sharp change in foraminiferal faunas from an agglutinated one (Arctic surface water) to a more calcareous fauna. This foraminiferal faunal suggests a time of more sea ice coverage/presence. But in both cores, there are still significant amounts of the brackish water tintinnids throughout. In short, the faunal changes in core CA-06 are very clear with a change from an agglutinated fauna (in the upper few centimeters) to a largely calcareous fauna (below 7 cm), while in core CA-18 the changes are more subtle (more calcareous species below 15 cm). The pronounced lithologic change found in core CA-18 without a faunal change, once again amplifying the fact that lithologic changes do not always reflect an environmental setting shift. In the case of site CA-18, the deeper water and the isolated "basin" nature may have dampened the bottom water environmental changes that occurred at the shallower sites. The deeper, more isolated water mass (less oxygen) at site CA-18 would certainly not have enhanced the preservation of calcareous foraminifera.

[32] In summary, these four sites provide interesting insights for determining what to expect in different parts of the Beaufort Shelf/Amundsen Gulf system. At least two of the sites that have some chronological control suggest more sea ice 100 years ago than is presently there. The core data provided from these four sites, as well as all the surface samples and piston cores, will enable us to hindcast much more accurately in terms of paleoceanography and more specifically paleo–sea ice cover.

4. Conclusions

[33] 1. The deep water area (i.e., CA-18, +500 m) of the Amundsen Gulf is less affected by changes in regional annual sea ice formation. Biological productivity has not declined in the last several 100 years.

[34] 2. The adjacent nearshore areas (i.e., CA-06, +100 m) of the Gulf, are strongly influenced by warming climate conditions with the freshening of the coastal areas as well as differential sea level changes.

[35] 3. The coastal shelf areas (i.e., 403, 415, ~50 m) at the mouth of the Gulf are responding differently to late Holocene sea level change. On the western shore (403B) sedimentation flux is high, owing to the Mackenzie River influence and open water conditions and probably increased subsidence resulting from sediment loading on the shelf. On

the eastern shore (415B) sedimentation fluxes is extremely low, or negative such that the area is actively eroding.

[36] 4. The Winter Flaw Lead formation has likely occurred in its present location between Banks Island and the Beaufort Shelf for at least the last ~100 years (i.e., sites 403, 415).

[37] 5. The ~l00 years of foraminiferal paleooceanographic proxy data show that the influence of the Arctic Surface waters has increased, and that sea ice coverage is more seasonally intermittent which agrees partly with *Overpeck et al.* [1997], who suggest that warming (here less sea ice) has accelerated in the last 50 years.

[38] **Acknowledgments.** Our many thanks to the captain and crew of the NGCC *Amundsen* for our safe passage; S. Blasco for the financial assistance in providing geotechnical support of R. Bennett and A. MacDonald (GSC-A, NRCan); the UNB Ocean Mapping Group J. Hughes-Clarke, J. Beaudoin, I. Church, and J. Bartlett (CHS) for providing the mapping images to choose our core sites; on-board student assistants B. Hill and G. Cauchon-Voyer; our core lab curator C. Younger; and D. Amiel and K. Cochrane (SUNY) for the Pb^{210} date. Thank you!

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T. J. Moss, T. M. Schell, and D. B. Scott, Centre for Environmental and Marine Geology, Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, Canada B3H 4J1. (dbscott@dal.ca)

A. Rochon, Institut des Sciences de la Mer de Rimouski (ISMER), Université du Québec à Rimouski, 310, allée des Ursulines, Rimouski, Québec, Canada G5L 3A1.