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ANIMIDA Task 5

Sources, Concentrations and Dispersion Pathways for Suspended Sediment in the Coastal Beaufort Sea

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EXECUTIVE SUMMARY

The Arctic Nearshore Impact Monitoring in the Development Area (ANIMIDA) Program was developed to monitor potential environmental changes related to oil and gas development in the Beaufort Sea with a special focus on the Northstar and Liberty developments. A variety of biological and chemical studies were included in the ANIMIDA Program. This report presents the results from study of suspended sediment. The study was designed to address the possibility that oil and gas activities might increase levels of suspended sediment in the coastal Beaufort Sea.

The concentrations and composition of suspended particles in the coastal Beaufort Sea directly influence a variety of important processes including the following:

(1) Penetration of light in the water column and the rate of primary productivity.
(2) Transport and fate of trace metals and organic substances in the water column.
(3) Adsorption of dissolved trace metals from seawater and partial control of concentrations of the more biologically available dissolved metals.

To better understand the sources and distribution of suspended sediment as they relate to the diverse processes listed above, the goals for this Task 5 study included the following:

(1) Determine the amounts and composition of suspended sediment carried to the coastal Beaufort Sea by the Sagavanirktok, Kuparuk and Colville rivers.
(2) Determine the concentrations, distribution patterns, composition and fate of suspended particles in the coastal Beaufort Sea, especially in areas such as Northstar Island and Liberty Prospect where construction activities now or in the future may influence concentrations of suspended sediment.

One goal of this effort was to understand the importance of river inputs and storm activity to the transport, distribution, composition and fate of suspended sediment in the coastal Beaufort Sea. In other words, natural processes and natural variations in levels of suspended sediment must be understood before attempting to identify anthropogenic perturbations. Field activities for this Task 5 study included sampling rivers during spring breakup in May-June 2001 and 2002 (Figure ES-1), through ice sampling of the Beaufort Sea during spring floods (2001 and 2002) and sampling rivers and offshore waters during the open-water periods of June-August 2000, 2001 and 2002.

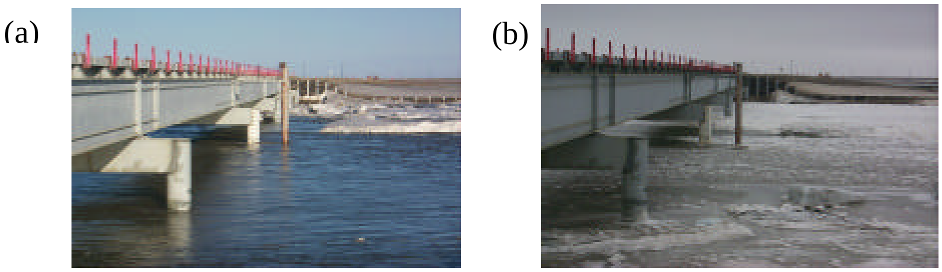


Figure ES-1. The Sagavanirktok River at a bridge near the Prudhoe Bay Operations Center (a) flowing on May 22, 2002 and (b) re-frozen on May 29, 2002.

Rivers are an important source of water and sediment to the study area during the period of spring runoff and on an annual basis. Determining the amounts and composition of river-borne suspended sediment was a key task during 2001 and 2002. The Sagavanirktok River was sampled daily during late May and June and the other two rivers were sampled every two to five days as logistics permitted. Samples of water and suspended sediment from the Sagavanirktok River also were collected at mile 401 on the Dalton Highway and at a gauging station maintained by the U.S. Geological Survey, about 100 miles south of Deadhorse (mile 327 on the Dalton Highway).

Concentrations of total suspended solids (TSS) in the Sagavanirktok River near the Prudhoe Bay Operations Center (PBOC) increased from ~40 mg/L on June 1 when flow began to 600 mg/L on June 12, 2001, and then decreased to ~30 mg/L by June 18 (Figure ES-2). During late July and August 2001, concentrations of TSS were ~2 mg/L. Concentrations of TSS followed similar trends for the Colville River with maximum levels of about 600 mg/L on June 13, 2001. In contrast, concentrations of TSS reached peak values of only 60 mg/L in the Kuparuk River on June 10, 2001 and decreased to <5 mg/L after June 16, 2001. Peak flow recorded for the Kuparuk River was about 600 m^3/sec on June 12, 2001, decreasing to <50 m^3/sec after June 28, 2001. During 2002, the same trend of increasing concentrations of TSS was observed; however, freezing temperatures led to refreezing of the rivers and put a hiatus in the spring flood for the Sagavanirktok River (Figure ES-2). However, the dramatic two-day flood of the Kuparuk River in 2002 occurred during the period prior to refreezing.

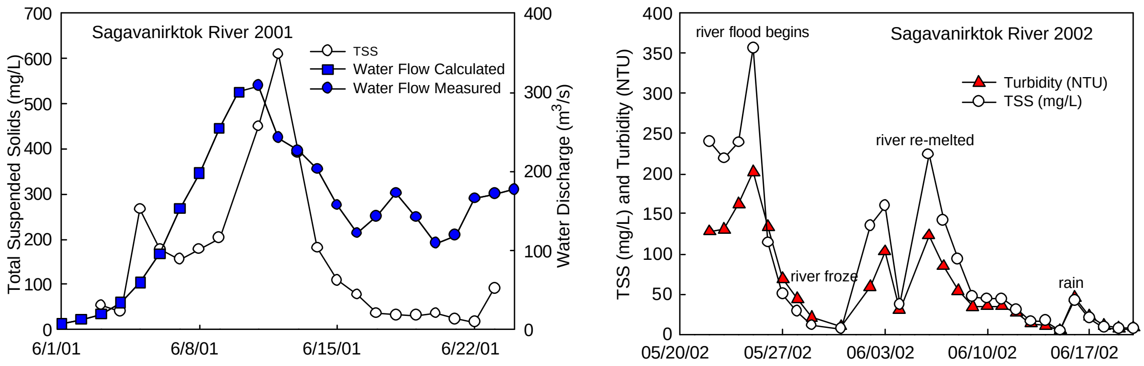


Figure ES-2. Water discharge (from U.S. Geological Survey), turbidity and concentrations of total suspended solids (TSS) in the Sagavanirktok River near the Prudhoe Bay Operations Center during May-June 2001 and 2002.

For the Sagavanirktok River, the calculated annual sediment transport was ~0.33 million metric tons for 2001, with ~87% of the annual transport of suspended sediment occurring during just 12 days in June. Total transport of suspended sediment by the Kuparuk River was 0.02 million metric tons for 2001 with ~90% of the annual sediment load of the river being carried during just three days in June. Previous estimates for the Colville River of 5 million metric tons of sediment per year are supported by recent measurements during high flow. These natural inputs by rivers can be compared with ~1.6 million metric tons of sand and gravel used to construct Northstar Island [(800,000 yd^3 x 0.76 m^3/yd^3 x 2.6

metric tons/m^3 = 1.6 million metric tons). Coastal erosion also is an important source of sediment to the coastal Beaufort Sea, including the ANIMIDA study area. Estimates from previous studies state that coastal erosion may contribute sediment to the coastal Beaufort Sea at levels that are equal to or several times greater than inputs of sediment by rivers. Studies of erosion were not part of the ANIMIDA program; however, available results are reviewed in this report.

Samples of suspended sediment also were collected under the ice, seaward of the rivers during the early days of spring runoff in 2001 and 2002 when the coastal Beaufort Sea was still ice covered. Concentrations of TSS averaged ~40 mg/L in a 2-m thick lens of freshwater immediately under the ice that extended >10 km offshore (Figure ES-3). The suspended sediment was very rich in fine-grained aluminosilicates as shown by the levels of Al and other metals in the particles. Metal/Al ratios in suspended particles collected under the ice showed that the composition of river-borne particles was similar to that found for bottom sediment.

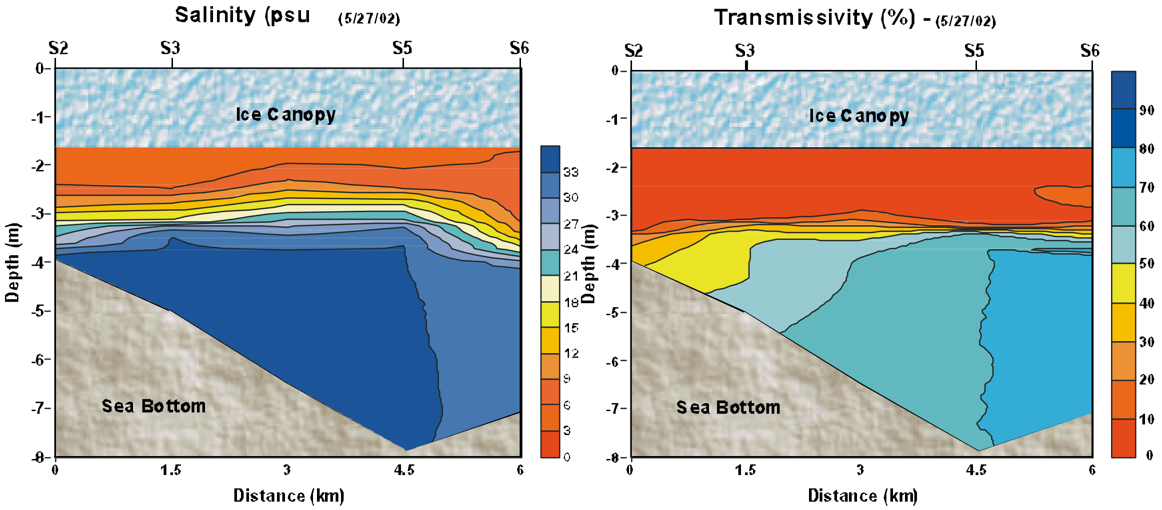


Figure ES-3. Vertical profiles for salinity and transmissivity (turbidity) along a transect (distances on lower x axis) seaward of the Sagavanirktok River for May 27, 2002.

During the open-water period in 1999-2002, numerous vertical casts and horizontal tows in the water column were made throughout the coastal Beaufort Sea to measure turbidity, salinity, temperature and current speed and direction. Turbidity was measured by in situ turbidimeter, by laboratory turbidimeter using discrete samples and by filtration/gravimetry using discrete samples.

The day-to-day turbidity and distribution of TSS in the coastal Beaufort Sea were dependent on river flow, ice cover and sea state. In the protected, relatively quiescent waters under ice during most of the year, levels of TSS were low at a few tenths of a milligram per liter relative to average levels of ~40 mg/L in surface waters under the ice during the spring floods. During the brief open-water period, after the spring floods, concentrations of TSS were typically <20 mg/L and varied as a function of sea state and the presence of floating sea ice. Sea state was directly related to the strength and duration of winds. Concentrations of TSS increased to >50 mg/L during the summer only following a period of several days with winds greater than 20 knots. In contrast, levels of TSS <2 mg/L were observed under conditions where calm water had prevailed for several days. This later condition was most likely to occur when floating ice dampened any wind effects. No significant deviations in levels of turbidity were observed adjacent to Northstar Island during 2000-2002 while towing a turbidimeter-CTD package along transects at distances as close as 100-500 m from the island.

The chemical composition of river suspended sediment was compared with results for bottom sediment to help identify possible anthropogenic inputs of suspended sediment or contaminant metals to the coastal environment. Differences in the elemental composition of suspended sediment were observed among rivers. The Colville River contained greater amounts of particulate Al, Fe and trace metals relative to the more Ca-rich particles of the Sagavanirktok River and the more organic carbon-rich particles of the Kuparuk River. However, the metal/Al ratios for all elements, except Ca, were not significantly different among rivers and bottom sediment from the coastal Beaufort Sea.

Concentrations of trace metals also were determined for samples of suspended matter collected from the coastal Beaufort Sea. The fine-grained aluminosilicates suspended in the water column were enriched with Al and trace metals. However, concentrations of most metals in suspended sediment for 2000 and 2001 plotted within the 99% prediction intervals for metals versus Al that were developed using data for bottom sediment. Thus, in most instances, concentrations of trace metals associated with suspended particles were within the limits established for uncontaminated sediment. Suspended particles are potentially a more sensitive indicator of recent metal contamination than sediment because the small amounts of suspended particles typically found in the water column lead to a larger relative enrichment of anthropogenic metal concentrations. This sensitivity was demonstrated with several samples of suspended sediment that were collected very near Northstar Island during construction in August 2000 and contained Pb at levels that were 20-50% above background.

With respect to sedimentation, the ANIMIDA area appears to be a net erosional environment at this time. Based on our observations, much of the large sediment load of the rivers is carried across the nearshore environment to deeper waters of the Beaufort Sea along a freshwater channel under the ice during spring or with summer and fall storms. Therefore, sediment monitoring for contaminants must be coordinated with measurements of radionuclides such as ^{137}Cs, excess ^{210}Pb, ^{234}Th or ^{7}Be that help ensure that samples are recent and not relict deposits.

Overall, no significant differences in concentrations of TSS that could be directly linked to oil and gas operations were observed in the ANIMIDA area. Periodic enhancement in levels of TSS in the coastal Beaufort Sea can be related to river runoff and resuspension of bottom sediment by strong winds. Natural inputs of suspended sediment from runoff and erosion are large relative to any anthropogenic inputs of sediment.

1.0 INTRODUCTION

The Arctic Nearshore Impact Monitoring in the Development Area (ANIMIDA) Program was developed to monitor potential environmental changes related to oil and gas development in the Beaufort Sea with a special focus on the Northstar and Liberty developments. This report presents the results from study of suspended sediment. The study was designed to address the possibility that oil and gas activities might enhance levels of suspended sediment in the coastal Beaufort Sea. Suspended sediment were collected from three area rivers and an area of coastal Beaufort Sea that encompassed the Northstar and Liberty developments (Figure 1-1).

The concentrations and composition of suspended particles in the coastal Beaufort Sea directly influence a variety of important processes including the following: (1) the penetration of light in the water column and thus the rate of primary productivity, (2) the transport and fate of trace metals and organic substances within the water column and the ANIMIDA study area, and (3) adsorption of dissolved trace metals and organic substances from seawater and, thus, partial control of the concentrations of the more biologically available dissolved fraction. The chemical and mineralogical compositions of suspended particles also provide a sensitive tracer of contaminant inputs and the cycling of organic carbon. During Phase 1 (1999-2000) of the ANIMIDA Program (Boehm et al., 2001) a good overview of the distribution and composition of suspended particles in coastal water was developed. The key conclusions of that work are as follows: (1) after the spring runoff from the rivers subsides, the concentrations and distribution of suspended sediment during the open-water season appear to be a function of wind conditions, water currents and water depth, and (2) the composition of suspended particles during the open-water season appears to match that of river suspended sediment and the fine-grained fraction of bottom sediment.

Based on the results of the suspended sediment component of the Phase 1 effort, several goals were established for the Task 5 of the Phase 2 study (2000-2002) that specifically focus on suspended sediment. These goals include the following:

(1) Determine the annual amount of suspended sediment carried to the coastal Beaufort Sea by the Colville, Kuparuk and Sagavanirktok rivers.

(2) Determine the major element, trace element and organic carbon content of river-borne particles.

(3) Continue to develop a picture of the concentrations, distribution patterns and composition of suspended particles in the coastal Beaufort Sea.

(4) Monitor the distribution and composition of suspended particles in the area of Northstar Island during the period of start-up and continuing operation.

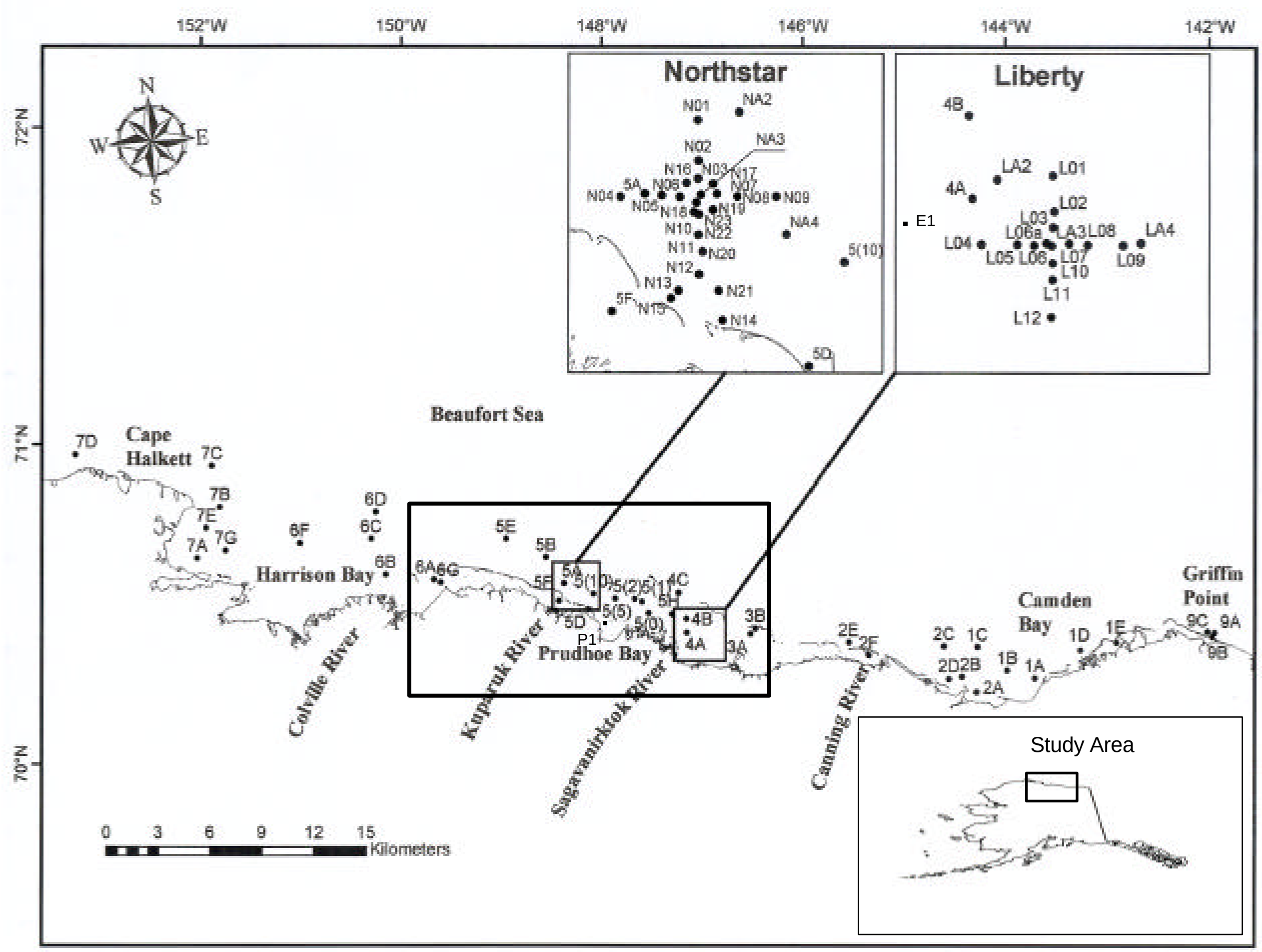


Figure 1-1. Map showing the western portion of the coastal Beaufort Sea with inset maps of Alaska, the oil production site at Northstar Island and a possible future drilling site at Liberty Prospect. The ANIMIDA study focused mainly on the area shown in the shaded box.

(5) Identify the fate of river-borne suspended sediment in the coastal Beaufort Sea.

One underlying theme in these stated goals is that the natural process and natural variations in levels of suspended sediment must be well understood before attempts to identify anthropogenic perturbations can be successful.

Coastal erosion also is an important source of sediment to the coastal Beaufort Sea. Reimnitz et al. (1988) calculated an annual sediment yield from erosion of about 5 million tons along a 200-km stretch of the coast from Prudhoe Bay to Drew Point (at the western boundary of the map in Figure 1-1). Reimnitz et al. (1988) further estimated that this level of sediment input was about seven times greater than inputs from rivers. However, they calculate a value for river input that is about seven times lower than reported by Arnborg et al. (1967). Even with the higher value for river input of sediment, the two processes appear to be, at minimum, equivalent.

This report will focus on the concentrations and composition of suspended sediment in the following three aspects of the system:

(1) Source rivers.
(2) Under-ice flow into the coastal Beaufort Sea during spring breakup.
(3) Open-water period in the coastal Beaufort Sea.

Concentrations of dissolved components along these same pathways are presented in Trefry et al. (2004). Data for dissolved components are introduced to this Task 5 report only as pertinent to discussion of the results for suspended sediment.

2.0 METHODS

2.1 Source Samples

Water samples for suspended sediment were collected from the Sagavanirktok, Kuparuk and Colville Rivers in 1-L, acid-washed, low-density, polyethylene bottles (LDPE). Some samples were obtained by wading into the river, waiting until disturbed sediment was washed down stream, and then opening an acid-washed 1- or 2-L LDPE bottle below the surface of the water. When the bottle was full, it was sealed beneath the surface, retrieved, placed in a plastic bag, labeled and stored in a cooler for return to the on-site laboratory facilities to be filtered. During June 2001 and May-June 2002, samples from the Sagavanirktok and Kuparuk rivers were collected using a polyvinyl chloride (PVC) water sampler that held acid-washed, LDPE bottles and could be lowered from one of the bridges across the river.

2.2 Under-Ice Sampling

2.2.1 Navigation and Logistics

Two snowmobiles equipped with freight sleds were used to transport personnel and sampling gear from the Prudhoe Bay Seawater Treatment Plant (STP) to the sampling stations. Due to the hazardous nature and potential of being cutoff from land while working offshore during river breakup conditions, emergency survival gear, communication equipment, emergency position indicating radiobeacon (EPIRB), and other safety equipment were included on each field trip. A portable hand-held global positioning system (GPS) was used for positioning and relocation of sampling stations. Stations were spaced ~1.5 km apart extending from the leading edge of the river overflow plume offshore in a northerly direction with additional stations located perpendicular to the main transect for the Sagavanirktok River plume in both 2001 and 2002. Documentation at each station included station logs and field notes with date, time, position, sampling information, and other observations including 35-mm and digital photographs, and video recordings of sampling activity.

2.2.2 Offshore Hydrographic Profiles

To obtain hydrographic profiles and seawater samples at each offshore station, holes were drilled in the ice using a gasoline-powered ice-auger equipped with a 25-cm diameter auger bit. Measurements were then made of the bottom depth with a sounding line and ice thickness with a graduated rod and recorded in the field logs. Hydrographic profiles were measured *in situ* with a Sea-Bird® Electronics, Inc. SEACAT SBE-19 conductivity, temperature, and depth (CTD) recorder. The SBE-19 was configured to measure and internally record temperature, conductivity, transmissivity, and pressure once every half-second while being lowered and raised through the water column. The transmissivity sensor was a 25-cm path length transmissometer manufactured by Sea Tech®, Inc. The CTD was equipped with a submersible profiling pump system, capable of maintaining flow across the sensors, even during a slow cast rate in shallow water.

Data from the CTD were uploaded onto a portable field computer upon returning back to the STP each day. Salinity, sigma-t (density), and depth were determined during post processing from the conductivity, temperature, and pressure measurements.

The SEACAT SBE-19 CTD was factory calibrated prior to each field season and re-checked in the field during each survey. In-field calibration checks involved comparison against a graduated line for depth measurements, thermometer readings for temperature, collection of Quality Control (QC) samples for salinity, and a zero and full-scale linear calibration for the transmissometer. Field QC samples were analyzed in the laboratory and then compared against the *in situ* recordings. In addition, duplicate CTD casts were performed at select stations to determine instrument repeatability and field sampling variability.

2.2.3 Suspended Sediment

During 2002, water samples were collected by lowering an acid-cleaned Tygon® tube attached to a Teflon® weight through the ice into the seawater and pumping with a hand-operated peristaltic pump. The first two liters of water were discarded and the next two liters were pumped directly into a 2-L, LDPE bottle. The sample containers were sealed in plastic bags, labeled and placed in coolers for transport back to the onshore laboratory. During 2001, samples of water from under the ice were collected using a Wheaton® pole that was rigged with a 1-L sample bottle. In the lab, the water samples were brought to room temperature, shaken to resuspend the particles and the turbidity of each sample was determined using a Hach® Model 2100A turbidimeter. The salinity of each seawater sample also determined using a Reichert-Jung® Model 10419 optical refractometer.

In the on-site laboratory at the STP, the water samples were vacuum filtered through polycarbonate filters (Poretics®, 47-mm diameter, 0.4-µm pore size). Prior to the field effort, the filters were acid washed in 5N HNO_3, rinsed three times with distilled-deionized water (DDW), dried and then weighed to the nearest µg using a Sartorius® Model M3P electronic balance under cleanroom conditions. Vacuum filtration on site was carried out in a Class-100 laminar-flow hood using acid-washed glassware. The particle-bearing filters were sealed in acid-washed petri dishes, labeled and then double-bagged in plastic and stored until dried and re-weighed at Florida Institute of Technology (FIT).

2.3 Sampling during Open-Water Periods

In-situ profiles of seawater turbidity, conductivity, temperature, depth, current speed and direction were obtained during 2000, 2001 and 2002 using an Aanderaa® Instruments system consisting of a Model 3500 Doppler current sensor, Model 3231 CTD sensor and Model 3712 turbidity/temperature sensor. The raw data were received by an Aanderaa® Model 3660 Datalogger and stored in a Model 2990 data storage unit. The raw data were transformed to appropriate units using equations provided with the Aanderaa® 5059 software package. The processed data were stored on hard disk with multiple backups on floppy diskettes.

Samples of surface seawater for turbidity and total suspended solids (TSS) were collected from the bow of a small rubber boat while rowing upstream or upwind. An acid-washed 1- or 2-L LDPE bottle was opened at about 10 cm below the surface of the water. When the bottle was full, it was sealed beneath the surface, retrieved, and placed in a plastic bag for storage. Subsurface samples were collected by lowering a Teflon®-lined Niskin® sampler attached to a Kevlar® hydrowire beneath the sea surface and tripping it with a Teflon® messenger for 1999 through 2001. After retrieval, the water samples were transferred to acid-washed 5-L plastic containers through a Tygon® tube. During 2002, a peristaltic pumping system (Masterflex® model 75-45-30 pump with high-capacity pump head) was used to collect water samples through acid-cleaned Tygon® tubing attached to a Teflon® weight. Approximately 10 L of water were discarded before the sample was pumped directly into an acid-washed 5-L plastic container. All water samples were sealed in plastic bags, labeled, packed in coolers and taken to an on-site laboratory at the STP.

In the lab, the water samples were shaken to resuspend the particles in the water; then, the turbidity of each sample was determined using a Hach® Model 2100A turbidimeter that was calibrated with sealed standards. The salinity of each seawater sample also was determined using a Reichert-Jung® Model 10419 optical refractometer that was calibrated with standard seawater. Salinity was determined for selected seawater samples by inductive salinometer upon return to FIT to validate the data obtained with the Aanderaa® system and the optical refractometer. In the on-site laboratory, the water samples were vacuum filtered through polycarbonate filters as described above for the river water.

2.4 Laboratory Analyses

2.4.1 Particulate Organic Carbon

Samples for particulate organic carbon (POC) were prepared by filtration of seawater and river water through pre-combusted Gelman® Type A/E glass fiber filters mounted on acid-washed filtration glassware within a Class-100 laminar-flow hood. The POC filters were sealed in acid-washed Petri dishes, labeled and double bagged in plastic.

At FIT, the POC filters were treated with H_3PO_4 to remove inorganic carbon phases, rinsed with DDW, dried and their particulate mass determined. The filters were then placed in ceramic boats and combusted at 900°C in a Shimadzu® TOC-5050A carbon system with SSM-5000A solid sampling module following the manufacturer's instructions. The POC content of the samples was determined using a four-point calibration curve with pure sucrose as the standard. The calibration curve was checked every 10 samples by analyzing the certified reference material (CRM) MESS-2 and MESS-3, marine sediment samples issued by the National Research Council of Canada (NRC).

2.4.2 Trace and Major Metals in Suspended Sediment

Filters bearing field samples of suspended sediment, as well as separate milligram quantities of standard reference material (SRM) #2704, a river sediment SRM issued by the National Institute of Standards and Technology (NIST), were digested in stoppered, 15-mL Teflon® test tubes using Ultrex II® HNO_3, HF and HCl. The sealed test tubes were placed in an 80°C water bath where refluxing of the acids completely dissolved the particles on the filters. After processing, the resultant solutions were transferred to acid-washed, 15-mL polyethylene bottles, diluted to ~6 mL with DDW rinses of the Teflon® test tubes and stored in a plastic bag until analyzed.

Metal concentrations for the digested particulate samples, SRMs and blanks were determined by FAAS, GFAAS or ICP-MS in a manner compatible with EPA Series 7000, 6010A and 7470 (U.S. EPA, 1991), respectively (Table 2-1). Concentrations of particulate Al, Ca, Fe, K, Mg, Mn, Na and Zn were determined by FAAS using a Perkin-Elmer® Model 4000 AAS. Concentrations of Cr and Cu were quantified by GFAAS using a Perkin-Elmer® Model 4000 AAS equipped with an HGA-400 graphite furnace and AS-40 autosampler. Concentrations of As were determined by GFAAS using a Perkin-Elmer® model 5100 instrument equipped with an HGA-600 graphite furnace and an AS-60 autosampler. Values for Ba, Cd and Pb were determined by ICP-MS using a Perkin-Elmer® ELAN 5000 spectrometer. In all cases, the instrument manufacturers' specifications were followed and adherence to QA/QC requirements was maintained.

2.4.3 Scanning Electron Microscopy

Selected samples were studied by scanning electron microscopy (SEM) at the University of Miami. The dried particles were spread across double-sided tape on a standard SEM stub and coated with Pd. A Philips/FEI® ESEM-FEG instrument was used for the investigation. The instrument was equipped with an Oxford/Link® ISIS 300 energy dispersive X-ray spectrometer (EDS). With the EDS, elemental analysis was carried out at selected areas on the particles.

Table 2-1. Summary of instrumental methods and method detection limits (MDL) for metal analysis of suspended sediment.

	Suspended sediment	
Metal	**Method**	**MDLs (μg metal/g, dry weight)**
Al – aluminum	FAAS	1500
As – arsenic	GFAAS	1.8
Ba – barium	ICP-MS	9
Ca – calcium	FAAS	230
Cd – cadmium	ICP-MS	0.03
Cr – chromium	FAAS	0.33
Cu – copper	FAAS	0.4
Fe – iron	FAAS	250
K – potassium	FAAS	250
Mg – magnesium	FAAS	40
Mn – manganese	FAAS	170
Ni – nickel	ICP-MS	0.7
Pb – lead	ICP-MS	0.2
Na – sodium	FAAS	82
Zn – zinc	FAAS	2
POC/DOC	Shimadzu® Carbon System	0.01%

Notes:
CVAAS = Cold Vapor Atomic Absorption Spectrometry
FAAS = Flame Atomic Absorption Spectrometry
GFAAS = Graphite Furnace Atomic Absorption Spectrometry
ICP-MS = Inductively Coupled Plasma-Mass Spectrometry
MDL = Method Detection Limit

2.5 Quality Assurance and Quality Control

2.5.1 Sample Tracking Procedure

All sediment samples were collected by, transported by and stored by personnel from FIT. Upon return-to or arrival at the laboratory, each sample was carefully inspected to insure that it was intact and that the identification number was clearly readable.

2.5.2 Quality Control Measurements for Analysis

For this project, QC measures included balance calibration, instrument calibration (FAAS, GFAAS, CVAAS, ICP-MS, TOC analyzer, and *in-situ* instrument sensors), matrix spike analysis for each metal, duplicate sample analysis, analysis of CRMs and SRMs, procedural blank analysis and standard checks. With each batch of up to 20 samples, two procedural blanks, two CRMs or SRMs, two duplicate samples and two matrix-spiked samples were analyzed. Data quality objectives (DQOs) for these quality control measurements are provided in Table 2-2.

2.5.3 Instrument Calibration

Electronic balances used for weighing samples and reagents were calibrated prior to each use with certified, NIST-traceable standard weights. All pipets (electronic or manual) were calibrated prior to use. Each of the spectrometers used for metal analysis was initially standardized with a three- to five-point calibration with a linear correlation coefficient of $r \geq 0.999$ required before experimental samples could be analyzed. Analysis of complete three- to five-point calibrations and/or single standard checks alternated every 5-10 samples until all the analyses were complete. The relative standard deviation (RSD) between complete calibration and standard check was required to be <15% or recalibration and reanalysis of the affected samples were performed.

2.5.4 Matrix Spike Analysis

Matrix spikes were prepared for a minimum of 5% of the total number of samples analyzed and included each metal to be determined. Results from matrix spike analysis using the method of standard additions provides information on the extent of any signal suppression or enhancement due to the sample matrix. If necessary (i.e., spike results outside 80-120% limit), spiking frequency was increased to 20% and a correction applied to the metal concentrations of the experimental samples.

2.5.5 Duplicate Sample Analysis

Duplicate samples from homogenized field samples (as distinct from field replicates) were prepared in the laboratory for a minimum of 5% of the total samples. These laboratory duplicates were included as part of each set of sample digestions and analyses and provide a measure of analytical precision.

2.5.6 Procedural Blank Analysis

Two procedural blanks were prepared with each set of 20 samples to monitor potential contamination resulting from laboratory reagents, glassware and processing procedures. These blanks were processed using the same analytical scheme, reagents and handling techniques as used for the experimental samples.

Table 2-2. Data quality objectives and criteria.

Element or Sample Type Criteria	Minimum Frequency	Data Quality Objective/Acceptance
Initial Calibration	Prior to every batch of samples Standard Curve	3-5 point curve depending on the element and a blank Correlation coefficient r = 0.999 for all analytes
Continuing Calibration	Must end every analytical sequence; for flame, repeat all standards every 5 samples; for graphite furnace and ICP-MS recheck standard after every 8-10 samples	% RSD ?15% for all analytes
Certified and Standard Reference Materials	Two per batch of 20 samples	Values must be within 20% of accepted values for >85% of the certified analytes and within 25% for Hg
Method Blank	Two per batch of 20 samples	No more than 2 analytes to exceed 5x MDL
Matrix Spike and Spike Method Blank	Two per batch of 20 samples	80-120%
Lab Duplicate	Two per batch of 20 samples	RSD <25% for 65% of analytes

2.5.7 CRM and SRM analysis

A common method used to evaluate the accuracy of environmental data is to analyze reference materials, samples for which consensus or "accepted" analyte concentrations exist. The following CRMs and SRMs were used: Buffalo River sediment SRM#2704 (NIST) and Marine Sediment CRM MESS-2 (NRC). Metal concentrations obtained for the reference materials were required to be within ?20% of accepted values for >85% of other certified analyses. Results for the CRMs and SRMs were well within the limits set in the DQOs (Table 2-3).

Table 2-3. Results for reference materials.

Analyte	Certified Concentrations for SRM #2704[a] (µg/g)	This study[b] (µg/g)
Al (n = 38)	6.11 ± 0.16 (%)	6.14 ± 0.08 (%)
As (n = 38)	23.4 ± 0.8	23.4 ± 0.8
Ba (n = 38)	414 ± 12	418 ± 7
Ca (n = 8)	2.60 ± 0.03 (%)	2.59 ± 0.03 (%)
Cd (n = 30)	3.45 ± 0.22	3.44 ± 0.11
Cr (n = 30)	135 ± 5	134 ± 3
Cu (n = 40)	98.6 ± 5.0	99.7 ± 2.8
Fe (n = 40)	4.11 ± 0.1 (%)	4.13 ± 0.05 (%)
K (n = 8)	2.00 ± 0.04 (%)	2.00 ± 0.03 (%)
Mg (n = 10)	1.20 ± 0.02 (%)	1.19 ± 0.03 (%)
Mn (n = 10)	555 ± 19	566 ± 12
Na (n = 10)	0.547 ± 0.014 (%)	0.55 ± 0.03 (%)
Ni (n = 8)	44.1 ± 3.0	45.7 ± 3.8
Pb (n = 38)	161 ± 17	159 ± 9
Zn (n = 42)	438 ± 12	436 ± 8
POC (n = 25)	2.14 ± 0.03 (%)[c]	2.00 ± 0.05 (%)

[a] ± 95 confidence limits.
[b] ± 1 standard deviation.
[c] MESS-2 (NRC).

Results for QA/QC measurements for each data set are given with along the complete data sets in Appendices A, B and C.

3.0 RESULTS AND DISCUSSION

The Results and Discussion are organized so that they begin with the input of suspended sediment by rivers and then transition to the transport and distribution of suspended sediment in the coastal Beaufort Sea. Specifically, sediment transport by the Sagavanirktok, Kuparuk and Colville rivers will be presented for 2001 and 2002. Then, the composition of the river particles will be introduced and contrasted with bottom sediments in the coastal Beaufort Sea. The transport and composition data are used to calculate riverine inputs of suspended sediment as well as particulate metals and particulate organic carbon to the Beaufort Sea. Next, the spring flow of suspended sediment over and under the 2-m thick ice in the Beaufort Sea is introduced along with data for suspended sediment in ice cores. Subsequently, the distribution and composition of suspended sediment in the Coastal Beaufort Sea during the open-water period is presented. Finally, a brief overview of sediment accumulation is provided.

3.1 River Sources of Suspended Sediment

Most rivers that drain into the Arctic Ocean carry 40 to 80% of their annual volume of water during peak flow in May, June and July (Arnborg et al., 1967; Gordeev et al, 1996). Studies in the Alaskan Arctic have shown that concentrations of total suspended solids (TSS) in the Colville River follow the same trend as water flow with >70% of the annual discharge of TSS occurring during May and June (Arnborg et al., 1967). Large seasonal discharges of water and suspended sediment at high latitudes emphasize the importance of annual spring floods to the arctic hydrologic cycle.

The three rivers studied during the ANIMIDA program, the Sagavanirktok, Kuparuk and Colville rivers (Figure 3-1), lie within the Arctic climatic zone where annual temperatures average -12°C and mean precipitation is ~12 cm y^{-1} (Telang et al., 1991). The drainage basins of these Arctic rivers include the following three physiographic provinces: the Arctic Mountain Province, the Arctic Foothills Province, and the Arctic Coastal Plain Province (Payne et al., 1951). Based on the classification scheme proposed by Craig and McCart (1975), the Sagavanirktok and Colville rivers can be classified as mountain streams that drain snowfields and glaciers in the Brooks Range. In contrast, the yellow-colored water of the Kuparuk River is more representative of a tundra stream (Lock et al., 1989). All three rivers flow into the coastal Beaufort Sea.

Rivers are an important source of water and sediment to the ANIMIDA study area during spring runoff and on an annual basis. The river-borne water and sediment carry a full, natural complement of dissolved and particulate elements that are physically and chemically weathered from the mountains and tundra bordering the coastal Beaufort Sea. To understand possible anthropogenic perturbations to the ANIMIDA study area, one must first understand the composition, flow characteristics and amounts of incoming sediment and water. In this regard, the Sagavanirktok, Kuparuk and Colville rivers (Figure 3-1 and Table 3-1) were sampled during spring runoff (May-June) in 2001 and 2002 and during the summers (July-August) of 2000, 2001 and 2002. During breakup, the Sagavanirktok River was sampled daily and the other two rivers were sampled every two to five days as logistics permitted.

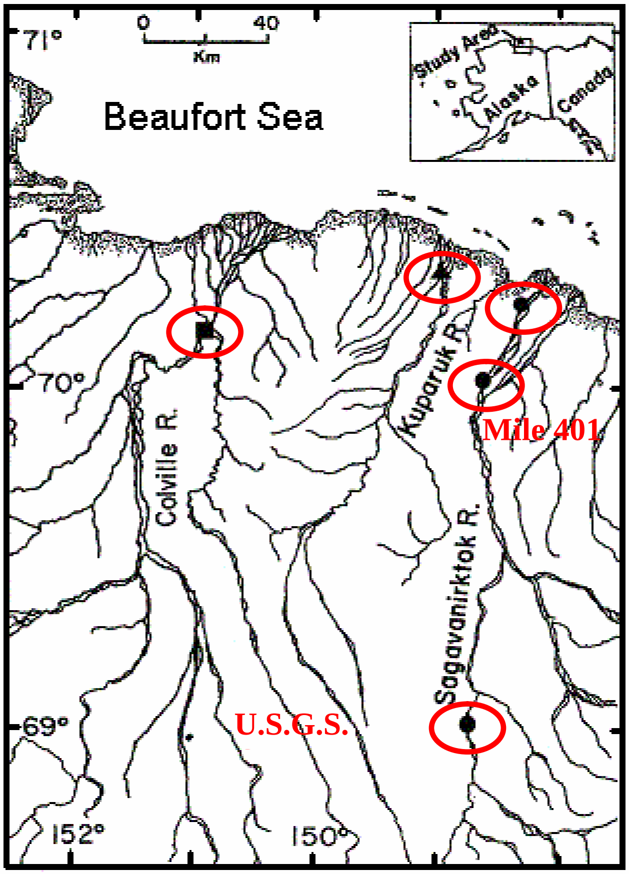


Figure 3-1. Map showing locations of sampling sites in the Sagavanirktok, Kuparuk and Colville rivers with inset map showing study area in northern Alaska.

Table 3-1. Locations of river sampling sites.

Site	Latitude (N)	Longitude (W)
Sagavanirktok River (near Prudhoe Bay)	70° 15.033?	148° 18.484?
Sagavanirktok River (~30 km upstream at mile 401 on the Dalton Highway)	70° 01.684?	148° 37.781?
Sagavanirktok River (U.S.G.S. gauge at mile 327 on the Dalton Highway)	69° 00.527?	148° 49.214?
Kuparuk River	70° 19.812?	149° 00.527?
Colville River	70° 09.519?	150° 56.791?

3.1.1 River Breakup and Summer: 2001

3.1.1.1 Sagavanirktok River

Water began to flow in the Sagavanirktok River on June 3, 2001 (Figure 3-2). Samples were collected daily from June 3 to June 23 and later on July 30 and August 8 from the bridge near the Prudhoe Bay Operations Center (PBOC). Samples also were collected at mile 401 on the Dalton Highway on June 5, 11, 12, 16, 19 and 21 and at the site of a gauging station (mile 327 on the Dalton Highway) maintained by the U.S. Geological Survey (U.S.G.S.) on June 14 and 21, about 150 km south of Deadhorse.

Figure 3-2. Sagavanirktok River on May 25, June 3, June 5, and June 11, 2001 at bridge near Prudhoe Bay Operations Center.

Concentrations of total suspended solids (TSS) in the Sagavanirktok River at PBOC increased from ~40 mg/L on June 3 to 600 mg/L within 10 days on June 12 and then decreased to ~30 mg/L by June 18 (Figure 3-3). A secondary pulse occurred about June 23 when concentrations of TSS rose to ~90 mg/L following a rain storm (Figure 3-3). Data for water flow at the U.S.G.S. gauge, located ~150 km upstream, followed a similar trend. A 1- to 2-day offset between the peaks in TSS and water flow is due to the 150 km difference in location between the gauge and primary sampling site (Figure 3-1). Concentrations of TSS in the Sagavanirktok River at mile 401 on the Dalton Highway and the U.S.G.S. gauge site (mile 327 on the Dalton Highway) were similar to values

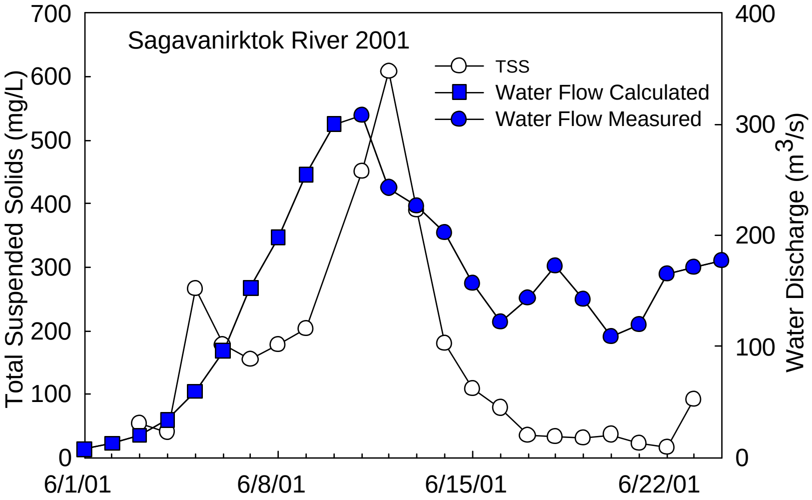


Figure 3-3. Water discharge (near mile 327 on Dalton Highway, U.S. Geological Survey, 2001) and concentrations of total suspended solids (TSS) in the Sagavanirktok River at PBOC during June 2001.

obtained from the PBOC bridge, considering a lag time of several hours (mile 401) to 2 days (mile 327). However, the gauge in the Sagavanirktok River was not installed by the U.S.G.S. until the river was free of ice on June 10, 2001, ~7 days after water flow began. Thus, during 2001 and most other years, the ascending limb of the hydrograph is calculated, not measured, for the Sagavanirktok River. Furthermore, because the gauge is upstream in the western drainage basin of the Sagavanirktok River, the gauge records water flow for only ~20% of the watershed and may not characterize flow patterns for the entire basin. During 2001, the total volume of water measured at the U.S.G.S. gauge in the Sagavanirktok River was ~1.3 km^3, yielding a total extrapolated (from 20% to 100%) flow of ~6.5 km^3 y^{-1} (U.S.G.S., 2001).

The conductivity of the water in the Sagavanirktok River during June 2001 (Figure 3-4) was inversely related to water flow (Figure 3-3) because at peak flow the concentrations of dissolved solids are diluted with large amounts of snowmelt that has had limited contact with soils and surface waters. The conductivity of melted snow was 7 µS. Between June 3, 2001, and June 7, 2001, the conductivity of the Sagavanirktok River decreased by almost 50% (Figure 3-4). Extensive discussion of dissolved components in the Sagavanirktok River during June 2001 is given in Trefry et al. (2004).

During late July and August 2001, concentrations of TSS were ~2 mg/L and the conductivity was ~320µS.

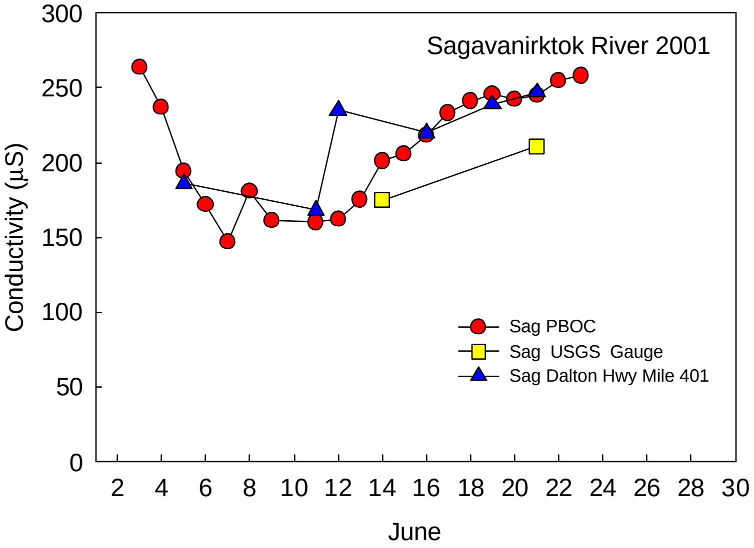


Figure 3-4. Conductivity for water from the Sagavanirktok (Sag) River for June 2001 near Prudhoe Bay Operations Center (PBOC), US Geological Survey gauge, and at mile 401 on the Dalton Highway.

3.1.1.2 Kuparuk River

In the Kuparuk River, concentrations of TSS reached peak values of 60 mg/L on June 10, 2001, and decreased to <5 mg/L after June 16 (Figures 3-5 and 3-6). Peak flow recorded for the Kuparuk River was about 600 m^3/sec on June 12, 2001, decreasing to <50 m^3/sec after June 28, 2001. Values for TSS were ~0.6 mg/L during August 2001 for the Kuparuk River.

Figure 3-5. Kuparuk River causeway/bridge (eastern segment of river) shown under water during peak flow on June 11, 2001 and then high and dry and rebuilt on June 20, 2001.

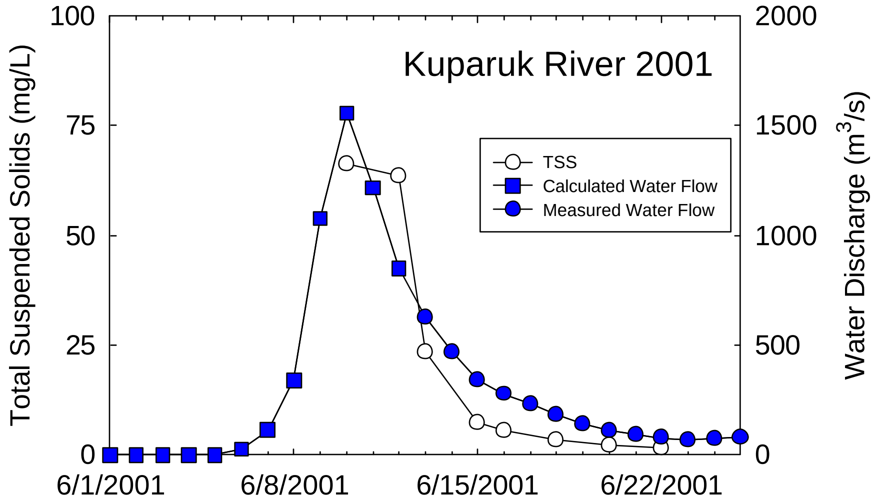


Figure 3-6. Concentrations of total suspended solids (TSS) and water discharge for the Kuparuk River (flow data from US Geological Survey) for June 2001.

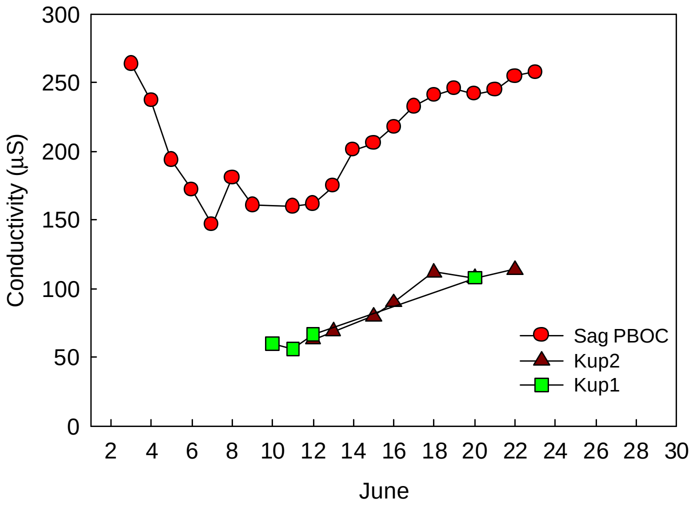


Figure 3-7. Conductivity for water from the Kuparuk (Kup) and Sagavanirktok (Sag) rivers for June 2001.

Water conductivity in the Kuparuk River during June 2001 was indirectly related to water flow with lowest values for conductivity during highest flow as the concentrations of dissolved substances were diluted by the increased volumes of fresh snowmelt (Figure 3-7). Samples from the eastern stem of the Kuparuk River were collected at two different locations (separated by <1 km) during peak flow due to problems with accessibility during the flood period. However, subsequent sampling on the same days at both sites showed no significant differences in TSS or conductivity (e.g., Figure 3-7 for Kup1 and Kup2). Conductivities for the Kuparuk River were two to three times lower than found for the Sagavanirktok River due to the greater amount of limestone weathered and dissolved in the Sagavanirktok River as discussed in Trefry et al. (2004). During August, the conductivity for the Kuparuk River was about 50% higher at ~160 µS.

3.1.1.3 Colville River

Concentrations of TSS in the Colville River followed similar trends to those observed for the Sagavanirktok River with maximum levels of about 600 mg/L on June 13, 2001 (Figures 3-8 and 3-9). Values for TSS were about 6 mg/L during August 2001 for the Colville River. Flow data for the Colville River were collected only during the period of peak flow by Baker et al. (2001); the U.S.G.S. does not maintain a gauge on the Colville River. During the spring snow melt, flow in the Colville River (6,000 to 9,000 m^3/sec) was an order-of-magnitude greater than in the Sagavanirktok or Kuparuk rivers. As observed for the other rivers, conductivity decreased during peak flow (Figure 3-10). The conductivity of water in the Colville River was similar to that found for the Kuparuk River, with both rivers more two-fold lower in conductivity that the carbonate-rich waters of the Sagavanirktok River.

Figure 3-8. Colville River at Monument 1 during peak flow on June 9, 2001 and at lower flow on June 20, 2001.

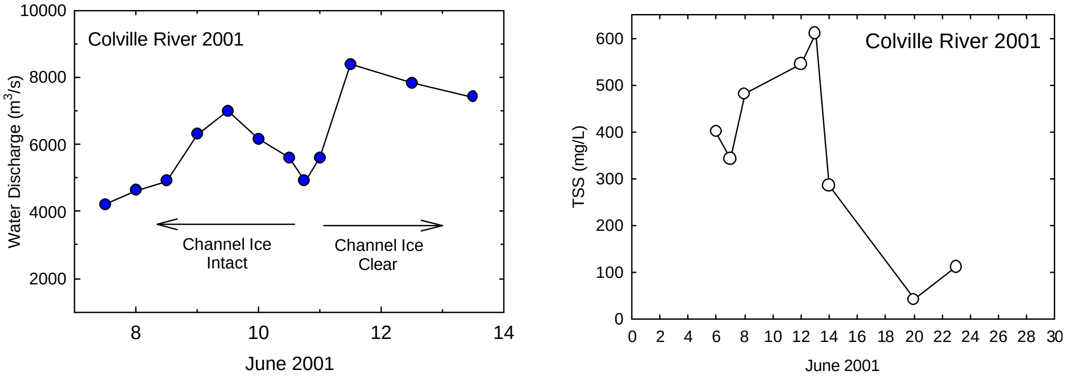


Figure 3-9. Water flow and concentrations of total suspended solids (TSS) for the Colville River during June 2001. Water data during peak flow are from Baker et al. (2001); the U.S.G.S. does not maintain a water flow gauge on the Colville River.

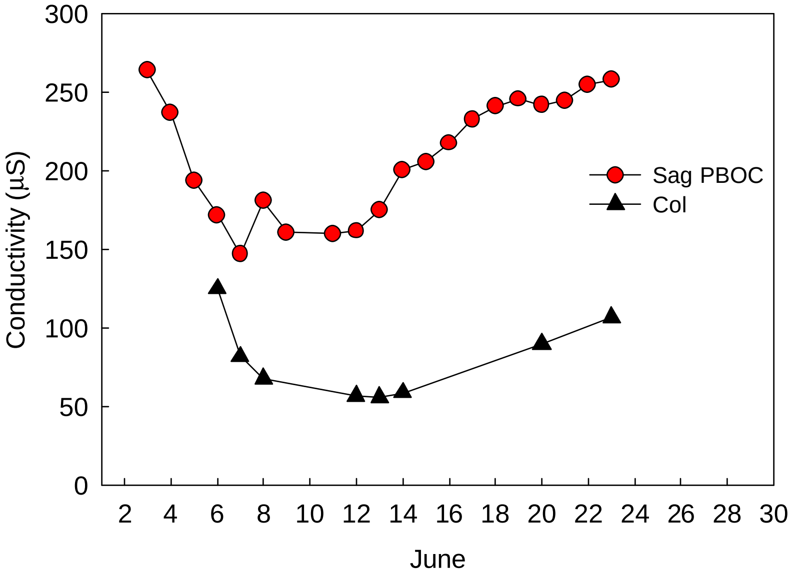


Figure 3-10. Conductivity for water from the Colville (Col) River and the Sagavanirktok (Sag) River at the Prudhoe Bay Operations Center (PBOC) for June 2001.

In addition to TSS, conductivity and water flow, concentrations of particulate and dissolved trace metals (As, Ba, Cu, Fe, Mn, Ni, Pb and Zn), particulate Al, K, Mg and Na, and DOC and POC were determined for the three rivers during June to August 2001. Particle composition is presented in this report following the TSS, conductivity and water flow results for 2002 and the dissolved data are presented in Trefry et al. (2004).

3.1.2 River Breakup and Summer: 2002

3.1.2.1 Sagavanirktok River

Spring breakup in the Sagavanirktok River for 2002 was very different from what was observed in 2001. First, the start of river flow was almost two weeks earlier (May 20, 2002 versus June 2, 2001). Second, after flow had been ongoing for about one week, the air temperatures cooled well below freezing and the river refroze (Figure 3-11). The same trend was observed offshore as river water initially flowed out over and under the ice and then the surface layer of river water froze over the 2-m thick layer of winter ice. The river re-thawed within four days, but water flow was less than during the earlier discharge period (Figure 3-12).

The TSS and turbidity for 2002 showed the same initial steep increase in levels of suspended particles to ~350 mg/L (Figure 3-12), similar to, but lower than the observed peak TSS of ~600 mg/L in 2001 (Figure 3-3, page 19). However, subsequent cold temperatures and freezing of the river truncated the flooding process and TSS levels decreased to <10 mg/L on May 31, 2002, the final day of operations before the ice prevented sampling for two days. Then, as the river re-melted, the increase in flow led to another peak in discharge of suspended sediment at >200 mg/L (Figure 3-12). Data for turbidity also are shown on Figure 3-12 to point out that turbidity data sets are available

Figure 3-11. Sagavanirktok River flowing on May 22, frozen on May 29, and flowing again on May 31 and June 12, 2002 at bridge near Prudhoe Bay Operations Center.

for all water samples (Appendix A) and that the two indicators of suspended sediment content track one another very well.

Unfortunately, the U.S.G.S. was not able to install their gauge for water flow until June 6, 2002 (Figure 3-12), and therefore no data are available for the events described above.

Even without flow data for late May and early June, 2002, the plots for concentrations of TSS for 2001 versus 2002 support much lower net transport of sediment during 2002. Some of the sediment carried by the river in 2002 may have settled upstream and then washed out to the Beaufort Sea during a later storm in 2002 or even during the 2003 spring flood.

Conductivity in the Sagavanirktok River followed a more compressed trend in 2002 with a shorter time of 4 days at <200 µS (Figure 3-13) relative to the 8-day period of water flow with conductivity <200 µS observed in 2001 (Figure 3-4, page 20). Concentrations of TSS decreased to ~3 mg/L in late June and were ~1 mg/L in August, similar to levels observed in 2001.

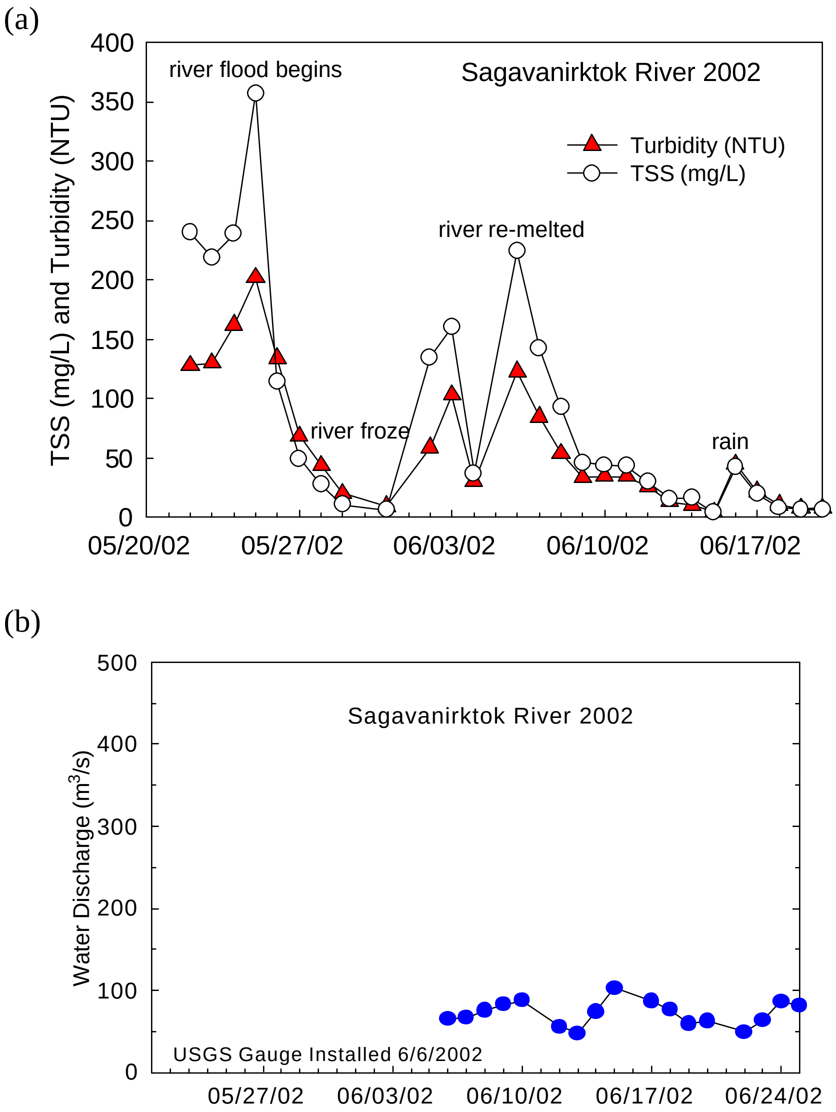


Figure 3-12. (a) Concentrations of total suspended solids (TSS) and turbidity for the Sagavanirktok River during May-June 2002. (b) Water discharge (from U.S. Geological Survey) in Sagavanirktok River for June 2002.

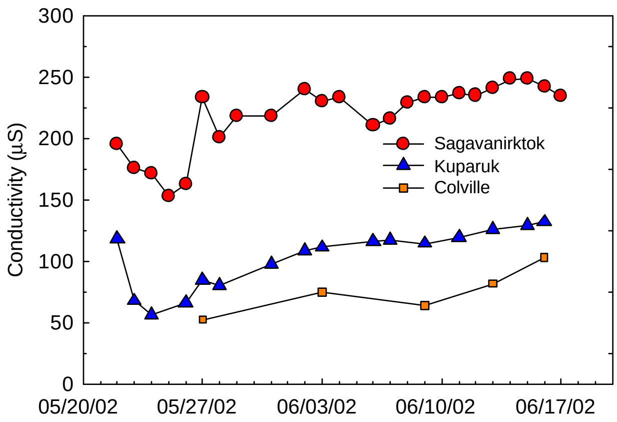


Figure 3-13. Conductivity in the Sagavanirktok, Kuparuk and Colville rivers during May-June 2002.

3.1.2.2 Kuparuk River

During 2002, we were fortunate to directly observe and sample the Kuparuk River during its brief (1 to 2 day) flood (Figures 3-14 and 3-15). The strong pulse of water that characterizes flooding in the Kuparuk River occurred on May 23, 2002. The pictures in Figure 3-14 show the swelling river on May 22, overflow of the eastern bridge on May 23, a broad floodplain on May 24 and the receded water after the flood on May 25. The complete flood cycle in the Kuparuk River occurred before the onset of colder temperatures and refreezing of the rivers.


May 22, 2002
May 23, 2002
May 24, 2002
May 25, 2002

Figure 3-14. Kuparuk River during flood period in May 2002.

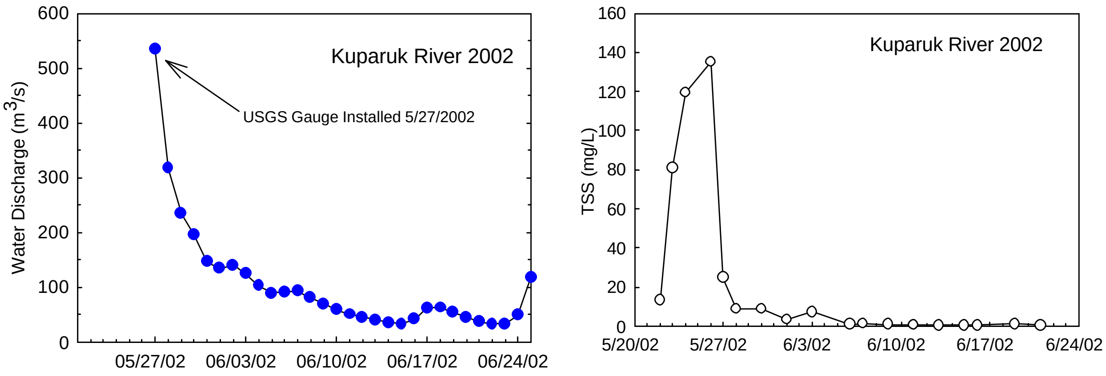


Figure 3-15. Water flow and concentrations of total suspended solids (TSS) and turbidity for the Kuparuk River during May-June 2002 (flow data from U.S. Geological Survey).

Maximum levels of TSS in the Kuparuk River during 2002 were similar to maximum levels of ~60 mg/L during 2001. Turbidity and concentrations of TSS in the Kuparuk River during both years may have peaked at higher levels than observed during maximum flood stage (Figure 3-15). Unfortunately, due to washing out of the road and the intense flow conditions, sampling was restricted to the eastern-most braid of the river during peak flow. Concentrations of TSS in the Kuparuk River decreased to ~0.5 mg/L in late June and were ~0.2 mg/L in August, similar to levels observed in 2001. Conductivity in the Kuparuk River during 2002 (Figure 3-13) followed a similar trend at similar values to those observed in 2001 (Figure 3-7) with a minimum of ~50 µS at peak flow, increasing to ~120 µS after the spring flood receded.

3.1.2.3 *Colville River*

Access to the Colville River by helicopter was limited during 2002 due to the early onset of the spring floods and an increased focus on the under-ice effort near Prudhoe Bay. Data from Baker et al. (2002) show a short, strong pulse of water at >6000 m^3/sec for 4-5 days (Figure 3-16). Duplicate samples for TSS on May 27, 2002, showed levels >600 mg/L. Levels of TSS decreased to 112 mg/L on June 3 and <50 mg/L on and after June 12 (Figure 3-17). Conductivity for the Colville River during the 2002 flood (Figure 3-13) event was very similar to that observed during 2001 (Figure 3-10). During both years, the Colville River had the lowest conductivity of the three rivers, most likely due in part to the higher water flow of the river that led to dilution of dissolved solids.

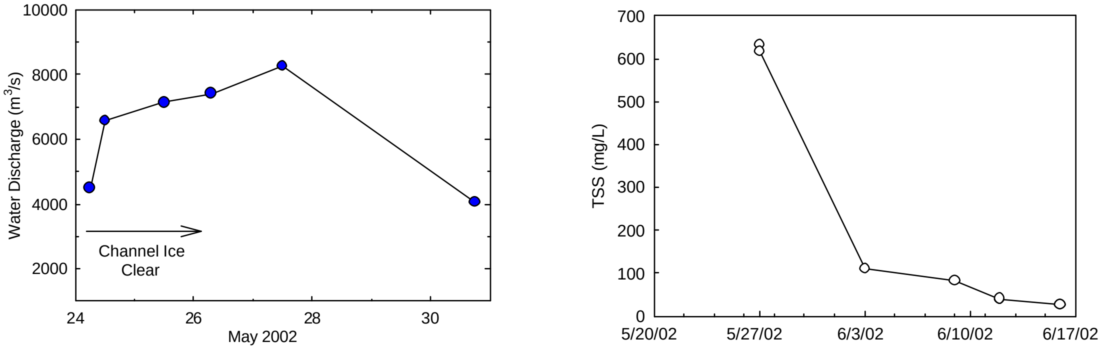


Figure 3-16. Water flow and concentrations of total suspended solids (TSS) in the Colville River during May-June 2002.

Figure 3-17. Colville River after the spring flood during June 2002.

3.2 Composition of River Suspended Sediment

The composition of river suspended matter can provide a well-defined signature that may allow differentiation between incoming natural suspended sediment and anthropogenic contributions of various solids from industrial activity in the coastal Beaufort Sea. Furthermore, changes in the composition of the river-borne particles may help identify future shifts in mechanical and chemical weathering in the Brooks Range and across the North Slope. Results for both 2001 and 2002 are discussed in this section.

Figure 3-18 shows a scanning electron micrograph of a subset of the particles carried by the Sagavanirktok River on June 9, 2001. The small holes in the background are the 0.4 µm pores in the membrane filter. Thus, on June 9 as flow increased, platy, clay-size-particles in the range of 1-5 µm are intermixed with larger fragments on the order of 5-10 µm. The particles from the Sagavanirktok and Colville Rivers (Figure 3-18 and 3-19) include an abundance of K-rich aluminosilicates as described below.

Summary data for major elements (Al, Fe, Ca, K, Mg and Na), trace metals (As, Ba, Cd, Cu, Mn, Ni, Pb and Zn) and POC for suspended sediment collected from the three rivers during 2001 and 2002 are presented in Tables 3-2 and 3-3. Distinct differences in the Al content of the suspended sediment were observed with Colville>Sagavanirktok>Kuparuk (Tables 3-2 and 3-3). In contrast, concentrations of Ca are about 7 to 10 times greater in the Sagavanirktok River than in the Kuparuk or Colville rivers. The distinction is very clear in the Al versus Ca plot shown in Figure 3-20. These differences are directly related to the greater abundance of aluminosilicates in the Colville River relative to the Sagavanirktok and Kuparuk Rivers as well as a much greater abundance of particulate calcite and dolomite in the Sagavanirktok River. During 2002, a clear, indirect relationship was observed between particulate Ca and particulate Al in the Sagavanirktok River (Figure 3-20) due to the greater amounts of coarser-grained carbonate particles during high flow and the greater clay content during low flow. Unfortunately, the distinction in the Ca/Al ratios among the rivers is not easily observed in coastal sediment due to the addition of marine shell material to the coastal sediment.

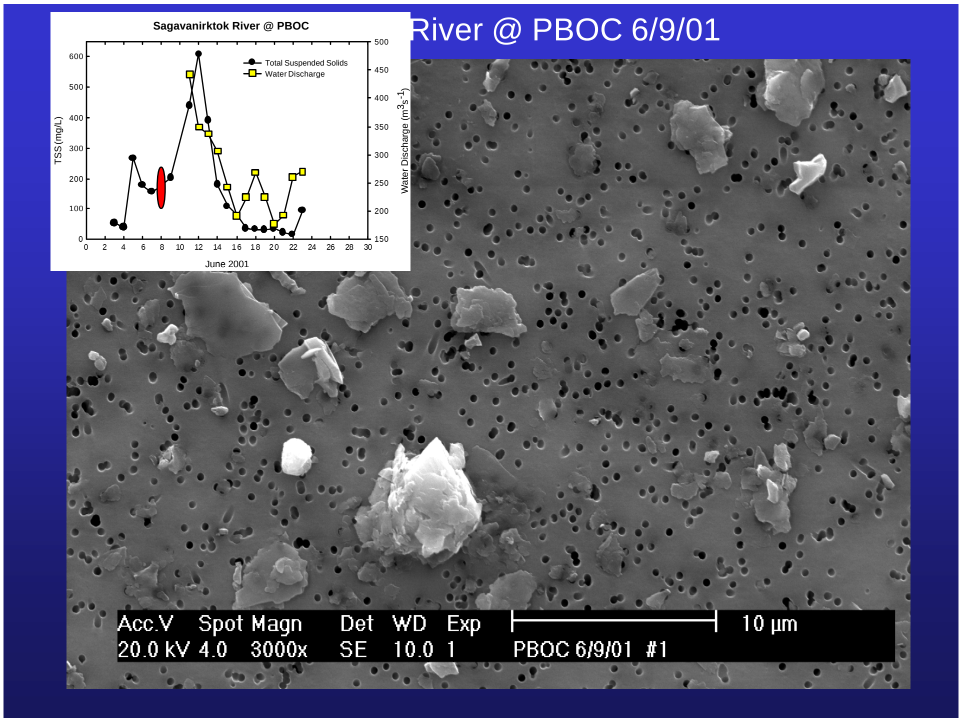


Figure 3-18. Scanning electron micrograph showing suspended sediment collected from the Sagavanirktok River on June 9, 2001. Red mark on inset hydrograph shows that sample was collected as levels of suspended sediment and water flow were increasing.

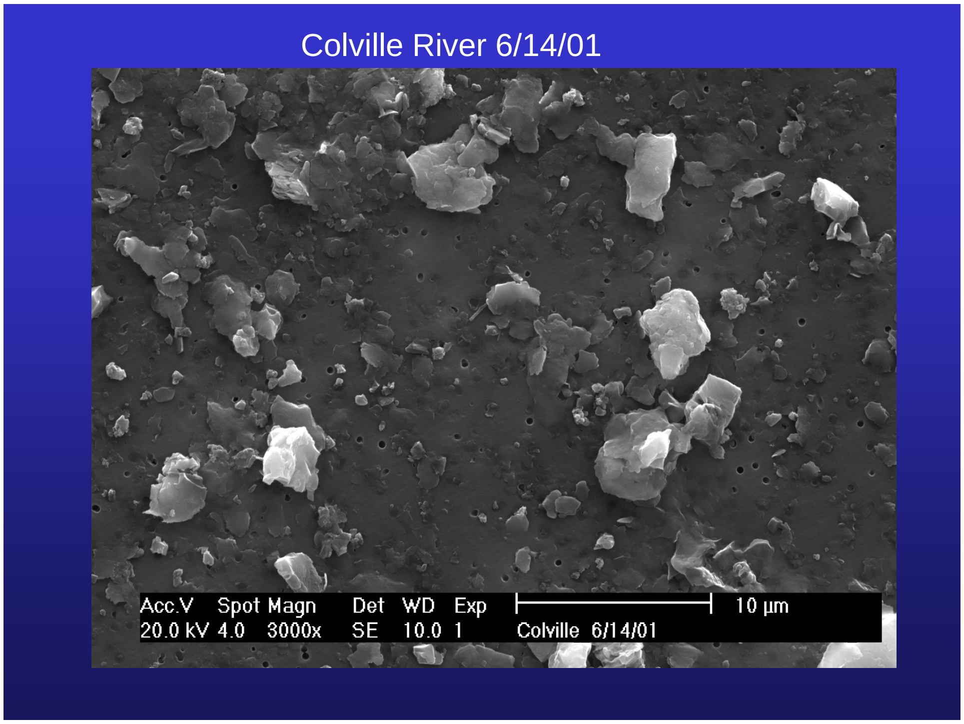


Figure 3-19. Scanning electron micrograph showing suspended sediment collected from the Colville River on June 14, 2001, during peak flow.

Table 3-2. Concentrations of metals and organic carbon in suspended sediment from the Sagavanirktok, Kuparuk and Colville rivers during June 2001.

Sample Identification		Al (%)	As (µg/g)	Ba (µg/g)	Ca (%)	Cu (µg/g)	Fe (%)	K (%)	Mg (%)	Mn (µg/g)	Na (%)	Ni (µg/g)	Pb (µg/g)	Zn (µg/g)	POC (%)
Sagavanirktok R. at PBOC (n=22)	Mean ± SD	5.6 ± 0.9	11.1 ±1.6	702 ±112	6.7 ±1.0	32.6 ±2.8	3.3 ±0.4	1.7 ±0.2	0.8 ±0.1	583 ±27	0.3 ±0.1	60.9 ±5.1	18.0 ±2.0	123 ±7	1.6 ± 0.5
Sagavanirktok R. (mile 401 Dalton Highway) (n=6)	Mean ± SD	5.9 ± 0.6	13.1 ±3.5	663 ±118	7.4 ±2.0	32.2 ±2.7	3.4 ±0.3	1.6 ±0.2	0.9 ±0.1	602 ±43	0.3 ±0.1	59.0 ±7.8	16.7 ±1.5	124 ±11	1.5 ± 0.4
Sagavanirktok R. (mile 327 Dalton Highway) (n=2)	Mean ± SD	7.0 ± 1.0	15.8 ±1.3	729 ±52	5.0 ±3.6	39.8 ±9.4	4.3 ±1.0	2.0 ±0.3	0.8 ±0.1	799 ±140	0.3 ±0.1	75.0 ±8.5	25.8 ±7.1	130 ±8	- -
Kupuruk R. (n=9)	Mean ± SD	4.4 ± 1.0	16.6 ±8.1	562 ±98	1.0 ±0.2	31.4 ±4.6	3.7 ±0.3	1.1 ±0.2	0.5 ±0.2	836 ±144	0.4 ±0.1	643.8 ±7.6	15.1 ±5.1	110 ±23	4.8 ± 1.5
Colville R. (n=5)	Mean ± SD	8.3 ± 0.3	14.2 ±1.3	989 ±125	0.7 ±0.1	40.8 ±2.3	5.0 ±0.3	1.9 ±0.3	1.1 ±0.2	957 ±55	0.5 ±0.1	68.7 ±10.0	24.0 ±6.8	130 ±11	2.2 ± 0.6

Table 3-3. Concentrations of metals and organic carbon in suspended sediment from the Sagavanirktok and Kuparuk rivers during June 2002.

Sample Identification		Al (%)	As (µg/g)	Ba (µg/g)	Ca (%)	Cu (µg/g)	Fe (%)	K (%)	Mg (%)	Mn (µg/g)	Na (%)	Ni (µg/g)	Pb (µg/g)	Zn (µg/g)	POC (%)
Sagavanirktok R. at PBOC (n=23)	Mean ± SD	6.2 ± 1.1	14.3 ± 4.3	693 ± 153	8.9 ± 1.7	33.5 ± 5.8	3.4 ± 0.5	1.7 ± 0.3	1.1 ± 0.1	586 ± 68	0.3 ± 0.01	52.1 ± 6.4	11.7 ± 4.2	143 ± 31	1.6 ± 0.3
Kuparuk R. (n=13)	Mean ± SD	4.0 ± 1.47	14.6 ± 3.7	537 ± 237	0.9 ± 0.2	28.4 ± 6.0	4.5 ± 0.8	1.1 ± 0.3	0.6 ± 0.2	1120 ± 287	0.2 ± 0.2	48.8 ± 11.3	18.9 ± 3.8	152 ± 61	5.3 ± 3.1

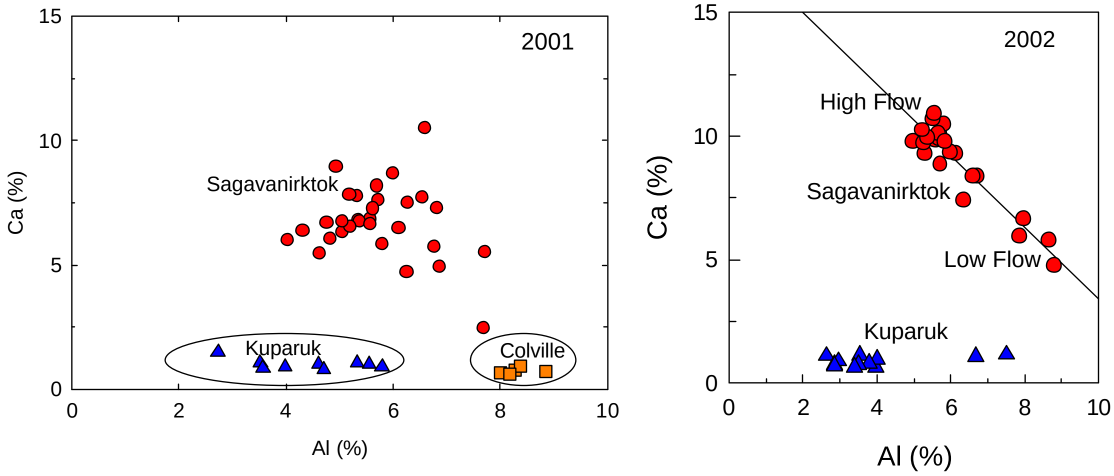
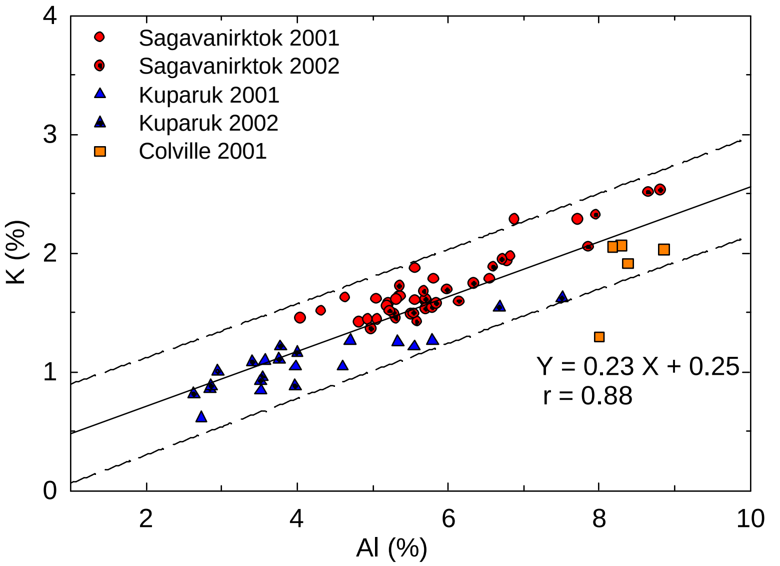


Figure 3-20. Concentrations of aluminum (Al) versus calcium (Ca) for suspended sediment from the Sagavanirktok (circles), Colville (squares) and Kuparuk (triangles) rivers during June 2001 and May-June 2002.

Previous studies have shown that the Sagavanirktok River drains primarily limestone deposits and has concentrations of dissolved Ca that are ~2 times higher than in the Kuparuk and Colville rivers (Telang et al., 1991). In addition to the Lisburne limestone and dolomite from the Tertiary, the Brooks Range also contains shales from the Triassic to Pennsylvanian age (Payne et al., 1951; Mull and Adams, 1989). The Gubik formation (Quaternary riverine and marine sediments) underlies the coastal plain and Quaternary sediments, older Cretaceous and Tertiary sandstones, conglomerates and siltstones are exposed in the foothills province (Payne et al., 1951; Mull and Adams, 1989).

As previously noted, the Sagavanirktok and Colville rivers can be classified as mountain streams that drain snowfields and glaciers in the Brooks Range according to the classification scheme proposed by Craig and McCart (1975). In contrast, the yellow-colored water of the Kuparuk River is more representative of a tundra stream (Lock et al., 1989). All three rivers flow into the coastal Beaufort Sea. These distinctions in source among the rivers help explain differences in both particulate and dissolved components among the rivers.

Differences in the K and Mg concentrations of river suspended sediment also were observed among the rivers with an overall trend of Colville>Sagavanirktok>Kuparuk (Tables 3-2 and 3-3, Figure 3-21). However, these differences were much less distinct than those previously shown for Ca (Figure 3-20). In fact, the K/Al and Mg/Al plots show good linear relationships for the combined data set for all three rivers (Figure 3-21). These trends suggest that the source minerals bearing K and Mg are similar for each river and that the linear variations are due to differences in the fractional amount of the K and Mg phases in the suspended sediment. Within the overall linear trend for the combined data set, concentrations of particulate K and Mg, relative to Al, are lower in the Kuparuk and Colville Rivers than for the Sagavanirktok River (Figure 3-21). This distinction among rivers is partially explained by the work of Walker and Webber (1979) that showed that westward of the carbonate-rich Sagavanirktok River, soil pH decreases from



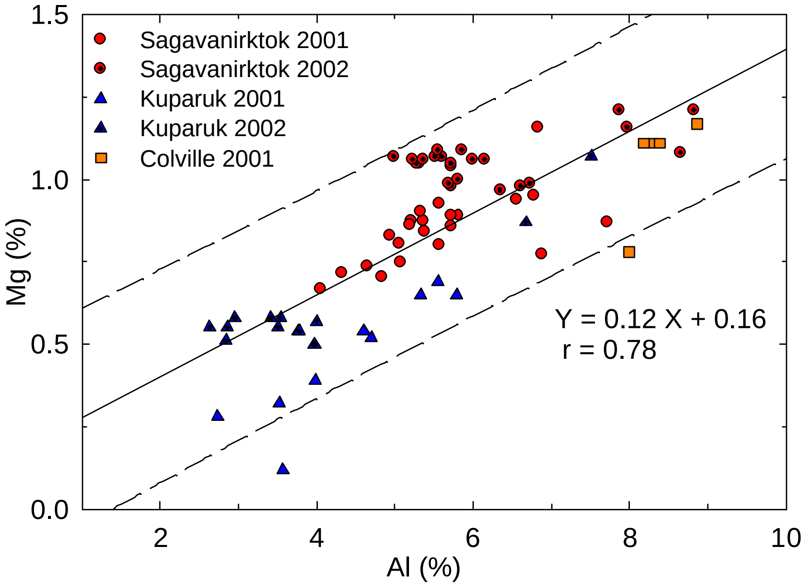


Figure 3-21. Concentrations of aluminum (Al) versus potassium (K) and magnesium (Mg) for suspended sediment from the Sagavanirktok (circles), Colville (squares) and Kuparuk (triangles) rivers during June 2001 and May-June 2002.

>7 to <6 as the tundra shifts from wet alkaline to wet acidic because soils become rich in organic acids. Other studies have shown that soil pH can decrease to 4.2 in tussock tundra and heath ecosystems (Valentine and Binkley, 1992). In addition, Parkinson (1977) found an inverse relationship between calcium carbonate equivalents and organic matter concentrations in the region. These data suggest that soils within the Kuparuk and Colville drainage basins may undergo more intense chemical weathering due to higher concentrations of organic acids and lower pH. By this scenario, Ca, K and Mg would be leached from the parent minerals to a greater extent in the Colville and Kuparuk river drainage basins.

Rember (2002) reconstructed the composition and amounts of the minerals that were chemically weathered to yield the dissolved major ions in the Sagavanirktok, Kuparuk and Colville rivers. The complete section from Rember (2002) is discussed in Trefry et al. (2004), including the details of the calculations. The dominant rock type that is chemically weathered in each of the three rivers is carbonate (limestone and dolostone) that accounts for >80% of the dissolved solids. However, the mass of rock weathered per liter of river water is much greater in the Sagavanirktok River than in the Kuparuk and Colville rivers as previously suggested by the conductivity data and discussed below.

During peak discharge in the Sagavanirktok River, a total of ~96 mg/L of rock were chemically weathered, with 58% carbonates, ~34% evaporates (S- and Cl-bearing minerals), and 8% silicates (Figure 3-22). During off-peak discharge in the Sagavanirktok River, the amount of rock weathered increased to 136 mg/L (Figure 3-22). This seasonal trend is consistent with the processes that occur during spring floods in northern Alaska. During peak discharge, runoff is confined to the O-horizon of the soil and snowmelt is proceeding at a rapid rate. Therefore, the lack of an active soil layer, combined with a relatively short residence time (contact time) of the snowmelt in the drainage basin, does not allow minerals to undergo extensive chemical weathering. However, during off-peak discharge, the volume of snow melting decreases and therefore the residence time of snowmelt in the mountains and coastal plain increases, thereby allowing for increased chemical weathering of the rocks in the drainage basin.

In the Kuparuk River drainage basin on the coastal plain, lower amounts of ~28 and 46 mg/L of rock (mostly carbonate with some silicate), respectively, were weathered during peak and off-peak discharge. These values are significantly lower (~2-3 fold) than the amount of rock weathered in the Sagavanirktok River. This trend shows that the chemical weathering of rocks from the Brooks Range (and additional sources of SO_4^{2-}) relative to chemical weathering on the coastal plain has a large impact on the chemical composition of river water.

The weathering of carbonates and evaporites in the Colville River accounts for 76% of the 36 mg/L of rocks weathered during peak discharge and 80% of the 60 mg/L of rocks weathered during off-peak discharge. However, the amount of rock weathered is more similar to the Kuparuk than the Sagavanirktok River. As previously discussed, the evaporite and carbonate minerals are primarily located in the drainage basin of the Sagavanirktok River and are more rapidly weathered than silicate minerals, especially in a low precipitation, cold environment. Therefore, the amounts of evaporite and carbonate rock weathered in the drainage basin of the Colville River are likely proportional to the amounts of evaporite and carbonate rock weathered in the drainage basins of the Kuparuk and Sagavanirktok rivers.

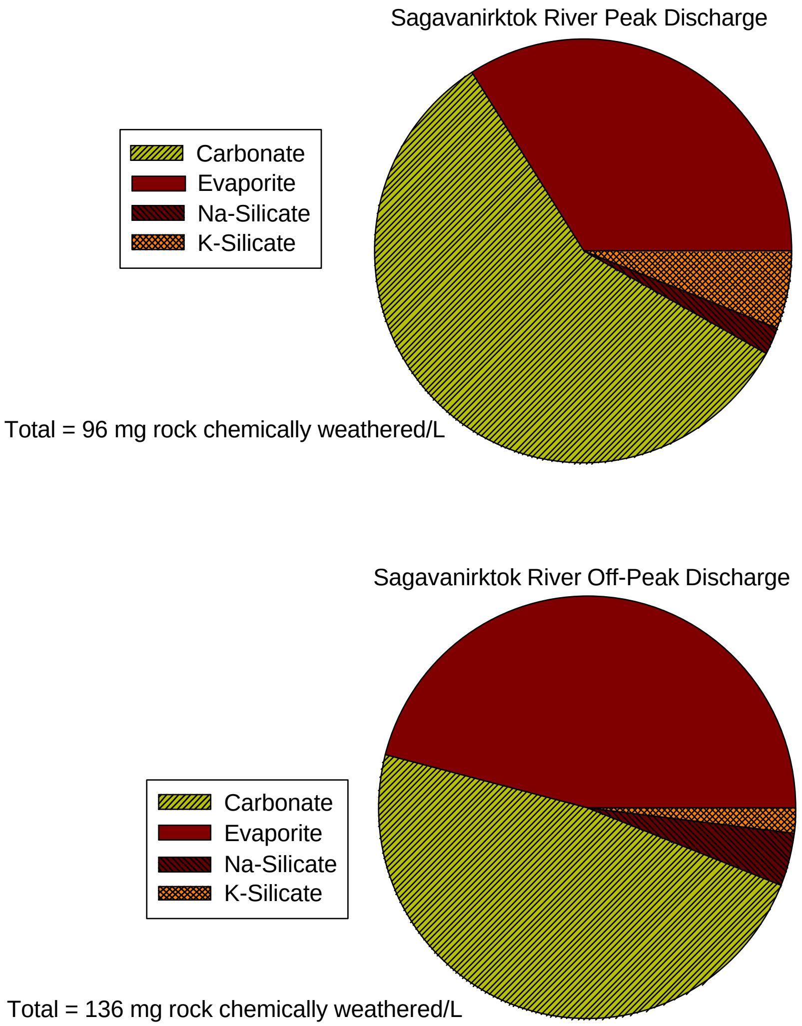


Figure 3-22. Fraction of different rock types that were chemically weathered to produce the observed concentrations of dissolved major elements in the Sagavanirktok River during peak and off-peak flow in 2001.

Concentrations of trace metals in river suspended matter provide another possible point of reference for differentiating among river sources of sediment and for comparison with bottom sediment in the ANIMIDA study area. Such comparisons enable us to determine whether incoming suspended particles have been modified by chemical processes in marine sediments or if metal concentrations have been enhanced by anthropogenic inputs.

Results for the Sagavanirktok River from June 2001 show that concentrations of particulate Cu, Pb and Zn (as $\mu g\ g^{-1}$ dry weight) as well as Fe (as % dry weight) are quite uniform with values for the coefficient variance (CV) = 8.5% for Cu, 11% for Pb, 16% for Fe, and 5.7% for Zn (Figure 3-23). Concentrations of these metals are poorly correlated with concentrations of organic carbon, and relatively well correlated with particulate Al (Table 3-4). The poor correlations for POC versus Cu, Fe, Pb and Zn suggest that POC does not play a significant role in controlling concentrations of particulate trace metals in the Sagavanirktok River, but that aluminosilicates (clays) are more important.

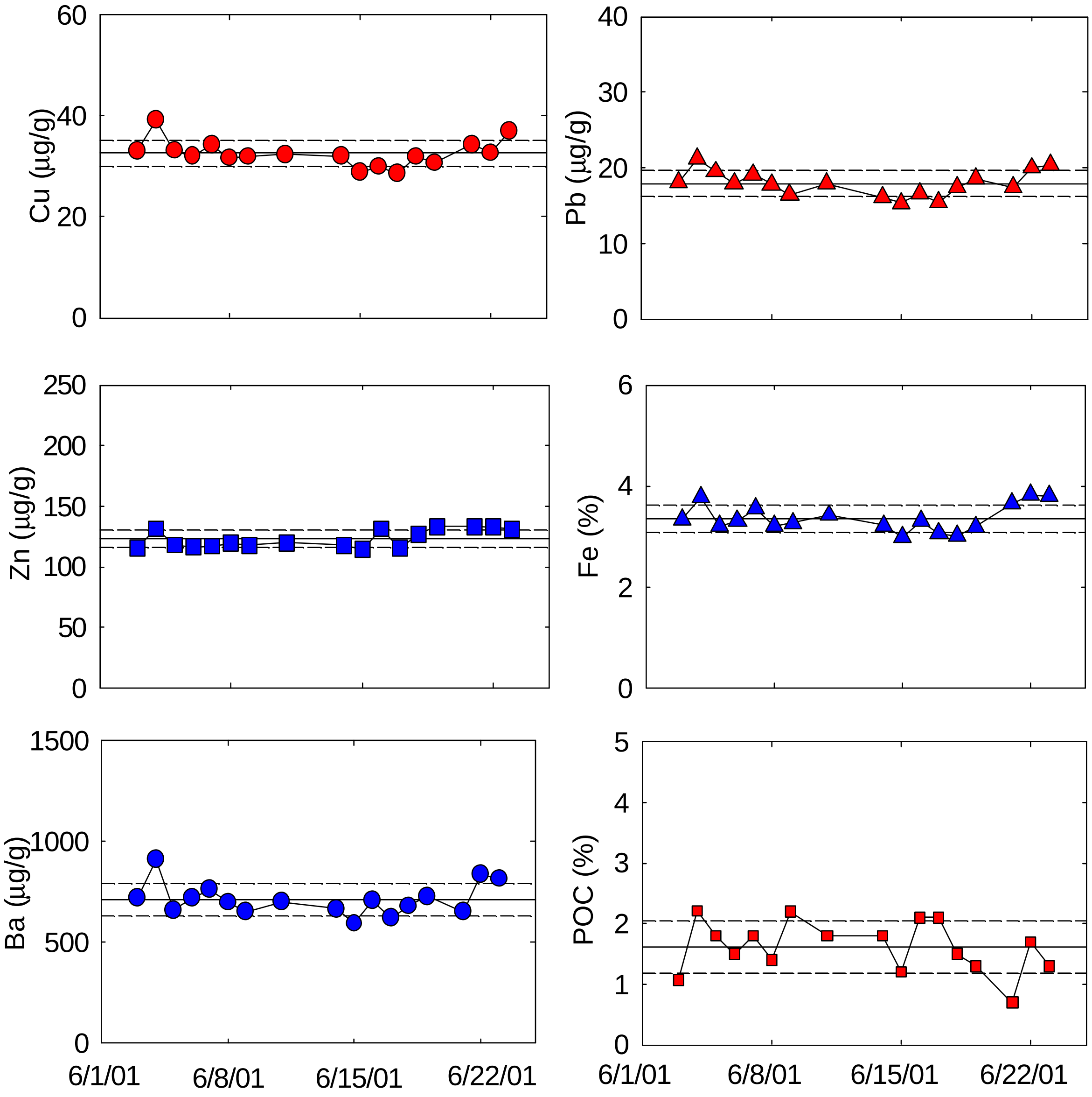


Figure 3-23. Concentrations of copper (Cu), lead (Pb), zinc (Zn), iron (Fe), barium (Ba) and particulate organic carbon (POC) for suspended sediment from the Sagavanirktok River during June 2001. Solid lines show means and dashed lines show ±1 standard deviation.

Table 3-4. Correlation coefficients for particulate trace metals and particulate organic carbon (POC) in the Sagavanirktok River during June 2001.

	Al	Ba	Cu	Fe	Pb	Zn
Al	1					
Ba	0.88**	1				
Cu	0.81**	0.83**	1			
Fe	0.97**	0.86**	0.85**	1		
Pb	0.82**	0.92**	0.87**	0.83**	1	
Zn	0.77**	0.63**	0.51*	0.64**	0.59	1
POC	-0.35	-0.18	-0.25	-0.25	-0.28	-0.29

** Correlation is significant at the 0.01 level.
* Correlation is significant at the 0.05 level.

The correlation coefficients for concentrations of particulate Ba and particulate Al in the Sagavanirktok River follow closely with those observed for Fe, Cu, Pb and Zn, suggesting that concentrations of particulate Ba also are controlled by the aluminosilicate content of the suspended solids (Table 3-4). When concentrations of particulate Ba from the Kuparuk and Colville rivers were pooled with data for the Sagavanirktok River (Figure 3-24), a strong relationship between Al and Ba is still observed (r = 0.91). The data in Figure 3-24 include values from all three rivers with a range of ~2 to >600 mg/L for TSS, and concentrations of POC ranging from <1 to >7%. Therefore, variations in concentrations of particulate Ba in the Sagavanirktok, Kuparuk and Colville rivers result from the dilution of fine-grained aluminosilicates by larger-grained sands and other non-aluminosilicate minerals and not levels of TSS or POC. Results for Ba from the 2002 samples follow those for 2001 with one exception each from the Sagavanirktok and Kuparuk rivers that we cannot explain at this time. The trend lines shown on Figure 3-24 were constructed using sediment data from the ANIMIDA study (Brown et al., 2004) and show that Ba levels in suspended sediment from the three rivers generally fit within the prediction intervals established for the sediments. Barium is of particular interest to the ANIMIDA study because barite ($BaSO_4$) is a common additive to drilling fluids and Ba levels in sediments at a few sites in the coastal Beaufort Sea have been previously shown to contain anthropogenic Ba contamination (Crecelius et al., 1991; Trefry et al., 2003).

Average concentrations of particulate Cu, Fe and Pb in the Colville River averaged 25 to 40% higher than concentrations found in the Sagavanirktok and Kuparuk rivers (Tables 3-2 and 3-3). However, particles from the Colville River also had 50% higher concentrations of Al indicating that sources of suspended sediment in the western Brooks Range are richer in fine-grained aluminosilicates or less diluted by non-aluminosilicate minerals (Tables 3-2 and 3-3).

When concentrations of particulate Fe were plotted versus Al (Figure 3-25), the results for the Sagavanirktok and Colville rivers, and the Kuparuk River during high flow, fit the

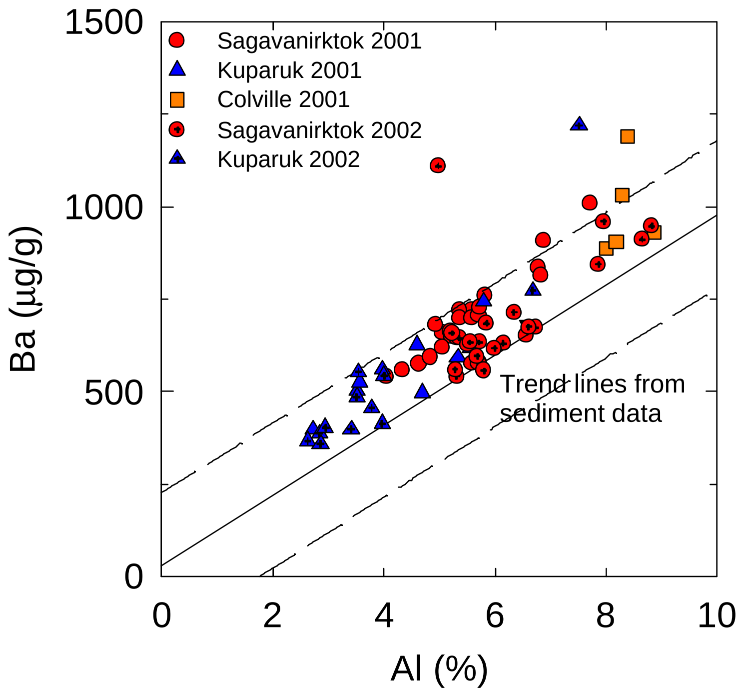


Figure 3-24. Concentrations of aluminum (Al) versus barium (Ba) for suspended sediment from the Sagavanirktok (circles), Colville (squares) and Kuparuk (triangles) rivers during June 2001 and May-June 2002. Solid line is from a linear regression for sediment data from the ANIMIDA study area and dashed lines show 99% prediction interval for sediment data.

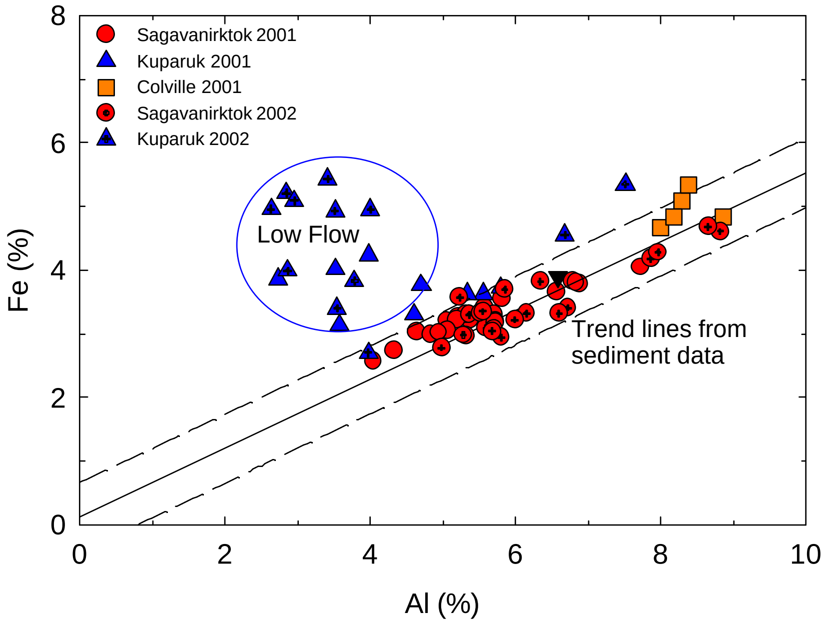


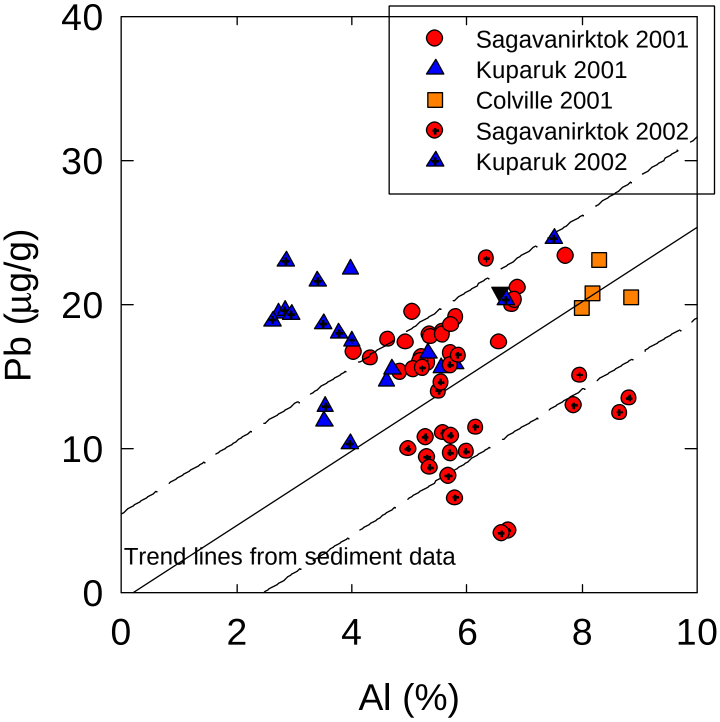
Figure 3-25. Concentrations of aluminum (Al) versus iron (Fe) for suspended sediment from the Sagavanirktok (circles), Colville (squares) and Kuparuk (triangles) rivers during June 2001 and May-June 2002. Solid line is from a linear regression for sediment data from the ANIMIDA study area and dashed lines show 99% prediction interval for sediment data.

same Fe/Al trend; however, the Colville River had higher absolute levels of both Fe and Al. When TSS concentrations decrease to an average of 4 mg/L in the Kuparuk River during off-peak discharge in June, the average Fe/Al ratio increased by ~35% relative to the Sagavanirktok River (Figure 3-25). These data suggest that elevated concentrations of particulate Fe (3.7% dry weight) relative to Al (3.5% dry weight) during off-peak discharge may be influenced by high concentrations of dissolved Fe (~60 µg/L) in the Kuparuk River that potentially enhance the formation of Fe hydrous oxides and increase levels of particulate Fe (Rember and Trefry, 2004).

Concentrations of Fe and Al fit relatively well within the prediction interval developed for these two metals using bottom sediment from the coastal Beaufort Sea and described in detail by Brown et al. (2004). Although samples collected from the Kuparuk River during low flow (<50 m^3/sec) and low levels of TSS (<3 mg/L) were enriched with Fe relative to Al (Figure 3-25), very minute amounts of these particles will be carried into the Beaufort Sea. Otherwise, the Fe/Al relationship for the suspended sediment collected from the rivers matches that found in bottom sediment from the ANIMIDA study area (Figure 3-25).

Good relationships were found for Al versus Pb and As (Figure 3-26) and other metals in river-borne particles. The few points that indicate elevated levels of Pb and As relative to Al in Figure 3-26 coincide with the more Fe-rich particles carried during low flow and at low levels of TSS. Otherwise, most data for suspended sediment fit within the prediction intervals established from the sediment data (Figure 3-26). Overall, no statistically significant distinction in metal/Al ratios among rivers has been observed for the metals studied, other than the results for the Kuparuk River at low flow (Figure 3-26).

Concentrations of POC for river suspended sediment ranged from <1 to 15 mg/L; however, the POC, as a percent of the TSS in the Sagavanirktok and Colville rivers were quite uniform with an average of ~2% (Tables 3-2 and 3-3, Figure 3-27). In contrast, concentrations of POC in the Kuparuk River averaged about 5% (Tables 3-2 and 3-3, Figure 3-27).



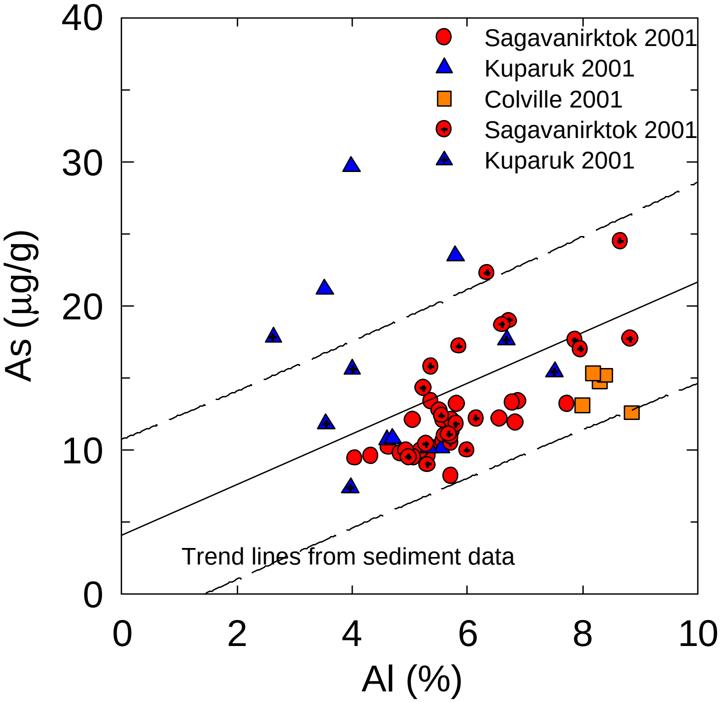


Figure 3-26. Concentrations of aluminum (Al) versus lead (Pb) and arsenic (As) in suspended sediment from the Sagavanirktok (circles), Kuparuk (triangles) and Colville (squares) rivers for June and August 2001 and May-June 2002. Solid lines on each graph show regression line for Al versus metal for natural bottom sediment; dashed lines show corresponding 99% prediction interval.

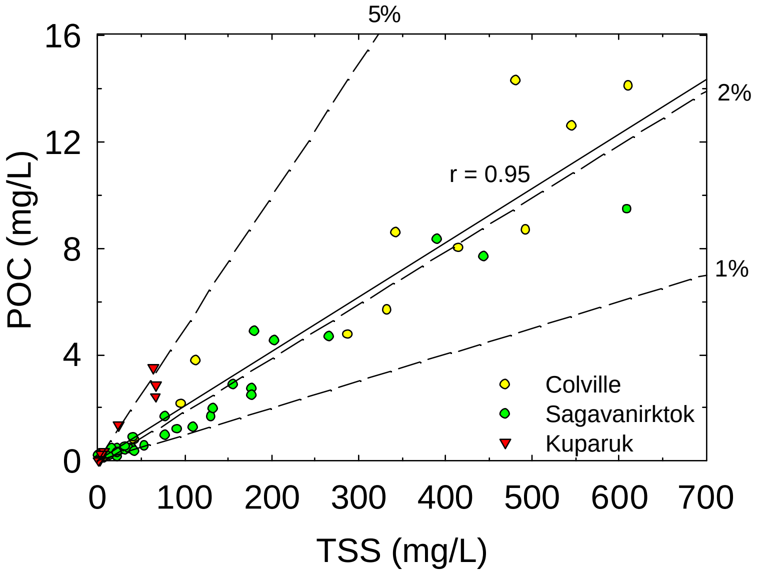


Figure 3-27. Concentrations of total suspended solids (TSS) versus particulate organic carbon (POC) for river suspended sediment. Solid line shows linear regression fit to the data with correlation coefficient (r). Dashed lines show where concentrations of POC are 1, 2 and 5% of the dry weight of the particles.

3.2 River Transport of Suspended Sediment, Particulate Metals and Particulate Organic Carbon to the Coastal Beaufort Sea

The TSS and water flow data can be used to calculate sediment transport by rivers to the coastal Beaufort Sea. Calculations for suspended sediment transport are presented in more detail here for the Kuparuk and Sagavanirktok rivers because more complete data sets for water flow are available (U.S.G.S., 1971-2001). Calculations for the Colville River will be based on previous estimates of sediment transport by Arnborg et al. (1967) with an attempt to validate the earlier data using the recent, data for peak flow from Baker et al. (2001, 2002). Riverine transport of particulate metals and organic carbon also can be calculated using available data. However, exact values for transport of suspended sediment, particulate metals and POC by rivers to the coastal Beaufort Sea are presently difficult to calculate due to limitations in flow and chemical data as well as possible contributions from summer rainstorms. Nevertheless, by comparing transport during peak discharge in June with transport during the remainder of the year, a sense of the relative importance of spring floods to annual budgets was obtained.

Water flow in the Sagavanirktok River for 2001 (data from U.S.G.S., 2001) was grouped as follows:

(1) 1.1 x 10^{12} L (17% of total) of peak flow during 12 days in June.
(2) 1.2 x 10^{12} L (18% of total) of off-peak flow during 16 days in June.
(3) 4.2 x 10^{12} L (65% of total) during the remaining 90 days of the water year.

Concentrations of TSS averaged 267 mg/L in the Sagavanirktok River during peak discharge in June 2001, yielding 294,000 t (metric tons), or 87% of the annual sediment load during the 12-day peak period. Concentrations of TSS average 31 and 1.3 mg/L during the off-peak period in June and the remainder of the summer, respectively, transporting an additional 36,000 t of sediment to the coastal Beaufort Sea. A total value for sediment transport by the Sagavanirktok River of 0.33 Mt/yr for 2001 will be used in this report (Table 3-5). The final data set for flow for 2002 has not yet been released by the U.S.G.S.

Particulate metal concentrations in the Sagavanirktok River did not vary greatly during peak and off-peak periods as shown by the standard deviations in Table 3-6; therefore, ~87% of 6 tons of particulate Pb (Table 3-5) carried per year (for 2001) were transported during the 12 days of peak discharge ([0.87)(18.3 µg/g)]/[(0.15)(18.3 µg/g) + (0.87)(18.3 µg/g] x 100%). The transport values for other particulate metals by the Sagavanirktok River during 2001 are given in Table 3-5. In each case, 87% of the total transport was during the 12 days of peak discharge in June.

Water discharge in the Kuparuk River during 2001 (data from U.S.G.S., 2001) was divided into three periods:

(1) 0.3 x 10^{12} L (25% of total) during three days of peak discharge in June.
(2) 0.4 x 10^{12} L (33% of total) during the 21 off-peak days in June.
(3) 0.5 x 10^{12} L (42% of total) during the remaining 90 days of the water year (U.S.G.S., 1971-2001).

Table 3-5. Amounts of suspended sediment, particulate metals and particulate organic carbon (POC) carried by the Sagavanirktok, Kuparuk and Colville rivers to the coastal Beaufort Sea.

River	TSS (Mt/yr)*	As (t/yr)	Ba (t/yr)	Cu (t/yr)	Fe (Kt/yr)	Pb (t/yr)	Zn (t/yr)	POC (Kt/yr)
Sagavanirktok (2001)	0.33	3.5	241	11	11	6	41	5
Kuparuk (2001)	0.02	0.3	12	0.7	0.7	0.3	2.4	1
Colville	5	70	4900	200	250	120	650	110

* Mt = megatons (1 x 10^{12} g)

Table 3-6. Concentrations of particulate trace metals and particulate organic carbon (POC) in the Sagavanirktok, Kuparuk and Colville Rivers during June 2001. Peak and off-peak concentrations are presented for the Kuparuk River due to distinct differences in the concentrations of some trace metals during those periods.

River		Al (%)	Ba ($\mu g\ g^{-1}$)	Cu ($\mu g\ g^{-1}$)	Fe (%)	Pb ($\mu g\ g^{-1}$)	Zn ($\mu g\ g^{-1}$)	POC (%)
Sagavanirktok (n = 17)	Mean Std. Dev. Range	5.8 ± 0.8 4.0-7.7	729 ± 105 542-1008	32.9 ± 2.9 29.7-39.2	3.4 ± 0.3 2.6-4.0	18.3 ± 2.1 16.0-23.4	124 ± 8 115-135	1.60 ± 0.49 0.7-2.7
Kuparuk Peak Discharge (n =3)	Mean Std. Dev. Range	5.2 ± 0.5 4.6-5.8	615 ± 88 497-743	32.3 ± 5.8 25.7-37.2	3.6 ± 0.2 3.3-3.8	15.7 ± 0.7 14.7-16.6	124 ± 13 110-145	4.6 ± 1.1 3.3-5.9
Kuparuk Off-Peak Discharge (n = 6)	Mean Std. Dev. Range	3.5 ± 0.5 2.7-4.0	469 ± 70 397-559	29.9 ± 1.3 28.6-31.2	3.7 ± 0.3 3.1-4.2	14.4 ± 8.3 4.0-22.5	92.1 ± 21 69-116	4.9 ± 2.0 2.8-7.6
Colville (n = 5)	Mean Std. Dev. Range	8.3 ± 0.3 8.0-8.9	989 ± 125 890-1190	40.8 ± 2.3 36.9-42.6	5.0 ± 0.3 4.7-5.3	24.0 ± 6.8 19.8-36.0	130 ± 11 116-147	2.24 ± 0.56 1.7-3.3

Calculations for annual transport of suspended sediment by the Kuparuk River also were based on three time periods. During the three days of peak water flow in the Kuparuk River in June 2001, TSS averaged 63 mg/L to yield a sediment discharge of ~19,000 t. During the off-peak period in June and the remainder of the summer, TSS values averaged 4 and ~0.5 mg/L, respectively, resulting in an additional total of 1,900 t of sediment discharged. Thus, total discharge of suspended sediment by the Kuparuk River during 2001 was about 21,000 t or 0.02 Mt (Table 3-5), about 15 times less than calculated for the Sagavanirktok River. Calculated transport of particulate metals for the Kuparuk River was based on the following two flow periods: (1) peak flow and (2) off-peak flow in June and the remainder of the water year because differences in concentrations of elements in the particulate form vary between peak and low flow periods (Table 3-6). Thus, >90% of the annual transport of 0.3 t/yr of particulate Pb occurred during peak flow in the Kuparuk River during three days ([(0.90)(15.7 µg/g)] /[(0.10)(14.4 µg/g) + (0.90)(15.7 µg/g)] x 100%). Results for transport of the other particulate metals by the Kuparuk River (Table 3-5) show the large difference in amounts of particulate metals carried by the Sagavanirktok River relative to the Kuparuk River.

In this report, we used the lower number of 5 Mt/yr for suspended sediment transport by the Colville River from Arnborg et al. (1967). To help validate this number, the flow data from Baker et al. (2001) for 6 days in June was combined with our TSS results for those same days. The average flow was ~6,000 m^3/sec and TSS averaged ~ 500 mg/L (500 g/m^3) to yield ~1.6 Mt of suspended sediment in 6 days [(6,000 m^3/sec)(86,400 sec/da)(6 da)(500 g/m^3) = 1.6 x 10^{12} g/6 da = 1.6 Mt/6 da]. The six-day value of 1.6 Mt is a reasonable check on the annual value of 5 Mt used in this report based on the relative importance of transport of suspended sediment during peak flow by the Sagavanirktok and Kuparuk rivers. Data for the transport of particulate metals by the Colville River (Table 3-5) are based on uniform composition of the particles over the short water season (Table 3-6). Thus, the amounts of suspended sediment and particulate metals transported by the Colville River to the coastal Beaufort Sea are about 15 to 20 times greater than the combined amounts of the Sagavanirktok and Kuparuk rivers.

The calculated inputs of 0.33 million metric tons per year of suspended sediment by the Sagavanirktok River and 5 million metric tons of sediment per year by the Colville River (Arnborg et al., 1967) can be used to provide perspective for the ANIMIDA project by comparing these river inputs with the total amount of material used to construct Northstar Island. About 1.6 million metric tons of sand and gravel were used construct Northstar Island (800,000 yd^3 x 0.76 m^3/yd^3 x 2.6 metric tons/m^3). Thus, annual river inputs of suspended sediment by the Colville River are >3 times the total amount of sand and gravel on Northstar Island. Annual inputs of suspended sediment from the Sagavanirktok River are ~15% of the complete complement of material in Northstar Island. The amount of material lost during and since construction of the island and pipeline is unknown, but certainly it must be much <10% of the total. Thus, natural inputs of suspended sediment to the ANIMIDA area are large relative to possible long-term releases of sediment from Northstar Island.

As discussed previously, the relative importance of coastal erosion to sediment loading in the coastal Beaufort Sea is reported to be equal to or several times greater than sediment inputs from river runoff (Reimnitz et al. 1988). Reimnitz et al. (1988) challenge the sediment runoff value of 5 million tons for the Colville River and note that variations in erosion processes range from erosion of 18 m of shoreline per year to accretion of 20 m of shoreline per year. However, the flow data of Baker et al. (2001), combined with levels of suspended sediment from this study, suggest that the sediment load of the Colville River is several times greater than the value of 0.7 Mt estimated by Reimnitz et al. (1988). As an aside, much of the sediment transport by area rivers may be from erosion of the steep banks relative to physical weathering throughout the drainage basin. Better resolution of the relative importance of erosion versus runoff as sources of sediment to the ANIMIDA study area is a challenge to consider in more detail during the upcoming continuation of the ANIMIDA program.

3.4 River Water Flow Under Ice

As much as 70% of the annual sediment load of the Sagavanirktok, Kuparuk and Colville rivers is carried to the Beaufort Sea during the two-week period of the spring floods. At that time, the Beaufort Sea is still covered with a 1.6- to 2-m thick layer of ice and thus the turbid river water flows out to sea above the ice and in a 1-2 m-thick lens of fresh water under the ice. This process moves a large fraction of the suspended sediment many kilometers offshore before settling begins and thereby contributes to the limited amount of modern sediment in the ANIMIDA study area.

Samples of suspended sediment were collected under the ice, seaward of the Sagavanirktok and Kuparuk rivers during the spring runoff of 2001 and 2002 when the coastal Beaufort Sea was still ice covered. Figure 3-28a shows the impact of flow from the Sagavanirktok River on the river delta and the adjacent Endicott development. Water flowed seaward under the ice for more than 10 km out to sea. In Figure 3-28b, water flowing over the ice from the Kuparuk River was partially restrained and diverted by thicker ice along the ice road and pipeline route to Northstar Island.

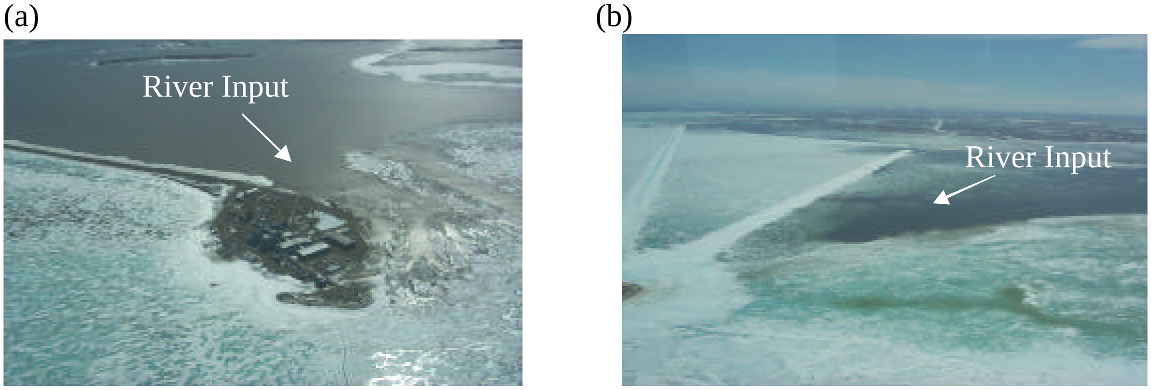


Figure 3-28. Aerial photographs from June 11, 2001 showing (a) Endicott Island with incoming flow from the Sagavanirktok River at top of photo and frozen sea in lower portion of photo and (b) incoming water from the Kuparuk River being diverted by ice roads to Northstar Island.

Vertical profiles for salinity, temperature and transmissivity (e.g., Figure 3-29) show sharp gradients under the ice as the fresher (<6 psu), warmer (~0°C) and more turbid (<50% transmissivity) water mass moved over the top of the colder (-1.8°C), more salty (33 psu) coastal water. The vertical profiles for salinity, temperature and transmissivity along part of a ~8-km transect offshore (Figure 3-30) are grouped in Figures 3-31, 3-32 and 3-33 to show the offshore movement of the freshwater mass under the ice. The layer of low salinity (<6 psu) water extended along a transect from station AN1 to AN7 on both June 9 and 11, 2001 (Figure 3-31). The layer of fresher water was slightly thicker with lower salinity (Figure 3-31) and higher temperature (Figure 3-32) on June 11, relative to June 9, as water flow neared peak levels at the U.S.G.S. gauge on June 12 (Figure 3-3, p. 19).

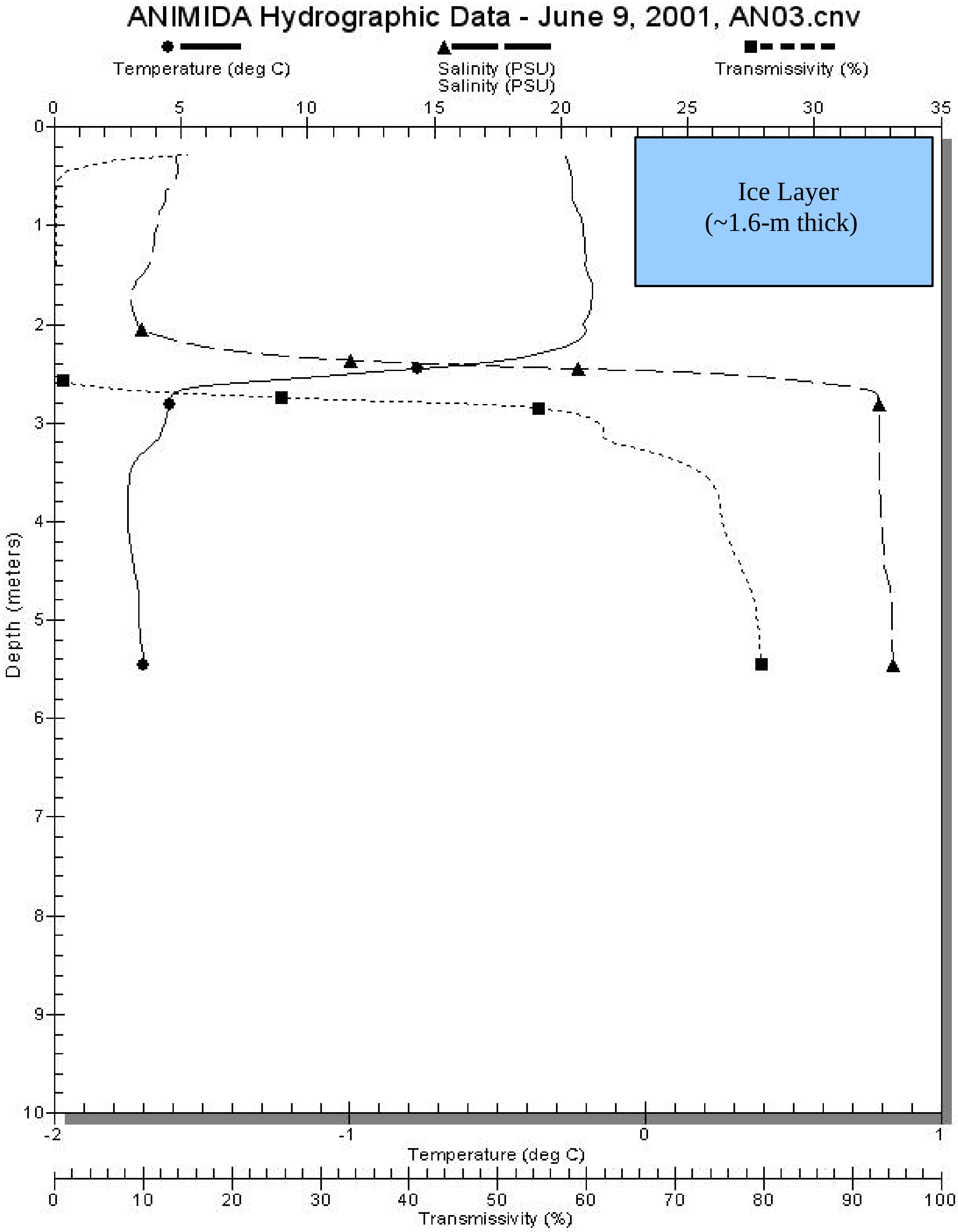


Figure 3-29. Vertical profiles for salinity, temperature and transmissivity for station AN03 (see map in Figure 3-30) during under ice sampling in June 2001. The remaining profiles are presented in Appendix B with the under ice data sets.

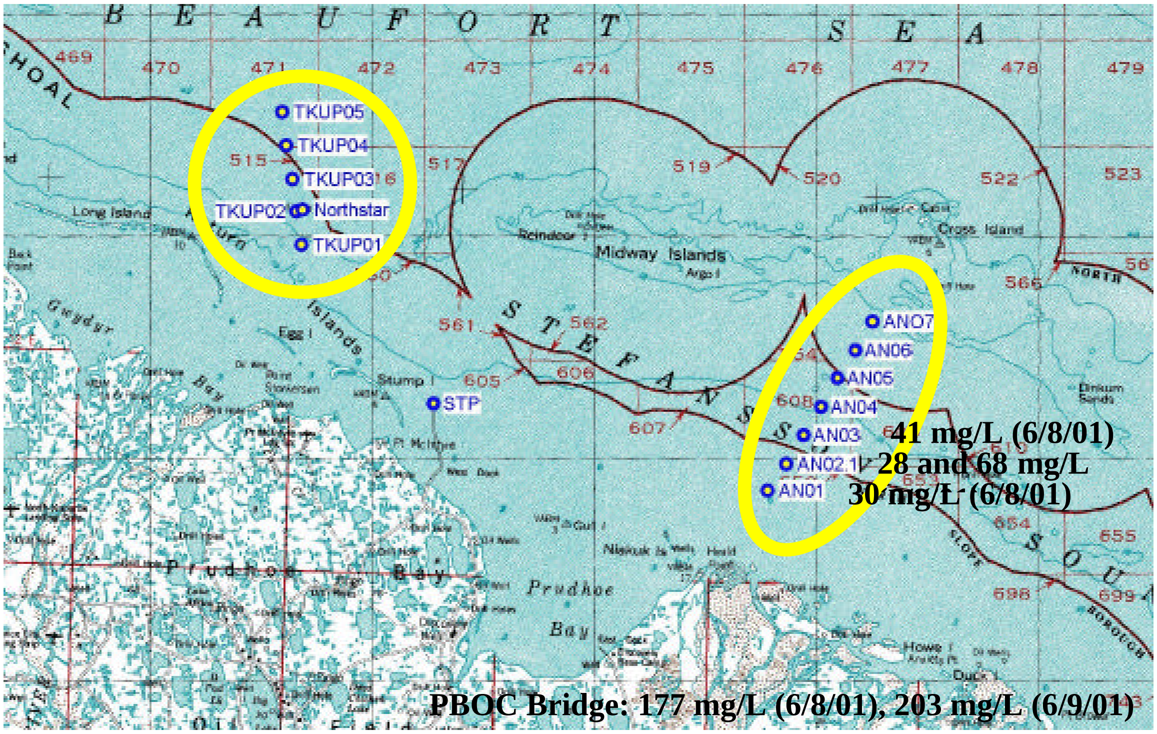


Figure 3-30. Map showing under ice and river sampling locations with concentrations of suspended sediment in river water and in the surface layer of river water under the ice for June 8 and 9, 2001.

Concentrations of TSS during the 2001 period of under-ice sampling were 177 to 203 mg/L in the Sagavanirktok River at the PBOC bridge (Figure 3-30). Concentrations of TSS in the 1- to 2-m thick lens of freshwater, immediately under the ice, averaged about 40 mg/L (Figure 3-30). The levels of TSS in the river water being carried under the ice on June 8 and 9 (Figures 3-30 and 3-33) remained relatively high (all ~30 mg/L or more) because the freshwater flow was channeled for at least 10 km offshore. The channeling effect was set up by the flow of the lower density river water over more dense seawater and by the formation of a thin layer of ice at the interface of the seawater/freshwater boundary due to freezing of the freshwater above the -1.8° C saltwater. Some settling of suspended sediment was observed in the transmissivity profile on June 11 at stations AN2 and AN3 (Figure 3-33). Settling of particles at these two sites closer to the river mouth (but under ice) is implied by a lack of any obvious tongues of lower salinity or warmer water accompanying the lower transmissivity. At distances of ~2 to 8 km along the transect, the suspended sediment seemed confined to the upper 1 m or so of the water under the ice (Figure 3-33), most likely aided by the channeling effect described above.

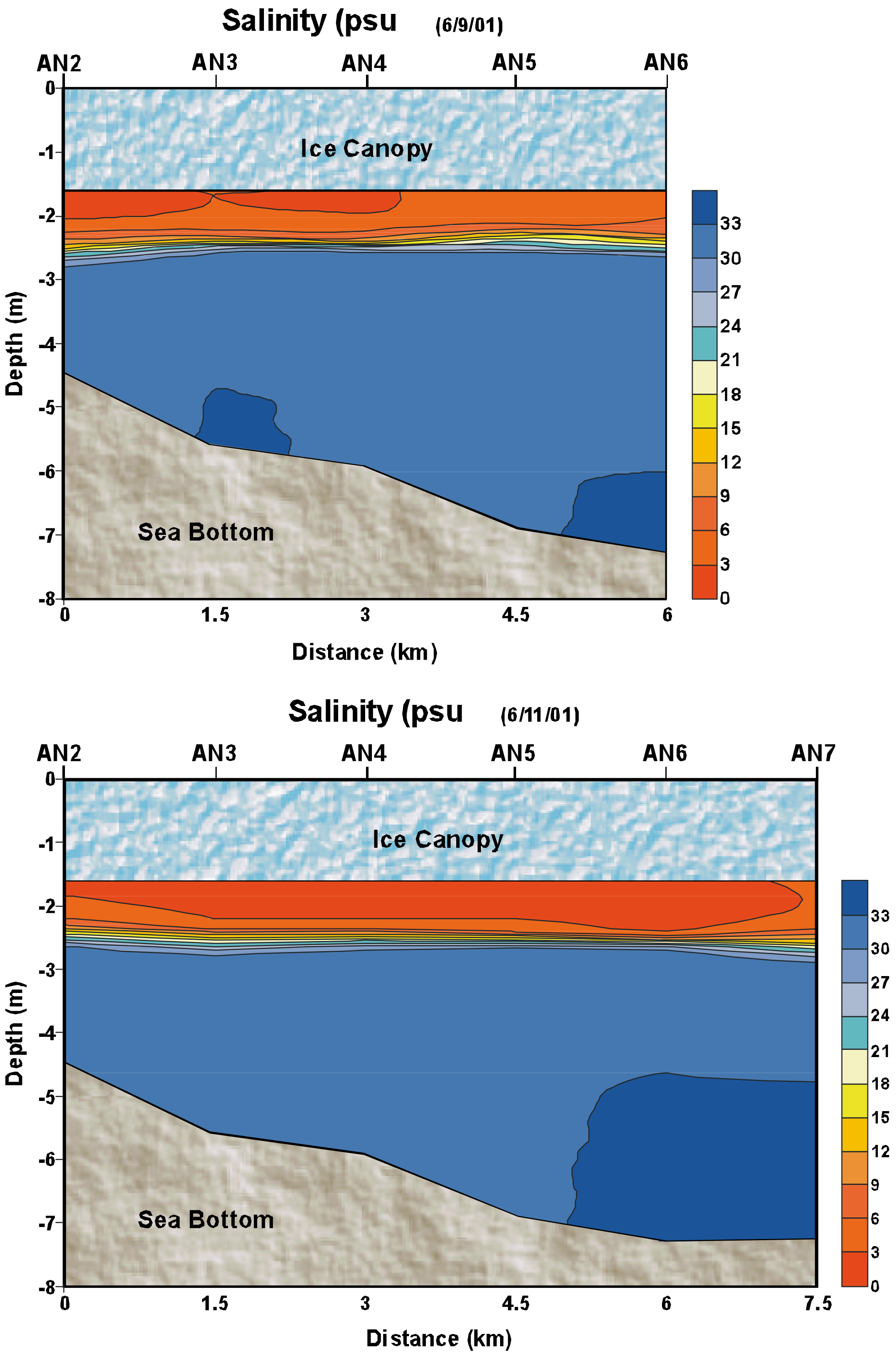
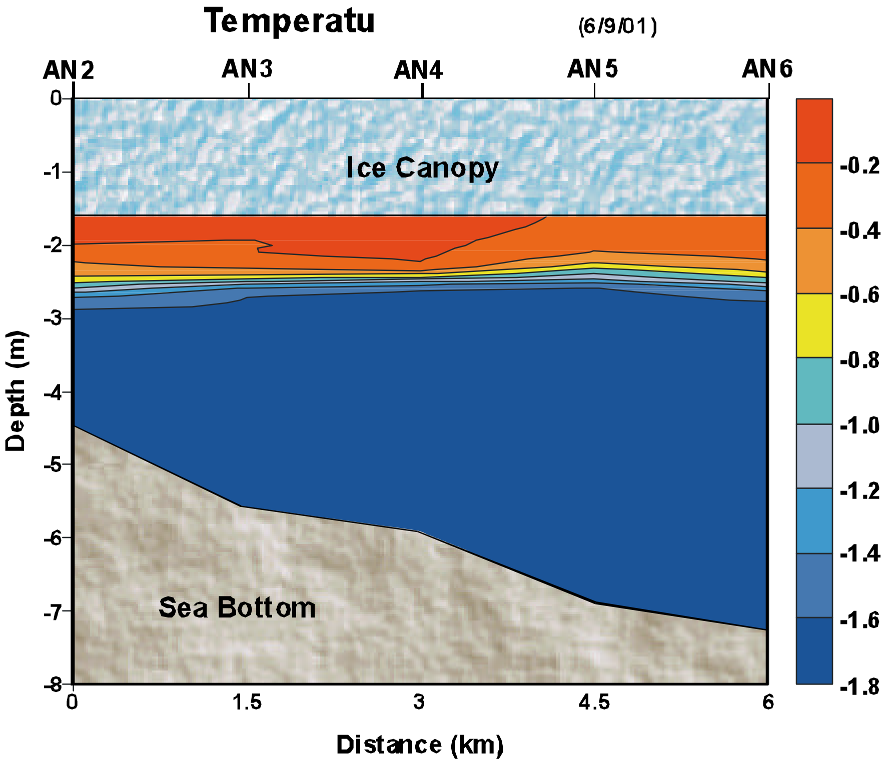


Figure 3-31. Vertical profiles for salinity along a transect seaward of the Sagavanirktok River delta (map in Figure 3-30) for June 9 and 11, 2001.



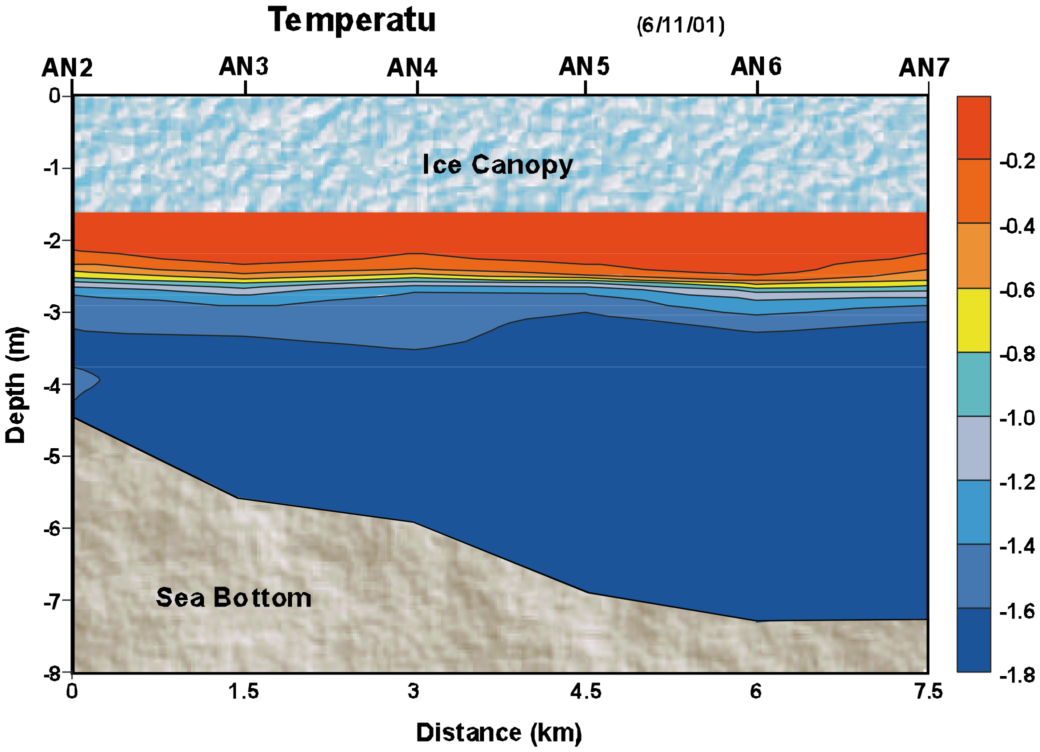


Figure 3-32. Vertical profiles for temperature along a transect seaward of the Sagavanirktok River delta (map in Figure 3-30) for June 9 and 11, 2001.

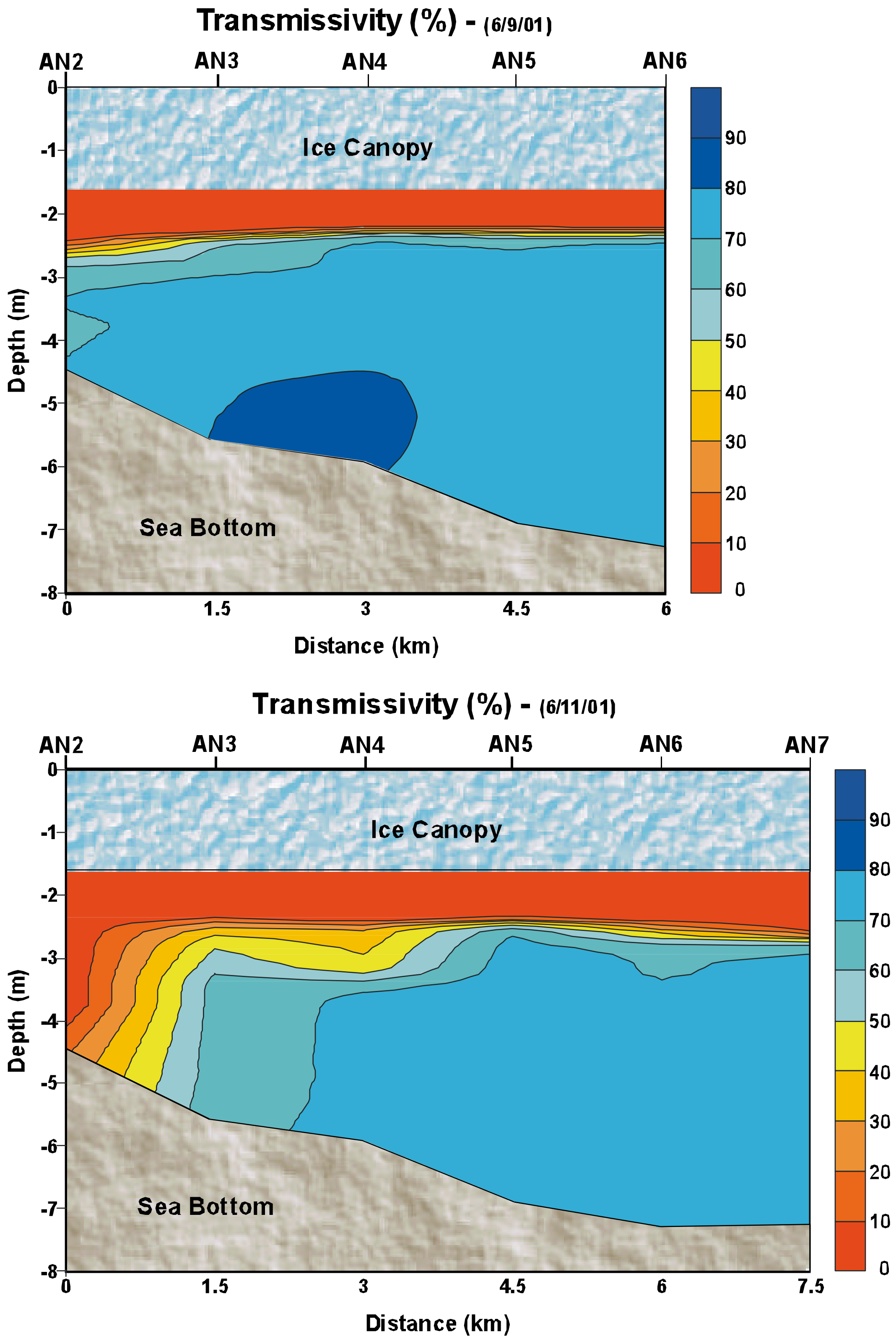


Figure 3-33. Vertical profiles for transmissivity along a transect seaward of the Sagavanirktok River delta (map in Figure 3-30) for June 9 and 11, 2001.

The implications of offshore transport of suspended sediment by what we have called the “under ice express” are potentially important to the sediment budget of the coastal Beaufort Sea. About 87% of the annual load of suspended sediment from the Sagavanirktok River during 2001 was carried to an ice covered coastal Beaufort Sea. Although some of this suspended sediment most likely was deposited in the river delta and in nearshore waters adjacent to the Endicott Causeway, a sizeable portion of the sediment was carried offshore by over and under ice transport. Such offshore movement of suspended sediment decreases the amount of sediment deposited along a broad portion of coastal Beaufort Sea, including such locations as the Boulder Patch. This observation is consistent with the lack of recent sediment in the ANIMIDA study area as described in Brown et al. (2004) and reiterated later in this report.

Freshwater flow from the Kuparuk River could be traced to just seaward of Northstar Island (Figure 3-34 and map in Figure 3-30). The transect seaward of the Kuparuk River shows the mixing and seaward extent of the river flow in vertical profiles for salinity, temperature and transmissivity (Figure 3-34). The distance from shore of the terminus of flow from the Kuparuk River is ~10 km, about the same distance offshore as station AN5 on the transect from the Sagavanirktok River (Figure 3-30).

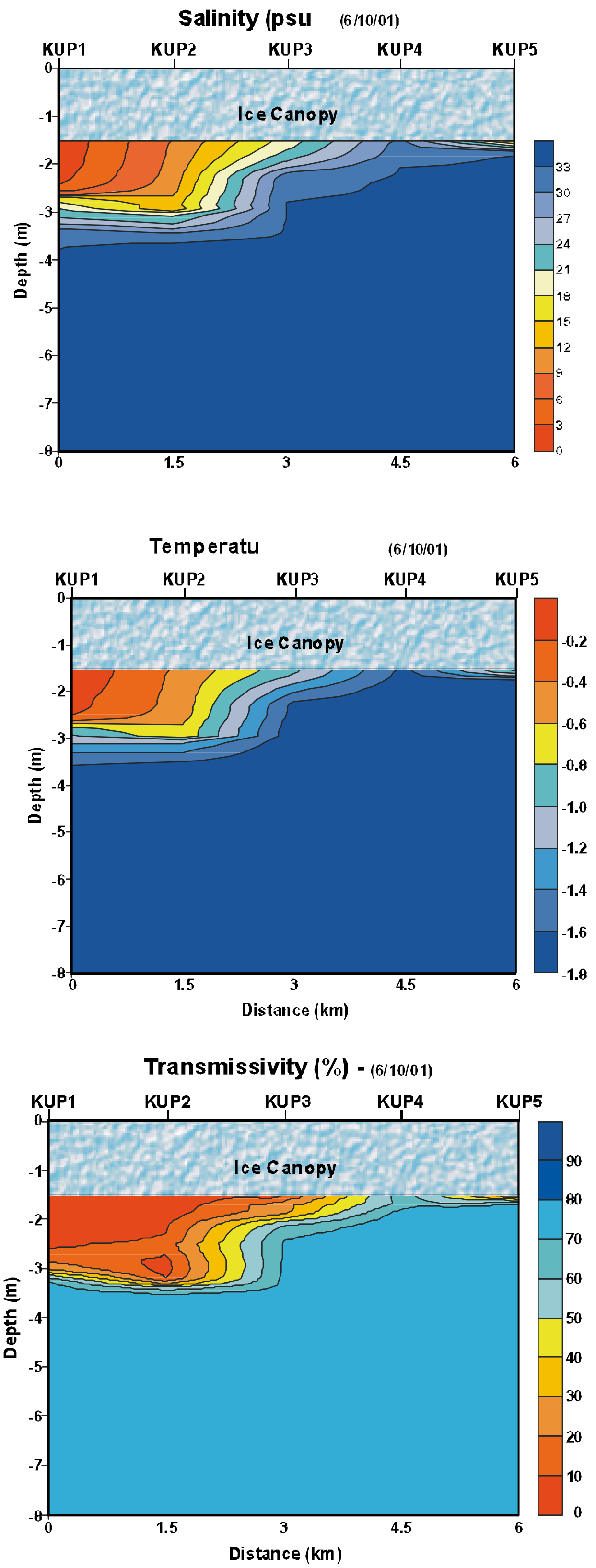


Figure 3-34. Vertical profiles for salinity, temperature and transmissivity along a transect seaward of the Kuparuk River delta for June 10, 2001.

During 2002, the scenario for discharge of water from the Sagavanirktok River during 2002 was similar to that observed in 2001 with the exception that flow was halted temporarily due to freezing conditions, as described previously. Data from the CTD-transmissometer and samples of water and suspended sediment were collected at nine locations during 2002 (Figure 3-35). Sampling along an L-shaped transect from the Sagavanirktok River (Figure 3-35) was carried out on May 27, 002 and June 4, 2002. Turbidity in the Sagavanirktok River at the PBOC bridge peaked on May 25 and again on June 5, 2002 (Figure 3-12, page 25); therefore the two sampling days coincided well with river runoff. The salinity in the surface layer of water under the ice along the offshore transect from the Sagavanirktok River was <10 psu at all sites and the salinity in the deeper water was rather uniform at 32 psu (Figure 3-36). Temperatures in the low salinity water under the ice were 0.2 to 0.6 °C and some slight downward mixing of surface water can be seen at stations S2 and S3 on June 4 (Figure 3-37). Vertical profiles for transmissivity on May 27 show that suspended sediment is confined to the upper layer (Figure 3-38) where concentrations of TSS were ~ 10 and 6 mg/L at stations S4 and S6 (on May 28), respectively. Evidence for settling of suspended sediment is observed at stations S2, S3 and S5 on June 4. The values for TSS plotted on the transmissivity profile (Figure 3-38) for June 4 are consistent with the transmissivity data and the TSS data for May 27.

At stations NS1 and NS2 on May 26, 2002, the surface water under the ice had salinity levels of about 10 and 30 psu, respectively (Figure 3-39). At 6 m below the surface, the salinity values at both stations were ~32 psu. Peak flow from the Kuparuk River occurred on May 23 and 24. The impact of the Kuparuk River flow is very clear at station NS1, about 4 km seaward of Northstar Island, but not at stations NS2, an additional 1.5 km seaward of station NS1 (Figure 3-39). The concentrations of TSS track the salinity well at the two NS stations with values of 9.5 and 0.21 mg/L at 3 m below the surface for stations NS1 and NS2, respectively (Figure 3-39). At a depth of 6 m, the levels of TSS were ~0.2 mg/L at both NS stations.

An overall comparison of levels of suspended sediment for the 2002 sites (Figure 3-39) shows that levels of TSS at 6 to 10 mg/L are common to the under ice layer of fresher water. Furthermore, the data for water at a water depth of 6 m along the transect from the Sagavanirktok River show about ten times greater levels of TSS (2 versus 0.2 mg/L) than for similar depths at the Northstar stations. This difference is best explained by distance from shore and water depth.

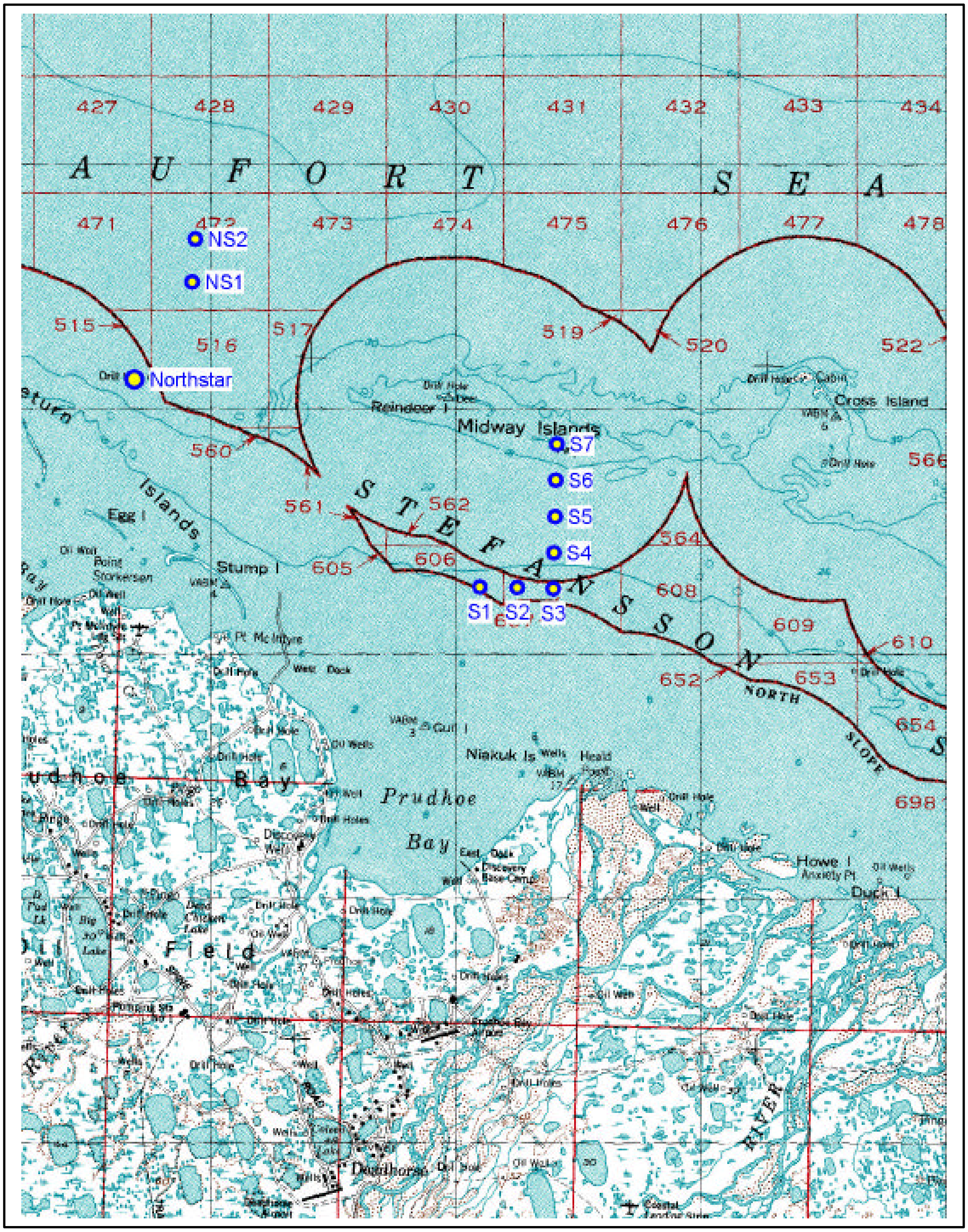
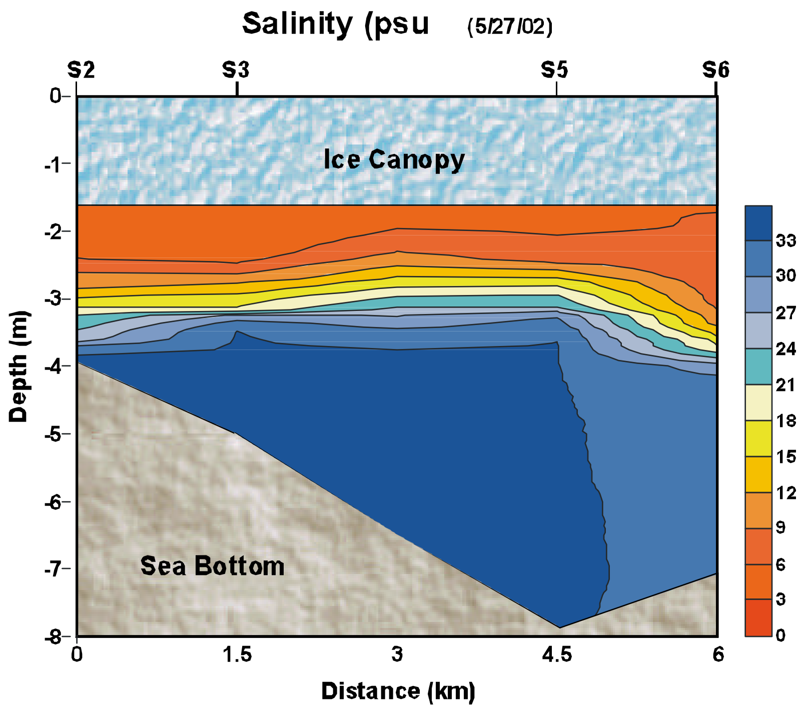


Figure 3-35. Map showing under ice and river sampling locations with concentrations of suspended sediment in river water and in the surface layer of river water under the ice for June 2002.



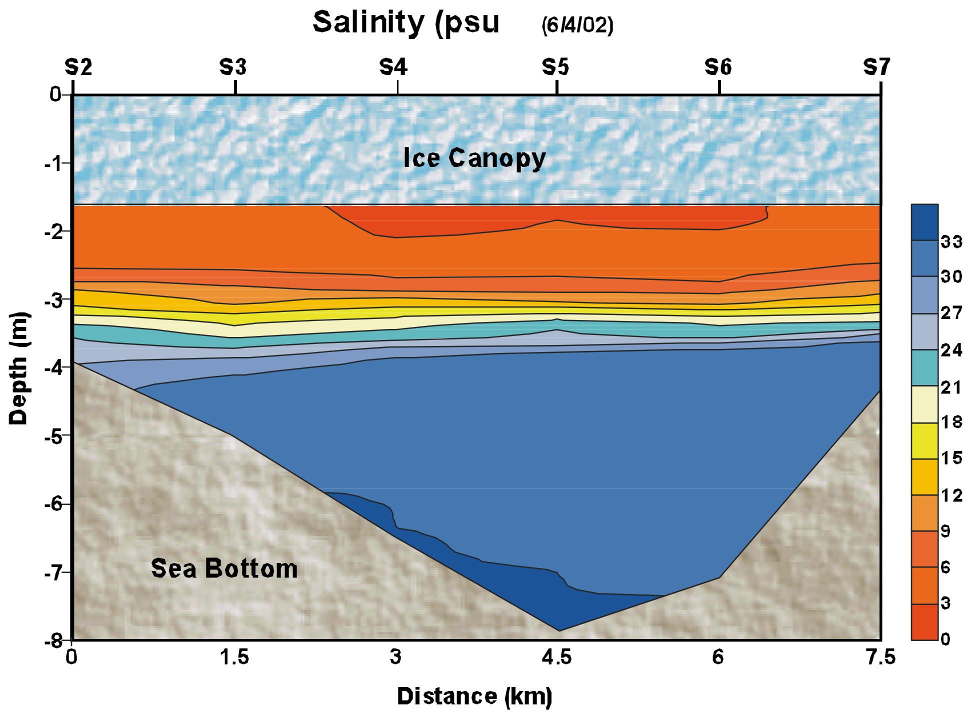
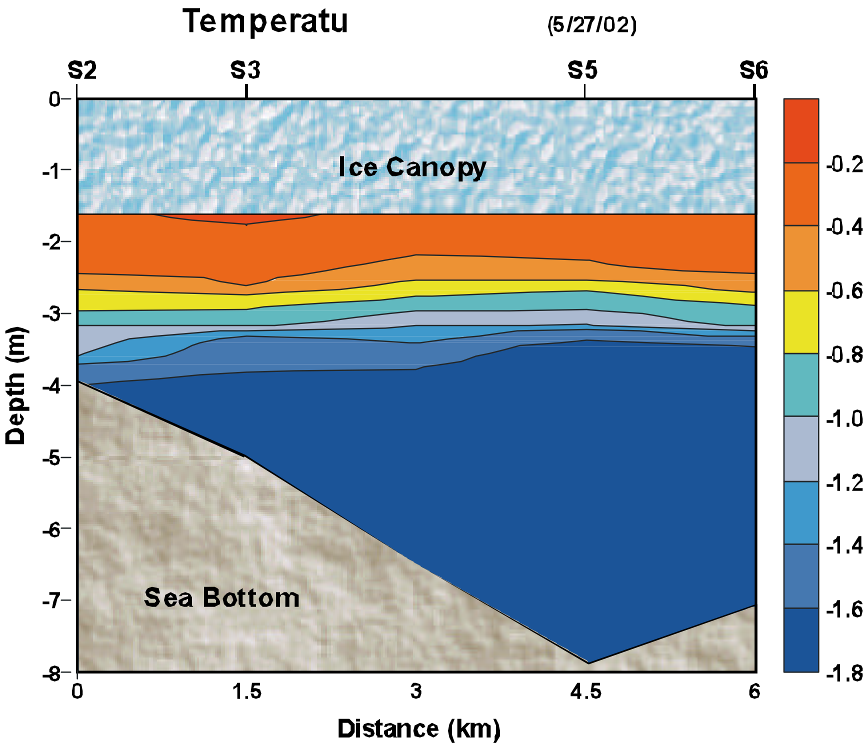


Figure 3-36. Vertical profiles for salinity along a transect seaward of the Sagavanirktok River delta (map in Figure 3-35) for May 27 and June 4, 2002.



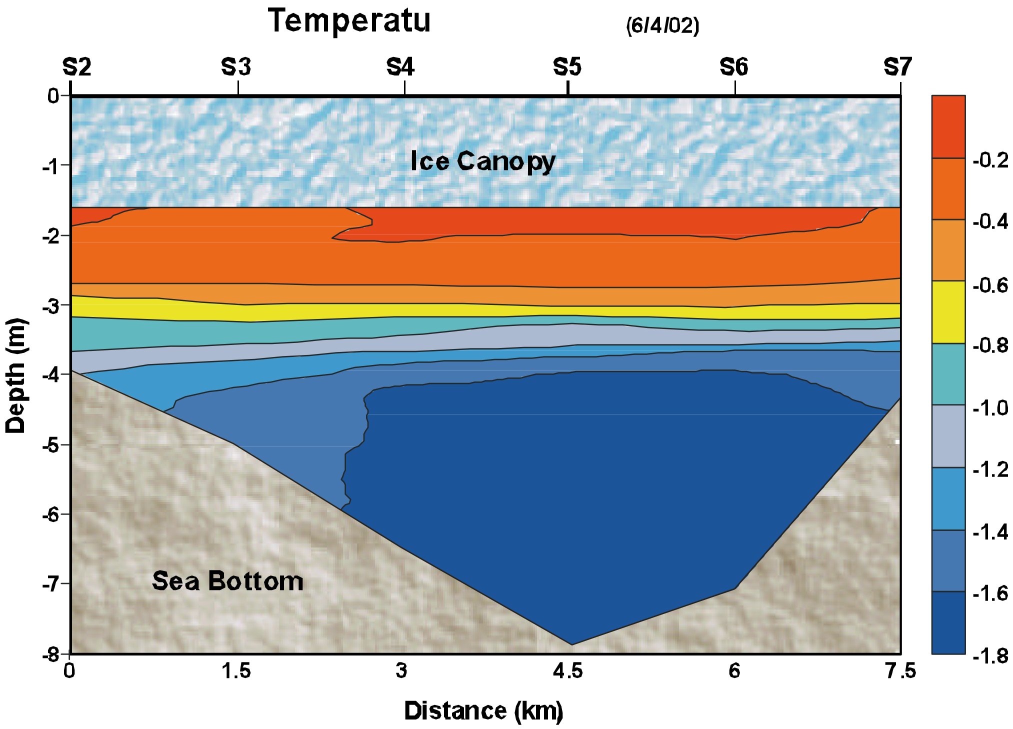


Figure 3-37. Vertical profiles for temperature along a transect seaward of the Sagavanirktok River delta (map in Figure 3-35) for May 27 and June 4, 2002.

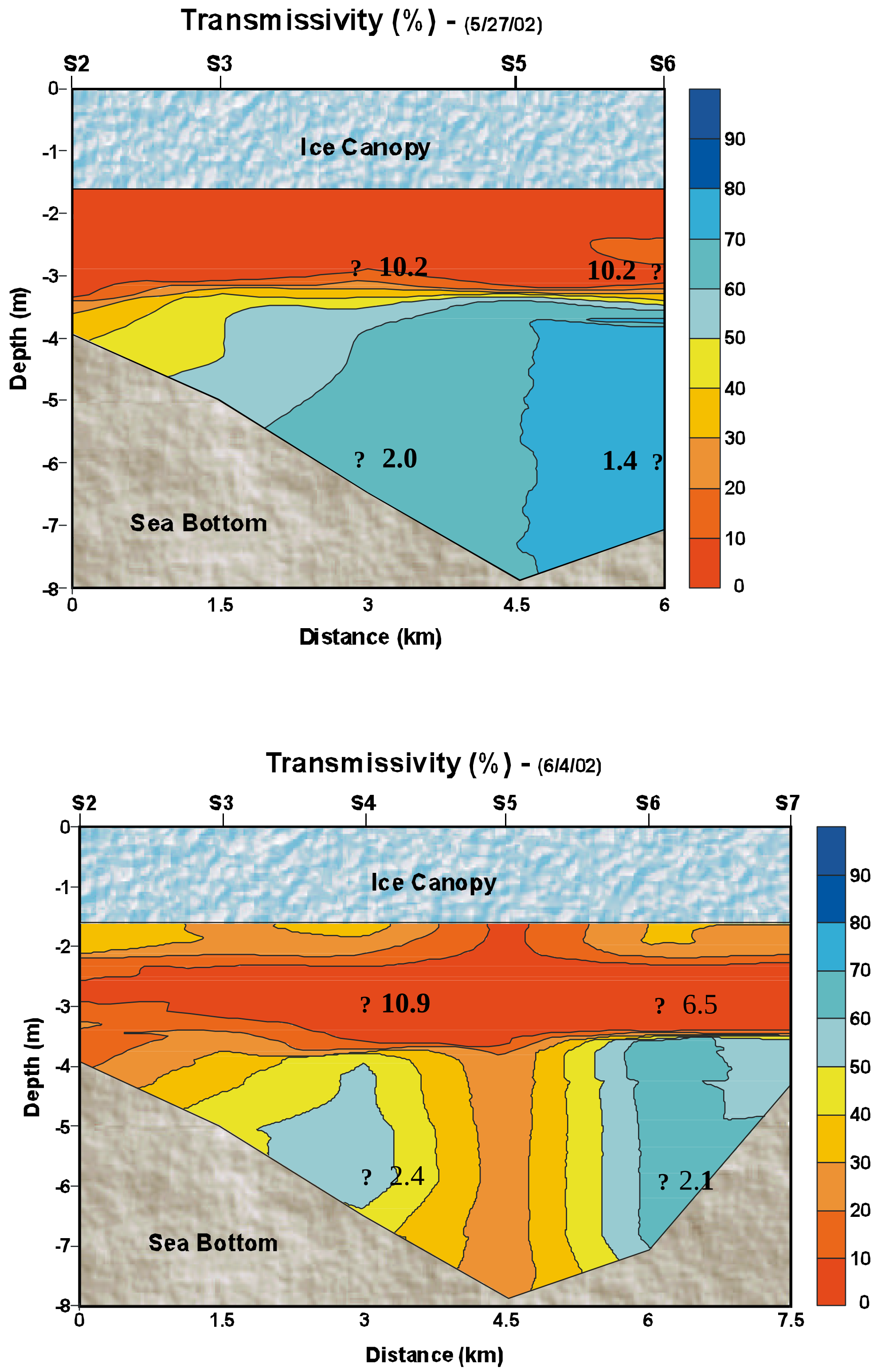


Figure 3-38. Vertical profiles for transmissivity along a transect seaward of the Sagavanirktok River delta (map in Figure 3-35) for May 27 and June 4, 2002.

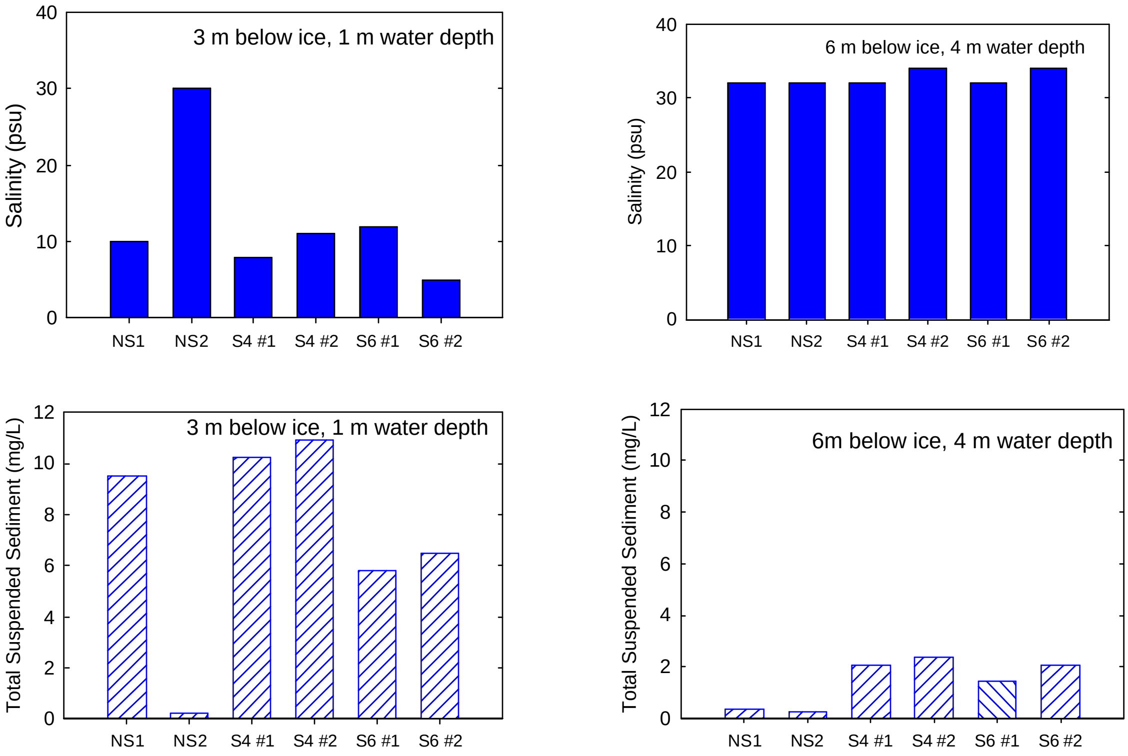


Figure 3-39. Bar graphs showing salinity and concentrations of total suspended solids for under ice samples from May 26, 2002 (with #1 or no extra number) and June 4, 2002 (with #2). Stations locations shown on Figure 3-35.

Suspended particles in the water column under the ice are generally similar in composition to the river suspended sediment. Concentrations of Al in these under-ice particles ranged from ~4.2 to 7.8% and concentrations of Fe ranged from ~3.4 to 6.4% (Figure 3-40). The Fe/Al ratios of the under ice particles from 2002 plot above the upper 99% prediction interval developed for bottom sediments (Figure 3-40); however, elevated Fe/Al ratios were found for suspended sediment from the Kuparuk River and for the under-ice particles collected in 2000. Under certain conditions, especially under ice or during periods of low TSS in the Kuparuk River, suspended particles seem to build-up more Fe-rich surface coatings. Dissolved Fe levels in river water during the spring floods are typically ten times higher than during off-peak periods and more than two-orders-of-magnitude greater than in coastal waters (Rember and Trefry, 2004; Trefry et al., 2004). This abundance of dissolved Fe increases the opportunity for particles to scavenge Fe as the pH increases from river water to seawater and as the absolute concentrations of particles decreases. At each site where suspended sediment were collected, concentrations Fe in suspended sediment were 15 to 70% greater in the surface fresher water than in the deeper saline water (Figure 3-40).

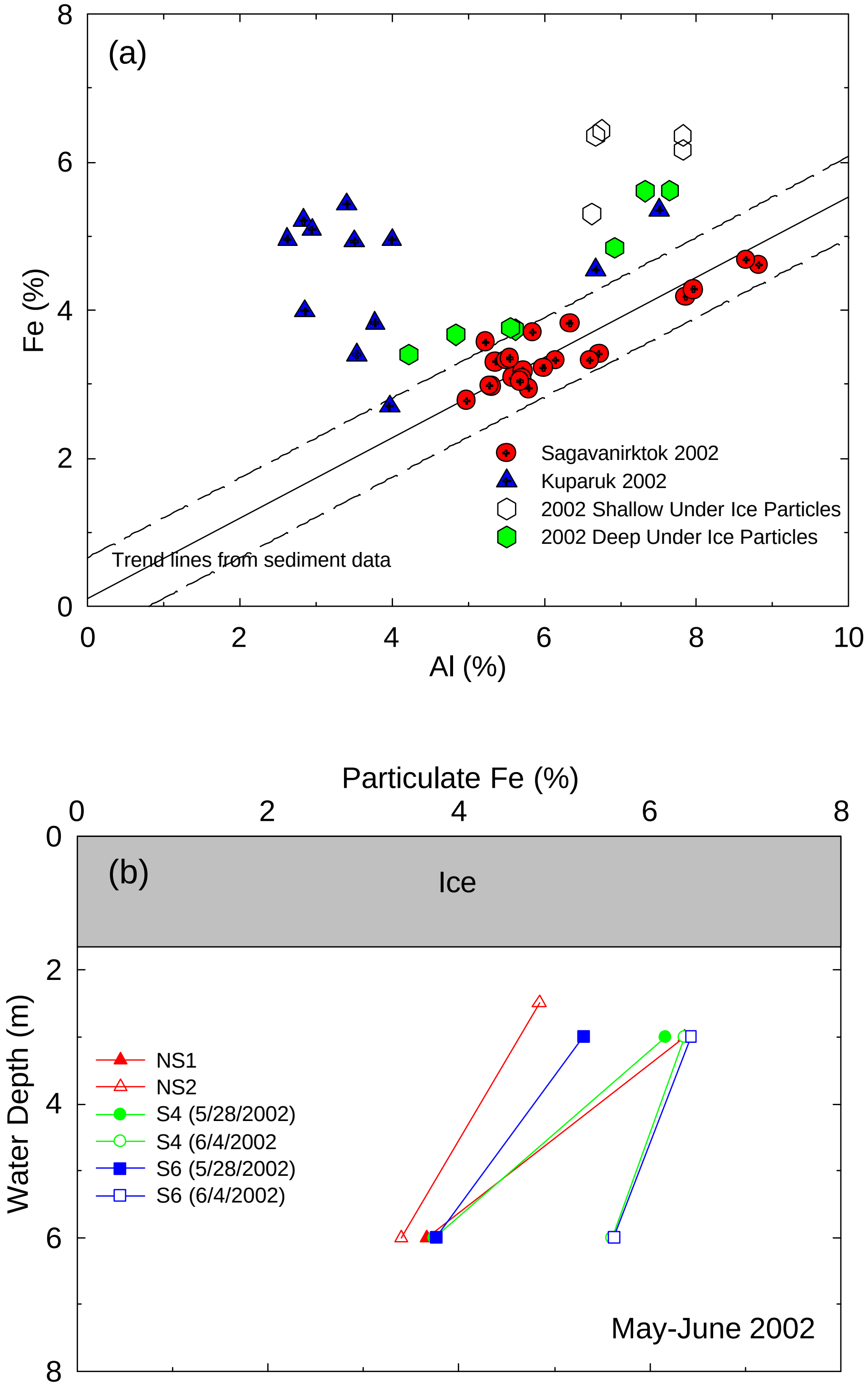


Figure 3-40. (a) Concentrations of aluminum (Al) versus iron (Fe) in suspended sediment from area rivers and under ice in the Beaufort Sea during spring floods. Solid line shows regression line for Al versus Fe for natural bottom sediment; dashed lines show corresponding 99% prediction interval and (b) concentrations of Fe in suspended sediment from under ice during May-June 2002 for stations at Northstar Island (NS) and the outflow of the Sagavanirktok River (S).

In contrast with Fe, concentrations of Ba and the Ba/Al ratios in suspended particles collected under the ice were similar to levels found in river suspended sediment (Figure 3-41). As discussed in Trefry et al. (2004), concentrations of dissolved and particulate Ba are not influenced by changes in river flow, concentrations of TSS or dissolved organic carbon, or minor shifts in redox conditions. Thus, the suspended sediment collected under the ice contains Ba at levels that are similar to both incoming river particles and bottom sediment in the coastal Beaufort Sea.

Trends for Pb (Figure 3-42), As, Cu, K, Mg, Mn and Zn follow those observed for Ba with metal/Al ratios for suspended sediment collected under ice that fit within the prediction intervals developed for bottom sediments and river suspended sediment (complete data set in Appendix B). A relatively large range in Pb content (2-3 fold) was observed among the under ice particles (Figure 3-42b) as the more Al-poor and organic-rich particles contain less Pb.

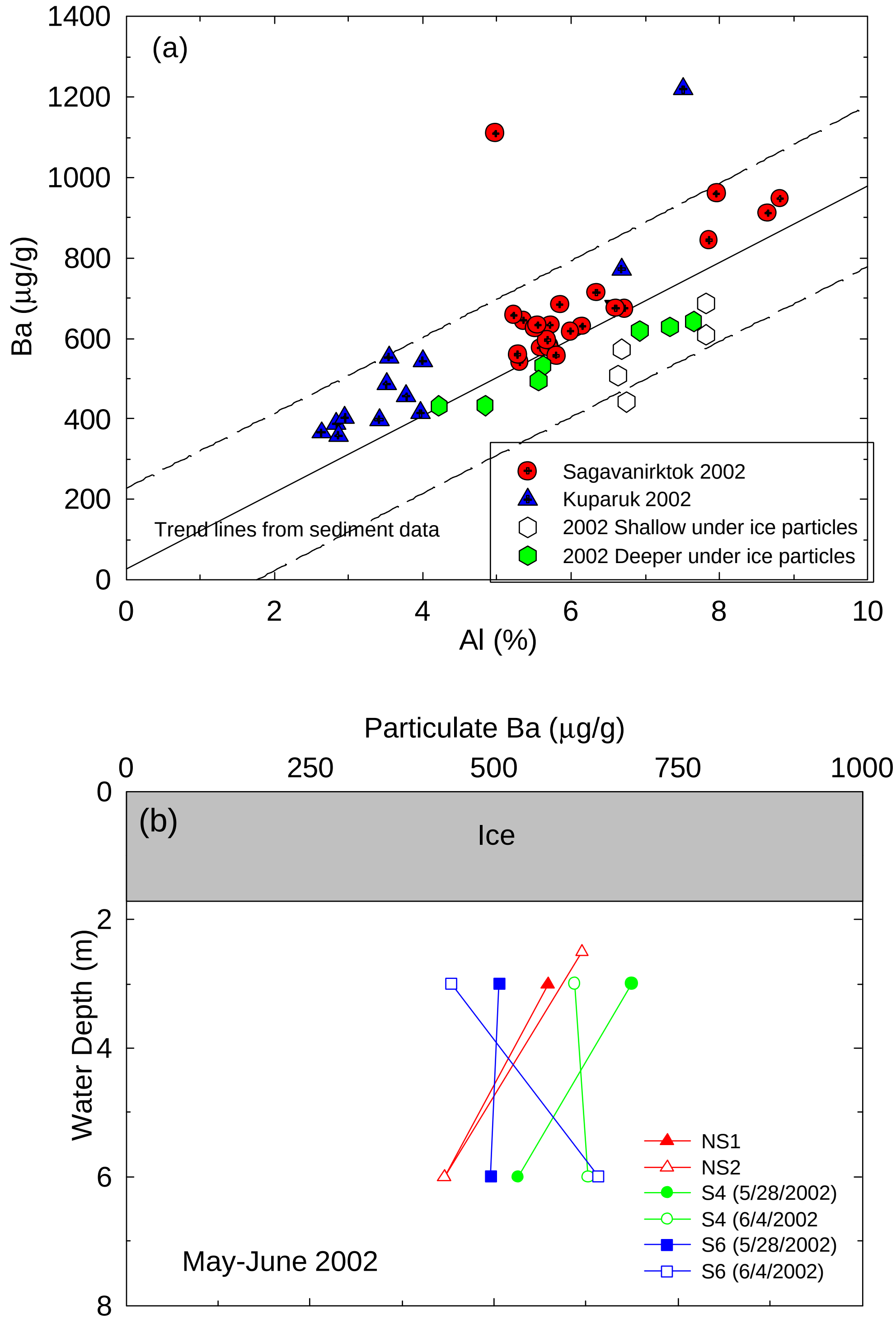


Figure 3-41 (a) Concentrations of aluminum (Al) versus barium (Ba) in suspended sediment from area rivers and under ice in the Beaufort Sea during spring floods. Solid line shows regression line for Al versus Ba for natural bottom sediment; dashed lines show corresponding 99% prediction interval and (b) concentrations of Ba in suspended sediment from under ice during May-June 2002 for stations at Northstar Island (NS) and the outflow of the Sagavanirktok River (S).

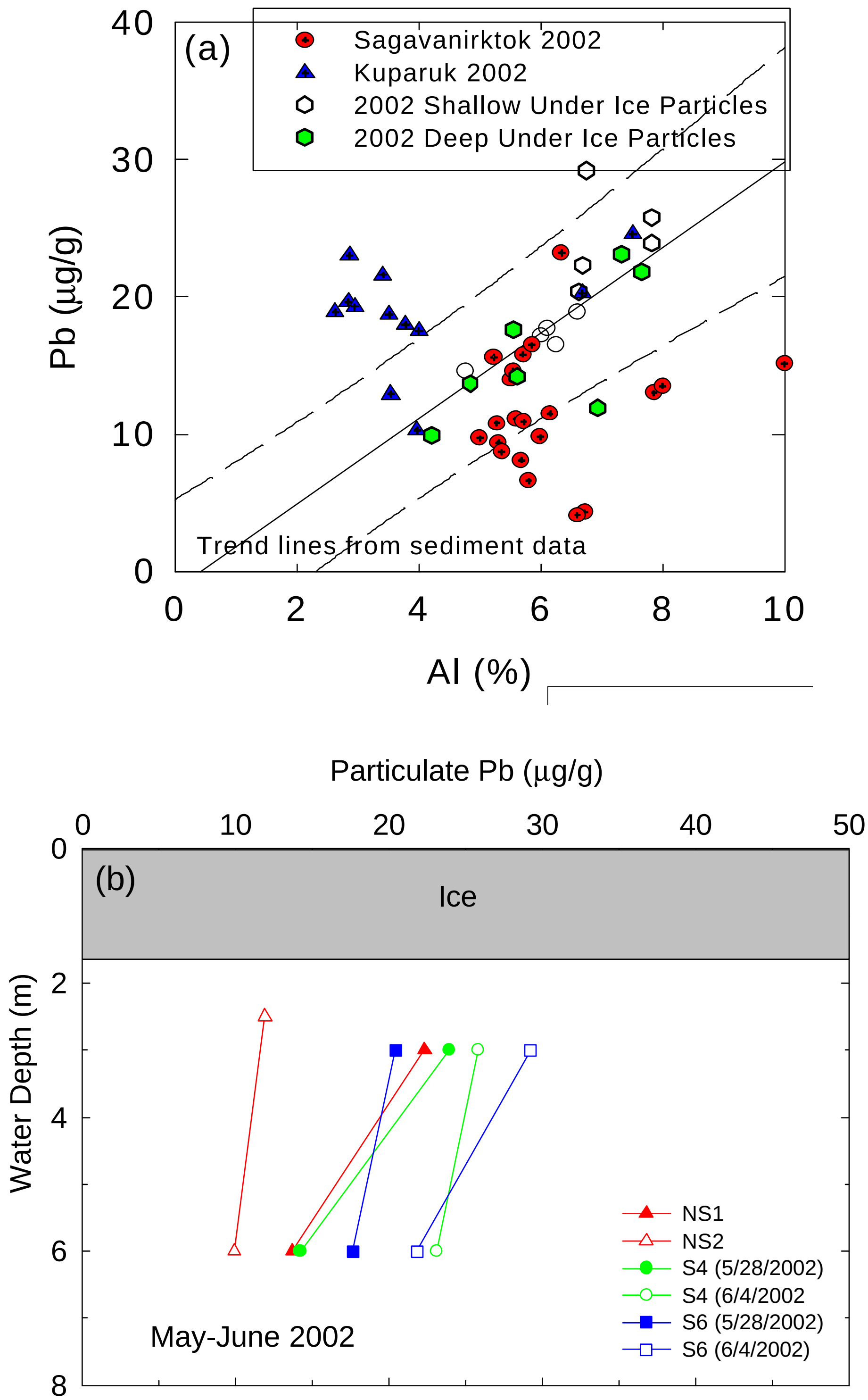


Figure 3-42 (a) Concentrations of aluminum (Al) versus lead (Pb) in suspended sediment from area rivers and under ice in the Beaufort Sea during spring floods. Solid line shows regression line for Al versus Ba for natural bottom sediment; dashed lines show corresponding 99% prediction interval and (b) concentrations of Pb in suspended sediment from under ice during May-June 2002 for stations at Northstar Island (NS) and the outflow of the Sagavanirktok River (S).

3.5 Ice Cores

Ice cores were collected during April 2000 and May-June 2002 to determine the quantities and composition of sediment trapped in the ice. This information can be used to identify natural trends and possible inputs of sediment to the ice from anthropogenic activities. Each core was subdivided into 3 to 5 sections over the 1.5 to 2 m length in the field. Then, each core was thawed upon return to the field laboratory, the volume measured and the particles in the core were obtained by filtration.

Concentrations of particles in the ice cores were highly variable, ranging from 0.3 to 248 mg/L. In general, concentrations of particles were lowest in the deeper portions of each core. At depths >100 cm in the cores, the mean concentration of particles was 4 mg/L in 2000 and 1 mg/L in 2002 with only one value in all samples from both years >3 mg/L (Figure 3-43). In contrast, the mean value for particles in the upper 100 cm of the cores was 54 mg/L in 2000 and 20 mg/L in 2002. At site LA2 in 2000, for example, the values for sediment in the ice cores were as follows: 205 mg/L (0-55 cm), 2.6 mg/L (55-95 cm) and 1.8 mg/L (95-155 cm) (Figure 3-43). Even at a more offshore site (NA2 in 2000) where the absolute values were lower, the same trend was observed with values of 11 mg/L at 0-35 cm), 3.6 mg/L at 35-70 cm, and 1.8 mg/L at 70-150 cm. Similar vertical trends with overall lower levels of sediment were found in 2002 (Figure 3-43).

The distribution of sediment in the ice cores is partially consistent with the pattern of formation of sea ice. The top layer (as sampled) forms first and freezes in the suspended sediment in the ambient water. Storms during the fall seasons can keep the TSS at levels of >10 to 100 mg/L in the coastal Beaufort Sea. Some time after the top layer of ice forms, the energy of the underlying water is dramatically decreased and suspended particles slowly settle out such that the ice that forms later from below contains considerably lower levels of sediment. In two ice cores from 2002 (stations S4 and S6), one or more layers of ice with higher levels of sediment than at the top of the ice core were found. These deviations from the most common trend may be related to late fall river runoff or resuspension events.

Data for Fe and Al in sediment from the ice cores provide some additional insight to differences between the composition of particles during the open-water and under-ice seasons. The Fe/Al ratios for sediments recovered from the top layers of the ice cores (0.56 ± 0.02) were consistent with the composition of suspended particles collected from the rivers and open water of the coastal Beaufort Sea (Fe/Al = 0.6). In contrast, the Fe/Al ratios for sediment collected from the lower portions of the ice cores averaged 1.6 ± 0.2. Particles from deeper in the ice cores were derived from the under-ice environment. Sediment from deeper in the ice cores had an Fe/Al ratio that was more consistent with the under-ice suspended particles. These results strengthen the argument that the under-ice particles were more Fe rich as discussed previously.

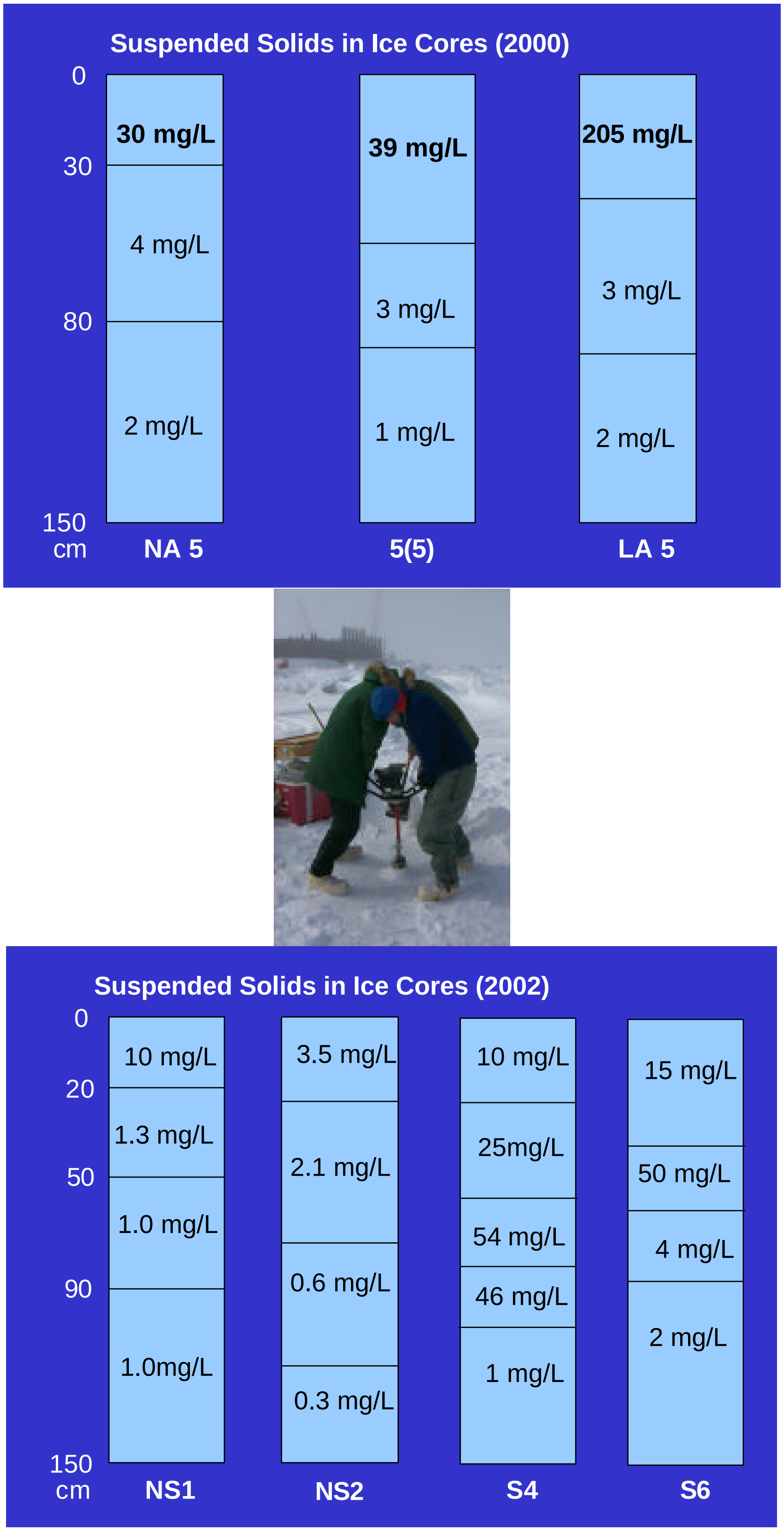


Figure 3-43. Schematic profiles showing amount of sediment suspended in ice cores collected during 2000 and 2002 with picture showing the ice coring process.

The ice core data facilitate calculation of the impact of sediment releases from melting ice on bottom sediment accumulation. Using the worst-case scenario (site LA5, 2002), the integrated amount of sediment in the ice core is about 6 mg/cm^2 (Figure 3-44). As the ice melts and releases this sediment, the impact on the seafloor is accumulation of only about 0.004 cm of sediment per cm^2 (Figure 3-44). This small impact is consistent for all ice cores collected. Certainly, increased loading may be possible at some locations; however, the net impact on sediment accumulation would appear to be small in the ANIMIDA study area. The average, integrated amount of suspended sediment in ice cores (~4 mg/cm^2) is larger than the calculated value of 0.3 mg/cm^2 in the water under the ice, but generally smaller than values of 3 to 50 mg/m^2 in the water column during the open-water period. Therefore, the overall impact of melting sea ice on suspended sediment concentrations in the water column is minor. Furthermore, no evidence has been found to show that the suspended sediment in these ice core samples is from other than natural processes.

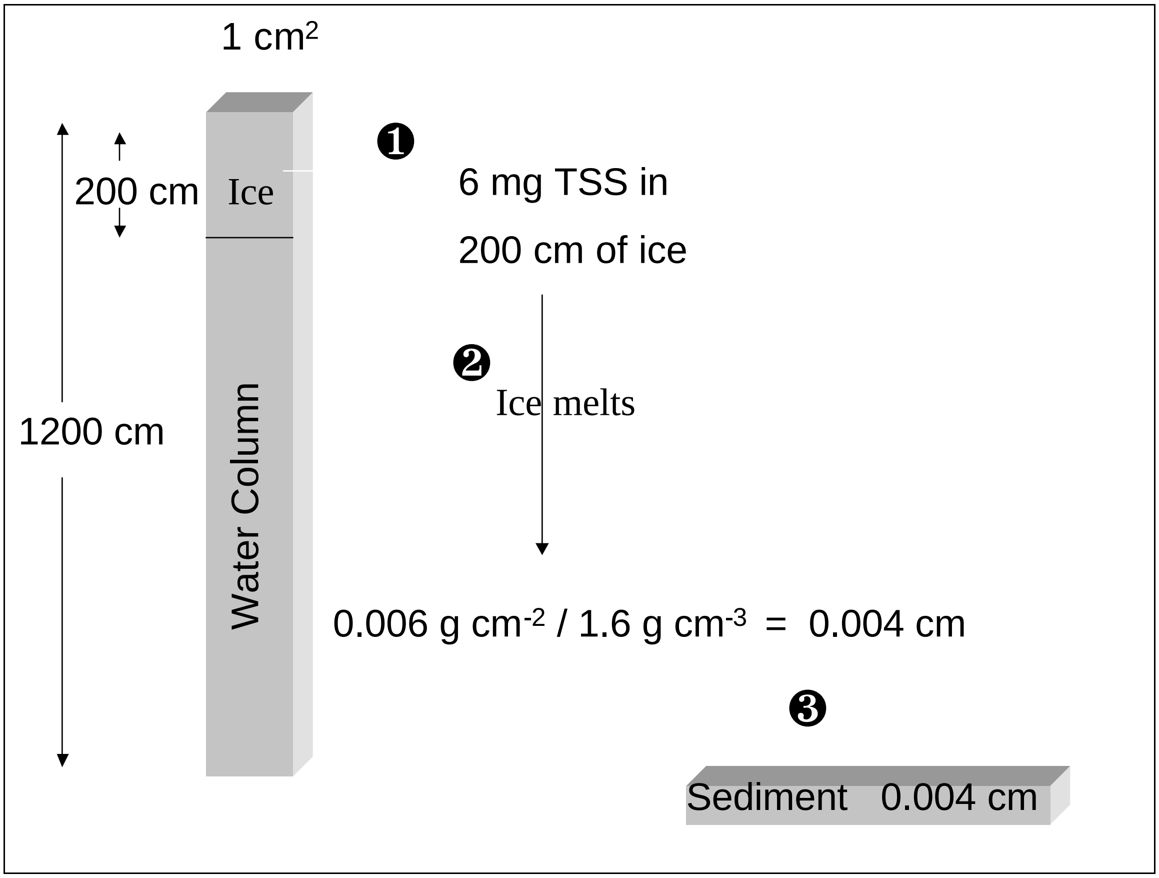


Figure 3-44. Schematic representation of the release of sediment from melting sea ice. The process is tracked as follows: 1. Integrated amount of sediment in the ice core as determined from core data, 2. Release of sediment to seafloor when ice melts, and 3. Calculated depth of sediment layer formed from sediment in sea ice.

3.6 Suspended Sediment in Waters of Coastal Beaufort Sea

In the ANIMIDA study area, numerous vertical casts and horizontal tows in the water column were made during 1999, 2000, 2001 and 2002 to measure turbidity, salinity, temperature and current speed and direction. These data help provide a picture of the distribution of suspended sediment under normal and storm conditions.

Turbidity is measured three ways, by in situ turbidimeter, by laboratory turbidimeter using discrete samples and by filtration for total suspended solids (TSS) using discrete samples. The correlation between TSS and laboratory turbidity was very good (r = 0.98) with the overall average value for TSS in mg/L equal to ~2 times the turbidity in NTU (Figure 3-45). Likewise, where good matches in depth of the in situ turbidimeter and the discrete sample were available, the relationship also was quite good (Figure 3-46).

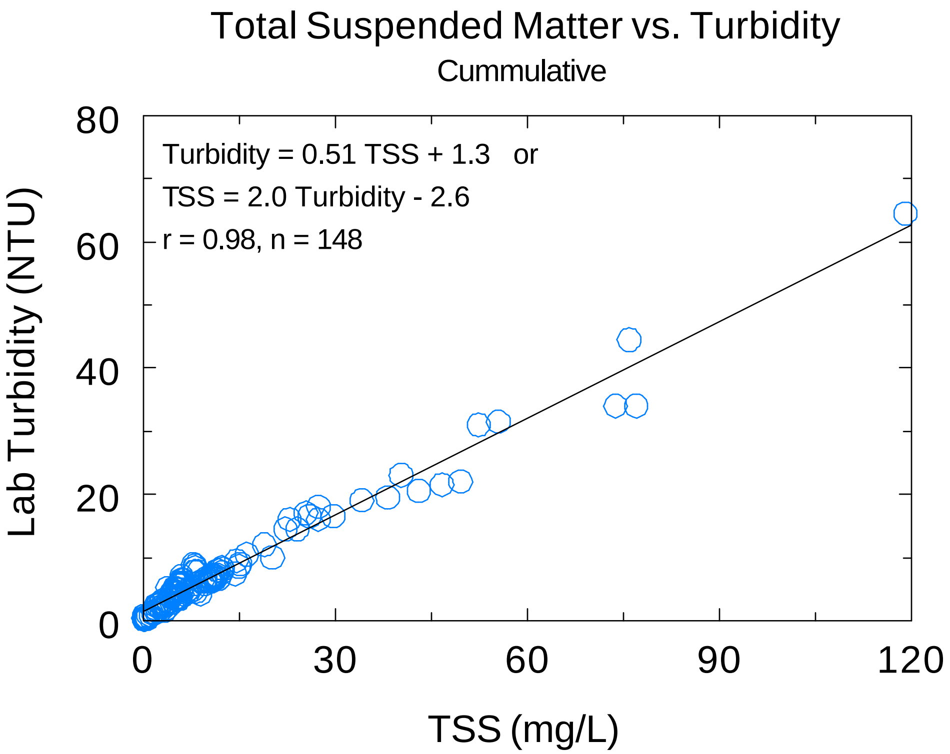


Figure 3-45. Relationship between concentrations of total suspended solids (TSS) and laboratory turbidity.

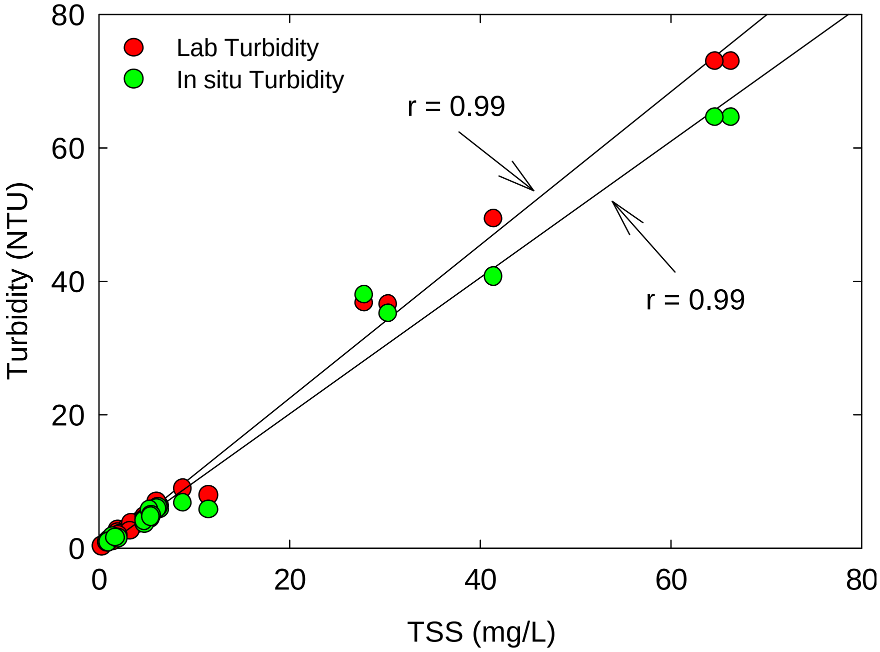


Figure 3-46. Relationship for concentrations of total suspended solids (TSS) versus laboratory turbidity and in situ turbidity.

Samples of suspended sediment and turbidity data were collected by way of vertical profiles and horizontal tows during 1999, 2000, 2001 and 2002. The activity focused on the area of Northstar Island with selected reference sites throughout the ANIMIDA study area (Figure 3-47). The day-to-day distribution of TSS was dependent on river flow, wind conditions and sea ice. No significant differences in levels of TSS or turbidity were observed near Northstar Island relative to other sites in the ANIMIDA area. The details of the story follow below; the complete data sets are presented in Appendix C.

Examples of typical vertical profiles for 2001 in Figures 3-48 and 3-49 show some typical trends. During late July and early August, 2001, winds were relatively calm and sea ice was close to station N1, north of Northstar Island (Figure 3-47); thus, the turbidity was quite low, yet higher in the surface 3 to 4 m than deeper in the water column (Figure 3-48). The turbidity increased in samples collected closer to shore; and, in shallow nearshore waters at stations N13 and N14 (Figure 3-48), the water column was well mixed and the turbidity was relatively uniform with depth. However, the absolute values for turbidity were still quite low at stations N13 and N14 relative to levels >50 NTU at the same stations immediately after the August storm of 1999.

In the area of Liberty Prospect during 2001, the water was relatively well mixed and turbidity was uniform as a function of location and water depth (Figure 3-49). The turbidity at the Liberty stations (water depths <6 m) were in the range of 5 to 8 NTU, similar to those in the more shallow water sites near Northstar Island, but higher than those in 12-m deep waters near Northstar Island.

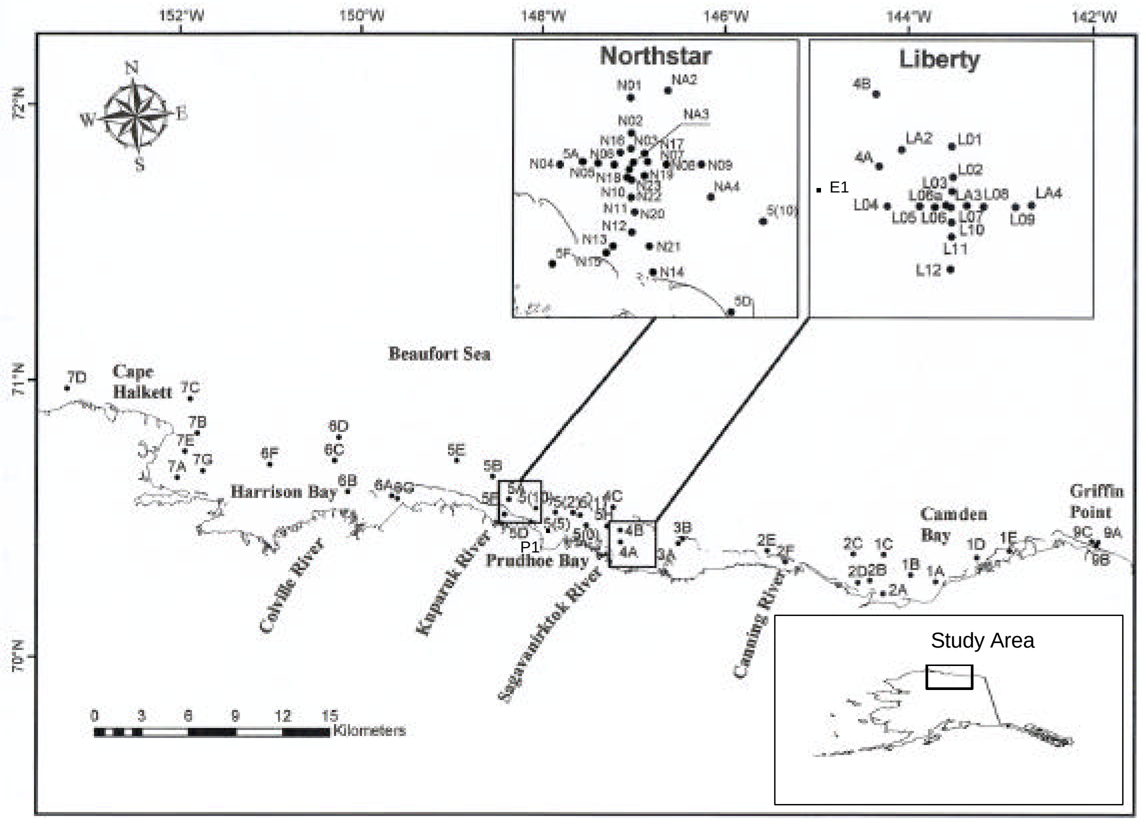


Figure 3-47. Map showing sampling stations in the ANIMIDA study area with inset maps of Alaska, the oil production site at Northstar Island and a possible future drilling site at Liberty Prospect.

In addition to the vertical profiles, CTD-turbidity tows (Figure 3-50) were carried at a variety of sites, most of which were located in the area around Northstar Island. Results from one series of tows are presented in Figure 3-51. These results show uniform levels of turbidity (~2.5 NTU) just above the pycnocline at a water depth of 1.5 m on either side of Northstar Island. The turbidity was lower below the pycnocline at 1.2-1.5 NTU. No significant deviations in levels of turbidity were observed during 2002 and 2001 along various transects adjacent to Northstar Island at distances as close as 100-500 m (Figure 3-51).

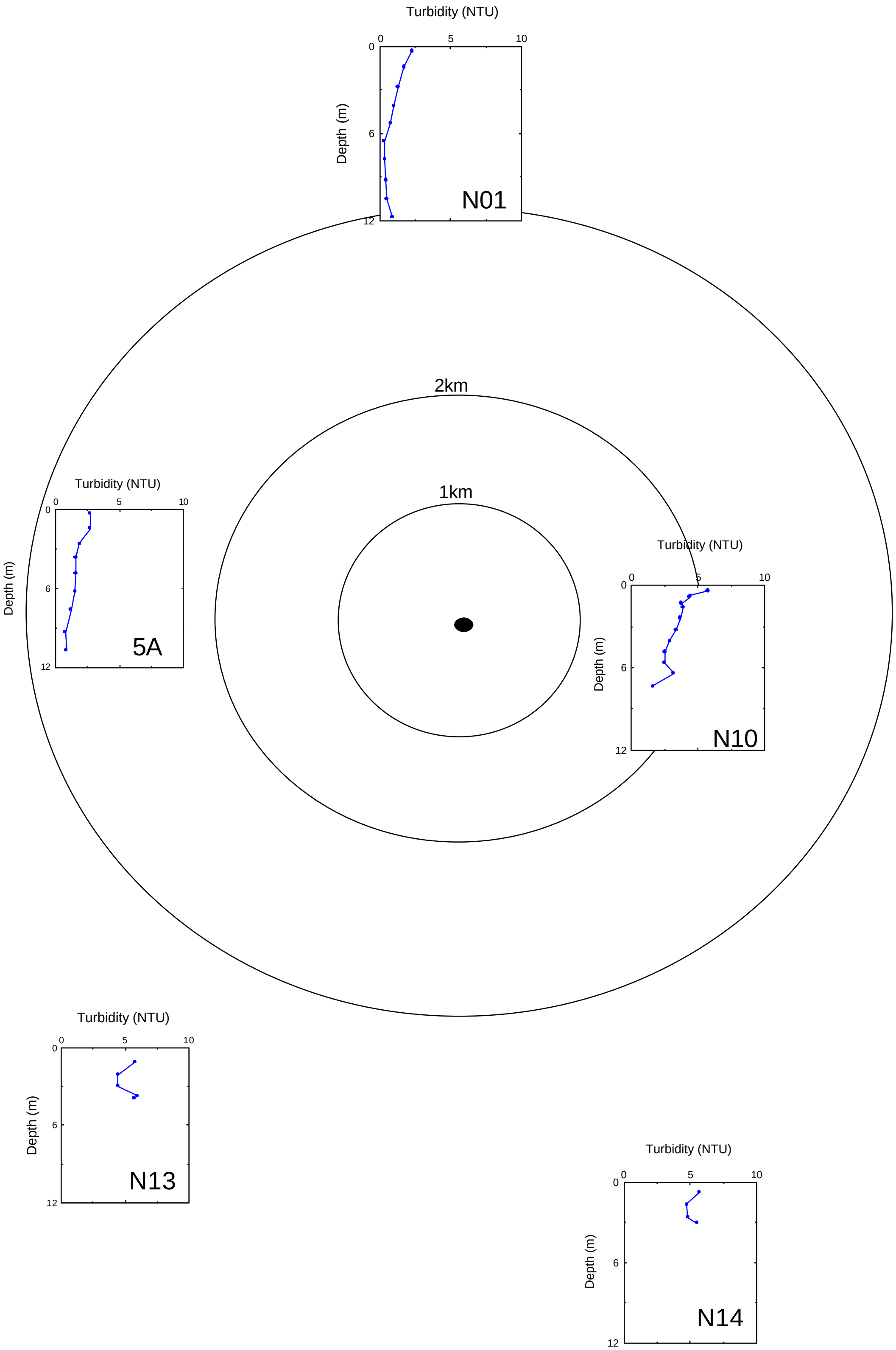

Northstar, 2001

Figure 3-48. Vertical profiles for turbidity at selected sites in the area of Northstar Island during August 2001. Profiles extend to within 0.5 m of the bottom in each case.

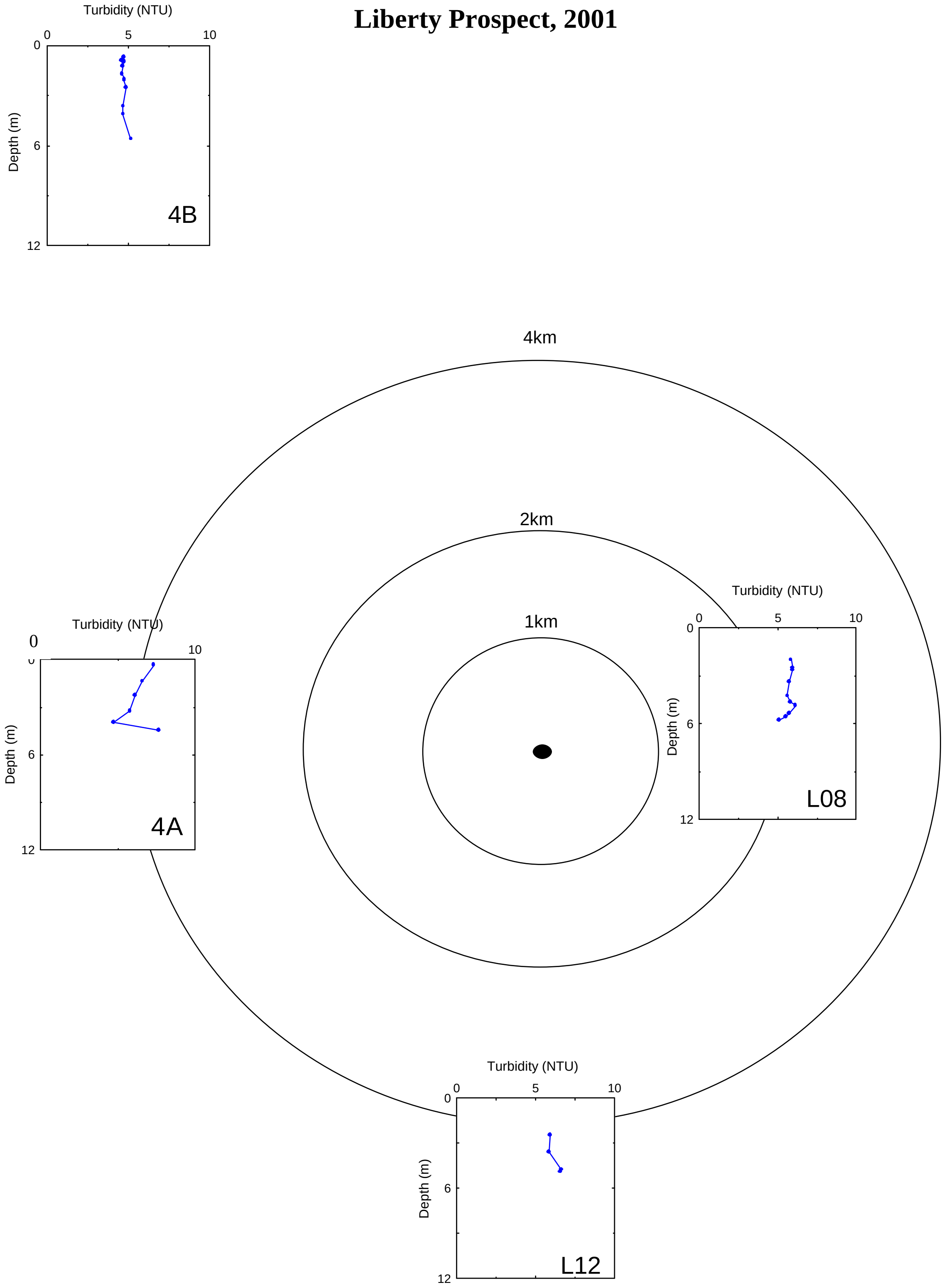

Liberty Prospect, 2001

Figure 3-49. Vertical profiles for turbidity at selected locations in the area of Liberty Prospect. Profiles extend to within 0.5 m of the bottom in each case.

Figure 3-50. Towing package with conductivity, temperature and turbidity sensors.

The overall picture of turbidity and distribution of TSS in the coastal Beaufort Sea is a function of river flow, ice conditions and sea state. In the protected, relatively quiescent waters under ice during most of the year, levels of TSS are low at a few tenths of a milligram per liter or lower (Table 3-7). During the brief open-water period, concentrations of TSS were directly related to sea state that is function of the strength and duration of winds (Table 3-7). To obtain TSS levels >50 mg/L during the summer, a period of several days with winds greater than 20 knots was necessary. Likewise, levels of TSS <2 mg/L are observed under conditions where calm water has prevailed for several days; this later condition is most likely to occur when floating ice dampens wind effects.

Table 3-7. Trends in concentrations of suspended sediment in the coastal Beaufort Sea as a function of wind and ice conditions. Complete data set in Appendix C.

Trends in Total Suspended Sediment (TSS)	
Under ice mg/L	TSS typically 0.1 – 0.5
Open Water	
Winds calm to 5 knots 2.5 m/sec)	TSS typically 1-4 mg/L
Winds 5-10 knots (2.5-5 m/sec)	TSS typically 3-8 mg/L
10-20 knots (5-10 m/sec)	TSS typically 5-15 mg/L
>20 knots (10 m/sec)	TSS = 50 - >100 mg/L

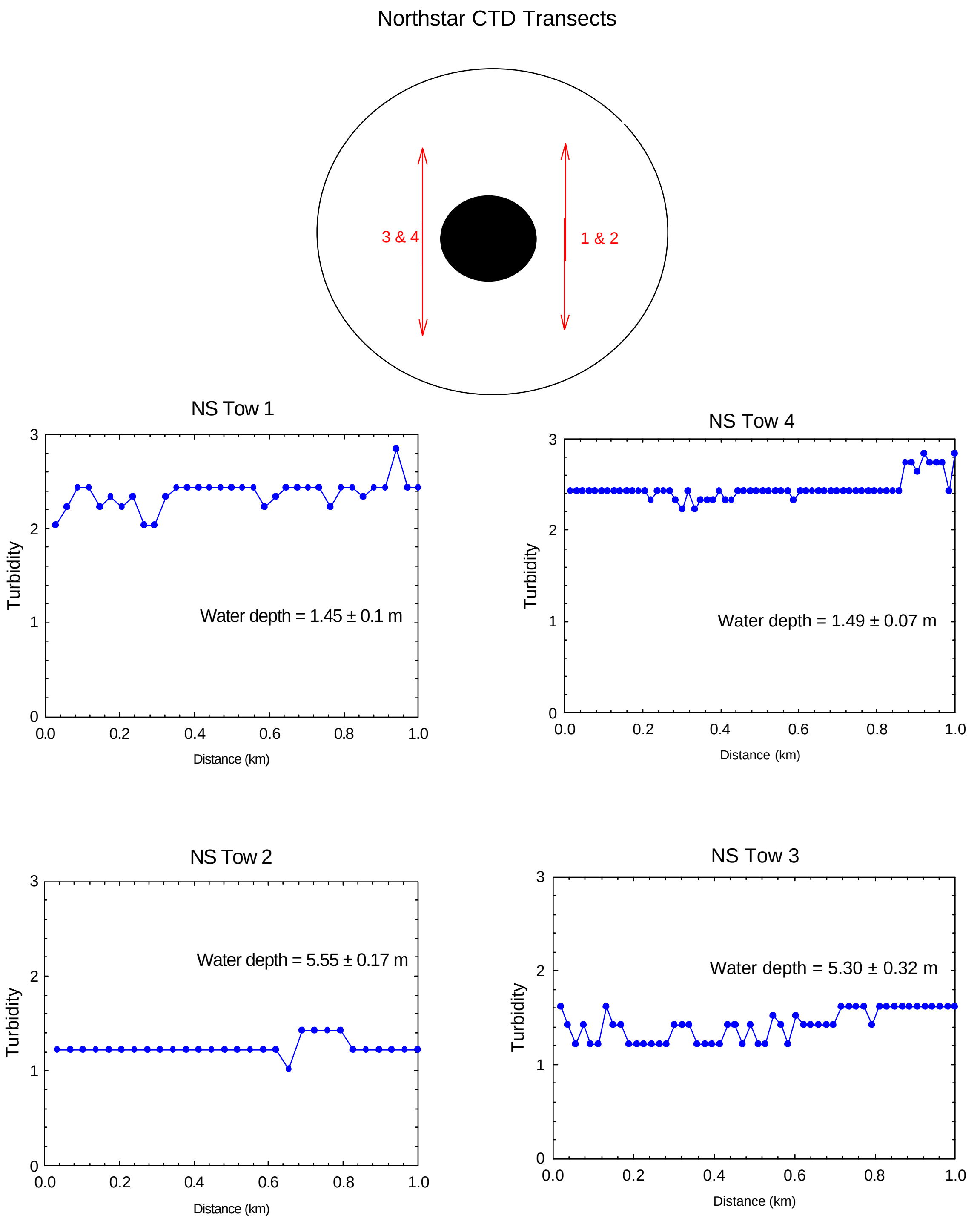


Figure 3-51. Data for turbidity (in NTU) during summer 2001 for horizontal transects upcurrent (Tow #3 at a water depth of ~5 m and Tow #4 at a water depth of ~1.5 m) and down current (Tow #1 at a water depth of ~1.5 m and Tow #2 at a water depth of ~5 m) at Northstar Island. Schematic map shows Northstar Island in black. The x-axis on each plot is distance in kilometers.

The overview presented in Table 3-7 provides a means for interpreting observed levels of TSS on a day-to-day or year-to-year basis. For example, the data in Table 3-8 show a steady trend of decreasing levels of TSS from 1999 to 2002 in the area of Northstar Island and throughout the AMIMIDA area. Northstar Island was not constructed until winter 2000. However, much of the 1999 data were collected following a 5-day storm with >20 knot winds whereas the 2002 data, for example, were collected during calm conditions with considerable sea ice throughout the study area. During the 2000 and 2001 sampling periods, conditions were moderate in the realm of 5 to 15 knot winds during most of the sampling times. Therefore, future assessments of the distribution of TSS should be presented within the context of wind conditions, sea state and the presence of ice that dampens wave activity.

Table 3-8. Summary data for total suspended solids (TSS) for all stations in the ANIMIDA study area and for subset of stations in the area of Northstar Island.

All Stations Year	n	TSS Mean ± SD (mg/L)	TSS Maximum (mg/L)	TSS Minimum (mg/L)
1999	31	30 ± 27	119	2.9
2000	51	8.2 ± 4.8	26	1.7
2001	34	5.1 ± 2.1	8.7	0.9
2002	32	2.1 ± 1.3	4.4	0.2

Northstar Area Year	n	TSS Mean ± SD (mg/L)	TSS Maximum (mg/L)	TSS Minimum (mg/L)
1999	17	38 ± 33	119	2.9
2000	35	7.3 ± 4.0	16	1.7
2001	15	4.1 ± 1.8	6.3	0.9
2002	11	2.5 ± 1.5	4.4	0.2

The data in Table 3-8, coupled with the results of many vertical profiles and horizontal tows (Figures 3-48, 3-49 and 3-51 and Appendix C) show no significant differences in turbidity or concentrations of TSS in proximity (100 to 500 m) to Northstar Island relative to other locations in the ANIMIDA study area. This result is consistent with the coarse-grained composition of the original sand and gravel used to construct the island and the armoring that covers the slope of the island to the seafloor (Figure 3-52).

Figure 3-52. Emplacement of concrete armoring on Northstar Island during Summer 2000.

Concentrations of Al, Fe, organic carbon and selected trace metals were determined for suspended matter samples collected during 2000, 2001 and 2002 (Tables 3-9, 3-10 and 3-11). Concentrations of Al in the suspended sediment varied from 1.3% to almost 10% (Figure 3-53). All suspended sediment that contained <5% Al were collected when levels of TSS were <2 mg/L (Figure 3-53). These same samples with low levels of Al also contained >4% POC as a general inverse relationship was observed between POC and Al (Figure 3-53). All of these Al-poor, organic carbon-rich samples of suspended sediment were collected during 2002. Overall, levels of TSS were lowest during 2002 because the water was calm and sea ice had not moved very far offshore following break up.

Table 3-9. Means and standard deviations (SD) for total suspended solids (TSS), turbidity (Turb.) and concentrations of metals and particulate organic carbon (PC) for suspended sediment collected from the coastal Beaufort Sea during August 2000.

2000 Station Grouping		TSS (mg/L)	Turb. (NTU)	Al (%)	As (µg/g)	Ba (µg/g)	Cd (µg/g)	Cr (µg/g)	Cu (µg/g)	Fe (%)	Pb (µg/g)	Zn (µg/g)	POC (%)
North Star Area (n=35)	Mean ± SD	7.3 ± 4.0	4.6 ±2.0	7.6 ±0.6	21.5 ±4.2	754 ±60	0.67 ±0.40	109 ±12	41 ±7	4.4 ±0.3	31 ±9	158 ±45	3.0 ±1.4
Liberty Area (n=5)	Mean ± SD	10.3 ± 1.6	6.7 ±0.1	7.1 ±0.2	16.6 ±2.0	661 ±21	0.57 ±0.08	94 ±9	36 ±2	3.8 ±0.2	27 ±1	157 ±47	2.6 ±0.4
Beaufort Sea Monitoring Program (n=11)	Mean ± SD	9.9 ± 7.3	7.1 ±5.4	7.0 ±0.7	19.9 ±2.3	724 ±61	0.67 ±0.34	94 ±16	38 ±3	4.2 ±0.3	29 ±8	140 ±20	2.5 ±0.6
Cumulative (n=51)	Mean ± SD	8.2 ± 4.8	5.2 ±3.1	7.4 ±0.7	20.6 ±3.9	738 ±64	0.66 ±0.37	104 ±14	40 ±6	4.3 ±0.3	30 ±8	154 ±41	2.8 ±1.2

Table 3-10. Means and standard deviations (SD) for total suspended solids (TSS), turbidity (Turb.) and concentrations of metals and particulate organic carbon (POC) for suspended sediment collected from the coastal Beaufort Sea during August 2001.

2001 Station Grouping		TSS (mg/L)	Turb. (NTU)	Al (%)	As (µg/g)	Ba (µg/g)	Cd (µg/g)	Cr (µg/g)	Cu (µg/g)	Fe (%)	Pb (µg/g)	Zn (µg/g)	POC (%)
North Star Area (n=15)	Mean ± SD	4.1 ±1.8	3.9 ±1.8	8.8 ±0.6	24.7 ±2.5	814 ±39	0.51 ±0.18	109 ±8	49 ±6	5.2 ±0.3	27 ±2	137 ±40	3.7 ±1.3
Liberty Area (n=6)	Mean ± SD	6.5 ±1.1	6.7 ±1.2	6.5 ±0.3	22.1 ±3.4	724 ±19	0.39 ±0.14	103 ±5	48 ±10	4.0 ±0.2	28 ±1	126 ±16	2.9 ±0.1
Beaufort Sea Monitoring Program (n=13)	Mean ± SD	5.5 ±2.2	5.5 ±2.3	7.8 ±1.0	17.0 ±2.6	754 ±61	0.50 ±0.15	118 ±8	45 ±5	4.8 ±0.5	27 ±5	129 ±19	3.9 ±1.0
Cumulative (n=34)	Mean ± SD	5.0 ±2.1	5.0 ±2.2	8.0 ±1.1	21.3 ±4.4	775 ±58	0.49 ±0.16	111 ±9	48 ±6	4.8 ±0.6	27 ±4	132 ±30	3.6 ±1.1

Table 3-11. Means and standard deviations (SD) for total suspended solids (TSS), turbidity (Turb.) and concentrations of metals and particulate organic carbon (POC) for suspended sediment collected from the coastal Beaufort Sea during August 2002.

2002 Station Grouping		TSS (mg/L)	Turb. (NTU)	Al (%)	As (µg/g)	Ba (µg/g)	Cd (µg/g)	Cr (µg/g)	Cu (µg/g)	Fe (%)	Pb (µg/g)	Zn (µg/g)	POC (%)
North Star Area (n=11	Mean ± SD	2.5 ±1.5	2.4 ±1.3	6.3 ±0.7	23.4 ±2.9	591 ±174	0.75 ±0.30	86.5 ±14	37 ±5	4.3 ±0.3	21 ±3	100 ±10	3.2 ±2.4
Beaufort Sea Monitoring Program (n=21)	Mean ± SD	1.9 ±1.2	2.0 ±1.1	5.7 ±1.4	30.0 ±6.7	550 ±168	0.71 ±0.31	79 ±21	40 ±7	4.0 ±0.6	20 ±5	104 ±14	4.1 ±2.1
Cumulative (n=32)	Mean ± SD	2.1 ±1.3	2.1 ±1.2	5.9 ±1.2	2.73 ±6.5	564 ±168	0.72 ±0.30	82 ±19	39 ±7	4.1 ±0.5	21 ±4	103 ±13	3.8 ±2.1

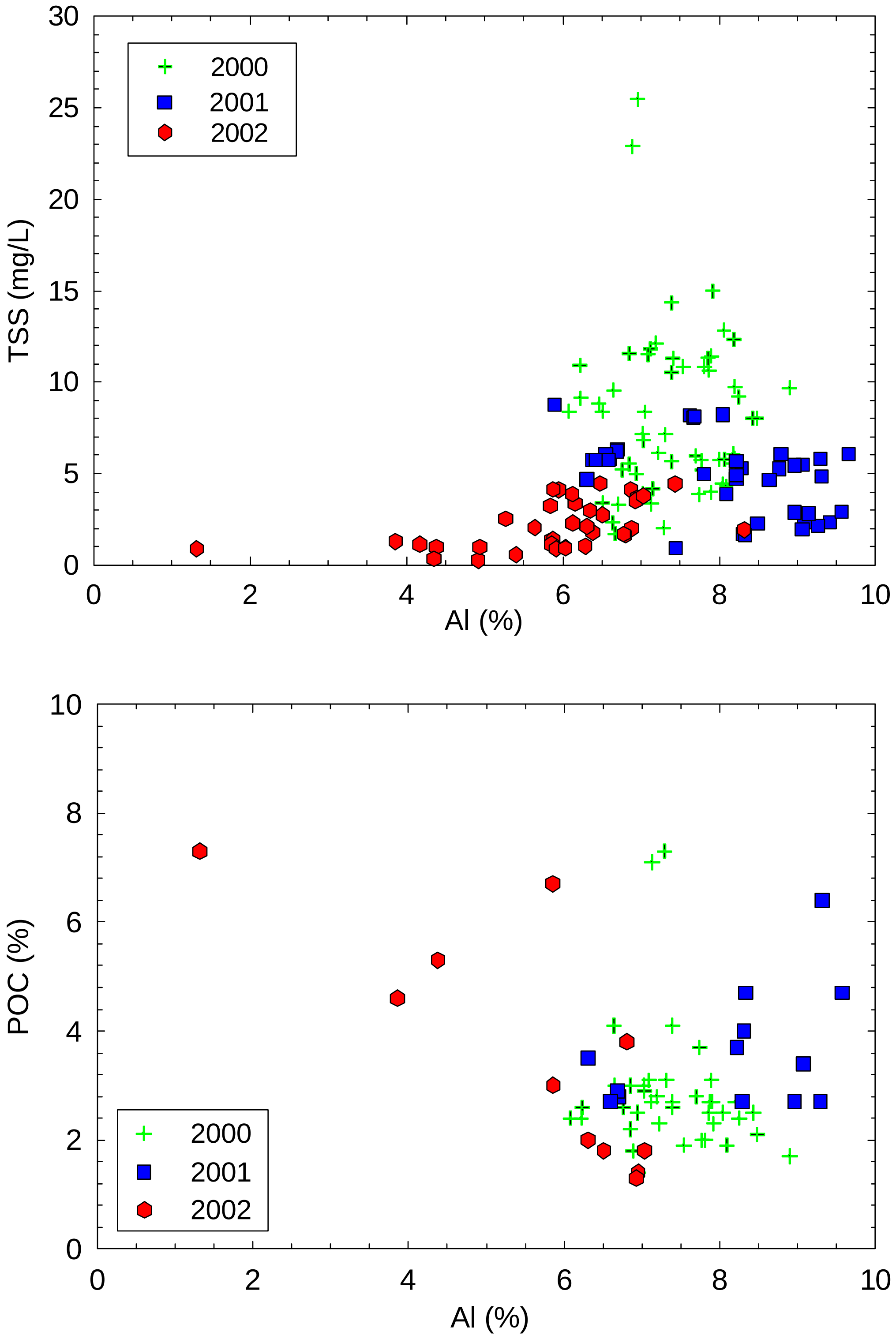


Figure 3-53. Concentrations of Al versus total suspended solids (TSS) and particulate organic carbon (POC) for suspended sediment from the coastal Beaufort Sea.

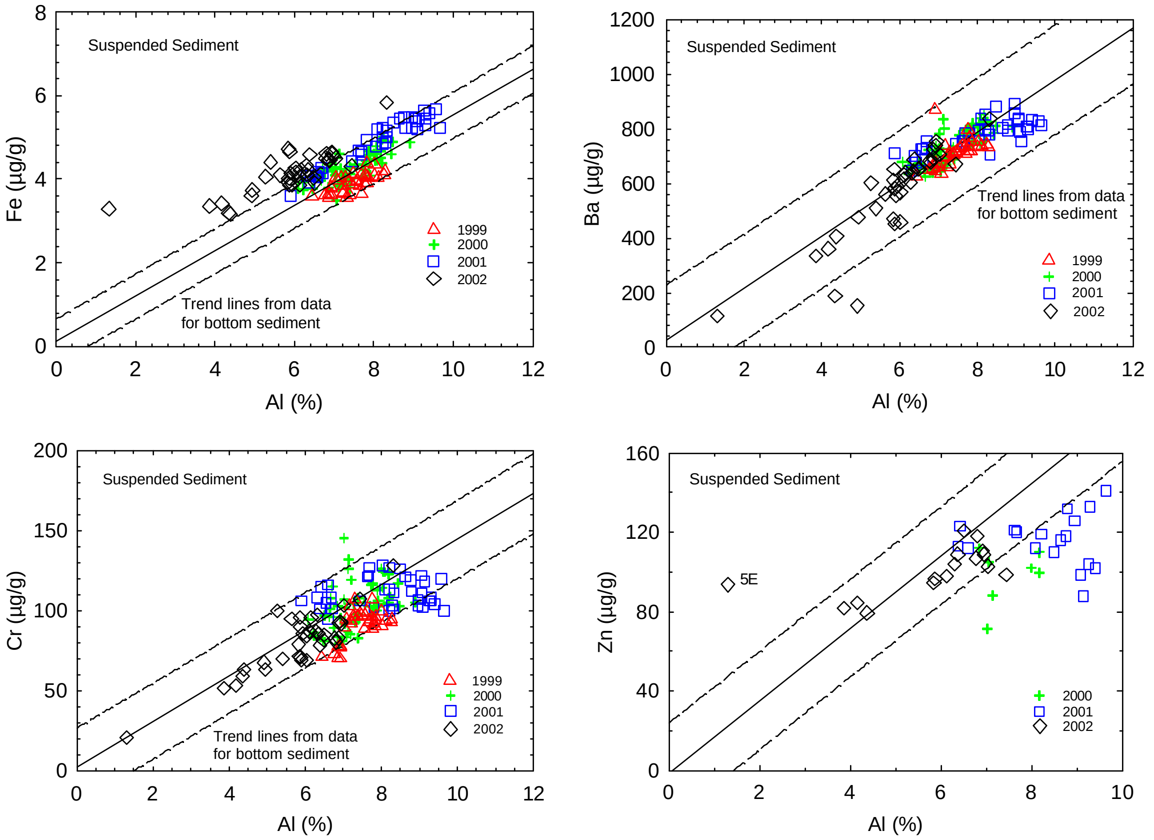


Figure 3-54. Concentrations of aluminum (Al) versus iron (Fe), barium (Ba), chromium (Cr) and zinc (Zn) for suspended sediment from the coastal Beaufort Sea during 1999, 2000, 2001 and 2002. Solid lines show linear regression fit to data and dashed lines show 99% prediction intervals.

Concentrations of Fe in the suspended sediment correlated relatively well with Al; and all data points, except most of those from 2002, plotted within the 99% prediction interval established for bottom sediments (Figure 3-54). The Fe-enrichment observed for 2002 is consistent with what was observed for under-ice particles. During 2002, we were most likely sampling many residual under-ice particles and the products of recent biological productivity. In contrast with Fe, concentrations of Ba and Cr in the suspended sediment from all four summer samplings, including 2002, plotted within the prediction intervals for Ba/Al and Cr/Al for bottom sediments (Figure 3-54). Both Ba and Cr are not enriched in biological materials (e.g., plankton) or under-ice particles, therefore, the Ba/Al and Cr/Al ratios in the suspended sediment fit the relationship developed for bottom sediments.

Concentrations of Zn were generally within or below the Zn/Al prediction interval based on bottom sediments (Figure 3-54). No explanation for the Zn values that plotted below the 99% prediction interval for sediments is available at this time. The data for particulate Zn in Figure 3-54 are from surface samples collected carefully from the front of a Zodiac slowly moving upcurrent or upwind or by pumping water from the Zodiac using a peristaltic pump and acid-washed tubing. During 2000, some surface and subsurface samples appear to have been contaminated during sampling from the MMS Launch 1273 and that practice was discontinued in 2001 and 2002. The data for one sample that plot above the upper prediction interval in Figure 3-54 may be due to the abundant, more Zn-rich plankton in that sample or to anthropogenic inputs as described in the discussion of Cu, Cd, Pb and As below.

Nine sample points from 2002 on the Al versus Cu graph plotted above the upper prediction interval developed from data for bottom sediments. A similar trend was observed for Cd and As, but not distinctly for Pb in the 2002 samples (Figure 3-55). These anomalous samples were low with respect to TSS and generally enriched with respect to POC. Copper, Cd and As are often enriched in plankton relative to sediments. Enrichment of Cu, Cd and As in the organic-rich samples from 2002 is consistent with a planktonic source.

In contrast, concentrations of Pb (like Ba and Cr) are generally low in plankton and thus the positive anomalies on the Pb/Al graph were fewer in number. However, Pb levels in suspended sediment at several stations near Northstar Island during 2000 and one during 2001 were enriched with Pb relative to values observed for bottom sediment (Figure 3-

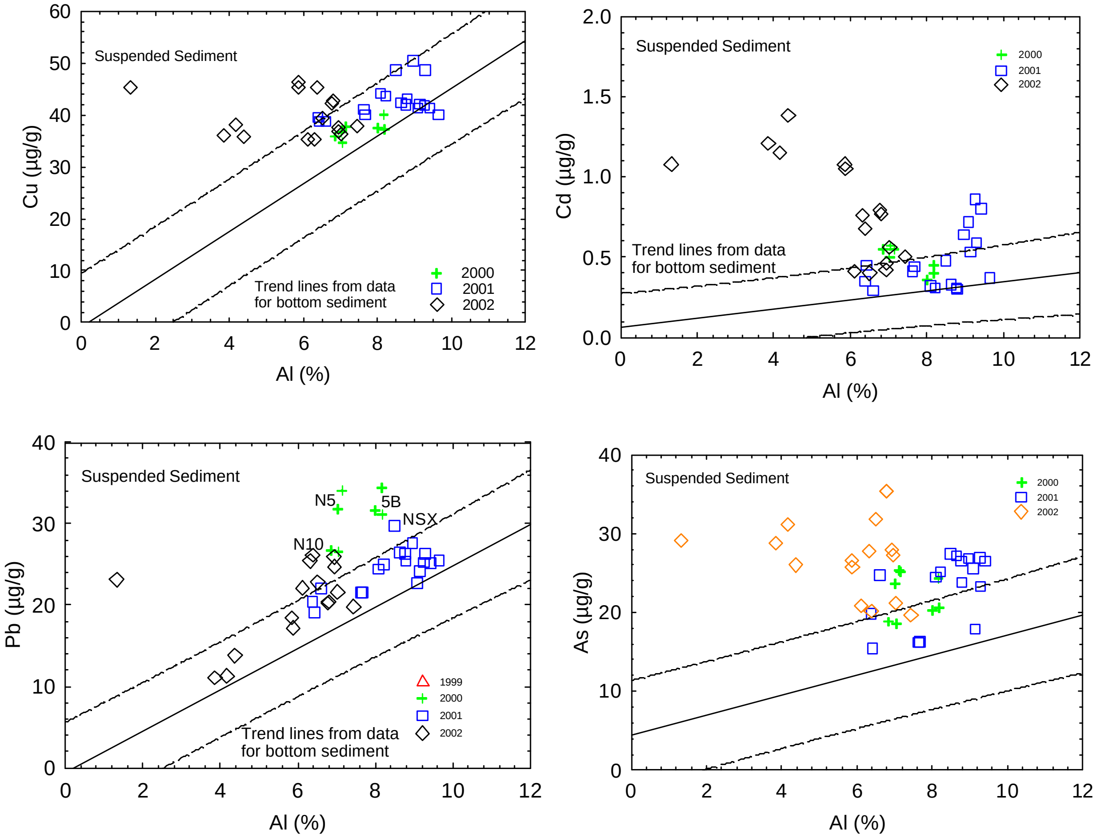


Figure 3-55. Concentrations of aluminum (Al) versus copper (Cu), cadmium (Cd), lead (Pb) and arsenic (As) for suspended sediment from the coastal Beaufort Sea during 1999 (triangles), 2000 (squares) and 2001 (+ signs). Solid lines show linear regression fit to data and dashed lines show 99% prediction intervals.

55). The few surface samples of TSS with Pb levels that were 20-50% above the upper prediction interval in Figure 3-55 were collected as near as 100 m from Northstar Island. This apparent enhancement in Pb levels in the few samples of suspended sediment may be the result of uptake of anthropogenic Pb on the small levels of particles (2-6 mg/L) in the water column. The apparent anomalies may be detected because Pb is readily adsorbed to particles and because the low levels of TSS magnify the apparent enrichment of Pb. However, as suggested above for the anomalous data points for Cu, Cd and As, additional analyses of plankton and continued assessment of background levels of metals in suspended sediment are required before the metal/Al ratios in suspended sediment can be as useful as previously demonstrated for bottom sediment (Trefry et al., 2003).

3.7 Sediment Accumulation

The final chapter in the story of suspended sediment that began in the mountains during spring is the deposition of these particles as bottom sediment in the Beaufort Sea. As detailed in Brown et al. (2004), the accumulation of modern sediments in the ANIMIDA study area is patchy. Results show that sedimentation rates range from ~0.04 cm/yr to ~0.10 cm/yr with several sites having little or no net accumulation of sediment during at least the past 50 years (Figure 3-56). At three sites, only 3- to 5-cm thick layers of sediment were deposited since development began during the 1960s. Overall, these results are consistent with those of Naidu et al. (2001) for the same area. The presence of fine-grained sediment at a given location can vary from year to year and sedimentary processes along much of the shallow, coastal Beaufort Sea are quite dynamic.

Additional support for low sedimentation rates at stations P01 and E01 can be developed from data for river inputs of sediment. The Sagavanirktok River, the major river carrying sediment into the area near stations P01 and E01, is estimated to have an annual sediment load of about 6 x 10^5 metric tons. The depositional area for this sediment in coastal Beaufort Sea is about 1000 km^2 to yield an estimated deposition rate of ~0.04 cm/y based on a sediment bulk density of 1.6 g/cm^3 ([0.6 x 10^{12} g dry sediment/10 x 10^{12} cm^2] x [(1.6 g wet sediment/cm$^{3)}$/(2.6 g dry sediment/cm^3)]). As previously noted, however, the coastal Beaufort Sea in this area may be net erosional at this time (Reimnitz and Wolf, 1998). Based on our observations, much of the large sediment load of the rivers must be carried across the nearshore environment during spring on the freshwater channel under the ice to be deposited in deeper waters of the Beaufort Sea. Therefore, sediment monitoring for contaminants must be coordinated with measurements of radionuclides such as ^{137}Cs, excess ^{210}Pb, ^{234}Th or ^{7}Be in sediments to ensure that samples are recent and not relict deposits.

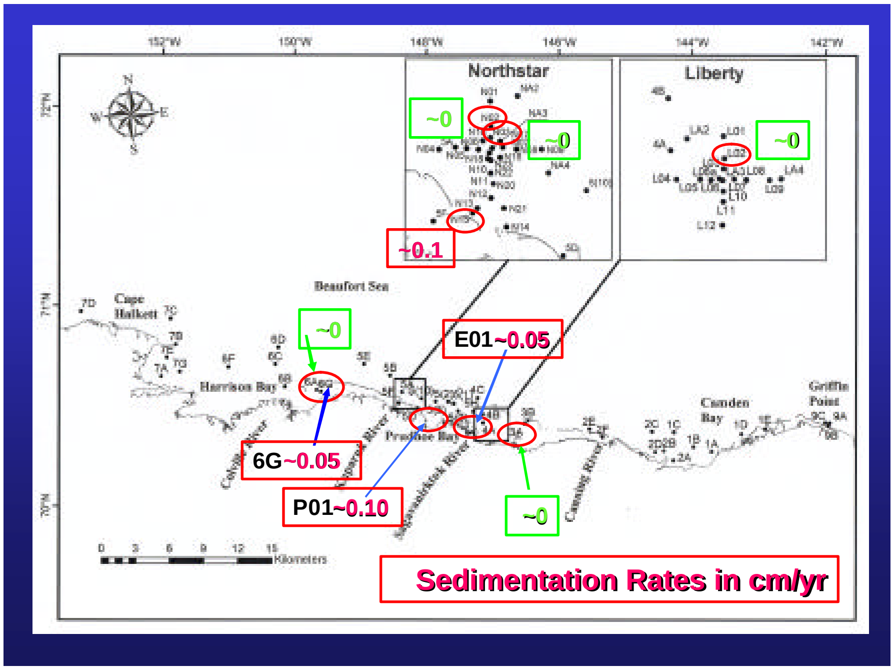


Figure 3-56. Sedimentation rates for the coastal Beaufort Sea based on data for ^{137}Cs and excess ^{210}Pb.

4.0 SUMMARY AND CONCLUSIONS

Rivers are an important source of water and suspended sediment to the study area during the period of spring runoff and on an annual basis. For example, concentrations of TSS in the Sagavanirktok River near the Prudhoe Bay Operations Center increased from ~40 mg/L on June 1 when flow began to 600 mg/L on June 12, 2001, and then decreased to ~30 mg/L by June 18. During late July and August 2001, concentrations of TSS were only ~2 mg/L. Concentrations of TSS followed similar trends for the Colville River with maximum levels of about 600 mg/L on June 13, 2001. In contrast, concentrations of TSS reached peak values of only 60 mg/L in the Kuparuk River on June 10, 2001 and decreased to <5 mg/L after June 16, 2001. Peak flow recorded for the Kuparuk River was about 600 m^3/sec on June 12, 2001, decreasing to <50 m^3/sec after June 28, 2001. During 2002, the same trend of increasing concentrations of TSS was observed; however, freezing temperatures led to refreezing of the rivers and put a hiatus in the spring flood for the Sagavanirktok River. However, the dramatic two-day flood of the Kuparuk River in 2002 occurred during the period prior to refreezing.

For the Sagavanirktok River, the calculated annual sediment transport was ~0.33 million metric tons for 2001, with ~87% of the annual transport of suspended sediment occurring during just 12 days in June. Total transport of suspended sediment by the Kuparuk River was 0.02 million metric tons for 2001 with ~90% of the annual sediment load of the river being carried during just three days in June. Previous estimates for the Colville River of 5 million metric tons of sediment per year are supported by recent measurements during high flow. These natural inputs by rivers can be compared with ~1.6 million metric tons of sand and gravel used to construct Northstar Island [(800,000 yd^3 x 0.76 m^3/yd^3 x 2.6 metric tons/m^3 = 1.6 million metric tons). Coastal erosion also is an important source of sediment to the coastal Beaufort Sea, including the ANIMIDA study area. Estimates from previous studies state that coastal erosion may contribute sediment to the coastal Beaufort Sea at levels that are equal to or several times greater than inputs of sediment by rivers.

River runoff during the spring floods is carried to a coastal Beaufort Sea that is covered with 2-m thick ice. Concentrations of TSS averaged ~40 mg/L in a 2-m thick lens of freshwater immediately under the ice that extended >10 km offshore. The suspended sediment was very rich in fine-grained aluminosilicates as shown by the levels of Al and other metals in the particles. Metal/Al ratios in suspended particles collected under the ice showed that the composition of river-borne particles was similar to that found for bottom sediment.

During the open-water period in 1999-2002, the day-to-day turbidity and distribution of TSS in the coastal Beaufort Sea were dependent on river flow, ice cover and sea state. In the protected, relatively quiescent waters under ice during most of the year, levels of TSS were low at a few tenths of a milligram per liter relative to average levels of ~40 mg/L in surface waters under the ice during the spring floods. During the brief open-water period, after the spring floods, concentrations of TSS were typically <20 mg/L and varied as a function of sea state and the presence of floating sea ice. Sea state was directly related to the strength and duration of winds. Concentrations of TSS increased to >50 mg/L during the summer only following a period of several days with winds greater than 20 knots. In contrast, levels of TSS <2 mg/L were observed under conditions where calm water had prevailed for several days. This later condition was most likely to occur when floating ice dampened any wind effects. No significant deviations in levels of turbidity were observed adjacent to Northstar Island during 2000-2002 while towing a turbidimeter-CTD package along transects at distances as close as 100-500 m from the island.

The chemical composition of river suspended sediment was compared with results for bottom sediment to help identify possible anthropogenic inputs of suspended sediment or contaminant metals to the coastal environment. Differences in the elemental composition of suspended sediment were observed among rivers. The Colville River contained greater amounts of particulate Al, Fe and trace metals relative to the more Ca-rich particles of the Sagavanirktok River and the more organic carbon-rich particles of the Kuparuk River. However, the metal/Al ratios for all elements, except Ca, were not significantly different among rivers and bottom sediment from the coastal Beaufort Sea.

Concentrations of trace metals also were determined for samples of suspended matter collected from the coastal Beaufort Sea. The fine-grained aluminosilicates suspended in the water column were enriched with Al and trace metals. However, concentrations of most metals in suspended sediment for 2000 and 2001 plotted within the 99% prediction intervals for metals versus Al that were developed using data for bottom sediment. Thus, in most instances, concentrations of trace metals associated with suspended particles were within the limits established for uncontaminated sediment. Suspended particles are potentially a more sensitive indicator of recent metal contamination than sediment because the small amounts of suspended particles typically found in the water column lead to a larger relative enrichment of anthropogenic metal concentrations. This sensitivity was demonstrated with several samples of suspended sediment that were collected very near Northstar Island during construction in August 2000 and contained Pb at levels that were 20-50% above background.

With respect to sedimentation, the ANIMIDA area appears to be a net erosional environment at this time. Based on our observations, much of the large sediment load of the rivers is carried across the nearshore environment to deeper waters of the Beaufort Sea along a freshwater channel under the ice during spring or with summer and fall storms. Therefore, sediment monitoring for contaminants must be coordinated with measurements of radionuclides such as ^{137}Cs, excess ^{210}Pb, ^{234}Th or ^{7}Be that help ensure that samples are recent and not relict deposits.

Overall, no significant differences in concentrations of TSS that could be directly linked to oil and gas operations were observed in the ANIMIDA area. Periodic enhancement in levels of TSS in the coastal Beaufort Sea can be related to river runoff and resuspension of bottom sediment by strong winds. Natural inputs of suspended sediment from runoff and erosion are large relative to any anthropogenic inputs of sediment.

5.0 REFERENCES

Arnborg L., Walker H.J. and Peippo J. (1967) Suspended load in the Colville River, Alaska, 1962. *Geog. Annaler*. **49A (2-4)**, 131-144.

Baker, M. (2001, 2002, 2003) Alpine Facilities Spring Breakup and Hydrologic Assessment. Report for Conoco Phillips.

Boehm, P., et al. (2001) ANIMIDA Phase 1: Arctic Nearshore Monitoring in the Development Area, Final Report, OCS Study MMS2001-104.

Brown, J., Boehm, P., Cook, L., Trefry, J. and Smith, W. (2004) Hydrocarbon and metal characterization of sediments, bivalves and amphipods in the ANIMIDA study area. Final Report to MMS, OCS Study MMS2004-24.

Craig, P.C. and McCart, P.J. (1975) Classification of stream types in Beaufort Sea drainage basins between Prudhoe Bay, Alaska, and the Mackenzie delta, N.W.T., Canada. *Arctic Alpine Research* **7**:183-198.

Crecelius, E. A., Trefry, J.H., Steinhauer, M.S. and Boehm, P.D. (1991) Trace metals in sediments from the inner continental shelf of the western Beaufort Sea. *Environmental Geology and Water Science* **18**:71-79.

Gordeev V.V., Martin J.M., Sidorov I.S. and Sidorova M.V. (1996) A reassessment of the Eurasian input of water, sediment, major elements, and nutrients to the Arctic Ocean. *Amer. J. Sci.*, **296**, 664-691.

Lock, M.A., Ford, T.E., Fiebig, D.M., Miller, M.C., Hullar, M., Kaufman, M., Vestal, J.R., Peterson, B.J. and Hobbie, J.E. (1989) A biogeochemical survey of rivers and streams in the mountains and foothills province province of arctic Alaska. *Arch. Hydrobiol.* **115**:499-521.

Mull, C.G. and Adams, K.E. (1989) Dalton Highway, Yukon River to Prudhoe Bay, Alaska. Alaska Division of Geological and Geophysical Surveys, Guidebook 7, vol. 1 and 2.

Naidu, A.S., Goering, J.J., Kelley, J.J. and Venkatesan, M.I. (2001) Historical changes in trace metals and hydrocarbons in the inner shelf sediments, Beaufort Sea: Prior and subsequent to petroleum-related industrial developments. Final Report to MMS, OCS Study 2001-061, 80 pp.

Parkinson, R.J. (1977) Genesis and Classification of Arctic Coastal Plain Soils, Prudhoe Bay, Alaska. M.S. thesis, Ohio State University.

Payne, T.G., Dana, S.W., Fischer, W.A., Yuster, S.T., Krynine, P.D., Morris, R.H., Lathram, E. and Tappan, H. (1951) Geology of the arctic slope of Alaska, U.S. Geological Survey Oil and Gas investigations, map OM-126.

Reimnitz, E., Graves, S.M. and Barnes, P.W. (1988) Beaufort Sea coastal erosion, sediment flux, shoreline evolution, and the erosional shelf profile. U.S. Geological Survey Miscellaneous Investigations Series Map I-1182-G,22 p, scale 1:82,000.

Reimnitz, E. and Wolf, S.C. (1998) Are north slope surface alluvial fans pre-Holocene relicts? U.S.G.S. Professional Paper 1605, 9 pp.

Rember, R.D. (2002) Composition of dissolved and suspended matter transported by the Sagavanirktok, Kuparuk and Colville rivers in the Alaskan arctic. Ph.D. Dissertation, Florida Institute of Technology, 106 pp.

Rember, R.D. and Trefry, J.H. (2004) Increased concentrations of dissolved trace metals and organic carbon during snowmelt in rivers of the Alaskan Arctic. *Geochimica et Cosmochimica Acta* **68**:477-489.

Telang S.A., Pocklington R., Naidu A.S., Romankevich E.A., Gitelson I.I. and Gladeyshev M.I. (1991) Carbon and mineral transport in major North American, Russian Arctic, and Siberian Rivers: the St. Lawrence, the Mackenzie, the Arctic Alaskan Rivers, the Arctic Basin Rivers in the Soviet Union, and the Yenisei. In: Degens E.T., Kempe S., and Richey J.E. (Eds) *Biogeochemistry of Major World Rivers.* SCOPE Report **42**, John Wiley, Chichester, 75-104.

Trefry, J.H., Rember, R.D., Trocine, R.P. and Brown, J.S. (2003) Trace metals in sediments near offshore oil exploration and production sites in the Alaskan Arctic. *Environmental Geology* **45**:149-160.

Trefry, J.H., Rember, R.D., Trocine, R.P. and Brown, J.S. (2004) Partitioning of potential contaminants between dissolved and particulate phases in waters of the coastal Beaufort Sea. Final Report to MMS,OCS Study MMS 2004-031.

U.S. Environmental Protection Agency. 1991. Methods for the Determination of Metals in Environmental Samples. Office of Research & Development, U.S. EPA, Cincinnati, OH.

U.S. Geological Survey (1971-2001) Water Resources Data for Alaska. Anchorage, AK.

Valentine, D.W. and Binkley, D. (1992) Topography and soil acidity in an Arctic landscape. *Journal of the Soil Science Society of America* **56**:1553-1559.

Walker, D.A., and Webber, P.J. (1979) Relationships of soil acidity and air temperature to the wind and vegetation at Prudhoe Bay, Alaska. *Arctic* **32**:224-236.

6.0 LIST OF APPENDICES

The appendices listed below are tabulated on the CD attached to hard copies of this report or as separate files on this CD.

Appendix A: Data for Suspended Sediment from Rivers for 2001 and 2002

Appendix B: Data for Suspended Sediment Under Ice for 2001 and 2002
    Appendix B1: CTD Under Ice for 2001
    Appendix B2: CTD Under Ice for 2002

Appendix C: Data for Suspended Sediment Offshore for 2000, 2001 and 2002
    Appendix C1: Aanderaa Data for Summer 1999-2002

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Royalty Management Program** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.