STUDIES OF SEDIMENT TRANSPORTED BY
BEAUFORT GYRE PACK ICE, ARCTIC OCEAN,
1993: CONCENTRATIONS, TEXTURAL AND
CARBON DATA

By
Michael McCormick
Peter W. Barnes

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1 USGS, Menlo Park, CA 94025
Abstract

Two sampling expeditions to the coastal and offshore Beaufort Sea to study the sediment in the ice of the Beaufort Gyre encountered high sediment concentrations. Sediment concentrations in the sea-ice obtained during the Spring expedition averaged 49.5 mg/L, but ranged up to 821 mg/L. Concentrations measured during an offshore icebreaker cruise in August and September averaged 364 mg/L and ranged up to 10002.7 mg/L in part of a subsampled core. This average concentration is an order of magnitude greater than measured during similar field efforts in 1992. Spring studies indicated that sediment was prevalent in ice offshore of the stamukhi zone while ice inshore was relatively sediment-free. Studies at the end of summer found significant concentrations found as far as 79.5°N in the relatively sparse ice pack. Much of the sediment was found in pockets on the surface of first-year ice, although laterally discontinuous bands of sediment were seen within turbid ice in core sections suggesting entrainment by anchor ice. Most of the sediment consisted of clays and silts, although a 100km-wide belt of dirty ice off Point Barrow in the Fall included sands and gravels, as well as wood and leaves. Sediment was rare in samples from multi-year ice. Sediment concentrations in snow samples averaged 56.3 mg/L in the Spring and 2.4 mg/L in the Fall suggesting that aeolian processes are not major sediment contributors to offshore ice but may be an important local contributor to nearshore ice.

Introduction

As part of a continuing effort to discern climate change in geologic history, and to understand the relationship between climate change, and the Arctic Ocean ice pack, the U.S. Geological Survey undertook two expeditions to the Beaufort Gyre in 1993 (Figure 1). The first sampled ice in April and May and was incidental to a study of methane gas concentrations in Beaufort shelf water and ice (Kvenvolden et al., in press) (Figure 2). The second used the US Coast Guard Cutter Polar Star as a base for ice sampling during the fall of 1993 (Figure 3). Operations included geophysical transects, piston and box coring, water mass sampling and analyses, and the investigation of physical characteristics of the ice pack. This report presents data concerning the last of these emphases. Preliminary reports on other research can be found in Grantz et al. (1993).

Our study of the pack ice centered on three major research thrusts; First, the quantity and type of sediment contained in the Arctic ice pack and its method of entrainment. Second, the post-entrainment fate of the sediment in the Beaufort Gyre circulation patterns (Figure 1), and the metamorphosis of the ice/sediment mixture with age. Thirdly, the effect of the sediment on visible wavelength spectral signals and the ice albedo. The first two questions have been addressed recently by Barnes et al. (1982), Osterkamp and Gosink, (1984), Kempema et al. (1986; 1989; 1993), McCormick et al. (1993), Reimnitz et al. (1987; 1990; 1992; 1993a; 1993b; 1993c ), Reimnitz and Kempema, (1987), and Clayton et al. (1990) primarily from studies of coastal areas. The effect of sediment on the albedo will be the subject of future publications.

Studies on the Beaufort Sea shelf indicate the inshore region (0-30 m; ranging down to 50 m) as the source for ice rafted sediment in the deep basin (Reimnitz et al. 1992; 1993a,c). However, only two major sediment entrainment events producing turbid ice occurred during 20 years of study (Kempema et al., 1989; Reimnitz et al., 1993e). The sediment load carried by the pack over the Canada Basin is highly variable (Reimnitz et al., 1993a, 1993c). The 1992 Polar Star cruise (McCormick et al., 1993) found little turbid ice. Considering the observed variability and the small portion of the polar ice pack that has been sampled, our knowledge is insufficient to permit generalizations about sea-ice sediment transport during interglacial times. This year's cruises were aimed at broadening that data base, determining the
Figure 1: Map of Arctic Ocean showing Beaufort Gyre and study area. Shelf areas shallower than 30m are stippled.
Figure 3: POLAR STAR 1993 Ice Stations

- Ice core only
- Bulk sample and core
character of ice rafted sediment, and to compare ice-rafted sediment with that accumulating on the sea floor today.

Methods

We took ice samples, snow samples and water samples wherever opportunities were provided during the two 1993 expeditions (Figures 2, 3; Appendix A). Global Positioning Satellites (GPS) provided navigation control for all tracklines and sample sites. Sample logs are presented as Appendices B and C.

Ice samples were taken by a variety of methods. While cruising and breaking ice, small ice fragments were scooped out of the ocean using a dip net. When on the ice, ice cores were obtained. Some cores were split into sections to determine the variability of particle content down section. In some cases, fractures occurred in the cores at points of different physical properties in the ice such as slushy layers or granular ice. In such circumstances the splits were made at these fractures, and thus appear to have been made at random intervals. Melting of ice and snow samples was accomplished in a microwave oven. Water samples were filtered through pre-weighed 0.4 μm polycarbonate filters using a vacuum pump. The salt was removed by rinsing with distilled water. Filters were then re-weighed in the laboratory to determine particulate concentration in the ice in milligrams per liter of melt water (SPM-suspended particulate matter). Filters were also examined under a binocular microscope. The density of selected ice cores was determined by comparing the volume of ice with the volume of melt water. The snow was sampled to determine differences in particulate load between sea ice and snow. Care was taken during the snow collection to avoid particulate contamination from the ship or helicopter exhaust. These samples were treated identically to the ice samples.

Larger sediment samples were obtained by scraping sediment-rich ice, melting, and concentrating the sediment by flocculation using table salt. These samples were analyzed for textural characteristics by sieving and pipetting procedures described in Galehouse (1971) and for total carbon and inorganic carbon content using a CO₂ coulometer with an induction furnace and acid digester (Huffman, 1977). Statistical analyses for texture follow Folk and Ward (1957). Organic carbon was determined as the difference between total carbon and acid-digestible carbon. Carbonate percentage was derived by multiplying inorganic carbon by 8.33, a constant which assumes all carbonate is in CaCO₃.

Sea water sampling was abandoned shortly after the start of cruise PS93. Due to the sparse ice pack, the ship was able to maneuver around floes, therefore little sediment was released from the ice by the ship. Where sampled, water was obtained from a sea-water intake forward of the ship’s discharge at about five meters depth. The water was pumped into a 20 L tank over periods of up to several hours where sediment was allowed to settle before being sampled, filtered and examined.

In order to facilitate a comparison between the sediment in the ice pack and that on the sea floor, we collected samples of the upper-most millimeter of certain box cores and of overlying water. These sediments are presumed to represent the most recent sedimentation and should contain any modern ice-rafted components.

The spring and fall expeditions use different conventions for station/sample numbers. The spring expedition's samples all have ABS93 (Alaska-Beaufort Sea 1993) as a preliminary modifier followed by a station number. The fall cruise's sample number's first modifier is PS93 representing Polar Star 1993. The second modifier is the Julian Day, followed by the station number for that day, and then the sample number. For example, sample 242-1-4 was taken on Julian Day 242, at station 1, and was the fourth sample at that station.

In addition visual observations were made of regional ice cover and types, percentages of discolored ice, thickness and extent throughout the cruises.
Results

The results of analyses are presented in Appendices D, E, and F, and are summarized in Tables 1 and 2.

Table 1. Summary of sediment concentrations of melt water and density of ice cores.

<table>
<thead>
<tr>
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<th>SPM (mg/L)</th>
<th>Density</th>
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<tr>
<td></td>
<td>n</td>
<td>Avg.</td>
</tr>
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<td></td>
<td></td>
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<tr>
<td>Ice</td>
<td>71</td>
<td>49.5</td>
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<tr>
<td>Snow</td>
<td>21</td>
<td>56.3</td>
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<tr>
<td>PS93</td>
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<td>61</td>
<td>364.7</td>
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<td>Water</td>
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<td>4.2</td>
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<td>Snow</td>
<td>2</td>
<td>2.4</td>
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</table>

Table 2: Summary of textural characteristics and carbon contents from 7 sea-ice samples collected on Polar Star 1993 cruise.

<table>
<thead>
<tr>
<th></th>
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<th>Range</th>
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<tr>
<td>Gravel (%)</td>
<td>9.1</td>
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<tr>
<td>Sand (%)</td>
<td>4.9</td>
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<td>Silt (%)</td>
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<td>Clay (%)</td>
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<td>Mean Grain Size (μm)</td>
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<td>Sorting (phi)</td>
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<td>Skewness</td>
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<td>Total Carbon</td>
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<td>Inorganic Carbon</td>
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<tr>
<td>CaCO₃</td>
<td>0.490</td>
<td>0.04-2.28</td>
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</table>

Eight broad categories of particulate matter were found on the filters. These are:

Algae: Seen as green silt-sized or finer particles, and as white powdery material.
Diatoms: 
Foraminifera: Benthic or planktic foraminifera.
Metallic Spherules: Silt to sand-sized, metallic beads.
Red specks: Glassy red, silt-sized specks of unknown affinities, but probably resulting from contamination.
Sand: Sand-sized material.
Silt: Silt-sized mineral material was seen on all filters in varying amounts.
Wood: Woody material distinct from algae.
Larvae: Crustacean larvae.

**ABS93**

71 ice samples from 31 stations yielded sediment concentrations averaging 349.48 mg/L, ranging from 0.71-821.40 mg/L (Table 1). 21 snow samples from 19 stations had sediment concentrations averaging 56.3 mg/L which ranged from 1.5-528.7 mg/L. 23 measurements of ice densities ranged from 0.8-1.0, and averaged 0.9. Many filters had large amounts of well-sorted silts, with occasional sand grains. Algae was abundant in the bottom of some cores as noted in Appendices B and D. The reader is referred to Appendix D for individual sediment concentrations, density results, and a listing of particle types on the filters.

Aerial and surface observations of the coastal and nearshore ice indicate two major zones of turbid ice concentration during our spring, 1993 observations. The ice inshore of the stamukhi zone (Reimnitz et al., 1977, 1978) was composed of first-year (FY) fast ice 130-180 cm thick, covered with 10-15 cm of snow. Occasional ridges and hummocks exposed clean-appearing ice as reflected in samples 1, 19, 27, & 30. Turbid ice was also seen in patches (less than 30% of the inshore ice cover) as represented by samples 3 & 5. When sediment was present, multiple cores at the same station indicated that the sediment was laterally discontinuous over distances of 5 or more meters. Algal discoloration was common in the bottom 5-10 cm of the ice cover.

Turbid ice was widespread in the first-year ice offshore of the inner edge of the stamukhi zone (Samples 14, 25, & 17) where ridging exposed sea ice surfaces and edges through the snow cover. Aerial estimates of turbid ice ranged from 30-80% of the ice cover. The pervasive but muted occurrence of sediment was influenced by the snow cover. The particulate matter occurred as either disseminated 10-25 cm bands within ice blocks and ice cores, or as discrete horizontal, 1mm bands of sediment also within the ice. The latter are similar to surface ablation concentrations observed in summer. Their occurrence within the ice is unusual. The offshore extent of this turbid ice is unknown except that samples from a refrozen lead and adjacent ridge more than 200 km offshore (Sample 15) had very little particulate matter.

**PS93**

The 61 ice samples' sediment concentrations ranged from 12.7 to 10002.7 mg/L with an average of 364.7 mg/L. (Table 1). Ice densities in 30 measurements ranged from 0.7 to 1.0, averaging 0.8. Sediment concentrations in 2 water samples ranged from 0.9-7.4 mg/L, averaging 4.2 mg/L. Concentrations in snow ranged from 1.1-3.8 mg/L, averaging 2.4 mg/L (Appendix D).

Total carbon values averaged 1.6% of total weight, ranging from 1.1-2.2% (Table 2; Appendix E). Carbonate values averaged 0.49, ranging from 0.04 to 2.30%.

The mean grain size of ice-rafted material was 347 micrometers although this number is skewed due to the extreme coarseness of sample 230-1 which contained 64% gravel (Table 2; Appendix F). Most samples were primarily composed of muds. All samples were poorly sorted and positively skewed.

Algae were found on many ice-sample filters. Quartz and other sand-sized fragments rarely occurred. Diatoms were rather common, while foraminifera and other biogenic components were found infrequently. Particulate matter on snow-sample filters was primarily algae, but other components were seen. Water-sample filters contained similar particulates. Core top slurries primarily contained silts and planktic foraminifera. Full results of the microscopic analyses can be found as Appendix D.
Shipboard and aerial observations showed large amounts of turbid ice throughout the first half of the cruise. A zone of extremely dirty, rotten first-year ice (represented by sample 230-1) was encountered north of Barrow to about 100km offshore. Dirty ice in this 1-4/10ths total ice cover was 8-9/10ths of the total. The sediment in this belt had concentrations of coarse grains in small patches, and commonly contained wood and leaves. Sediment was concentrated at the surface, but the ice was turbid to about 50 cm. Stations following 230-1 contained less sediment, most of which was finer grained. This sediment occurred as concentrations under a slightly frozen snow cover and was thus, commonly hidden from direct view from the passing ship. However, it was recognized that hummocks of snow covered FY ice were often slightly discolored. Close examination found sparsely separated sand grains on the surface of the frozen snow. When this was removed sediment was often found concentrated as a layer that was laterally discontinuous on the solid ice’s upper surface. Occasionally sediment was seen in clumps down core. Sediment commonly occurred in cryoconite holes and on submerged ice rams. Sediment was found in this mode as far north as 79°29’N, although as we proceeded farther north, the amount of multi-year (MY) ice increased. This ice had less sediment. The ice encountered towards the end of the cruise over the Canada Basin was very dense, multi-year and clean.

In general, there was a very sparse ice cover during the cruise as far north as 79° enabling the ship to transit through large open leads most of the time.

A brown leafy algae was seen throughout the cruise. This often was observed growing on the underside of the ice and floated to the surface as the ice was broken.

**Discussion**

The average sediment concentrations of 1993 samples were unusually large being a magnitude greater than 1992 (McCormick et al., 1993). This may partially reflect the number of 1993 ice cores sub-sampled at small intervals which included dense sediment concentrations.

Sediment concentrations showed indications of having been entrained by anchor ice. These include the findings of sediment concentrated into clumps within turbid bands of ice and the occurrence of coarse material and wood. Future analysis of enclosed fauna will test this hypothesis.

Much of the sediment sampled in 1993 was hidden from view by a thin crusty semi-frozen snow layer. This indicates that sediment in the Beaufort Gyre is not easily delineated by aerial observations when snow is present. This observation also complicates tracking of sediment pulses using visible band remote sensing.

Sediment concentrations in snow samples averaged 56.3 mg/L in the Spring and 2.4 mg/L in the Fall suggesting that aeolian processes are not major sediment contributors to the offshore ice sampled from the *Polar Star* but may be an important local contributor to nearshore ice sampled in the Spring.

Almost all the sediment seen in 1992 (McCormick et al., 1993) occurred along the southern edge of the Gyre. The 1993 cruise showed substantial sediment-laden ice in the central-western portions as well as the southern fringe of the Gyre. Little sediment seems to be present in the central Gyre.

A further difference between PS92 and PS93 concerns the amount and type of algae seen. In 1992, there was an abundance of a fine filamentous algae seen growing within the ice, often forming melt voids within the ice. Little of this algae was seen in 1993 except on the underside of the ice during the spring observations, although as noted, there was an abundance of leafy algae growing on the underside of the ice.

In conclusion, the 1992 and 1993 observations from the *Polar Star* encountered different ice regimes in terms of total coverage and sediment concentrations. These
observations suggest it is unwise to extrapolate ice conditions from one year to another.

Acknowledgments
We thank all those that helped us collect and analyze these samples. This includes the entire crew of the USCGC Polar Star and chief-scientist Art Grantz. A very constructive review by Mark McLaughlin improved the manuscript.

References Cited


**APPENDIX A - Station locations**

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude (N)</th>
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**POLAR STAR 1993**

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| PS93-230-1 | 72°52.73 | 155°46.15 | 1 | 2 | BC1 | |
| PS93-232-1 | 74°48.08 | 157°09.46 | 1 | snow | | |
| PS93-233-1 | 74°42.69 | 157°58.61 | 1 | 2 | | |
| PS93-234-1 | 74°44.46 | 157°13.47 | 3 | | | |
| PS93-234-2 | 74°44.59 | 157°13.47 | 1 | | | |
| PS93-235-1 | 74°50.69 | 156°47.89 | 1 | 2 | | |
| PS93-236-1 | 74°49.40 | 156°44.58 | 1 | 2 | | |
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| PS93-240-1 | 76°51.80 | 154°12.86 | 1 | 3 | | |
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| PS93-247-1  | 75°49.14 | 155°00.27 | 1 | 4 |
| PS93-247-2  | 75°56.39 | 158°44.76 | 2 |   |
| PS93-249-1  | 75°20.62 | 150°02.44 | 2 |   |
| PS93-251-1  | 75°35.92 | 142°05.07 | 1 |   |
| PS93-251-2  | 75°21.0  | 140°31.1  | 2 |   |
| PS93-252-1  | 73°41.42 | 143°34.64 | 2 |   |
| PS93-254-1  | 73°53.21 | 140°29.67 |   | ice |
| PS93-254-2  | 73°51.33 | 140°22.47 | 1 |   |
| PS93-254-3  | 73°52.43 | 140°36.47 |   | BC17 |
APPENDIX B - Alaska-Beaufort Sea 93 sample notes

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Vol. filtered (ml)</th>
<th>Filter #</th>
<th>Sample type</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS-93-1-1</td>
<td>850</td>
<td>426</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-1-2</td>
<td>870</td>
<td>427</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-1-3</td>
<td>765</td>
<td>428</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-2-1</td>
<td>505</td>
<td>434</td>
<td>Snow</td>
</tr>
<tr>
<td>ABS-93-2-2</td>
<td>530</td>
<td>433</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-2-3</td>
<td>795</td>
<td>432</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-3-1</td>
<td>195</td>
<td>440</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-3-2</td>
<td>790</td>
<td>437</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-3-3</td>
<td>193</td>
<td>441</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-3-4</td>
<td>490</td>
<td>431</td>
<td>Snow</td>
</tr>
<tr>
<td>ABS-93-4-1</td>
<td>294</td>
<td>443</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-4-2</td>
<td>780</td>
<td>435</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-4-3</td>
<td>425</td>
<td>430</td>
<td>Snow</td>
</tr>
<tr>
<td>ABS-93-5-1</td>
<td>101</td>
<td>444</td>
<td>Ice core</td>
</tr>
<tr>
<td>ABS-93-5-2</td>
<td>98</td>
<td>438</td>
<td>Ice core</td>
</tr>
</tbody>
</table>

Segments 20-30 and 55-65cm in ice core.

Segments 105-115 and 150-160 in ice core - can be used for density

0-10cm segment of ice core.

Snow sample at core site 1 mile southeast of Thetis ice island and north of the ice road from pad 3M to the SE tip of the island.

0-13cm in ice core.

30-41cm plus 67 -71cm in ice core.

460ml remainder decanted into vial for bulk sample (103-2-1). Thus total melt from 0-15cm section of ice core was 655ml.

(103-2-1) Bulk sample

55-75cm section of ice core.

Total melt from 0-20cm section of core was 793ml. Core hole adjacent to 93-3-2.

Upper 10cm of snow.

0-20cm section of ice core. Total melt from section was 784ml.

50-70cm section of ice core.

Snow sample of upper 10cm of snow.

0-20cm of turbid ice core. Total melt volume of core section was 751ml.

45-55cm of turbid ice core. Total melt from section was 437ml.
ABS-93-5-3 400 436 Snow
Snow sample from upper 10cm northeast of Oliktok seawater plant.

ABS-93-5-4 725 442 Ice core
Core sample of congelation ice.

ABS-93-4A-1 810 445 Ice core
0-20cm of 155cm ice core taken on Thetis ice road nearest mainland coast. Turbid ice at 8-12cm.

ABS-93-4A-2 925 446 Ice core
110-122 and 135-145cm of 155cm core.

ABS-93-2A-1 750 447 Ice core
Clean ice. Can not see granularity seen at surface of Station 93-2. Taken 1 mile from Thetis Island.

ABS-93-2A-2 750 448 & 449 Ice core
152-172 segment of ice core that had algal discoloration at 165-172cm.

Blank filter
100 450

ABS-93-6-1 800 451 Ice core
0-20cm segment of 164cm ice core with discoloration at 8-12 cm.

ABS-93-6-2 705 452 Ice core
142-162cm of core with algal discoloration in bottom 10cm. Algae stuck to the side of the filter funnel.

ABS-93-6-3 470 453 Snow
Snow sample -- Drill rig NE of this location. Contains noticeable sand particles.

ABS-93-7-1 820 454 Ice core
0-20cm of clean core offshore?? of small island where we ran into bed at base of core at 164cm. May contain sand particles.

ABS-93-7-2 840 455 Ice core
110-130cm of 164cm long core. Some slight discoloration. May contain sand particles.

ABS-93-7-3 365 456 Snow
Snow sample - drill rig to the ENE about 1km.

ABS-93-8-1 370 457 Snow
Dirty surface snow at Dunes site on East Dock Road 30m south of road.

ABS-93-8-2 470 458 Snow
Clean snow between surface discoloration and dirty snow below.

ABS-93-8-3 100 459 Snow
Dirty granular snow above the tundra surface at Dunes site.

ABS-93-9-1 925 460 Ice
Representative clear clean ice from Lake Colleen.
ABS-93-9-2  220  461  Snow
Surface discolored snow from upper 1-2cm on Lake Colleen.

ABS-93-9-3  385  462  Snow
Underlying cleaner snow above lake ice on Lake Colleen.

ABS-93-10-1  815  466 & 467  Ice core
0-20cm of 85cm-long ice core
0-10cm is clean. 10-35cm has dirty bands which are dirtiest between 15 and 25cm.
35-85cm consists of clean ice.

ABS-93-10-2  815  468  Ice core
65-85cm section was same core as 10-1.

ABS-93-10-3  675  469  Ice core
Representative cuts of 80cm-long core taken 25m away from 10-1 and 10-2. Less
 turbid than those previous core. 0-3cm clean, 3-14cm turbid, 14 to base is clean.
Blank filter  100  470

ABS-93-11-1  800  471 & 472  Ice core
0-10cm plus 70-80cm of clean ice core. 2.8m water depth Filtered very slowly.

ABS-93-11-2  785  473  Ice core
0-10cm plus 75 to 85cm of clean ice core.

ABS-93-11-3  100  481  Algae from ice core
Algae from 160-165cm at base of core.

ABS-93-12-1  780  464  Ice core
Representative sample of 85cm ice core. Turbid band at 30-35cm, clean above and
below. 14.3m water depth.

ABS-93-12-2  765  474  Ice core
Representative sample of ice core taken 25m away from 12-1.

ABS-93-12-3  75  483  Algae from ice core
Algae from base of core.

ABS-93-12A-1  200  482  Ice
Sample of turbid ice (50+% of ice) from 50x100mx10m high ice ridge between stations
12 and 13. Also took bulk sample in vial.

ABS-93-13-1  445  475  Snow
Snow sample at 20m water depth station.

ABS-93-13-2  815  478  Ice core
Clean ice core representative sample.

ABS-93-13-3  820  480  Ice core
Ridge ice core 100m to south of 13-2. Has 10% turbid ice +/- 20%.

ABS-93-14-1  815  465  Ice core
Representative sample of ice core. 0-14cm is clear, 14-18cm has slight discoloration, 18-79cm is clear, 79-85cm is turbid, 85-110cm is clear.

<table>
<thead>
<tr>
<th>Code</th>
<th>No.</th>
<th>Ice core</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS-93-14-2</td>
<td>775</td>
<td>479</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ice core</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sampled 0-20cm.</td>
</tr>
</tbody>
</table>

ABS-93-14-3 360 476 Snow sample.

ABS-93-14-4 100 477 Ice Selected turbid ice from shear ridge rubble within 50m of sta. 14. Most of sample in vail.

ABS-93-15-1 630 463 Ice Ice cuttings from 40cm-thick refrozen lead offshore.

ABS-93-15-2 not filtered Ice Sample of discolored cuttings.

ABS-93-15-3 not filtered Ice Sample of multiyear ice ridge. Looks clean.

ABS-93-16-1 905 484 Ice core 0-22cm clear ice core from east end of Endicott Causeway.

ABS-93-16-2 475 485 Snow sample.

ABS-93-17-1 605 486 Ice core Representative vertical cut of upper 60 cm of clear ice core.

ABS-93-17-2 420 487 Snow sample.

ABS-93-17-3 100 approx. 488 Algae from ice core Algal layer from 175-178cm in ice core.

ABS-93-19-1 885 500 Ice core Representative cut of clean 135cm ice core from Camden Bay.

ABS-93-19-2 890 551 Ice core Representative cut of second ice core from Camden Bay.


ABS-93-19-4 497 Algae from ice core Algal stain at bottom of core (130-135cm).

ABS-93-20-1 905 552 Ice core Representative cut of clean 135cm ice core from Camden Bay.

ABS-93-20-2 865 566 Ice core
Representative cut of clean ice core 25m west of 20-1.

<table>
<thead>
<tr>
<th>Code</th>
<th>Value1</th>
<th>Value2</th>
<th>Code</th>
<th>Value1</th>
<th>Value2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS-93-20-3</td>
<td>390</td>
<td>498</td>
<td>ABS-93-20-4</td>
<td>553</td>
<td>Ice</td>
</tr>
<tr>
<td>Snow sample</td>
<td></td>
<td></td>
<td>Non-representative dirty ice sample from ridges. Also took sample in vial.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABS-93-20-5</td>
<td>496</td>
<td>Algae from ice core</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Algae from 130-135cm in ice core</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ABS-93-21-1</td>
<td>775</td>
<td>555</td>
<td>Ice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean looking ice from Canning Delta. Layers of sediment near base.</td>
<td></td>
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<tr>
<td>ABS-93-22-1</td>
<td>740</td>
<td>556</td>
<td>Ice core</td>
<td></td>
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<tr>
<td>Clean ice core in shallow water off Canning Delta.</td>
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<tr>
<td>ABS-93-22-1</td>
<td>310</td>
<td>557</td>
<td>Snow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow sample</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABS-93-23-1</td>
<td>820</td>
<td>558</td>
<td>Ice core</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Representative sample of ice core with turbid ice from stamukhi zone.</td>
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<td></td>
</tr>
<tr>
<td>Blank Filter</td>
<td>100</td>
<td>560</td>
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<td></td>
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<tr>
<td>ABS-93-23-2</td>
<td>895</td>
<td>561</td>
<td>Ice core</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Representative sample of ice core taken 25m away from 23-1.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ABS-93-23-3</td>
<td>not filtered</td>
<td>vial</td>
<td>Ice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediment sample from the ridges.</td>
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</tr>
<tr>
<td>ABS-93-24-1</td>
<td>815</td>
<td>562</td>
<td>Ice core</td>
<td></td>
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</tr>
<tr>
<td>Representative sample of ice core from 1.6m of ice from Leffingwell Lagoon.</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABS-93-24-2</td>
<td>820</td>
<td>564</td>
<td>Ice core</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Representative sample of ice core taken 25m west of 24-2.</td>
<td></td>
<td></td>
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<tr>
<td>ABS-93-24-3</td>
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<td>565</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Snow sample</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABS-93-25-1</td>
<td>860</td>
<td>489</td>
<td>Ice core</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Representative sample of ice core from stamukhi zone.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blank filter</td>
<td>100</td>
<td>490</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABS-93-25-2</td>
<td>795</td>
<td>493</td>
<td>Ice core</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Representative sample of ice core taken 25m away from 25-1.</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>ABS-93-25-3</td>
<td>not filtered</td>
<td>563</td>
<td>Ice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-representative sample of dirty ice. Also took sample in vial.</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>ABS-93-26-1</td>
<td>775</td>
<td>491</td>
<td>Ice core</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Representative sample of 130cm clean ice core from stamukhi zone north of Cross Island.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ABS-93-26-2  800  492  Ice core
Representative sample of ice core taken 25m northeast from 26-1.

ABS-93-26-3  559  Algae from ice core
Algal layer from base of core.

ABS-93-27-1  875  494  Ice core
Representative sample of 160cm clean ice core taken south of Cross Island.

ABS-93-27-2  860  495  Ice core
Representative sample of clean ice core taken 25m north of 27-1.

ABS-93-27-3  not filtered  554  Algae from ice core
Algal material from base of core.

ABS-93-30-1  785  581  Ice core
Harrison Bay core taken in 10m water. "Thinly" turbid; upper 15cm granular.

ABS-93-30-2  875  582  Ice core
Representative ice core 5m from 30-1. Similar appearance.

ABS-93-30-3  325  583  Snow
Snow sample.

ABS-93-31-1  770  584  Ice core
180cm long ice core. Taken in Harrison Bay. Discoloration at 25-50cm.

ABS-93-31-2  840  585  Ice core
Ice core taken 5m from 31-1.

ABS-93-31-3  not filtered  586  Algae from ice core
Algal discoloration at base of core.

ABS-93-32-1  810  587  Ice core
Representative sample of ice core from 16m of water in Harrison Bay. Very dirty
cores which are variable from site to site.

ABS-93-32-2  825  589  Ice core
Ice core representative sample taken 5m from 32-1 Similar to 32-1.

Blank filter  100  590

ABS-93-32-3  435  588  Snow
Snow sample.

ABS-93-32-4  591  Ice core
Non-representative 13cm section of ice core with sediments.

ABS-93-33-1  780  592  Ice core
Clean ice core although slight and random sediments can be seen in surrounding
ridges when examined very carefully.

ABS-93-33-2  840  593  Ice core
Representative core taken 5m away from 33-1.

**ABS-93-34-1** 805 594 Ice core
Clean ice core taken at this site in 14m of water.

**ABS-93-34-2** 805 595 Ice core
Clean ice core duplicate from this site.

**ABS-93-34-3** 410 596 Snow sample.

**ABS-93-35-1** 825 597 Ice core
Very dirty ice began between last station and this one. This core is representative of one end of the variability of turbidity.

**ABS-93-35-2** 825 598 Ice core
Representative cut of second core at this site. Includes some layering.

**ABS-93-35-3** 599 Ice core
4cm of core with a lot of dirt that occurred as a nearly discrete layer. Also took bulk sample in vial.

**ABS-93-35-4** not filtered Ice sample
Selected chips and scrapes of ridge 50m south of site collected for bulk sediment sample analysis. This is in first-year ice and has not been concentrated as much as it will later this year. However there were abundant bands running at angles, presumably rafted.
APPENDIX C - *Polar Star* 93 sample notes

All Filter Numbers have the prefix 93- (i.e. 93-1). All sample numbers have the prefix PS93-. Italicized notes are notes made after visual analysis of sand fraction from grain size residue.

**AUGUST 17, JD 229**

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Vol. filtered (ml)</th>
<th>Filter #</th>
<th>Sample type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>229-1-1</td>
<td>150</td>
<td>1</td>
<td>Ice</td>
<td>Ice sample taken from dip net while underway. Mostly algae.</td>
</tr>
<tr>
<td>229-2-1</td>
<td>960</td>
<td>2</td>
<td>Water</td>
<td>Water sample taken while steaming from 1700-2000hrs.</td>
</tr>
</tbody>
</table>

**AUGUST 18, JD 230**

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Vol. filtered (ml)</th>
<th>Filter #</th>
<th>Sample type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>230-1-2(0-15cm)</td>
<td>270</td>
<td>3</td>
<td>Ice core</td>
<td>48 cm core from same station as above. Top 2 cm is dirty. The rest appears clean.</td>
</tr>
<tr>
<td></td>
<td>(15-30)</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(30-48)</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>230-1-3(0-91)</td>
<td>420</td>
<td>5</td>
<td>Ice core</td>
<td>representative sample of a whole core taken at same station. Took 1/4 section length-wise of core using circular saw. Filter may contain some rust flakes from saw blade. Top 5 cm is turbid. There are occasional mottled turbid layers below: especially from 58cm-75 cm.</td>
</tr>
<tr>
<td>230-1-4</td>
<td>None</td>
<td></td>
<td>BC slurry</td>
<td>Box core slurry from top of Box Core 1.</td>
</tr>
</tbody>
</table>

**AUGUST 20, JD 232**

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Vol. filtered (ml)</th>
<th>Filter #</th>
<th>Sample type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>232-1-1</td>
<td>645</td>
<td>7</td>
<td>Snow sample</td>
<td>Snow sample</td>
</tr>
<tr>
<td>232-1-2(0-90)</td>
<td>490</td>
<td>8</td>
<td>Ice core</td>
<td>Melt water from 90cm core of clean looking FY ice from area of minor ridging.</td>
</tr>
</tbody>
</table>

**AUGUST 21, JD 233**

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Vol. filtered (ml)</th>
<th>Filter #</th>
<th>Sample type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>233-1-1(0-10cm)</td>
<td>150</td>
<td>9</td>
<td>Ice core</td>
<td>83cm ice core taken from small floe with some ridging that showed discoloration in cross-section. Surface was covered with algae balls. 0-10 cm was slushy with algae balls; 10-27cm was clean granular ice; 27-42 cm was solid clean, clear ice; 42-52cm</td>
</tr>
<tr>
<td></td>
<td>(10-27)</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(27-42)</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(42-52)</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(52-83)</td>
<td>13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
was clear ice—mostly clean except for a 1/2 cm laminae at 48 cm; 52-83 cm composed of clean granular ice.

233-1-2  None  Bulk
Surface ice scraped off. Included many algae balls.

233-1-3  463  15  Ice core
A second core which was taken for archiving but spilled out of tube onto ice. Thus all was melted for SPM value comparison to 233-1-1.

Blank Filter  16  Blank Filter

SUNDAY, AUGUST 22, JD 234
234-1-1(0-77)  Archive core
77 cm archive core taken from top of small pressure ridge — appears clean.

234-1-2(0-10 cm)  175  14  Ice core
(10-38)  204  17
(38-80)  450  18
(80-90)  100  19
90 cm core taken from area of small ridging. Appears clean throughout. Top 10 cm is slightly slushy, and did not hold together well. The rest of the core was hard, clean, clear and granular.

234-1-3(0-50 cm)  420  20  Ice core
Ice core taken. Entire core melted to give representative SPM. Total length unknown due to fractured nature of core but is estimated to be about 50 cm long.

234-2-1  405  21  Surface ice
Surface scrapings from a small ridged ice block (2 x 2 x 2 m) that appeared dirty. Taken 30 m from station 234-1. This location could not be cored because of the unstable nature of the floe.

MONDAY, AUGUST 23, JD 235
235-1-1(0-12 cm)  200  22  Ice core
(12-30)  270  23
(30-42)  225  24
(42-60)  235  25
(60-80)  165  26
80 cm granular core taken of small pressure ridge of FY ice. Sediment was concentrated on ice’s surface, under 12 cm of old snow (0-12 cm). The core revealed sediment in clumps at 35 and 46 cm, with small speckled inclusions throughout except for the snow on top.

235-1-2  Bulk sample
Bulk sample scraped off exposed areas on pressure ridge. Appears to be all fine. Mud in mud chips and pellets. Abundant muscovite, clear angular quartz. Rare black lithoclasts, angular ?limestone, coal, and metamorphics.

235-1-3  Archive core
Archive core taken adjacent to 235-1-1. Similar in every respect.

TUESDAY, AUGUST 24, JD 236
236-1-1(0-19 cm)  315  27  Ice core
91 cm core taken from area of low ridging in discolored ice. Much of the area was covered with sediment in cryoconites but neither core taken here had concentrations of sediment - rather it was speckled throughout.

236-1-2
Bulk
Bulk sample scraped off snow and scooped from cryoconite holes. 
*Abundant clear angular quartz. Common angular black grains.*

236-1-3(0-89 cm)
Archive core
Archive core similar to 236-1-1

**WEDNESDAY, AUGUST 25, JD 237**

237-1-1(0-90 cm) 490 31 Ice core
Ice core with minor amounts of sediment distributed throughout. Melted whole sample to get a representative SPM.

237-1-2
Bulk sample
Bulk sample from cryoconite hole. Originally in pellets which broke apart during sampling. 
*Abundant clear and white quartz grains. Common micas. Possible cherts*

237-2-1 950 32 Water sample
Water sample taken from 237/2045 - 238/0945 hrs.

**SATURDAY, AUGUST 28, JD 240**

240-1-1(0-77 cm) 295 33 Ice core
77 cm core from low relief area of MY floe. Appears clean throughout but there were a few speckles of sand/silt on the top. 1/4 section melted for representative sample.

240-1-2(0-88 cm) 408 34 Ice core
88 cm core from low ridge of MY floe. Appears clean throughout but there were a few speckles of sand/silt on the top. 1/4 section melted for representative sample.

240-1-3(0-91 cm) 350* 35 Ice core
91 cm core from 2 m high ridge of MY floe. Appears clean throughout but there were a few speckles of sand/silt on the top. 1/4 section melted for representative sample. (* amount approx.)

240-1-4 3300 36 Bulk sample
Surface ice scraped off ridges. Has rare sand particles.

**SUNDAY, AUGUST 26 JD 241**

241-1-1(0-13 cm) 107 36 Core
(13-35) 225 37
(35-55) 298 38
(55-79) 250 39

79 cm core from the top of small hummocks of old? FY ice. The top 1 cm was clean but underlying it was 1/2 cm layer of sediment. Sand was speckled on top, and randomly throughout. The total core was probably about 10 cm longer - some of the core was
slushy and did not core (around 20 cm deep). A few sediment concentrations were seen in the 13-35 cm section.

241-1-2
Archive core
As above but with less sediment at the surface.

241-1-3(0-52 cm) 380 40 Core
As above - some slush missing. Not as much sediment on surface.

241-1-4
Bulk sample
Frozen sediment scraped off of small ridges. Looks fine grained. Resembles previous sediment scraped off ridges and scooped from cryoconites but this was frozen solid. The fresh snow on the surface had melted faster than surrounding areas. Composed of mud in gray pellets. Rare black and sandstone lithofragments.

MONDAY AUGUST 30, JD 242
242-1-1(0-18 cm) 235 41 Ice core
Top 5 cm has sand and silt discoloring it. Sediment sprinkled throughout with a few large clumps at 25 cm that look like pellets. Appears clean below.

242-1-2(0-5 cm) 225 44
(5-89) 300 45
Same as 242-1-1 but without clumps of sediment below surface layer.

242-1-3
Bulk sample
Bulk sediment sample scraped off ice hummocks and out of frozen cryoconite holes. Much of the sediment looks to be in pellets. Mud in pellets. Angular coal fragment and clear quartz sand. Abundant biotite. Rare rounded clear quartz.

THURSDAY, SEPTEMBER 2, JD 245
245-1-1 453 46 Ice core
245-2-2 472 47 Ice core
Two cores of clean ice from 3 m thick MY floe. Both cores were entirely melted and a representative sample of melt water filtered.

FRIDAY, SEPT. 3, JD 246
246-1-1 230 48 Ice core
246-1-2 415 49 Ice core
Representative samples of two cores of clean FY ice. Taken 10 m away from each other. No apparent sediment anywhere on floe.

246-1-3 243 50 Snow sample
Fresh snow sample from same site.

SATURDAY, SEPT. 4, JD 247
247-1-1(0-14 cm) 160 51 Ice core
(14-38) 268 52
(38-70) 225 53
Core taken from base of ridge where melting had shearing/melted away half of it. Sediment could be seen in the cross section, and was concentrated at the base of the
cut where sediment had presumably washed down off the face and accumulated in melt puddles. The ice at the base was clear indicating that this was a melt pool. The sediment was seen in clumps - perhaps old cryoconite holes or anchor ice concentrations. There was a band of clumps from 14-38 cm and at 44-50 cm. The ice was turbid from 44-50 cm.

247-1-2(0-37 cm) 328 54 Ice core
Core taken 4 meters away from 247-1-1. Sediment was seen on the ice's surface but no concentrations were seen. The core had sediment sprinkled throughout this upper section. The core was taken to see how localized the sediment concentrations in the previous core were.

247-1-3(0-85 cm) 240 55 Ice core
Core taken 30 cm away from 247-1-1. A representative portion of melt water was filtered for SPM. Overall, the core was not as turbid nor did it have as many sediment clumps as sample 1. One turbid clump at 25-27 cm.

247-1-4(0-22 cm) 295 56 Ice core
Top 22 cm of a core taken 30 cm away from sample 1 in the opposite direction to sample 3 for comparison of SPM values.

247-1-5 Bulk sample
Bulk sample from the above location. Scraped off ice and out of frozen pockets in the ice. Some turbid slush/water from the core hole was added.
*Predominantly algae. Rare angular quartz, chert, ?coal. Possible highly dissolved foraminifera.*

247-2-1 295 57 Ice core
247-2-2 325 58 Ice core
2 cores of clean MY ice taken from snow covered floe with minor ridging.

MONDAY SEPT. 6, JD 249
249-1-1(0-73 cm) 370 59 Ice core
Clean core of MY ice. Top 10 cm slushy, then crystalline.

249-1-2((0-89 cm) 345 60 Ice core
Same as sample 249-1-1

Blank filter 200 61 Blank filter

WEDNESDAY SEPT. 8, JD 251
251-1-1(0-90 cm) 355 62 Ice core
Clean ice core from MY floe. Top 10 cm granular, but could have been recrystallized windblown snow.

251-2-1(0-70 cm) 270 63 Ice core
Clean MY core from small hummock.

251-2-2(0-70) 475 64 Ice core
Clean core from small hummock of MY floe. Taken 30 m from sample 1.

THURSDAY SEPT. 9, JD 252
252-1-1(0-86) 410 65 Ice core
252-1-2(0-92) Archive core
2 clean cores from MY floe with low hummocks. Cores taken from top of hummocks.

**SATURDAY, SEPT. 11, JD 254**

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<th>Date</th>
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<th>Temp</th>
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<td>325</td>
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<td>New frazil ice scooped with dip net.</td>
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<td>280</td>
<td>67</td>
<td>Ice core</td>
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<td>Core of very old MY ice. Very hard and clean. Comes from a floe 3 m thick but with only 30 cm of freeboard.</td>
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<td>Box core slurry from Box core 17.</td>
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*Abundant planktic foraminifera.*
## APPENDIX D - Filter summary and density results

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<tr>
<th>Sample #</th>
<th>SPM (mg/L)</th>
<th>Density</th>
<th>Notes</th>
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<tbody>
<tr>
<td>ABS-93-1-1 (20-30,55-65cm)</td>
<td>2.62</td>
<td>0.96</td>
<td>silt, wood, algae</td>
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<tr>
<td>ABS-93-1-2 (105-115,150-160)</td>
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<td>0.98</td>
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<td>ABS-93-1-3 (0-10)</td>
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<td>ABS-93-2-2 (0-13)</td>
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<td>ABS-93-2-3 (30-41,67-71)</td>
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<td>ABS-93-3-3 (0-20)</td>
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26
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**POLAR STAR 1993**

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APPENDIX E - *Polar Star* 1993 carbon results

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APPENDIX F - *Polar Star* 1993 grain size results

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<th>% sand</th>
<th>% silt</th>
<th>% clay</th>
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<th>skew.</th>
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* Box core top slurries.
** Algae from ice.