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Authors
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Characterization of Benthic Habitats and Contaminant Assessment in Arctic Lagoons and Estuaries

S. Ian Hartwell[1], Terri Lomax[2], Doug Dasher[3], Max Hoberg[3], Arny Blanchard[3], Stephen Jewett[3]

[1]NOAA/NOS/National Centers for Coastal Ocean Science
Stressor Detection & Impacts Division
Monitoring & Assessment Branch
1305 East West Hwy. (SSMC-4, N/SCI-1)
Silver Spring, MD 20910

[2]Alaska Department of Environmental Conservation (ADEC)
555 Cordova St.
Anchorage, AK, 99501

[3]University of Alaska Fairbanks
Institute of Marine Science
905 N. Koyukuk Dr.
245 O'Neill Building
Fairbanks, AK 99775-7220

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United States Department of Commerce	National Oceanic and Atmospheric Administration	National Ocean Service
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Secretary	Administrator	Assistant Administrator

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List of Acronyms

AAS	atomic absorption spectroscopy
ADEC	Alaska Department of Environmental Conservation
Ag	silver
Al	aluminum
AKMAP	Alaska Monitoring & Assessment Program
ANOVA	analysis of variance
AOOS	Alaska Ocean Observation System
As	arsenic
ASTM	American Society of Testing and Materials
Ba	barium
BOEM	Bureau of Ocean Energy Management
Cd	cadmium
CFR	Code of Federal Regulations
CIRCAC	Cook Inlet Regional Citizens Advisory Council
Cr	chromium
Cu	copper
DDT	dichlorodiphenyltrichloroethane
DO	dissolved oxygen
EMAP	Environmental Monitoring and Assessment Program
EPA	Environmental Protection Agency
ERL	Effects range - low
ERM	Effects range - median
EVOS	Exxon Valdez Oil Spill
Fe	iron
GC/ECD	gas chromatography/electron capture detector
GC/MS	gas chromatography/mass spectroscopy
gm	gram
H'	diversity (Shannon-Weiner)
HCH	hexachlorocyclohexane
HDPE	High density polyethylene
Hg	mercury
ICP	inductively coupled plasma
IMS	Institute of Marine Science
km	kilometer
l	liter
Li	lithium
m	meter
MDL	method detection limit
MDS	multidimensional scaling
mg	milligram
Mn	manganese
MS	matrix spike
MSD	Matrix spike duplicate
NCCA	National Coastal Condition Assessment
ng	nanogram
Ni	nickel

NIST	National Institute of Standards and Technology
NPRA	National Petroleum Reserve – Alaska
NPRB	North Pacific Research Board
NOAA	National Oceanic and Atmospheric Administration
NS&T	National Status and Trends
p	Probability
PAH	polycyclic aromatic hydrocarbon
Pb	lead
PCA	principal component analysis
PCB	polychlorinated biphenyl
PMEL	Pacific Marine Environmental Laboratory
POP	persistent organic pollutant
POTW	publically owned treatment works
ppt	parts per thousand
PWSRCAC	Prince William Sounds Regional Citizens Advisory Council
QA/QC	quality assurance/quality control
Sb	antimony
Se	selenium
Si	silicon
Sn	tin
SQG	sediment quality guidelines
SQT	sediment quality triad
SRM	standard reference material
TBT	tributyltin
TIC	total inorganic carbon
TOC	total organic carbon
UAF	University of Alaska Fairbanks
ug	microgram
Zn	zinc

EXECUTIVE SUMMARY

Baseline environmental characterizations of the lagoons and estuaries in the northeastern Chukchi and western Beaufort Seas, were conducted using a sediment quality approach based on water quality, sediment chemistry, and benthic invertebrate community structure. Resident fish body burdens were also assessed. The study area was subdivided into six estuaries/lagoons. Sampling sites were randomized within each embayment. Field operations were conducted off a smaller vessel launched from the RV Ron Brown. Concentrations of 194 organic and elemental contaminants were analyzed in sediment, plus stable isotopes of carbon and nitrogen. Habitat parameters (depth, salinity, temperature, dissolved oxygen, sediment grain size, organic carbon content) that influence species and contaminant distribution were also measured at each sampling site. A detailed benthic community condition assessment was performed at each site. Additional sites were established in the offshore zone near Wainwright in the path of previously proposed oil infrastructure development.

The estuaries are relatively shallow embayments, with little relief along the shorelines. Sediment characteristics varied widely depending on location, but were either sand or silt. The water columns were turbid, high salinity, and were not stratified. The estuaries on the Beaufort Sea side were colder than those on the Chukchi Sea.

Concentrations of arsenic and nickel were elevated throughout the region and appear to be naturally elevated in the watersheds. Concentrations of lead and mercury were uniformly low. Concentrations of PAHs were relatively high for places considered to be pristine locations, but did not appear to include petroleum hydrocarbons. Characteristics of the PAH compounds present indicate large contributions of terrestrial organic matter and peat and/or coal.

Concentrations of chlorinated pesticides and PCBs were uniformly low, but detectable in fish tissue. PCB and cyclodiene (e.g. chlordane) concentrations were, on average, half that seen in Nushagak and Kvichak Bays

in the southeast Bristol Bay. DDT was above detection limits in only one sample. Hexachlorobenzene was detected in all fish samples. In several cases, arsenic in fish tissue was elevated above the mean Alaska Fish Monitoring Program values reflecting the general elevated background concentrations. A composite sample of slender eel blennies (*Lumpenus fabricii*) from Elson Lagoon had anomalously high mercury levels, but this was not seen in other species from Elson Lagoon.

With the exception of Peard Bay, the sampled estuaries were shallow and subject to landfast ice throughout the winter season. This places a high stress on any animal living in or on the sediments. Animals older than one year were absent suggesting that macroinvertebrates moved as larvae or juveniles into the estuaries after ice breakup. No echinoderms were collected at any station. Species abundance varied by two orders of magnitude between sites. Peard Bay and Elson Lagoon were the most diverse systems. Wainwright Inlet was relatively sparsely inhabited. There was a subset of species found only in the Beaufort estuaries that were virtually absent in the Chukchi estuaries. Based on dual cluster analysis and nonmetric multidimensional scaling techniques, all the estuaries separate from each other based on species composition.

Benthic samples were sieved through nested 1.0 and 0.5 mm sieves to compare techniques. The information gained by looking at 0.5 mm improves estimates of diversity and abundance. There were twice the number of taxa on average in the 0.5 mm sieve than in the 1.0 mm sieve collections. There was an almost order of magnitude difference in abundance numbers, but this was due in part to high numbers of specific taxa at selected sampling sites. Diversity values were usually higher in the smaller mesh size. The difference in biomass was only 15%. These differences may bias interpretation of parameters such as feeding guilds, taxonomic composition of the community, organisms with or without hard parts (shells, carapace), diversity, biomass, dominance, and indicator species. Different multivariate statistical techniques applied to the data illustrate that the smaller sieve size produces a clearer distinction between community traits and the physical habitat drivers that influence them.

With the exception of Peard Bay, all the estuaries reflected the strong influence of terrestrial plant input with very low $\delta_{o/oo}$ values for carbon and nitrogen. Peard Bay has a very limited watershed and is strongly influenced by tidal exchange with marine waters. Stable isotope values for Peard Bay were bracketed by the offshore sites.

Field crew, from left to right– (back row) LTJG Rachel Pryor, Terri Lomax, Brian Stillie, Katie Beaumont; (front row) Ian Hartwell, and Max Hoberg. (Diomede Island [Russia] in the background).

Deploying the *Peggy D* launch.

1. INTRODUCTION

1.1 National Status and Trends Bioeffects Studies

As part of the National Status and Trends (NS&T) Program, NOAA conducts bioeffects studies to determine the spatial extent and severity of chemical contamination and associated adverse biological effects in coastal bays and estuaries of the United States. The NS&T Program encompasses a broad spectrum of research and monitoring studies, including long-term, nationwide monitoring of contaminant concentrations in sediments and resident organisms, sediment toxicity assessments in specific coastal areas, evaluation and application of biomarkers; and the development of ecological indices (Hartwell and Claflin 2005; Turgeon *et al*. 1998). The NS&T Program has conducted bioeffects assessment studies in coastal water bodies since 1991. Results from previous sediment bioeffects studies in over 20 coastal water bodies and estuaries have been published (Hartwell *et al.* 2001; Hartwell *et al.* 2009; Hartwell and Hameedi 2006; Hartwell and Hameedi 2007; Long *et al*. 1996 , Long 2000; Pait *et al*. 2006; Turgeon *et al*. 1998).

The mission of the State of Alaska Department of Environmental Conservation (ADEC) Division of Water, is to improve and protect the quality of all Alaskan waters and under the Clean Water Act (CWA) Sections 303(d) and 305(b), Alaska has the responsibility to report and identify causes and sources of water quality impairment. One way the Division carries out this mission is to monitor and report on water quality. The Alaska Monitoring and Assessment Program (AKMAP) as part of EPA's National Coastal Condition Assessment (NCCA) surveyed the National Petroleum Reserve – Alaska (NPRA) estuaries. The present NPRA estuary survey was a joint effort by the Alaska Department of Environmental Conservation (ADEC), University of Alaska Fairbanks (UAF) Institute of Marine Science (IMS), and the NOAA NS&T Bioeffects Program.

Sediment contamination in U.S. coastal areas is a major environmental issue because of potential toxic effects on biological resources and, often, indirectly on human health. A large variety of contaminants from industrial, agricultural, urban, and maritime activities are associated with bottom sediments, including synthetic organic chemicals, polycyclic aromatic hydrocarbons (PAHs), and trace elements. In many instances, fish consumption advisories are coincident with severely degraded sediments in coastal water bodies. Contaminants, particularly those that are lipophilic, can biomagnify in the coastal food chain with increasing concentration in predatory wildlife and humans. Thus, characterizing and delineating areas of sediment contamination and toxicity are viewed as important goals of coastal resource management. This is particularly important in Alaska, where subsistence food contamination is a health concern, especially in rural areas where large amounts of these foods are consumed as a primary source of protein (Wolfe 1996). Excessive levels of contaminants in the sediments, whether of natural or anthropogenic origin, can pose ecological and human-health risks. The presence of contaminants in coastal ecosystems can cause habitat degradation and loss of biodiversity through degraded habitats, loss of fauna, and biomagnification of contaminants in the coastal ecosystem. Human consumption of contaminated fish and wildlife is also a concern.

Macrobenthic organisms play an important role in the estuarine environment. Critical habitats and food chains supporting many fish and wildlife species involve the benthic environment. Benthic organisms are secondary consumers in the ecosystem, and represent an important link between primary producers and higher trophic levels for both planktonic and detritus-based food webs. They are composed of diverse taxa with a variety of reproductive modes and life history characteristics. They are a particularly important food source for juvenile fish and crustaceans. Furthermore, most benthic species have limited mobility and cannot physically avoid stressful environmental conditions. Benthic assemblages thus cannot evade, and must respond to, a variety of stressors, such as toxic contamination, eutrophication, sediment quality, habitat modification, and seasonal weather changes. Biological systems are able to integrate the complexity of natural habitat stressors and ambient pollutant mixtures, through physical contact with sediments, ingesting sediment, bioaccumulating contaminants in organisms, biomagnifying them in food webs, and expressing the synergetic effects of exposure to toxic chemicals.

Distributions of benthic organisms are predictable along estuarine gradients and are characterized by similar groups of species over broad latitudinal ranges. Benthic species composition, abundance, and biomass are influenced by habitat conditions, including salinity, sediment type, and environmental stressors, both natural and anthropogenic (Nanami *et al.* 2005; Slim *et al.* 1997). Information on changes in benthic population and community parameters due to habitat change can be useful for separating natural variation from changes associated with human activities. For that purpose, benthic community studies have a long history of use in regional estuarine monitoring programs and have been proven to serve as an effective indicator for describing the extent and magnitude of pollution impacts and habitat modification in estuarine ecosystems, as well as for assessing the effectiveness of management actions (Llanso *et al*. 2004; Long *et al.* 1995). Several examples exist in which marine benthic communities' response to contaminant and physical stressors have been documented. Impacts of organic enrichment on marine benthos have shown that total biomass, relative proportion of deposit feeders, and abundance of species with 'opportunistic' life histories (e.g. high fecundity, short generation time, and rapid dispersal) increase. Some opportunistic taxonomic groups are known to be tolerant of chemical toxicants. Others are capable of thriving in physically disturbed habitats (e.g. high sedimentation, dredging operations, etc.) but not necessarily in contaminated areas. In areas impacted by excessive sedimentation from terrestrial runoff, dominant organisms tend toward surface suspension feeding modes and high reproductive potential regardless of taxonomic relationship, whereas away from the sedimentation stress, feeding modes shift to species that are deep deposit feeders and the emergence of filter feeders (Pearson and Rosenberg 1978; Wlodarska-Kowalczuk *et al.* 2005). Experimental manipulation of habitats has shown that specific taxonomic lines, with opportunistic life history strategies, respond positively to organic enrichment (Lenihan *et al*. 2003). Other taxa respond negatively to both toxicants and excessive organic enrichment. The response of specific species to organic and toxic contamination is mediated by life history and feeding mode characteristics.

1.2 Bioassessments in Alaska

Although Alaska has an extensive coastline of 49,700 miles, (greater than the contiguous US (U.S. EPA, 2005; Shorezone, 2016), and vast natural marine and coastal resources, due to a small population and lack of infrastructure, Alaska lacks adequate data to provide baseline information necessary to assess future trends. More environmental monitoring and research is needed to assess not only areas of known pollution impact, but also the whole Alaskan coastal region. Historically, assessment in Alaska has been either limited or focused on areas of known impairment. The NS&T Bioeffects Program has analyzed contaminants in sediment and mussels collected from selected sites in the Gulf of Alaska (O'Connor 2002). The Alyeska Pipeline Service Company and the Prince William Sound Regional Citizens Advisory Council (PWSRCAC) have been assessing PAHs and other petroleum-related compounds in Port Valdez and Prince William Sound related to oil operations and the Exxon Valdez Oil Spill in 1989 (EVOS) (Blanchard *et al.* 2011; Page *et al*. 2001; PWRCAC 2018). In collaboration with the U.S. EPA Environmental Monitoring and Assessment Program, ADEC undertook a state-wide coastal ecological condition study (AKMAP) that encompasses assessment of contaminants and benthic assemblage in sediment along the Gulf of Alaska and the Aleutian Islands (Saupe *et al.* 2005). The Cook Inlet Regional Citizens Advisory Council (CIRCAC) assesses the impacts of oil and gas operations in Cook Inlet, including chemical and benthic community assessment, and undertook a comprehensive sediment and water quality survey of Cook Inlet in 2008. Sediment chemistry, toxicity, and benthos assessments were conducted in Kachemak Bay and Cook Inlet in 2007, 2008 and 2009 in coordination with the North Pacific Research Board (Hartwell *et al*. 2009) the CIRCAC and ADEC (Hartwell *et al*. 2016b). In 2010-2012 ADEC, the University of Alaska Fairbanks (UAF) and NOAA assessed chemistry and benthic community studies on the continental shelf in the Chukchi Sea in the vicinity of potential oil infrastructure development (Dasher *et al.* 2015). In 2013-14 the NOAA NS&T Bioeffects Program conducted sediment contamination, benthic community assessment, sediment toxicity and fish body burden studies in Kvichak and Nushagak estuaries in Bristol Bay in coordination with North Pacific Research Board, UAF Dillingham and the US Fish & Wildlife Service (Hartwell *et al*. 2016a).

The study reported here augments these efforts to provide detailed data on sediment quality in Arctic estuaries, where data are sparse. The goal of the project was to assess habitat and contamination conditions that influence biodiversity and distribution of the benthic infaunal community.

The resulting data of this project are georeferenced and could be integrated into the Alaska Ocean Observation System (AOOS) database. The data will help achieve the long-term goal of conducting research designed to address pressing fishery management or marine ecosystem information needs. The NS&T Program has produced a relational web-portal database on contaminants, toxicity, and benthic infaunal species distribution in coastal United States. The data portal is an "Internet doorway" to data and information products of NS&T. Data from this study are incorporated into this database and available to local managers as well to concerned citizens nationally. The comprehensive georeferenced data base of this and previous studies are available online in downloadable format through our data portal at https://products.coastalscience.noaa.gov/collections/ltmonitoring/nsandt/default.aspx The data will also be transmitted to EPA Storage and Retrieval Water Quality Exchange (Storet) by ADEC and can be found at https://www.epa.gov/waterdata/water-quality-data-wqx

1.3 Site Background

The region is largely undeveloped. Human occupation has been present for thousands of years, but populations are small and dispersed throughout the region. With no known industrial point sources of contamination, current sources of pollution in the study estuaries may include discharges from community wastewater lagoons or treatment plants, fuel tank leaks, dumps, military installations, and long-range atmospheric transport. Oil and gas development and increased shipping impacts including exhaust fumes, bilge water exchange, spills and collisions are likely to increase as global warming impacts the Arctic more intensively than at lower latitudes. The 11 lowest ice-extent winters in the Arctic have occurred in the last 11 consecutive years (NOAA 2017). With the exception of Peard Bay, all the estuaries are shallow embayments that freeze to the bottom with landfast ice in winter (Figure 1). Central Peard Bay reaches depths of up to seven meters. All freshwater input is from rain, snowmelt, and groundwater. The Utukok River flows into the Kasegaluk Lagoon. The watershed reaches as far south as the foothills of the Brooks Range. It enters the lagoon below Icy Cape which effectively bisects the lagoon into north and south embayments, each with multiple inlets through the barrier islands that form the lagoon. Wainwright Inlet is fed by the Kuk River and the smaller Kungok River to the east. There are exposed deposits of coal along the shoreline. Peard Bay lies behind Pt. Franklin and the Seahorse Barrier Islands. It has a very limited watershed via

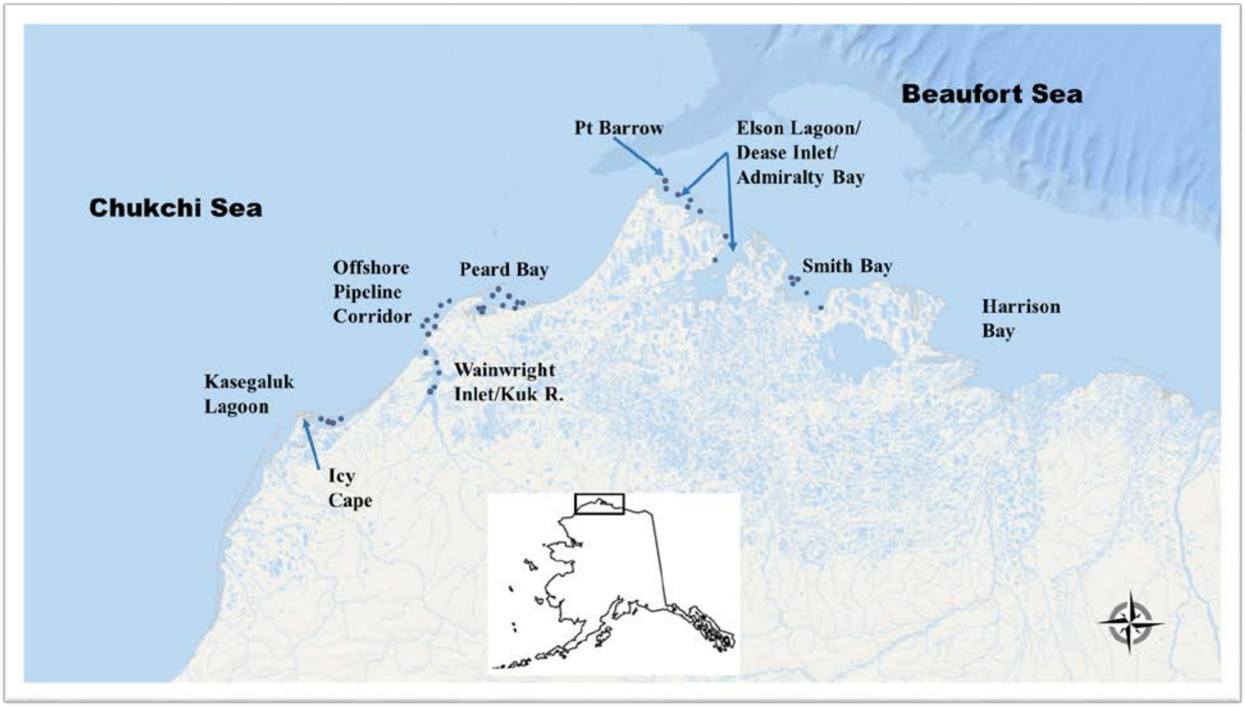

Figure 1 Map of northern Alaska (see inset) showing sampling locations.

Kugrua Bay which joins Peard Bay on the southwest side. The Bay is frequented by seals and the occasional gray whale (OCSEAP, 1985).

This section of the Chukchi coastal water mass is dominated by northward flowing currents originating in the Bering Strait which mix with the estuarine systems by tidal exchange. Frequent storm winds may overwhelm tidal exchange in both flood and ebb directions. Of particular importance is the proximity of Barrow Canyon where the flow of water from the Chukchi enters the Arctic Ocean. Strong flow reversals and upwelling from the canyon up onto shelf waters is common (Pickart et al. in press).

On the Beaufort Sea side of the study area, Elson Lagoon lies immediately east of Pt Barrow and is continuous with Dease Inlet further to the east. The Plover Islands rim the seaward side of the lagoons with multiple passes to the Beaufort Sea. South of Dease Inlet is the shallow embayment of Admiralty Bay bounded on three sides by land. Collectively these water bodies are fed by the Meade River draining the coastal plain, and various smaller rivers flowing into Dease Inlet and Elson Lagoon. To the east lies Smith Bay with freshwater input from the Ikpikpuk River, also a coastal plain watershed. Smith Bay is a shallow bay, open to the Beaufort Sea with no barrier island protection and an expanding delta at the river mouth. Harrison Bay is east of Cape Halkett. It is 80 km wide and is also a shallow bay without barrier island protection. The Coleville River which empties into Harrison Bay is the largest river in the Alaskan North Slope, draining land in the coastal plain and up into the Brooks range.

The dominant coastal currents in the western Beaufort Sea flow from east to west but are reversed by storms from the north west. The very large Canadian Mackenzie River along with the Coleville and numerous smaller rivers along the Beaufort coast supply enough fresh water to the system to maintain near-estuarine conditions along the coast (Dunton et al. 2012).

Winter freeze-up begins in late September to October and the estuaries freeze to the bottom with land-fast ice for 9-10 months of the year. During winter, brine pockets of very high salinity form under the ice, with no freshwater input from the frozen tundra. Tidal exchanges in the Chukchi and Beaufort are small, varying by a foot or less. Wind driven water exchange frequently overwhelms tidal flushing during ice-free periods. The vast majority of fresh water enters the systems during spring floods in June when the snow melts (Rember and Trefry 2004). Large volumes of sediment and terrestrial organic matter are delivered to the estuaries during these periods.

1.4 Objectives

The objectives of this project were to:

1) quantify concentrations of a suite of metals and metalloids and organic contaminants including, PAHs and persistent organic pollutants (POPs) in sediment and biota;

2) produce a comprehensive taxonomic list and distribution patterns of infaunal species in each of the embayments;

3) assess potential chemical contamination from distant sources;

4) assess sources of terrestrial and marine organic matter entering the systems;

5) contrast Chukchi Sea estuarine habitats with Beaufort Sea habitats;

6) Survey the offshore habitat near Wainwright Inlet to assess background environmental conditions prior to oil pipeline development.

2. METHODS

The NS&T Bioeffects Program and AKMAP use a stratified-random design for selection of sampling sites to determine the spatial extent of sediment contamination in U.S. coastal waters. One of the design principles is to apply the same suite of tests synoptically to all areas so that comparisons can be made without the confounding interference of using different methods in different areas. This approach combines the strengths of a stratified design with the random-probabilistic selection of sampling locations, allowing the data generated within each stratum to be attributed to the size of that stratum with a quantifiable degree of confidence (Heimbuch *et al*. 1995). Thus, comparison of spatial extent of impact between areas is possible even if the areas are not contiguous. It also allows for estimates of the areal extent of ecological condition based on stressors and indicators. Stressors, such as chemical contaminants and water quality parameters, and indicators, such as macroinvertebrate biodiversity, are used at each station to relate biological response, contaminant exposure and habitat condition. The survey was consistent with the 2010 National Coastal Condition Assessment (NCCA) design, Field Operations & Site Evaluation, Quality Assurance and Quality Control, used by the EPA (U.S. EPA, 2009) and NS&T standard methods (Apeti et al. 2012).

Five or more sampling sites were located on a random basis within each bay in the Chukchi and Beaufort Seas. A total of 20 stations in each sea were planned with the larger systems of Peard Bay and Elson Lagoon/Dease Inlet containing proportionately more stations. Within each bay, two randomly selected alternate sites were also selected for each primary sampling site. In instances where the primary site could not be sampled due to non-accessibility or an unsuitable substratum, the next sequential alternate site was sampled.

Ten additional sites in the vicinity of Wainwright were randomly chosen, five each in a nearshore and offshore transect. This area was added as a special study area outside of the primary estuary study, to assess a region where industry proposed installing an oil/gas pipeline corridor from offshore oil rigs in the BOEM lease 193 blocks.

The NOAA vessel *Ron Brown* served as the base of operations in August of 2015. The estuaries survey team utilized a smaller launch, the *Peggy D*, for the estuary sampling. Typically the *Peggy D* was launched in the mornings, and returned each evening to process and store samples. Field sampling operations were planned in upper Kasegaluk Lagoon, proceeding to Wainwright Inlet and the Kuk River estuary, Peard Bay (including the contiguous Kugrua Bay), Elson Lagoon/Dease Inlet/Admiralty Bay, Smith Bay, and Harrison Bay (Figure 1).

2.1. Sampling procedures

At each station the following sequence of sampling events were initiated:

1. The station location was confirmed within ± 0.02 nautical miles (37 m) against Peggy D GPS readings.

2. The Peggy D was anchored.

3. Salinity was checked to confirm ≥ 0.5 ppt.

4. If site was sampleable, e.g. ≥ 0.5 ppt, depth measurements were made.

5. An underwater camera was deployed to visually assess benthic habitat.

6. Secchi disk transparency measurements were taken.

7. The water column was profiled with a CTD (including measurements of pH, PAR).

8. Water samples were taken for nutrients, chlorophyll *a*, and total suspended solids with a Nisken bottle.

9. Sediment sampling was conducted for macroinvertebrates physical parameters (grain size, color, odor, and temperature), sediment chemistry, and stable carbon and nitrogen isotopes. Depending on the substrate, 4 – 8 grab samples were required.

10. One to two 1 meter beam trawls were run at one station in each estuary to collect epifauna and fish for contaminant assessment.

Sediment samples were collected with a stainless steel 0.04 m^2 PONAR grab sampler. At each site, the sampler was cleaned, rinsed with site water, alcohol, and deionized water immediately prior to sampling. Only the upper 2-3 cm of the sediment was retained in order to assure collection of recently deposited materials. A sediment sample was discarded if the jaws of the grab were open, or the sample was partly washed out. Sediments were removed with a stainless steel scoop. Sediment was composited from multiple grabs in a bucket with an alcohol washed, high-density polyethylene (HDPE) liner. Between each deployment of the sampler, the bucket was covered with an HDPE lid to minimize sample oxidation and exposure to atmospheric contamination. Additional grab samples were taken, and the top layer of sediment was collected and composited until sufficient volume (~1 1) of sediment for all the chemical analyses was collected.

The sediment samples were thoroughly homogenized in the field with an alcohol and distilled water-rinsed, stainless steel mixer attachment on an electric drill. This composite sample was subdivided for distribution to various testing laboratories. Samples for chemical analyses were stored in pre-cleaned glass jars with Teflon® liners and frozen. The bucket liners were not reused between sampling sites. Sampling locations are shown in Figs 2-5.

A second sample was taken for benthic community analysis with the grab

Figure 2. Station locations in Kasegaluk Lagoon.

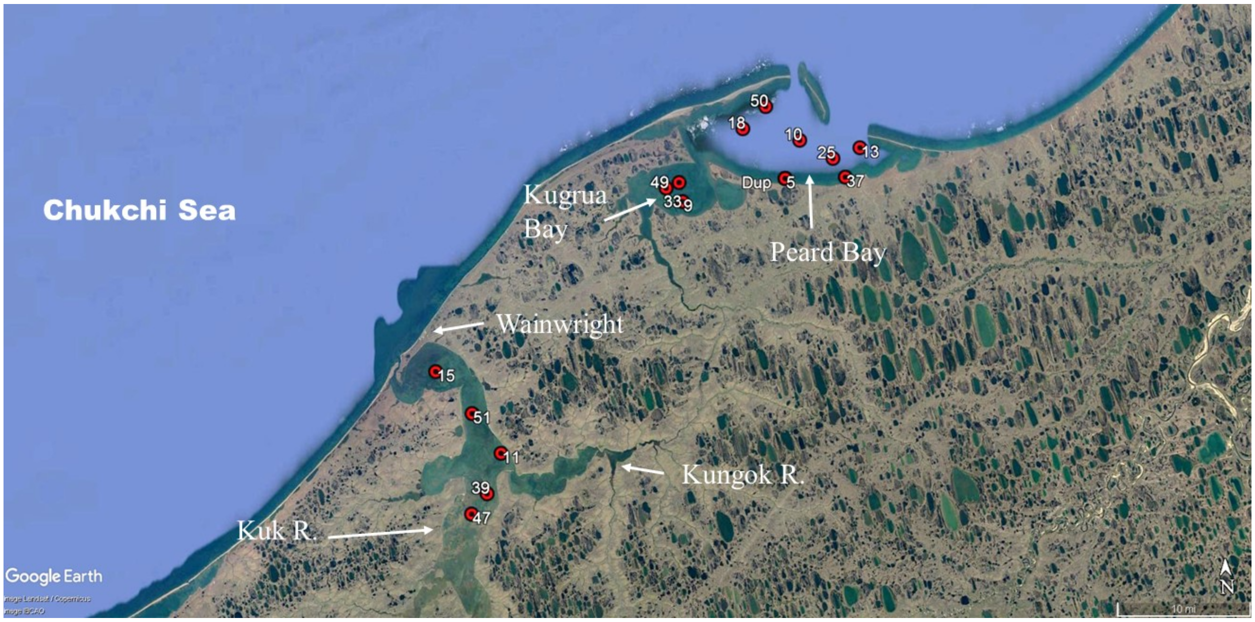

Figure 3. Station locations in Wainwright Inlet and Peard Bay.

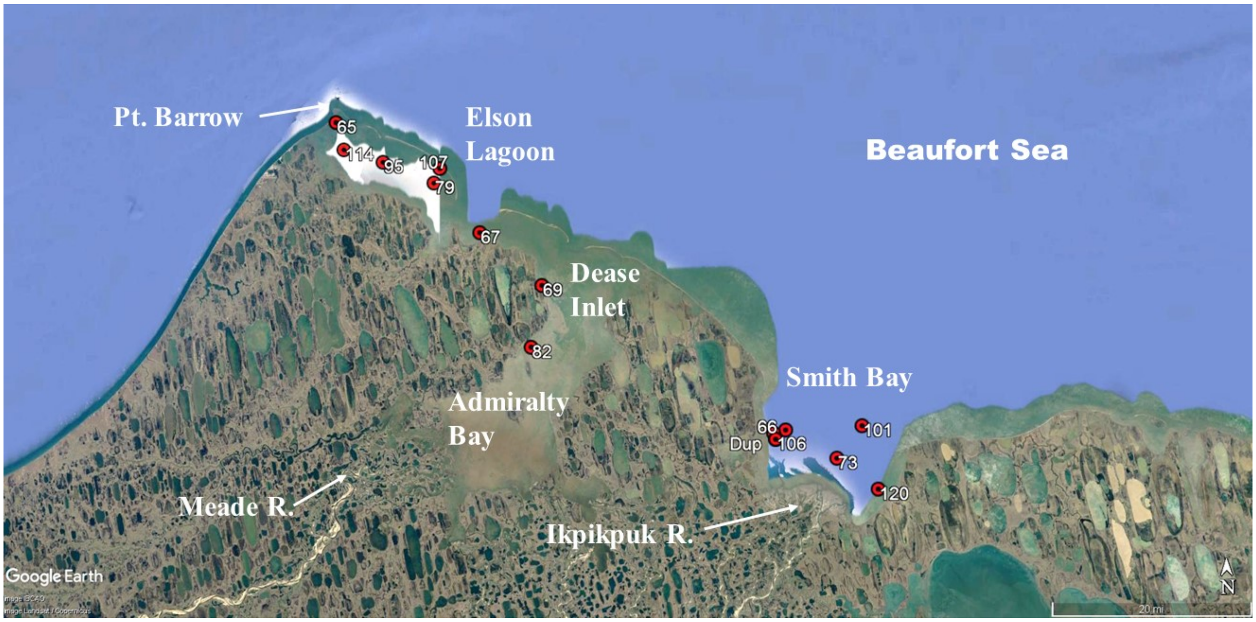

Figure 4. Station locations in Elson/Dease/Admiralty Bay and Smith Bay.

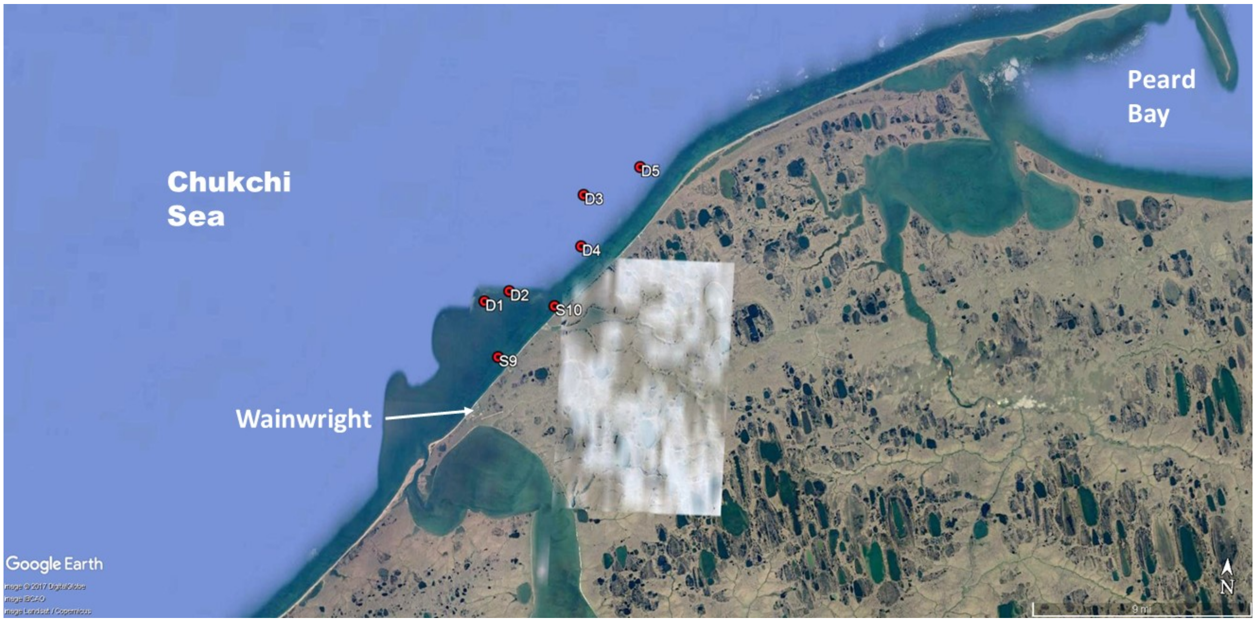

Figure 5. Offshore station locations near Wainwright in the Chukchi Sea.

sampler. The entire contents of an acceptable sample (at least 5 cm deep) were stored and returned to the ship where they were sieved through nested 1.0 and 0.5 mm mesh screens. All organisms were retained in Nalgene bottles and preserved in buffered formalin containing Rose Bengal stain.

Air samples were collected once in each estuary by leaving a sample jar open on deck during the entire station sampling period for subsequent PAH analysis.

Fish collections were attempted in each estuary with a 1 m trawl. All samples were frozen in double plastic zip lock bags and shipped to the laboratory for whole body analysis for trace elements, lipid content, PAHs, PCBs, chlorinated pesticides, and tributyltin at the NS&T contract analytical lab (TDI Brooks). Additional fish samples were exchanged with NOAA National Marine Fisheries Service (NMFS) researchers who were sampling in the vicinity at the same time.

The Wainwright offshore transect was sampled from the *RV Brown* with a Smith-McIntyre 0.1 m^2 sampler. Sampling and cleaning procedures were the same as those used on the launch. A CTD cast was conducted at each station, but water or trawl samples were not collected. The inner transect was sampled from the *Peggy D* due to depth considerations in these poorly charted areas.

2.2. Chemical analysis

Chemical analyses followed procedures routinely used in the NOAA NS&T Program (Kimbrough and Lauenstein 2006a, 2006b; ASTM 2004). A broad suite of sediment contaminants were analyzed at each station, including 59 PAHs, 35 saturated aliphatics from C_9-C_{40} plus pristane and phytane, stable isotopes of carbon and nitrogen and, 18 major and trace elements, (Tables 1 -3). Other parameters included grain size analysis, total organic/inorganic carbon (TOC/TIC), and percent solids. In addition to metals, fish tissues were analyzed for chlorinated pesticides, including DDT and its metabolites, 83 polychlorinated biphenyls (PCBs) (Tables 4-5), percent lipids and, mono-, di- and tributyltin.

2.2.1 Organics (PAHs, PCBs, chlorinated pesticides, aliphatics) Samples were shipped frozen to the laboratory and stored at -20 °C until analysis. Quantitation of PAHs and their alkylated homologues was performed by gas chromatography mass spectrometry (GC/MS) in the selected ion monitoring (SIM) mode. QA/QC controls included standard reference materials, matrix spikes, duplicate analyses, internal standards, and blanks. A solution containing 2- to 5-ring PAH compounds was used to fortify matrix spike samples. The actual analytical method detection limit (MDL) was determined following procedures outlined in CFR 40, part 136 (1999).

Quantitation of aliphatic alkanes of C-9 through C-40 plus pristane and phytane was performed by high resolution, capillary gas chromatography with flame ionization detection (GC/FID). Quality control procedures (blanks, duplicates, matrix spikes) were identical to the PAH procedures, except there are no certified SRMs for these materials.

Table 1. Polycyclic aromatic hydrocarbons (PAHs) measured in sediment and fish tissue samples.

Compound		
Naphthalene	Phenanthrene	Benz(a)anthracene
C1-Naphthalenes	C1-Phenanthrenes/Anthracenes	Chrysene/Triphenylene
C2-Naphthalenes	C2-Phenanthrenes/Anthracenes	C1-Chrysenes
C3-Naphthalenes	C3-Phenanthrenes/Anthracenes	C2-Chrysenes
C4-Naphthalenes	C4-Phenanthrenes/Anthracenes	C3-Chrysenes
Benzothiophene	Dibenzothiophene	C4-Chrysenes
C1-Benzothiophenes	C1-Dibenzothiophenes	Benzo(b)fluoranthene
C2-Benzothiophenes	C2-Dibenzothiophenes	Benzo(k,j)fluoranthene
C3-Benzothiophenes	C3-Dibenzothiophenes	Benzo(a)fluoranthene
C4-Benzothiophenes	C4-Dibenzothiophenes	Benzo(e)pyrene
Biphenyl	Fluoranthene	Benzo(a)pyrene
Acenaphthylene	Pyrene	Perylene
Acenaphthene	C1-Fluoranthenes/Pyrenes	Indeno(1,2,3-c,d)pyrene
Dibenzofuran	C2-Fluoranthenes/Pyrenes	Dibenzo(a,h)anthracene
Fluorene	C3-Fluoranthenes/Pyrenes	C1-Dibenzo(a,h)anthracenes
C1-Fluorenes	C4-Fluoranthenes/Pyrenes	C2-Dibenzo(a,h)anthracenes
C2-Fluorenes	Naphthobenzothiophene	C3-Dibenzo(a,h)anthracenes
C3-Fluorenes	C1-Naphthobenzothiophenes	Benzo(g,h,i)perylene
Carbazole	C2-Naphthobenzothiophenes	
Anthracene	C3-Naphthobenzothiophenes	
	C4-Naphthobenzothiophenes	

Table 2. Saturated aliphatic compounds measured in sediments in Arctic estuaries.

Compuund			
n-C9	n-C16	n-C24	n-C33
n-C10	i-C18	n-C25	n-C34
n-C11	n-C17	n-C26	n-C35
n-C12	n-C18	n-C27	n-C36
n-C13	n-C19	n-C28	n-C37
i-C15	n-C20	n-C29	n-C38
n-C14	n-C21	n-C30	n-C39
i-C16	n-C22	n-C31	n-C40
n-C15	n-C23	n-C32	

Table 3. Major and trace elements measured in sediment and fish tissue samples. For simplicity, the term metal is used without distinction between true metals and metalloids/nonmetals.

Symbol	Element		Symbol	Element		Symbol	Element
Ag	silver		Cu	copper		Pb	lead
Al	aluminum		Fe	iron		Sb	antimony
As	arsenic		Hg	mercury		Se	selenium
Ba	barium		Li	lithium		Si	silicon
Cd	cadmium		Mn	manganese		Sn	tin
Cr	chromium		Ni	nickel		Zn	zinc

Table 4. Chlorinated pesticides measured in Arctic fish tissue samples.

Class	Compound	Class	Compound
Cyclodienes	Aldrin	DDT & metabolites	DDMU
	Dieldrin		2,4'-DDD
	Endrin		4,4'-DDD
	Heptachlor		2,4'-DDE
	Heptachlor-Epoxide		4,4'-DDE
	Oxychlordane		2,4'-DDT
	Alpha-Chlordane		4,4'-DDT
	Gamma-Chlordane	Chlorinated benzenes	1,2,3,4-Tetrachlorobenzene
	Trans-Nonachlor		1,2,4,5-Tetrachlorobenzene
	Cis-Nonachlor		Hexachlorobenzene
Hexachlorocyclohexanes	Alpha-HCH		Pentachloroanisole
	Beta-HCH		Pentachlorobenzene
	Delta-HCH	Other	Endosulfan II
	Gamma-HCH		Endosulfan I
			Endosulfan Sulfate
			Mirex
			Chlorpyrifos

Table 5. Polychlorinated biphenyls (PCBs) measured in Arctic estuary fish tissue samples. (Co-eluting congeners are shown together.)

Congener(s)		
PCB1	PCB77	PCB153/132
PCB7/9	PCB81	PCB156/171/202
PCB8/5	PCB82	PCB158
PCB15	PCB83	PCB166
PCB16/32	PCB84	PCB167
PCB18	PCB85	PCB169
PCB22/51	PCB86	PCB170/190
PCB24/27	PCB87/115	PCB172
PCB25	PCB88	PCB174
PCB26	PCB92	PCB176/137
PCB28	PCB95	PCB177
PCB29	PCB97	PCB178
PCB31	PCB99	PCB180
PCB33/53/20	PCB101/90	PCB183
PCB40	PCB105	PCB185
PCB41/64	PCB107	PCB187
PCB42/59/37	PCB110/77	PCB189
PCB43	PCB114/131/122	PCB191
PCB44	PCB118	PCB194
PCB45	PCB126	PCB195/208
PCB46	PCB128	PCB196/203
PCB47/48/75	PCB129/126	PCB199
PCB49	PCB136	PCB200
PCB52	PCB138/160	PCB201/157/173
PCB56/60	PCB141/179	PCB205
PCB66	PCB146	PCB206
PCB70	PCB149/123	PCB209
PCB74/61	PCB151	

Chlorinated hydrocarbons (chlorinated pesticides and PCBs, (Tables 4 and 5) were quantitatively determined by capillary gas chromatography with an electron capture detector (ECD). QA/QC controls included standard reference materials, matrix spikes, duplicate analyses, internal standards, and blanks.

2.2.2 Trace and major elements

Samples were prepared for inductively coupled plasma/mass spectrometry analysis (ICP-MS) for major metals, while atomic fluorescence spectrometry was utilized to measure arsenic and selenium, and atomic absorption spectrometry was used for mercury analysis. For analysis of Hg, sediment samples were digested based on a modified version of U.S. EPA (1991) method 245.5, using a concentrated H_2SO_4 and HNO_3 digestion, followed by addition of $KMnO_4$, and $K_2S_2O_8$, and then the samples were again digested. QA/QC controls included standard reference materials, matrix spikes, duplicate analyses, internal standards, and blanks.

2.2.3 Tissue samples

Whole body tissue samples were homogenized using a variety of mechanical methods (Waring blender, Hobart meat grinder or Tissumisser), depending upon the tissue amount and type. After homogenization, an approximate 1 g aliquot is removed and dried in an oven at 105°C to a constant weight to determine % moisture. The remaining samples are stored in certified pre-cleaned jars frozen (-20°C) until analysis.

Prior to extraction, for PAHs and OCs, tissue samples were lyophilized. Samples were then extracted using a Dionex ASE200 Accelerated Solvent Extractor (ASE). The dried sample was loaded into stainless steel ASE extraction tubes and extracted in 100% dichloromethane at 100 °C and 1500 psi. The extract was processed through silica gel/alumina chromatography columns and High Performance Liquid Chromatography (HPLC). The concentrated extract was then analyzed by GC/MS for polycyclic aromatic hydrocarbons (PAHs) or GC/ECD for selected organochlorines (OCs).

For trace metals, tissue samples were digested with a mixture of ultrapure nitric acid, hydrochloric acid, and hydrogen peroxide in polypropylene vessels in a block digester. QA/QC procedures matched those used for sediment samples.

2.2.4 Butyltins

An aliquot of freeze dried homogenized tissue was weighed and appropriate amounts of surrogate standards were added to all samples, matrix spikes, and blanks. Samples were extracted three times by agitation with tropolone in dichloromethane. Hexylmagnesium bromide (2 M; Grignard reagent) was added to the sample extract under nitrogen and heated to hexylate the sample. The hexylated extract was dried by addition of anhydrous Na_2SO_4 and then concentrated. The extract was purified using silica gel/alumina column chromatography. The quantitative method was based on high resolution, capillary gas chromatography using flame photometric detection (GC/FPD). This method quantitatively determined tributyltin (TBT), dibutyltin (DBT), and monobutyltin (MBT). The method detection limit was determined following the procedures outlined in CFR 40, part 136 (1999).

2.2.5 Stable isotopes

$\delta^{15}N$ and $\delta^{13}C$ value were measured at the Univ. Alaska Fairbanks stable isotope laboratory using Elemental Analysis-Isotope Ratio Mass Spectrometry (EA-IRMS). This method utilizes a Costech Elemental Analyzer (ECS 4010), and ThermoScientific Conflo III (Conflo IV after Nov 18, 2013) interface with a ThermoScientific DeltaV Mass Spectrometer. Quality controls includes analyzing tin capsule blanks and laboratory working standards every 20 samples.

2.3. Benthic community characterization

In the IMS/UAF laboratory, samples were inventoried, rinsed gently through a 0.5 mm mesh sieve to remove formalin and residual sediment, stained with Rose Bengal, and stored in 50% isopropanol solution until processing. Sample material (sediment, detritus, and organisms) were placed in white enamel trays for sorting under dissecting microscopes. All macroinvertebrates were carefully segregated into major taxonomic groups (e.g. Polychaeta, Mollusca, and Arthropoda). The macroinvertebrates were then identified to the lowest practical identification level, which in most cases was to species level unless the specimen was a juvenile, damaged, or otherwise unidentifiable. The number of individuals of each taxon, excluding fragments was recorded. Data were synthesized into a data summary report for each site, which includes a taxonomic species list and benthic community parameters list. At a minimum, 10 percent of all samples were resorted and recounted on a regular basis. Also, 10 percent of samples were randomly selected and re-identified. The minimum acceptable sorting and taxonomic efficiency was 95%. A voucher collection composed of representative individuals of each species encountered in the project was accumulated and retained.

Taxa are distributed along environmental gradients, so there are generally no distinct boundaries between communities. However, the relationships between habitats and species assemblages reflect the interactions of physical and biological factors and can indicate major ecological trends. Quantitatively, the benthic communities were characterized as enumeration by abundance, species richness, and diversity, followed by pattern and classification analysis for delineation of taxa assemblages.

Abundance was calculated as the total number of individuals per square meter; taxa richness as the total number of taxa represented at a given site; and taxa diversity (H’) was calculated with the Shannon-Weiner Index (Shannon and Weaver, 1949), using the following formula:

Eqn1 $$H' = -\sum_{i=1}^{S} p_i (\ln p_i)$$

where, S = is the number of taxa in the sample,

i is the i_{th} taxa in the sample, and

p_i is the number of individuals of the i_{th} taxa divided by the total number of individuals in the sample.

2.4. Statistical contrasts

2.4.1 Contaminants

Spearman rank correlations were calculated to assess the degree of association between sediment characteristics, the concentration of trace metals and organic compounds, and benthic community metrics. PAH concentration data were used to calculate PAH ratios for source identification and composition. Twelve triterpanes and hopanes ratios and twelve steranes ratios were calculated and used in exploratory hierarchical cluster analysis (HCA) and principle component analysis (PCA).

2.4.2 Sediment quality guidelines

Numerical sediment quality guidelines (SQG) developed by Long and Morgan (1990) and Long *et al*. (1995) known as ERM and ERL (effects range-median, effects range-low), (Appendix A) express statistically derived levels of contamination, above which toxic effects would be expected to be observed with at least a 50% frequency (ERM), and below which effects were rarely (<10 %) expected (ERL). The mean ERM quotient (Long *et al*. 1998) is the average of the ratio of ERM value to sediment concentration for each chemical. The mean quotient of the ERMs and observed contaminant concentrations were calculated on a site by site basis for all the individual metals with ERMs.

2.4.3 Benthic community nodal analysis

Multivariate cluster analysis was employed to group site and species data. The objective was to produce a coherent pattern of association between sites and species. Cluster analysis is a two-step process including; 1) creation of a resemblance data matrix from the raw data, and 2) clustering the resemblance coefficients in the matrix. The input resemblance (similarity or dissimilarity) matrix can be created by a number of methods. Input data may or may not be standardized or transformed depending on the requirements of the method (e.g. Bray Curtis). Based on previous research (Hartwell and Claflin 2005), the Jaccard method (Goodall 1973) was used to generate the similarity matrix.

The Jaccard method is a binary method based only on presence/absence data, and thus ignores abundance values. Cluster analyses were calculated from the matrices using the Unweighted Pair-Group Method Using Arithmetic Averages procedure, which clusters coefficients based on arithmetic mean distance calculations (Sneath and Sokal 1973). To optimize the cluster analysis results, several manipulations of the input data were performed to remove confounding effects and bias.

1- Epiphytic species such as sea anemones and tunicates were eliminated from the data set as they are not truly infauna.

2- Artificial species (resulting from failure to identify some specimens all the way down to species) were identified as a data bias. For example, if specimens of 2-3 species were identified in genus A, and other specimens were identified only to genus A, this tends to artificially increase species richness and diversity of the sample when in fact that diversity is an artifact of imperfect taxonomic identification. In some instances, specimens were only identifiable to family, order or class. To address this problem, specimens not identified to species level were eliminated, unless they were identified to a taxonomic level below which no other specimens in the collection belonged. That is, even though they were not identified to species, they were the only representative of that taxonomic line and did represent a non-redundant taxon. In other cases, where a specimen was identified to genus and there was only one species identified in that genus, they were combined at the genus level.

3- Rare and unique taxa were defined as those species that were found at no more than two stations. Although they do contribute to the overall assessment of biodiversity, they were eliminated from the cluster analysis data set. Because of their limited distribution, by definition, they do not provide information on the impact of contaminant or other stressor gradients in the environment because they do not occur across the entire gradient. Although they may not contribute insight into contaminant trends, rare & unique species occurrence may provide important temporal benchmarks for examining climate change trends and other physical/biological changes in other studies.

The site and species clusters were also characterized by physicochemical habitat parameters, contaminant concentrations, and other site-specific data (Figure 6). For each species, the parameters were normalized to their abundance at each site. For example, if 100 specimens of species A were found at a site with a TOC value of 1.5% and 10 were found at a site where TOC was 2%, the abundance normalized TOC preference for species A would be [(100*1.5)+(10*2)]/110=1.55.

Univariate and multivariate methods were used to determine differences among sieve sizes and associated changes in community patterns. Paired t-tests compared means of biomass, density, and the number of taxon categories for 0.5-mm-mesh and 1.0-mm-mesh sieved components. Nonmetric multidimensional scaling (MDS) was applied to determine if patterns of community structure were different between the 0.5-mm-mesh and 1.0-mm-mesh sieved components. MDS included analysis of composition data collected from the 0.5-mm-mesh sieve component, composition data from the 1.0-mm-mesh sieve component, physical data, and both sieve sizes together. The four distance/similarity matrices were correlated to determine the strength of associations of patterns among the matrices. Paired t-tests were calculated in spreadsheet software and MDS relied on the PRIMER software package.

Cluster Characteristics

Tox	Metals	DDT	PCB	PAH	# Taxa	Abundance	TOC	GrainSize	Depth	PPT
x	100	2	150	1050	3	300	2.5	80	2	0
x	210	0	55	3100	8	100	3	80	10	0
0	100	2	50	1080	8	400	3.5	90	12	0
x	105	1	58	2000	2	50	3	80	5	0
0	200	2	50	1900	8	250	2	93	12	0
x	100	2	50	1000	8	500	3	80	8	0
0	19	1	15	150	4	38	2.5	60	12	7
x	110	0	55	310	3	500	3	80	10	8
0	100	2	50	180	10	40	1.5	70	22	5
x	15	1	58	700	5	500	3	80	5	2
0	20	1	20	190	3	250	2	53	12	10
0	10	1	15	15	24	1380	0.5	15	32	15
0	10	0	5	20	31	500	1	10	50	18
0	10	0	2.5	18	15	4000	0.5	15	21	25
0	5	1	8	70	25	590	0.1	10	35	18
0	20	0	20	190	3	250	0.5	5	32	29
x	10	0	15	15	24	138	0.5	5	32	15
0	15	0	5	20	21	500	1	10	40	18
0	10	0	25	18	10	200	0.5	5	25	25
0	5	1	8	70	25	590	0.1	10	35	18

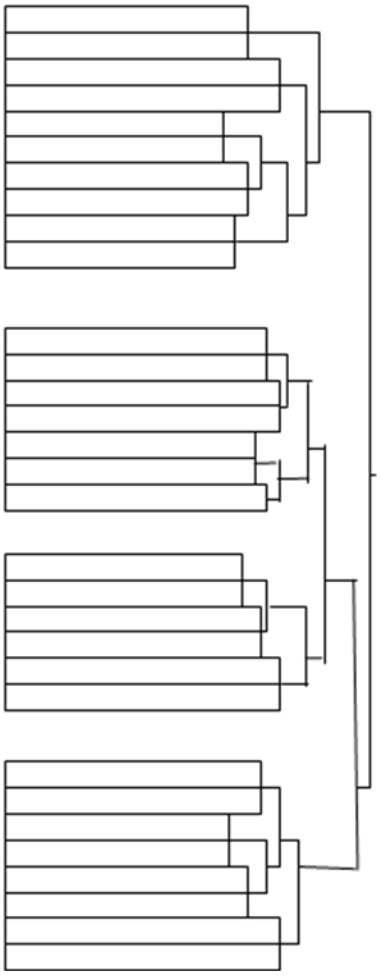

Figure 6. Conceptual representation of the distribution of physicochemical habitat parameters, contaminant concentrations, and other site-specific data used to characterize site and species clusters.

3. RESULTS AND DISCUSSION

A total of 32 sites were sampled for sediment chemistry and water quality (Figures 2-5). Due to impassable ice conditions and high wind, Harrison Bay could not be sampled at all. Only 21 sites contained sediment suitable for benthic infaunal sampling. The others consisted of hard packed silty sand that the sampler could not penetrate deep enough to collect sufficient material for a valid sample. Four of the sites in Kasegaluk Lagoon were sampleable for chemical analyses, but adequate benthos samples were not obtained. Three of five sites in Wainwright Inlet, eight of ten sites in Peard Bay, seven of eight sites in Elson Lagoon and three of five sites in Smith Bay yielded acceptable benthos samples. All five of the deep sites on the offshore transect were sampled (Figure 5). Two of the shallow offshore transect sites were sampled before bad weather conditions halted operations.

3.1. Habitat Conditions

Peard Bay was the deepest estuary sampled at seven meters (Figure 7). Most other sampling sites rarely exceeded three meters. Within the estuaries, sediment type was almost exclusively silt. A few locations very close to shorelines were composed of coarser sand or a mix of silt and sand (Figure 8). There were only tiny amounts of gravel or clay sized material. There are multiple shoals present in all locations. The watersheds are flat, low energy systems that do not deliver loads of variable sediment types, outside of the spring flood which is a short-lived phenomenon in the Arctic.

Due to tidal and wind mixing, the shallowness of the estuaries, and the silty nature of the sediment, water clarity was poor as measured by Secchi disk, averaging less than one meter over all sites. (Figure 9). This is consistent with the water column being well mixed in all places based on the salinity and temperature profiles (Figures 10 and 11). With the exception of sites far up the estuaries, most sites had relatively high salinities, reflecting the tidal influence of seawater into the estuaries, and the low input of freshwater in late summer. Temperatures were cooler on average in the Beaufort estuaries than in the Chukchi estuaries.

Dissolved oxygen levels were acceptable relative to AK DEC water quality standards (DEC 2015) (Figure 12), showed no depth stratification, but were slightly higher in the cooler waters on the Beaufort side.

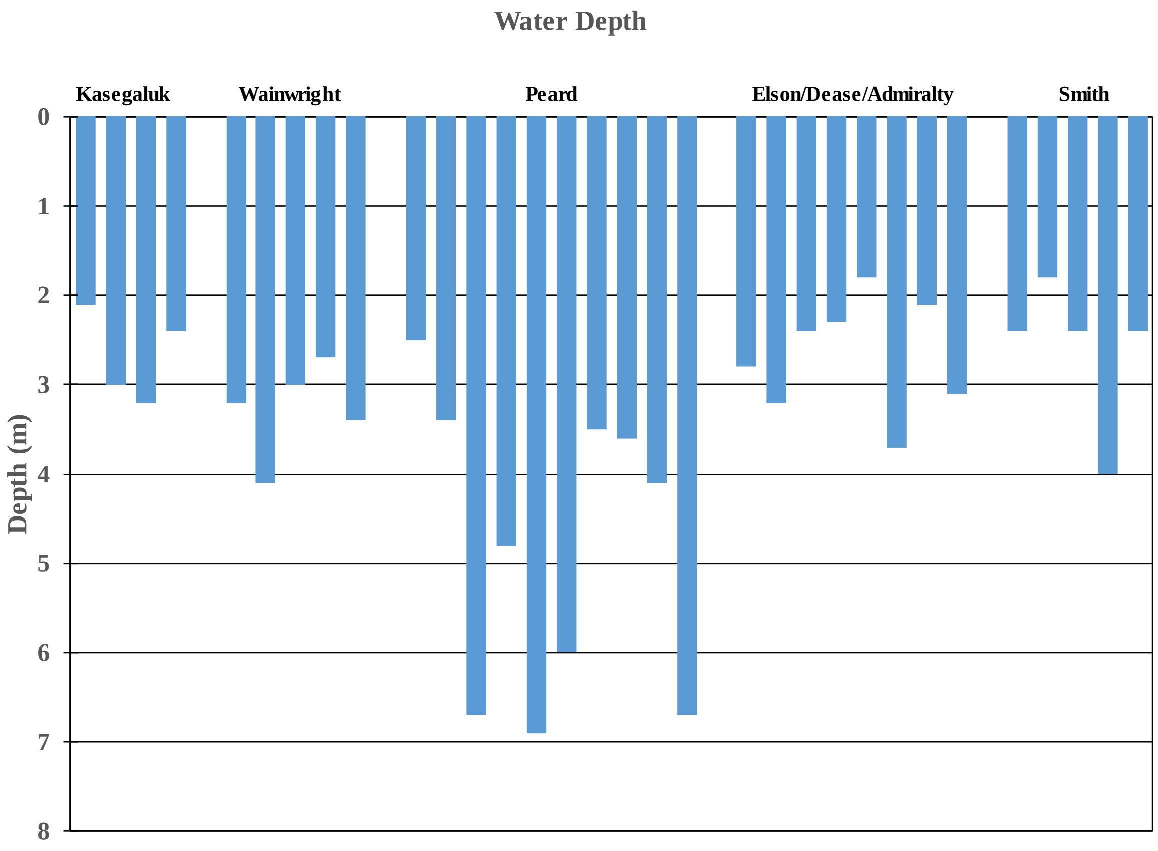

Figure 7. Water depths in estuaries and lagoons in the Chukchi and Beaufort Seas.

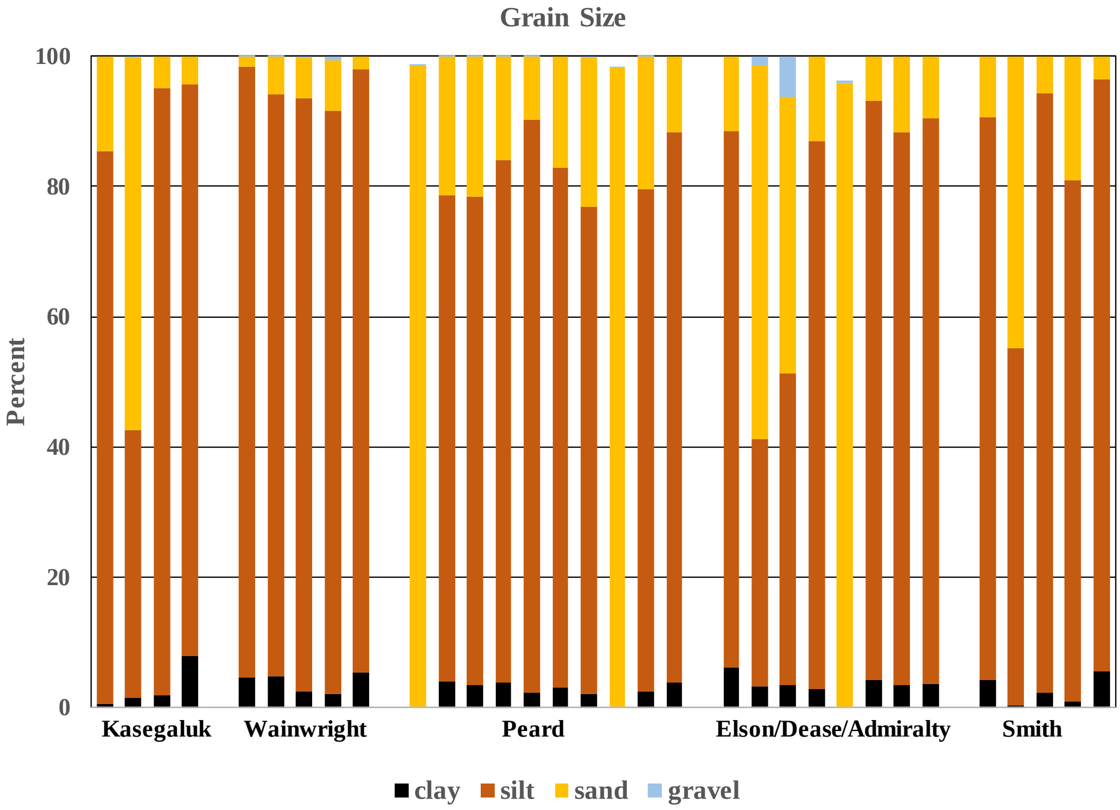

Figure 8. Grain size characteristics in estuaries and lagoons in the Chukchi and Beaufort Seas.

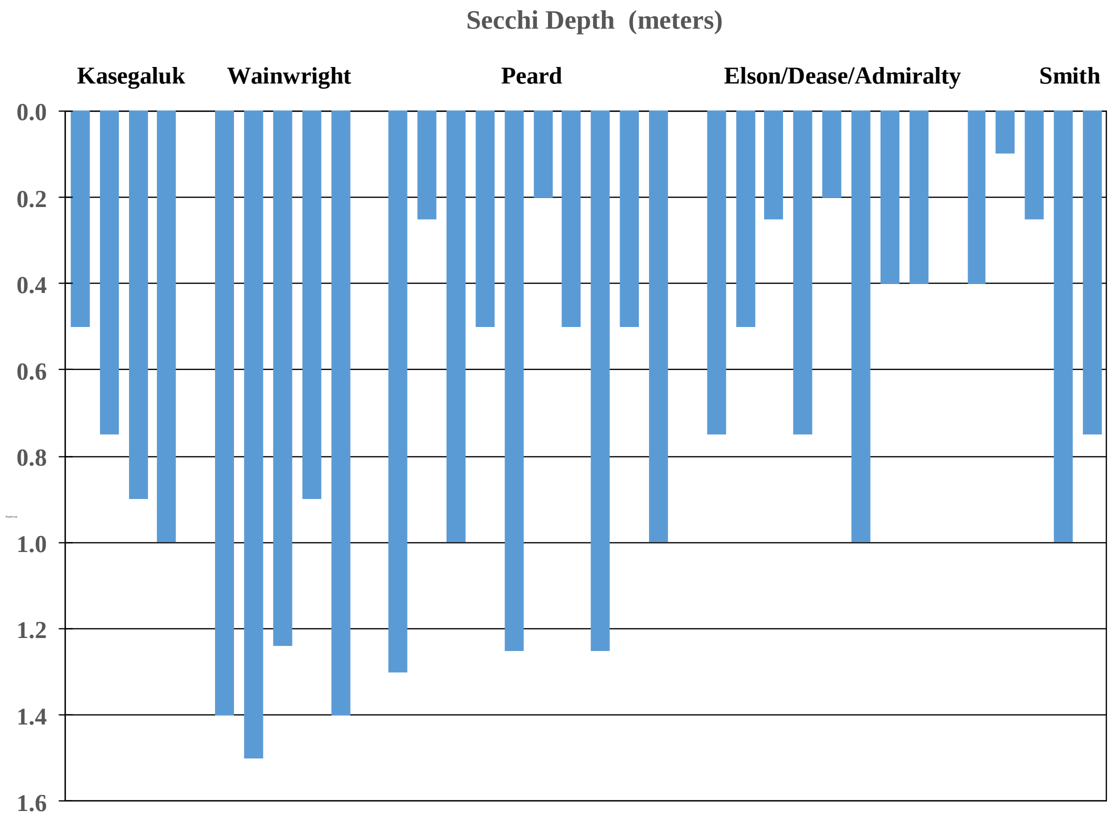

Figure 9. Water clarity in estuaries and lagoons in the Chukchi and Beaufort Seas.

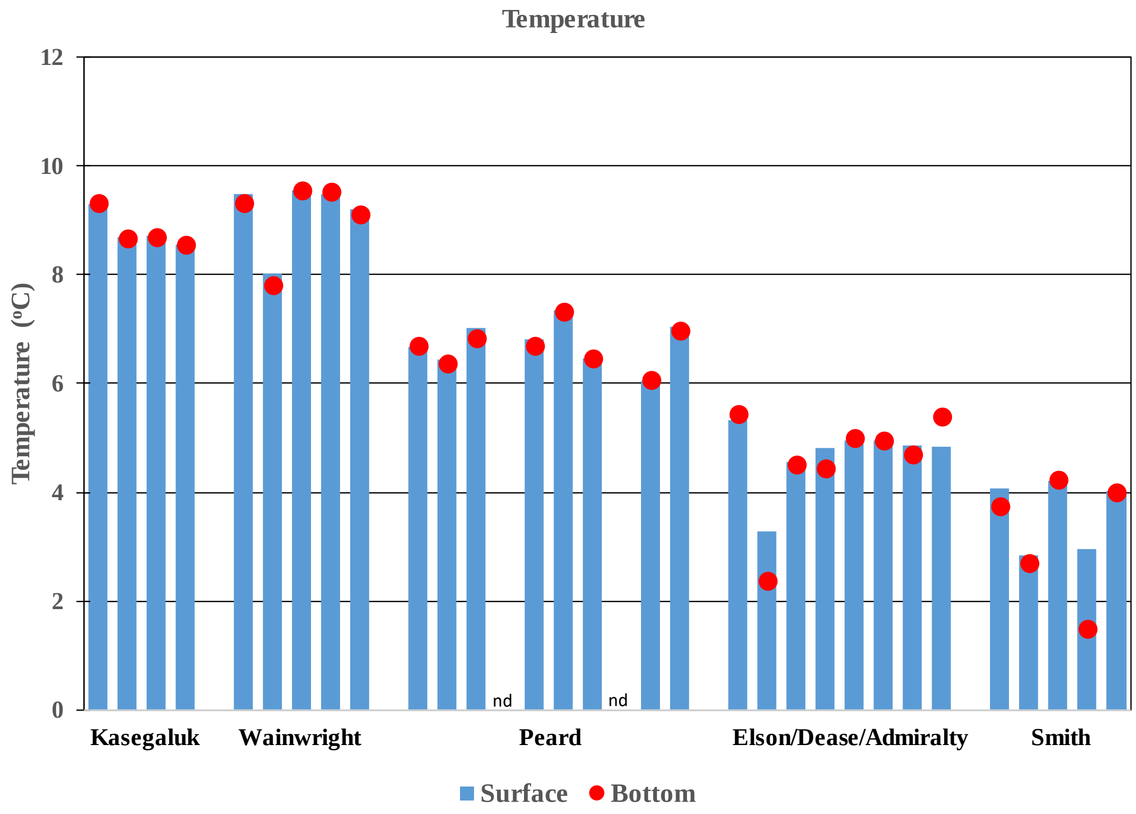

Figure 10. Surface and bottom water temperatures in estuaries and lagoons in the Chukchi and Beaufort Seas. (nd=no data)

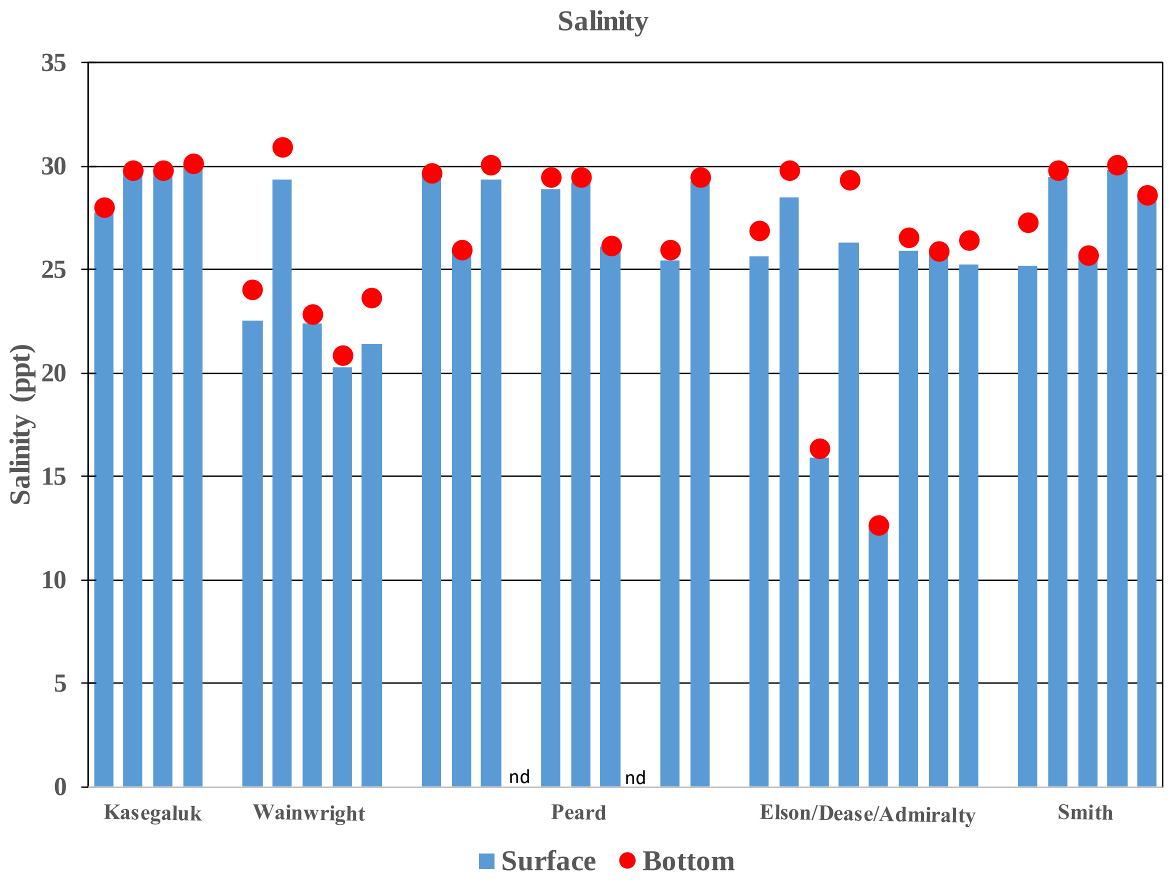

Figure 11. Surface and bottom water salinity in estuaries and lagoons in the Chukchi and Beaufort Seas. (nd=no data)

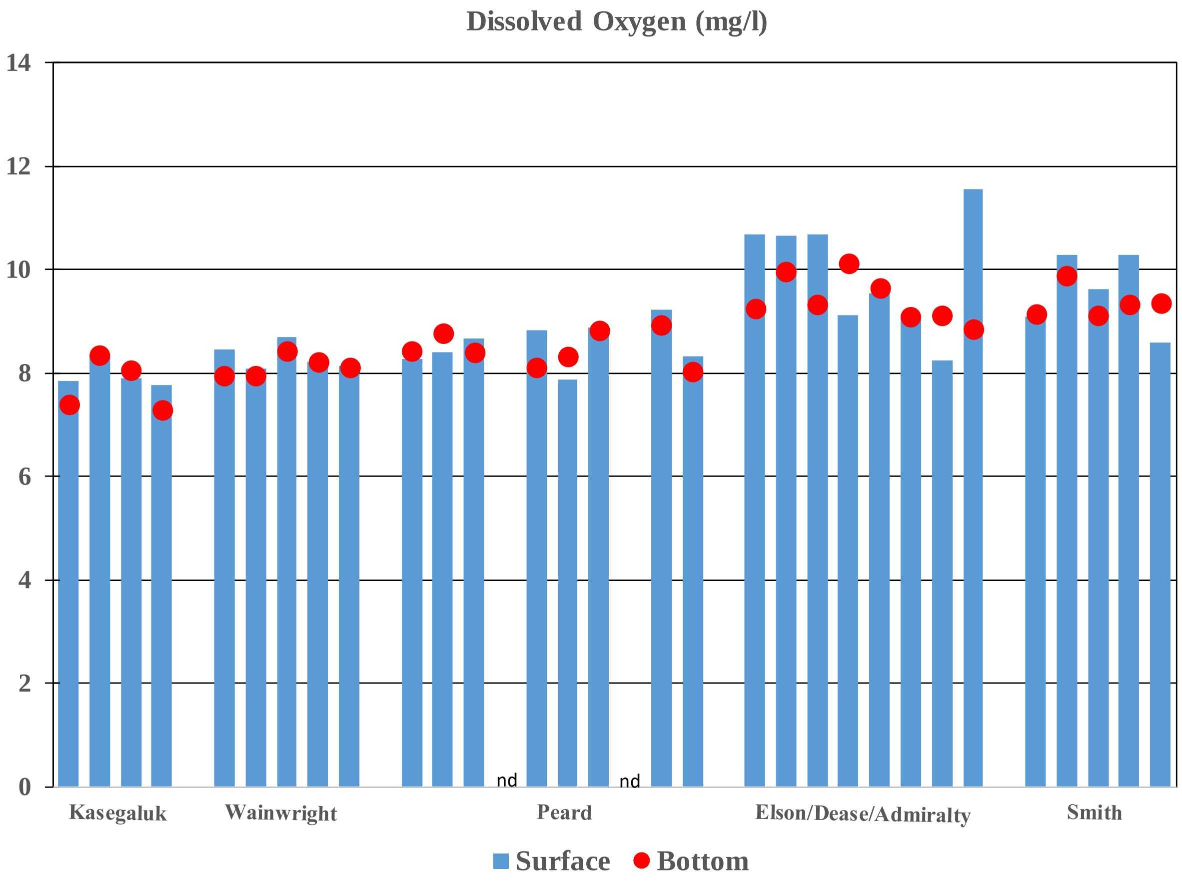

Figure 12. Surface and bottom water dissolved oxygen in estuaries and lagoons in the Chukchi and Beaufort Seas. (nd=no data)

3.2. Trace element and organic chemical concentrations

3.2.1 Metals and metalloids

There were no obvious spatial patterns in the distributions of the major and trace elements. Sediments that were primarily sand contained lower levels of all trace elements. Fine-grained sediment has a higher surface to volume ratio than sand. In addition, metals tend to bind to clays as a result of the charge characteristics of the clay particles. Thus, fine grained sediments tend to sequester higher concentrations of particle reactive elements through adsorption.

Concentrations of major and trace elements in sediment from the study area were generally low except for arsenic and nickel. Arsenic and nickel concentrations exceeded the ERL in

Table 6. Mean concentrations (ug/g dry) of elements in sediments from Arctic estuaries.

Element	Kasegaluk	Wainwright	Peard	Elson	Smith	ERL	ERM
Ag	0.063	0.078	0.094	0.111	0.106	1.00	3.70
Al	47200	72460	52980	51888	53540		
As	14.90	20.86	19.66	15.76	14.14	8.20	70.0
Ba	440.8	477.2	443.9	553.0	599.2		
Cd	0.081	0.128	0.106	0.124	0.143	1.20	9.60
Cr	50.7	74.3	59.2	63.7	65.6	81.0	370.0
Cu	27.8	29.9	22.9	31.9	30.8	34.0	270.0
Fe	28025	44160	31827	33213	33340		
Hg	0.041	0.078	0.048	0.055	0.055	0.15	0.71
Li	33.7	49.3	37.7	38.0	39.2		
Mn	236.8	536.2	205.0	364.8	397.4		
Ni	28.1	34.1	26.4	33.8	36.9	20.9	51.6
Pb	10.2	17.2	13.2	13.5	13.7	46.7	218.0
Sb	0.510	0.774	0.561	0.549	0.555		
Se	0.300	0.477	0.394	0.356	0.348		
Si	311250	261400	300900	305625	297000		
Sn	1.14	2.06	1.41	1.36	1.37		
Zn	83.1	117.0	80.4	93.2	95.2	150.0	410.0

virtually all locations (Table 6). The major constituents of sediments are Al and Fe, or Si, depending on the watershed geology and depositional environment (e.g. sand vs mud). Normally, there is a relationship between trace elements and the major elements (e.g. Al), either negative or positive. Plots of elements vs Al can be used to identify locations where outliers indicate anthropogenic pollution inputs or naturally occurring localities with unusual geologic inputs. The positive relationship between aluminum and iron is shown in Figure 13. This is a typical relationship. The negative relationship between aluminum and silicon is shown in Figure 14. Normal highly sandy sediments are primarily silica (depending on local geology) and show an inverse relationship between aluminum and silicon. A plot of aluminum and zinc is shown in Figure

15. This is typical of unimpacted sediments, e.g. there are no extreme outliers which would indicate anthropogenic inputs (pollutants). A plot of aluminum and arsenic is shown in Figure 16. This shows no outliers beyond the prediction limits but virtually all values are above the ERL. Nickel has even less variability with an R^2 = 0.7812. Arsenic and nickel appear to be ubiquitous and elevated throughout the region. Naidu *et al*. (2012) attributed elevated metals levels in a gradient from west to east in the Beaufort Sea to deposition of metals from Eurasia in Arctic haze. However, there is no consistent gradient from south to north or west to east in the current data set. Regional differences in arsenic concentrations have been observed in other Alaskan locations (Hartwell *et al.* 2009, 2016a, 2016b) (Figure 17). The only significant Spearman rank correlations with metals ERMq values were negative correlations with percent gravel and sand, and positive correlations with silt and clay (Table 7). This is consistent with the observation that elemental concentrations are elevated in finer sediments due to adsorption onto particle surfaces. The concentrations of metals measured in this study were comparable to previously published data by the U.S. Corps of Engineers Alaska District, (U.S. CEAD 2007), Naidu *et al.* 2012, and Trefry *et al.* (2003 , 2013) in coastal habitats in the Chukchi and Beaufort Seas. The offshore transect sites were not analyzed for trace metals.

However, ANOVA results contrasting Chukchi estuary sediments with Beaufort estuary sediments do show significantly higher concentrations of barium and silver on the Beaufort side ($p = 0.0008$ and 0.0214, respectively). The elevated barium may be residual from over 300 exploratory oil wells drilled primarily in the Harrison/Prudhoe Bay areas between 1970 and 2001. The concentrations in Table 6 are comparable to historical values from the Beaufort side presented by Naidu *et al.* (2012) .

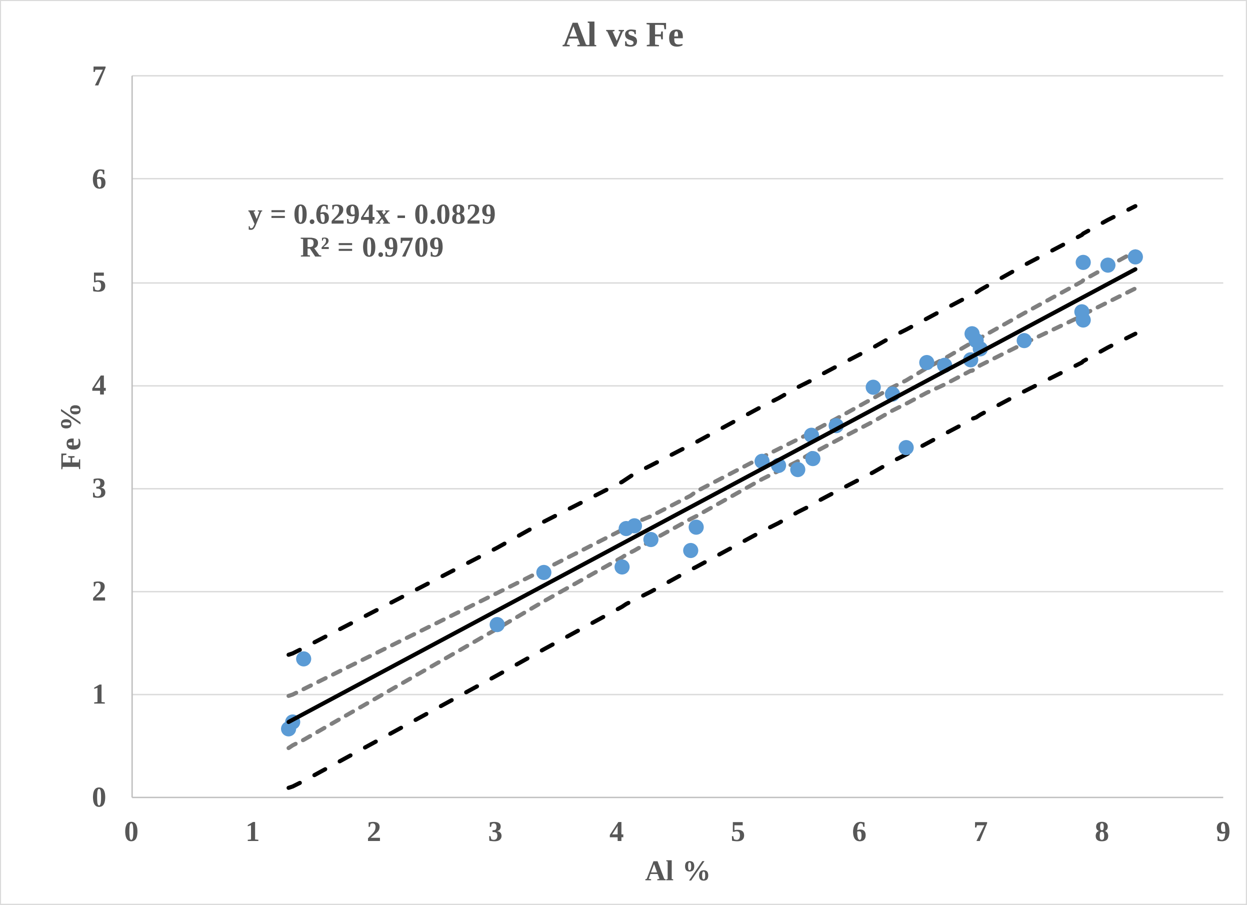

Figure 13. Relationship between sediment iron and aluminum in estuaries and lagoons in the Chukchi and Beaufort Seas, including sample confidence limits (light dashed lines) and 99% prediction limits (heavy dashed lines).

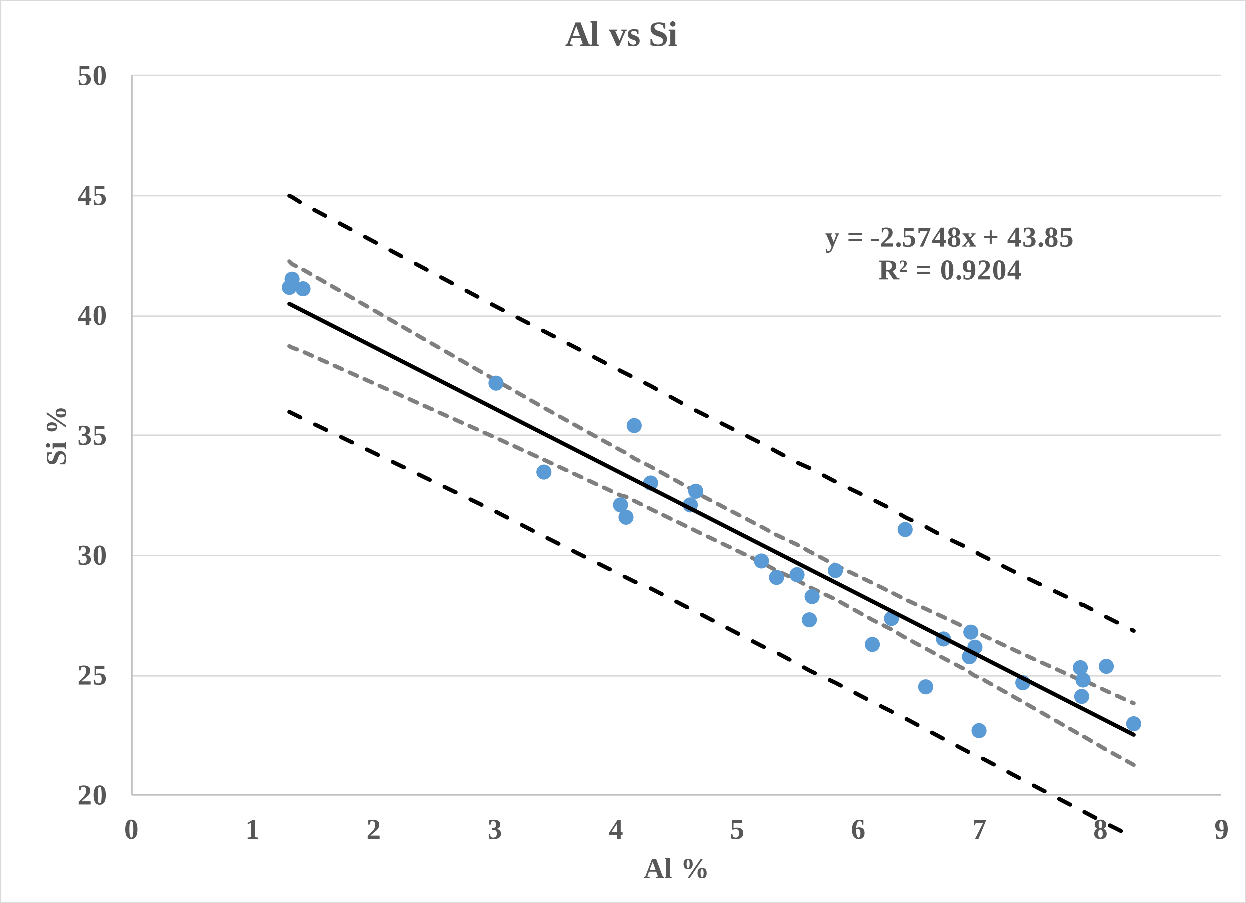

Figure 14. Relationship between sediment silicon and aluminum in estuaries and lagoons in the Chukchi and Beaufort Seas, including sample confidence limits (light dashed lines) and 99% prediction limits (heavy dashed lines).

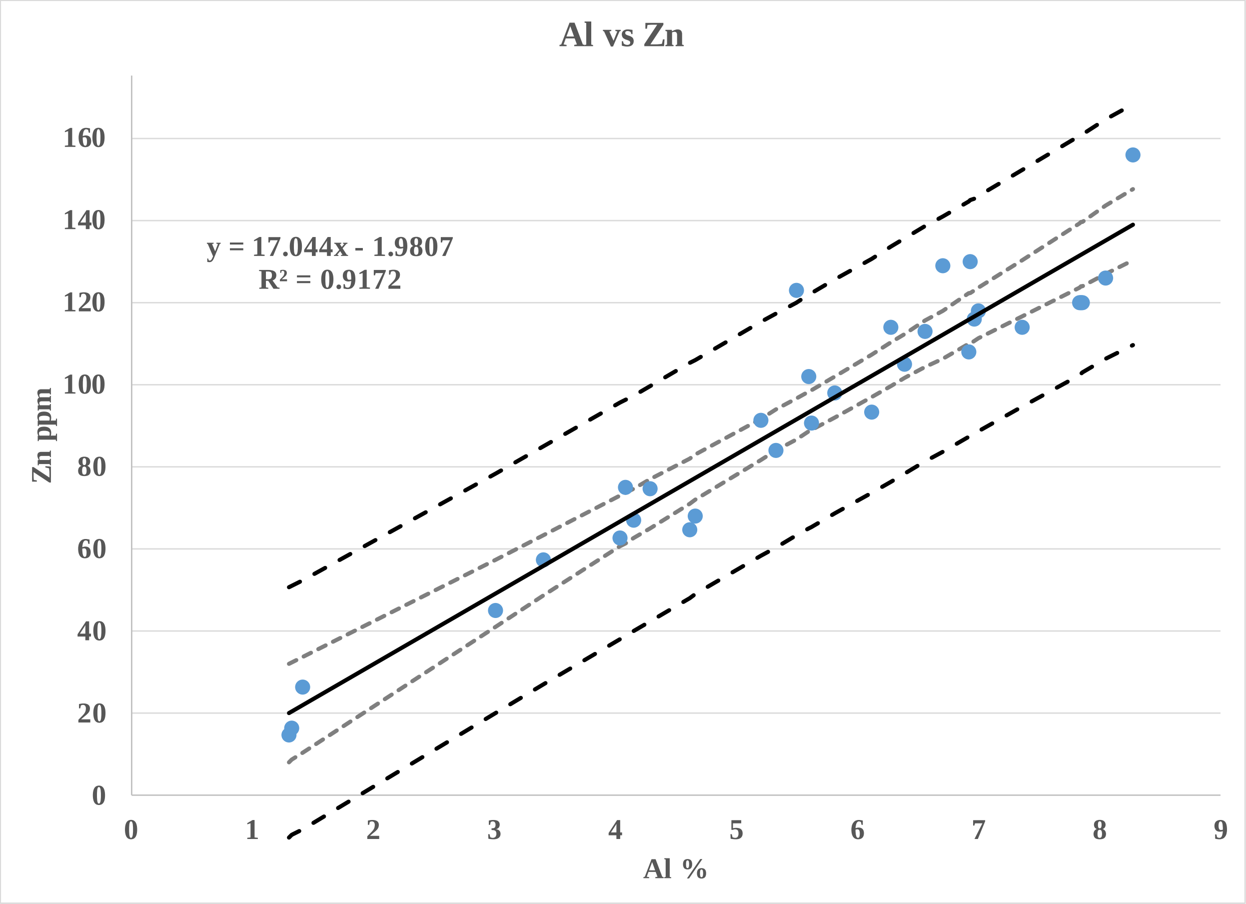

Figure 15. Relationship between sediment zinc and aluminum in estuaries and lagoons in the Chukchi and Beaufort Seas, including sample confidence limits (light dashed lines) and 99% prediction limits (heavy dashed lines).

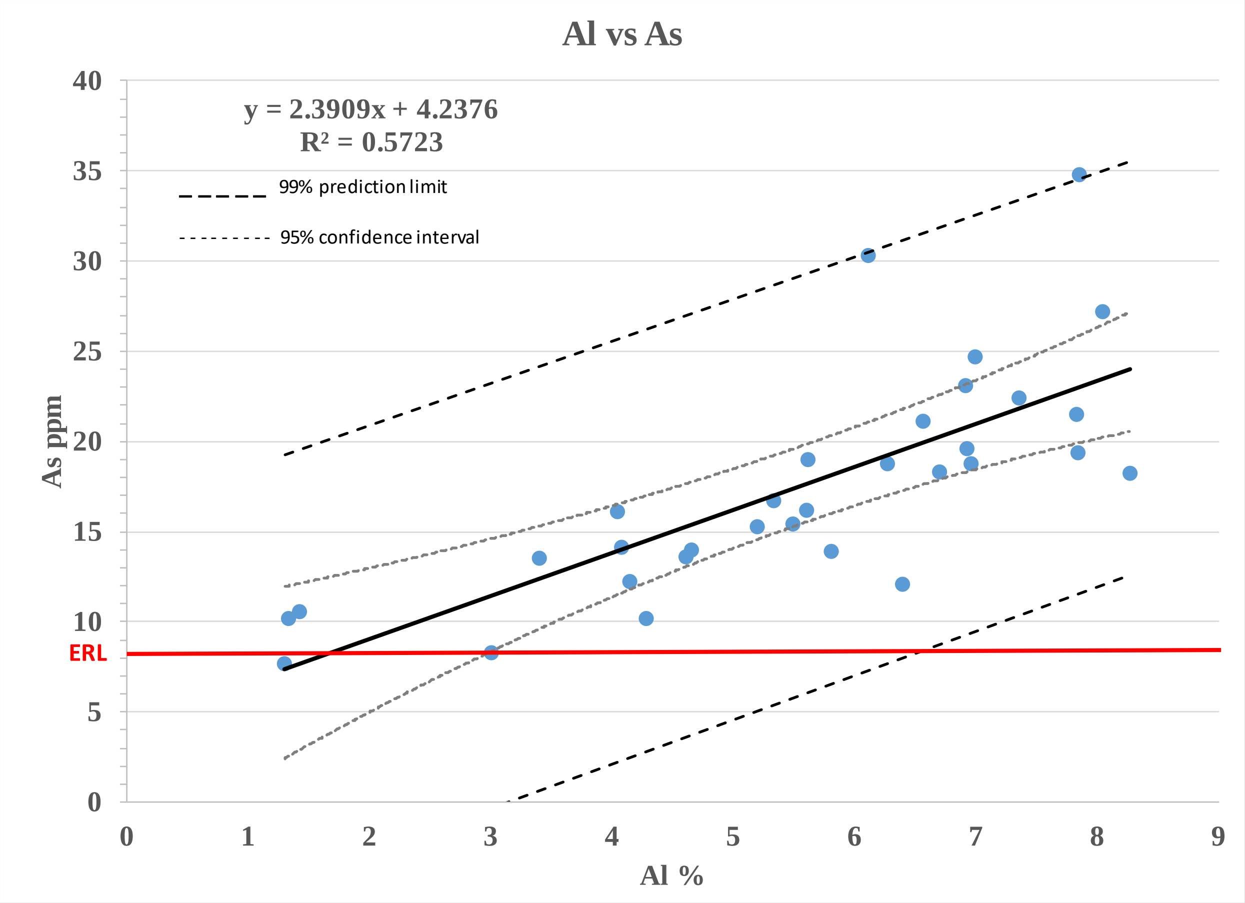

Figure 16. Relationship between sediment arsenic and aluminum in estuaries and lagoons in the Chukchi and Beaufort Seas, including sample confidence limits (light dashed lines) and 99% prediction limits (heavy dashed lines).

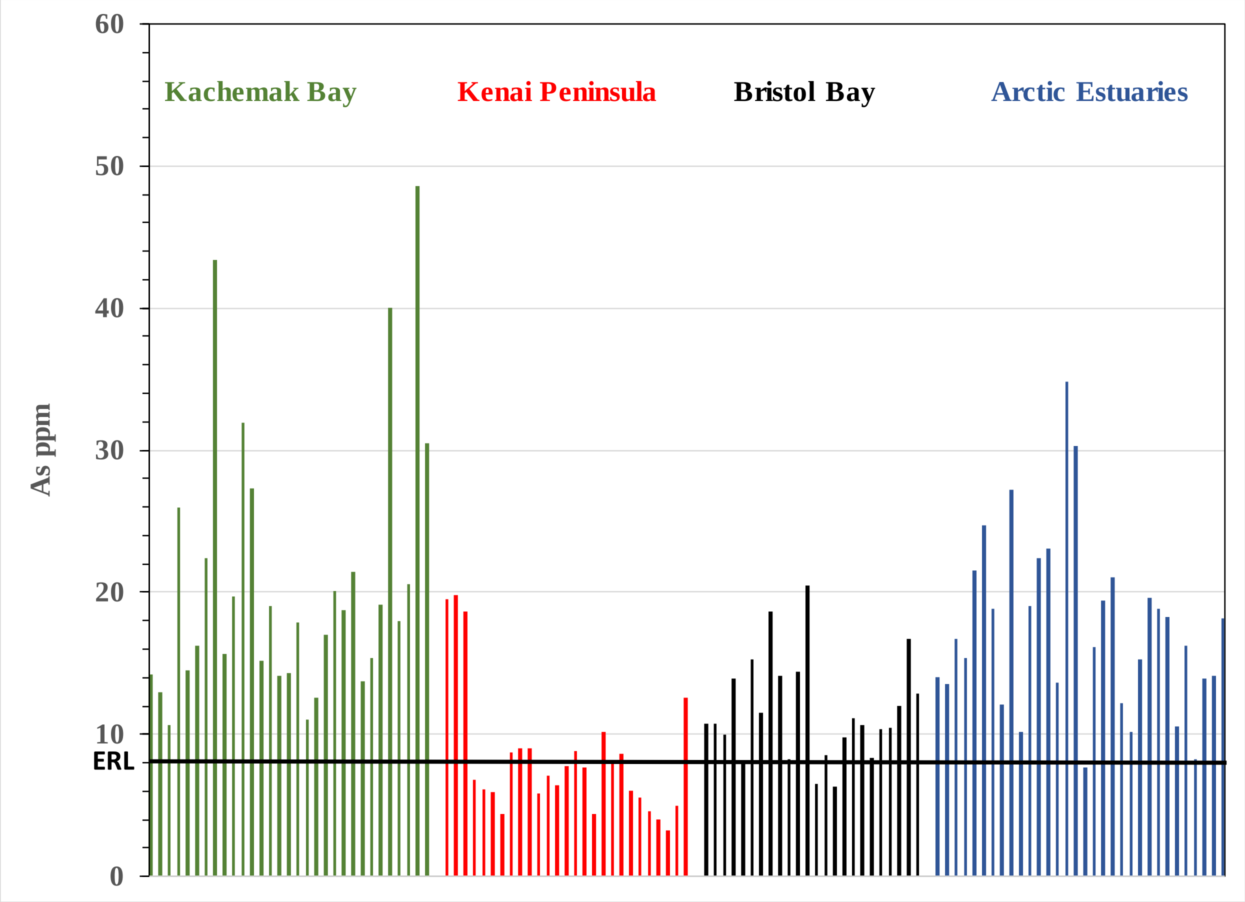

Figure 17. Arsenic concentrations in sediments from Alaska estuaries.

3.2.2 Organic contaminants

Pesticides and PCBs were not analyzed in sediments. Previous sampling in the Chukchi Sea coastal zone revealed few if any detections (Dasher *et al.* 2016)

Total PAH concentrations were highly variable between stations (Figure 18), with sandier sediments containing very low concentrations. The contribution of perylene, a natural by-product of decayed vegetation (NRC 1985) was relatively low, averaging only 6% of the totals. This is in contrast to other locations where perylene was a much larger proportion of total PAHs such as Kachemak Bay (44%), or Bristol Bay (29%). (Hartwell *et al.* 2009; 2016a). The Arctic tundra vegetation and watershed drainage characteristics are far different than further south.

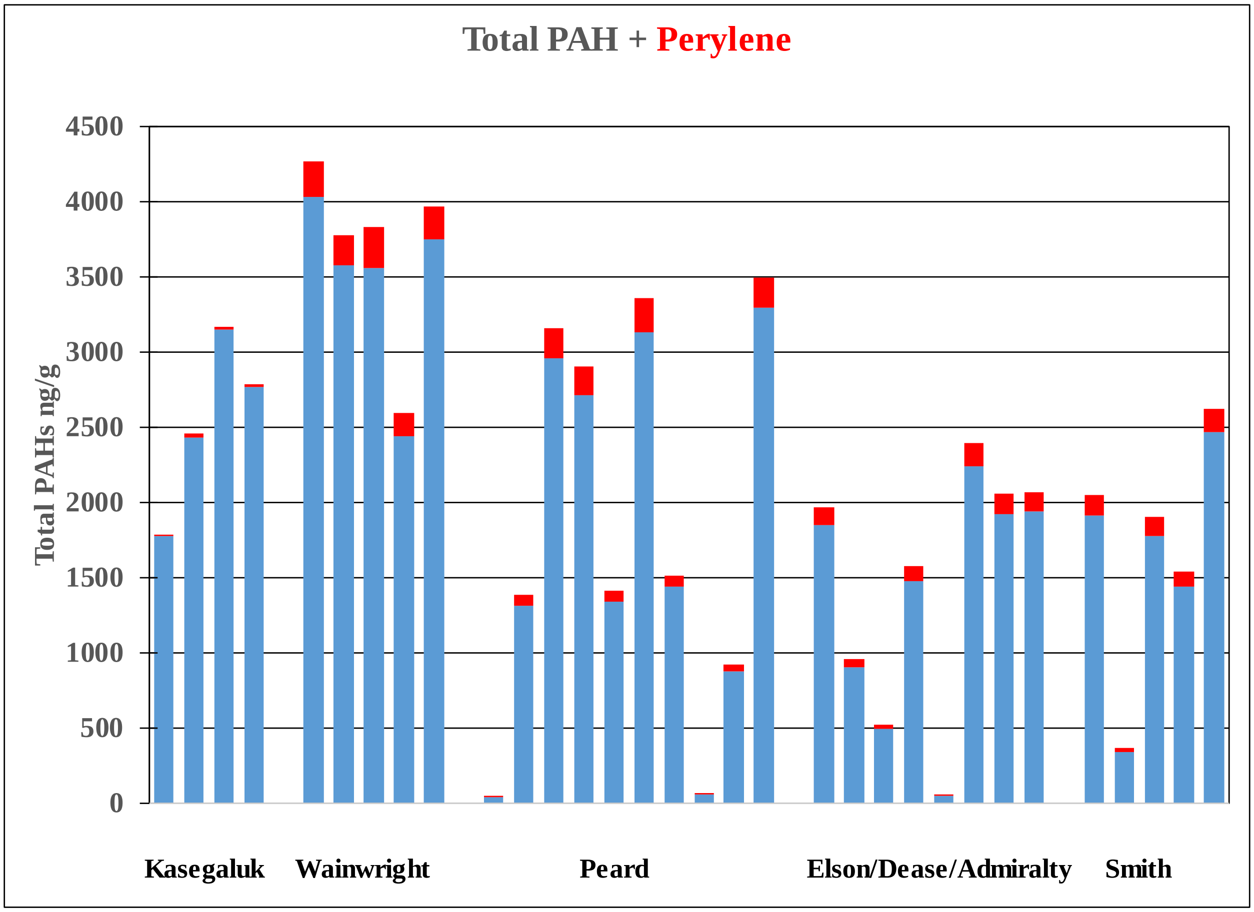

Figure 18. Total PAH concentrations with perylene (in red) in estuaries and lagoons in the Chukchi and Beaufort Seas.

Comparing the current PAH data to sediment concentrations throughout the rest of Alaska in the NS&T data base, the Arctic estuaries have relatively high concentrations of PAHs. Figure 19 shows the mean and range of PAH concentrations on all three Alaskan coasts, in harbors and open water. The Arctic estuary concentrations are higher than most locations. While the concentration of perylene is relatively low, terrestrial sources of organic carbon are an important input in Arctic lagoons (Dunton et al. 2006, 2012, Naidu et al. 2000). This is the result of abundant natural coal and peat deposits in the tundra. For example, Figure 20 shows the pattern of individual PAH concentrations in sediment from Wainwright Inlet and coal chips collected in the same vicinity in the Chukchi Sea.

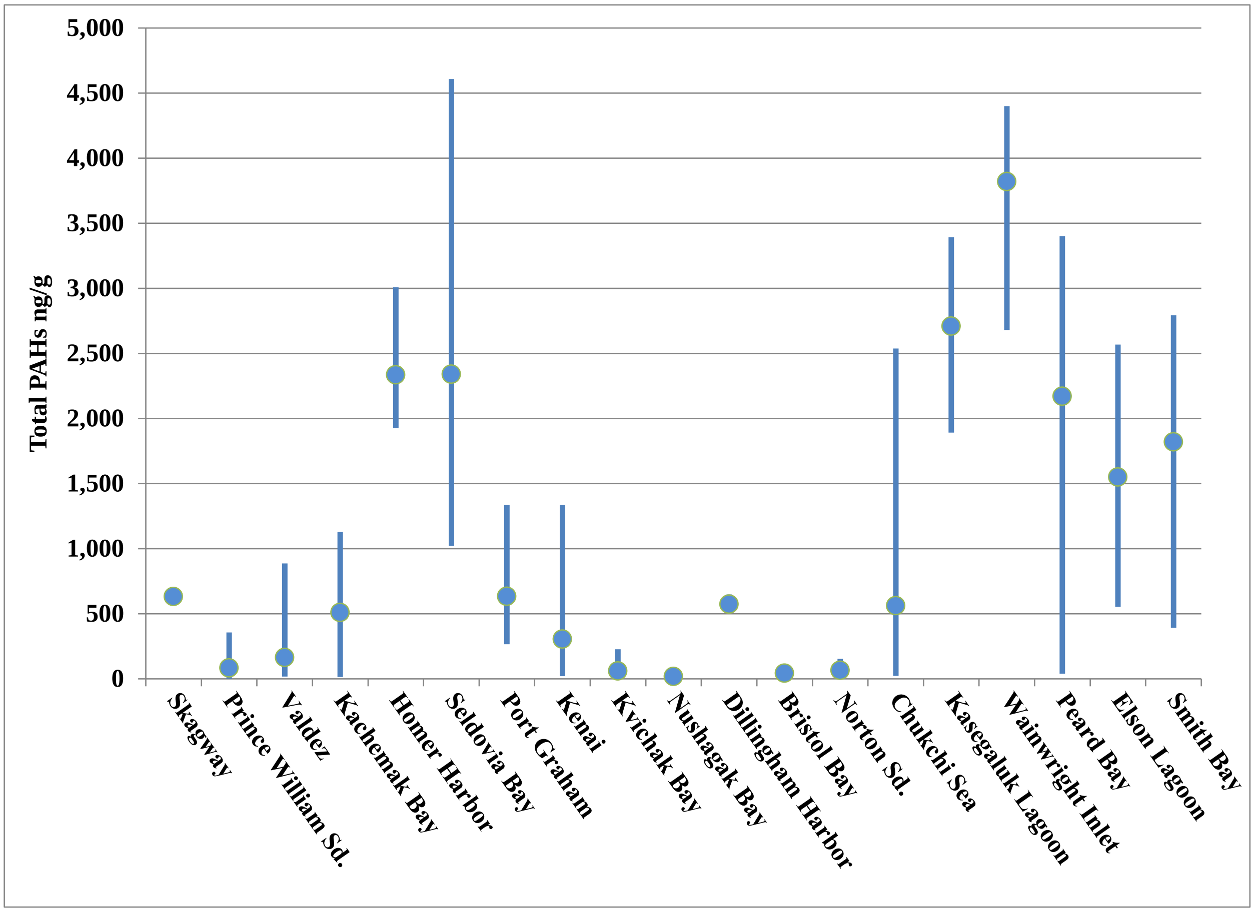

Figure 19. Mean, high, and low concentrations of PAHs from locations around Alaska. (Data from NS&T)

Figure 21 shows the pattern of individual PAH concentrations in sediment from Smith Bay and peat collected from there in the fish trawl. Spearman rank correlations between physical factors and chemical concentrations are shown in Table 7. As expected, most chemicals were significantly positively correlated with fine grained sediment and percent TOC and negatively correlated with coarse grained sediment. Depth did not appear to have an impact on these shallow estuaries.

Air samples collected during deck operations did not contain any PAHs above method detection limits.

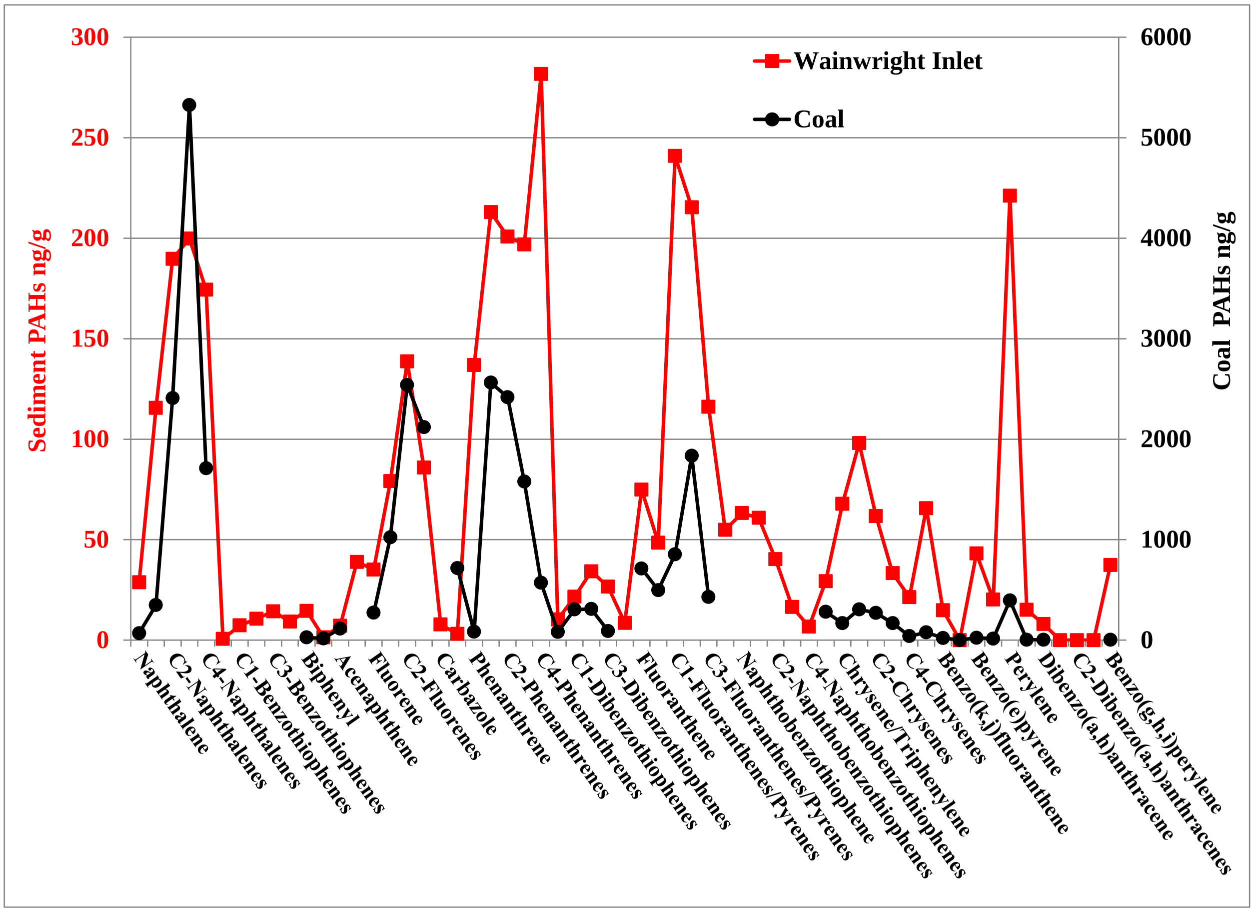

Figure 20. Individual PAH concentrations in sediment from Wainwright Inlet and coal chips in the Chukchi Sea. (For clarity, every other PAH compound is listed on the X axis.)

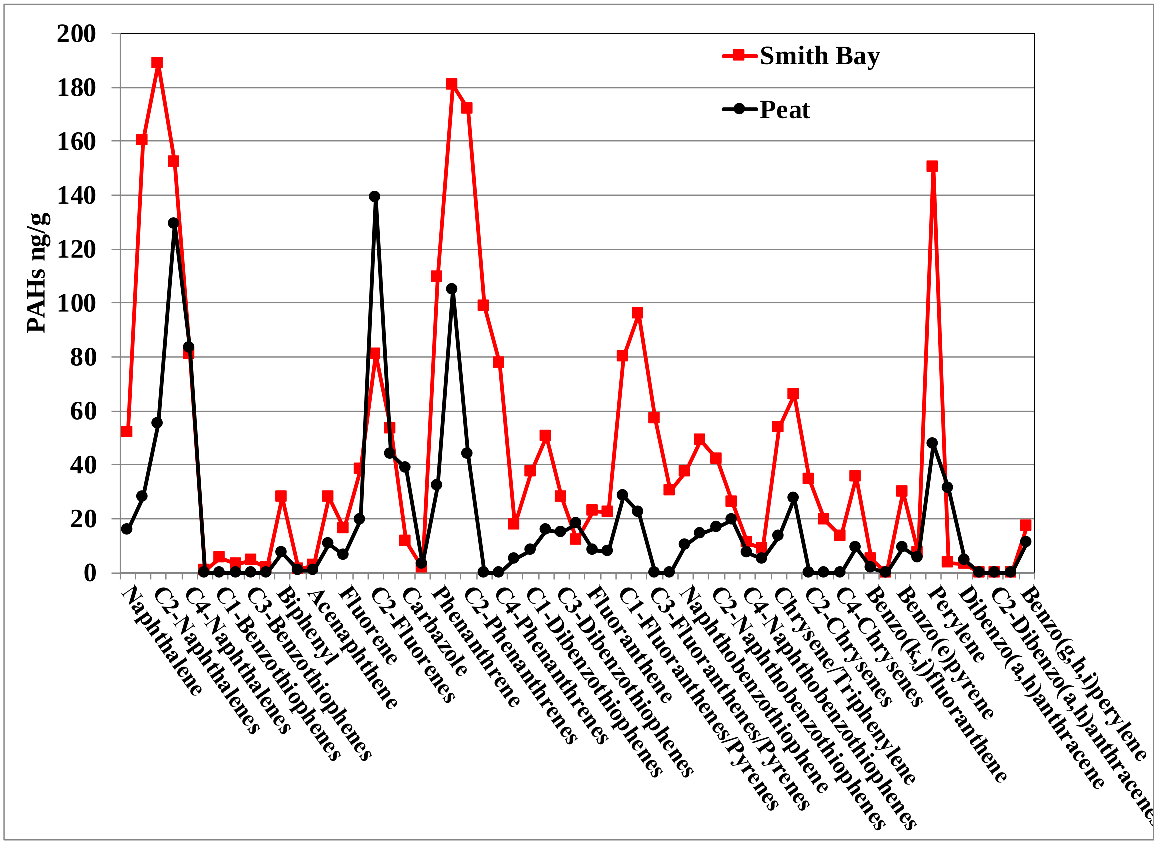

Figure 21. Individual PAH concentrations in sediment from Smith Bay and peat collected in the trawl. (For clarity, every other PAH compound is listed on the X axis.)

Table 7. Spearman Rank correlation coefficients (above) and probabilities (below) between chemical constituents and sediment characteristics.

Variable	**% TOC**	**% SAND**	**% SILT**	**% CLAY**	**Depth**
Total PAH	0.62246	-0.78094	0.75594	0.67249	-0.10994
	<.0001	<.0001	<.0001	<.0001	0.5052
Ave ERMq	0.62659	-0.62414	0.54221	0.77941	0.21901
	0.0001	0.0001	0.0013	<.0001	0.2285
% TOC		-0.66627	0.6442	0.61024	-0.17736
		<.0001	<.0001	<.0001	0.2801

Five of the seven offshore transect sites had sediments that were greater than 92% sand. Two had sediment that was half sand and half silt. The PAH content of the sandy sediments averaged 50.3 ppb, comparable to the sandy estuarine sites. The other two averaged 2,173.2 ppb, very close to the mean estuarine value (1,982 ppb). The sediment PAH profile shown in Figure 20 was mirrored in both the low and high samples indicating the predominant source of PAHs is terrestrial. However, there are known oil seeps along the shoreline and offshore in this region of the Chukchi and Beaufort Seas (Becker and Manen, 1988; K. Sherwood [BOEM], personal communication), but analytical data from these sources is not available.

Aliphatic and total petroleum hydrocarbon mean concentrations are shown in Table 8, along with selected descriptive ratios. Three of the offshore stations did not have aliphatic compounds above detection limits at all. All the estuarine locations had higher total petroleum hydrocarbon concentrations than the offshore locations, with the exception of the primarily sandy sites. The ratio of odd to even alkanes was greater than 1 in all cases. The carbon chains from biogenic sources tend to have more odd numbered alkanes. Long term degradation tends to increase the number of even numbered alkanes as the chains break down, and the ratio approaches 1. Degradation also produces increasingly higher proportions of lower weight alkanes. The ratio of low weight (n-C$\leq$20) to high weight (n-C$\geq$21) alkanes is also an indicator of biogenic vs petroleum sources. In all cases, this ratio is far less than 1. Both of these ratios indicate primarily biogenic sources predominate. The carbon preference index (CPI=2((C27 + C29)/(C26 + 2C28 +C30)) (Boehm *et al*. 1984) was greater than 3 in all cases, which is another indicator of biogenic sources. A ratio of pristane + phytane /n-C17 much greater than 1 indicates contamination by degraded oil (Gill and Robotham 1989). The calculated ratios are either below or very close to 1. Taken together, the aliphatic hydrocarbon data indicates pristine conditions at all locations. These results are consistent with the conclusions of Venkatesan *et al*. (2013) for nearshore sediments in the Beaufort Sea, including Elson Lagoon.

PAH concentration data was used to calculate double PAH ratios for source identification and composition. Oil biomarker concentration data was used to calculate ratios for exploratory hierarchical cluster analysis (HCA) and principle component analysis (PCA). All data treatments were performed to determine if there were other origins of PAHs besides terrestrial inputs in the sediment samples collected and to determine if there were differences within each site and among each site and sea region.

The PAH bar graph distributions for each sample were mostly petrogenic based on the concentration of parent PAHs compared to their alkyl homologs (i.e., parent PAHs were less than their alkyl homologs and each PAH family had a bell shaped curve) (Youngblood and Blumer, 1975; Short and Springman, 2007; Emsbo-Mattingly and Litman, 2018).

Double PAH ratio plots were adapted from Yunker et al. (2002), Wang et al. (2010), and Gallotta and Christensen (2018). Four PAH ratios commonly used for source identification and composition were calculated from the concentration data (Anthracene / (Anthracene + Phenanthrene; Fluoranthene / (Fluoranthene + Pyrene; Benz[a]anthracene / (Benz[a]anthracene + Chrysene/Triphenylene; Indeno[1,2,3-cd]pyrene / (Indeno[1,2,3-cd]pyrene + Benzo[g,h,i]perylene). The PAH ratios were plotted against each other within each sampling location and among the two sea regions (Figures 22a-c). The double ratio plots, for the most part, indicate mixed sources of petrogenic and pyrogenic origins within and among each sample stratum. There were differences between the combined Chukchi and Beaufort regions. Double PAH ratio plots show that there was more scatter in the samples collected from the Chukchi Sea estuaries compared to the Beaufort Sea sites where most samples were in a tight cluster. There were significant statistical differences (Student t-test, two tailed, d=0, α=0.05) between both seas for three of the four PAH ratios (i.e., FlA/(FlA+Pyr), BaA/(BaA+Chry), and IcdP/(IcdP+BghiP)). Overall, the double PAH ratio plots corroborate that terrestrial sources of PAHs are a major input into the lagoons. However, there are no PAH data from known oil seeps for comparison.

Exploratory HCA and PCA analysis of oil biomarker ratios also demonstrate widespread distribution of the triterpanes and hopanes, and steranes. Twelve triterpanes and hopanes ratios and twelve steranes ratios were calculated using concentration data. Tripteranes and hopanes ratios exhibited less variation than the steranes ratios among all the sample sites. This indicates a similar hopane assemblage throughout the region. There was much more variation in the steranes. Delineation between Chukchi and Beaufort Seas was not readily apparent in the exploratory HCA and PCA analyses.

Table 8. Alkane and petroleum hydrocarbon sediment concentrations (ug/g dry) in estuaries and lagoons in the Chukchi and Beaufort Seas.

	n	Total Carbon (mg/g dry)	%TOC	Total Aliphatic Hydrocarbons	Pristane	Phytane	Total Petroleum Hydrocarbon	Odd/Even	CPI	Low Wt/ High Wt	Prist. + Phyt./ n-C17
Kasegaluk Lagoon	**4**	2.09	1.49	24.47	0.18	0.08	123.95	3.60	6.94	0.18	0.80
Wainwright Inlet	**5**	3.45	3.01	24.35	0.21	0.14	201.48	3.97	7.36	0.14	1.11
Peard Bay	**10**	2.65	2.39	42.36	0.14	0.08	304.61	4.89	7.47	0.10	0.76
Elson Lagoon/Dease Inlet	**8**	2.79	2.32	33.57	0.13	0.07	267.39	4.02	8.23	0.11	0.79
Smith Bay	**5**	2.82	2.23	26.69	0.15	0.08	243.65	3.90	8.35	0.14	0.92
Offshore	**3**	0.78	0.49	2.73	0.05	0.02	38.78	3.32	5.20	0.28	1.21

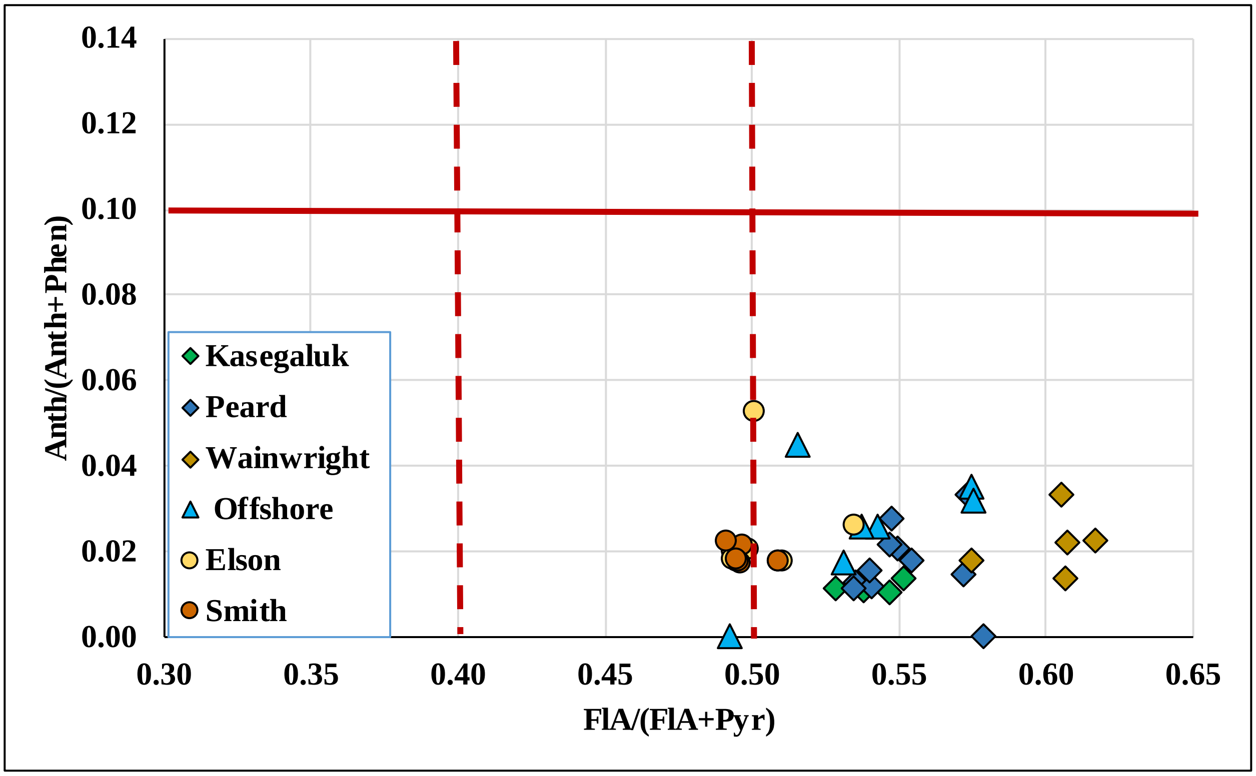

Figure 22a. Double PAH ratios for five Arctic estuaries and offshore sites in the Chukchi Sea.

FlA/(FlA+Pyr)	*>0.5*	*Grass, wood or coal combustion*
	0.5	*Petroleum/combustion transition point*
	<0.5	*Petroleum (most of the time); gasoline, diesel, fuel oil and crude oil combustion and emission*
	<0.4	*Crude oil*
Anth/(Anth+Phen)	*<0.10*	*Petrogenic*
	>0.10	*Pyrogenic*

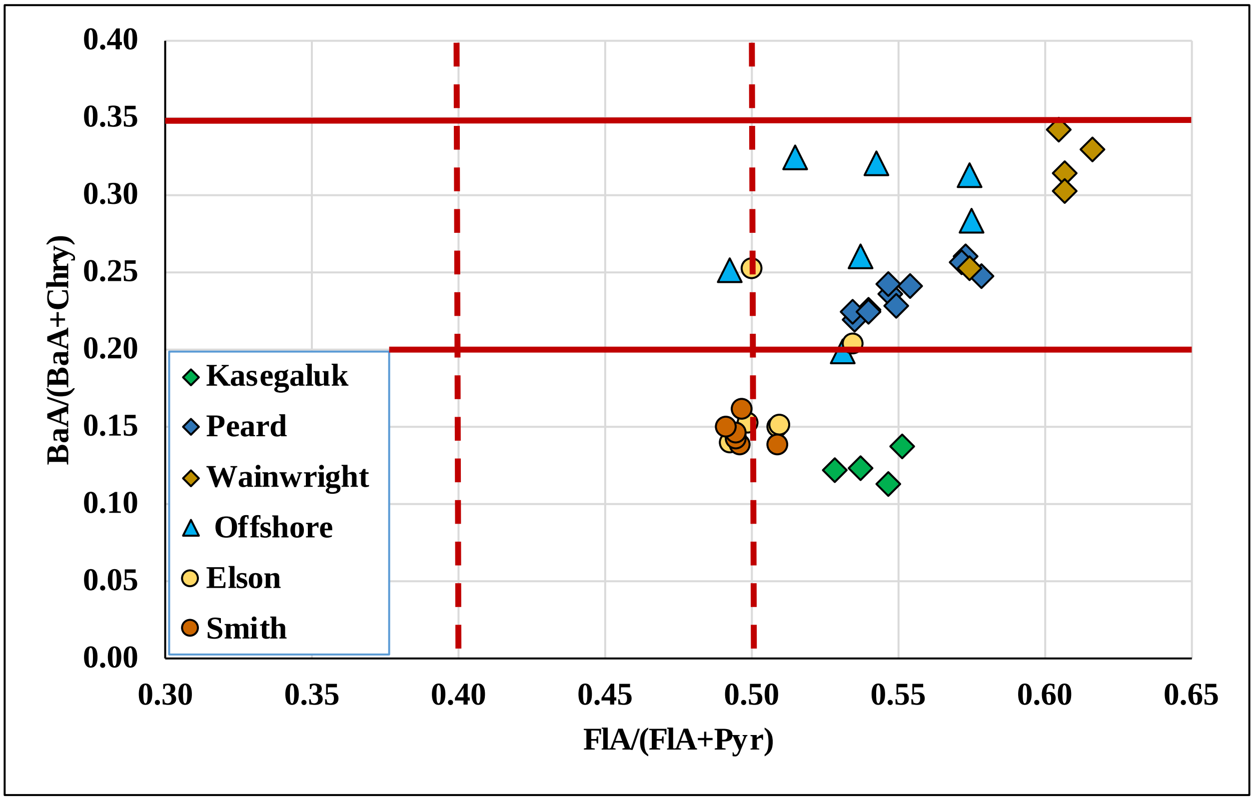

Figure 22b. Double PAH ratios for five Arctic estuaries and offshore sites in the Chukchi Sea.

FlA/(FlA+Pyr)	*>0.5*	*Grass, wood or coal combustion*
	0.5	*Petroleum/combustion transition point*
	<0.5	*Petroleum (most of the time); gasoline, diesel, fuel oil and crude oil combustion and emission*
	<0.4	*Crude oil*

BaA/(BaA+Chry)	*>0.35*	*Combustion*
	0.20 - 0.35	*Either petrogenic or combustion*
	<0.2	*Petroleum*

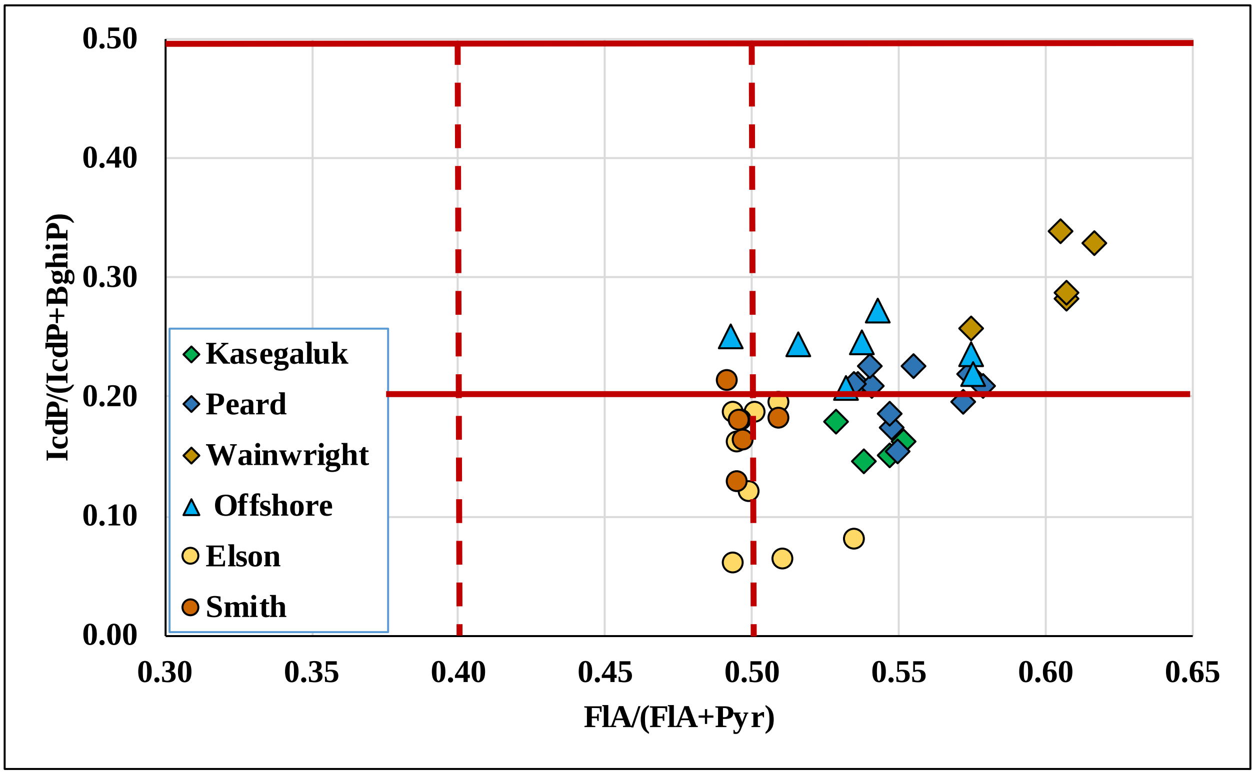

Figure 22c. Double PAH ratios for five Arctic estuaries and offshore sites in the Chukchi Sea.

FlA/(FlA+Pyr)	*>0.5*	*Grass, wood or coal combustion*
	0.5	*Petroleum/combustion transition point*
	<0.5	*Petroleum (most of the time); gasoline, diesel, fuel oil and crude oil combustion and emission*
	<0.4	*Crude oil*
IcdP/(IcdP+BghiP)	*>0.50*	*Grass, wood and coal combustion*
	0.20 - 0.50	*Liquid fossil fuel combustion (vehicle and crude oil)*
	<0.20	*Petroleum*

3.2.3 Stable isotopes

The δ values for stable isotopes of carbon (^{13}C) and nitrogen (^{15}N) in sediment are shown in Table 9 and graphed as a bi-plot in Figure 23. With the exception of Peard Bay, all the estuaries reflected the strong influence of terrestrial plant input with very low $\delta_{o/oo}$ values for carbon and nitrogen. Peard Bay has a very limited watershed and is strongly influenced by tidal exchange with marine waters. Input from marine phytoplankton would contribute higher $\delta_{o/oo}$ ^{13}C values. Ice algae is likely not a contributing factor as land-fast ice precludes the establishment of epontic algae (Craig *et al*. 1984). The offshore transect points also reflect the more typically marine values although the $\delta_{o/oo}$ values for carbon are slightly more depleted than characteristic marine particulate organic matter (Fry 2006), which may reflect sedimentary processes. They also bracket data collected in 2011 from the coastal Chukchi Sea in a related sampling project (Dasher *et al*. 2016). The other estuaries from both the Chukchi side and the Beaufort side exhibited similar values. This range of values for sediment has been reported in nearshore sediments in the Beaufort Sea (Dunton *et al.* 2006). Elson Lagoon and Smith Bay values were on average lower than the Chukchi estuaries, but the difference was slight. Schell *et al*. (1984) concluded the contribution by ice algae on the Alaskan Beaufort Sea shelf is an order of magnitude less than that recorded in the Chukchi Sea. Dunton *et al.* (2006) also observed a west to east decreasing gradient in ^{13}C content in organisms in the Beaufort Sea.

3.3 Tissue Body Burdens

Trawl collections yielded very few fish. None were captured in Kasegaluk Lagoon, Wainwright Inlet or Elson Lagoon. NMFS however provided fish subsamples from Elson Lagoon. Fish were not numerous, and those that were caught were small. Samples were composited by site and species. Thus, the sample size is very small but some observations can be made. All species collected were predators, feeding on either benthos or zooplankton and thus at the secondary consumer level in the food web. However, they were all young fish and have would not be expected to have acquired high levels of bioaccumulative substances.

Table 9. δ values for stable isotopes of carbon (^{13}C) and nitrogen (^{15}N) in the Chukchi and Beaufort Seas.

Stratum	**δ ^{13}C**	**δ ^{15}N**
Kasegaluk Lagoon	-26.05	1.67
Kasegaluk Lagoon	-25.59	2.87
Kasegaluk Lagoon	-26.27	2.39
Kasegaluk Lagoon	-26.35	2.58
Wainwright Inlet	-25.44	3.40
Wainwright Inlet	-25.23	4.13
Wainwright Inlet	-25.86	2.37
Wainwright Inlet	-26.46	0.84
Wainwright Inlet	-25.38	2.62
Peard Bay	-20.95	8.95
Peard Bay	-25.88	4.43
Peard Bay	-24.74	5.31
Peard Bay	-24.83	4.30
Peard Bay	-24.82	4.57
Peard Bay	-24.57	4.84
Peard Bay	-25.56	4.59
Peard Bay	-21.95	8.22
Peard Bay	-25.54	3.48
Peard Bay	-24.17	4.99
Elson Lagoon	-26.80	1.72
Elson Lagoon	-26.79	1.88
Elson Lagoon	-27.50	1.39
Elson Lagoon	-26.12	1.91
Elson Lagoon	-25.95	2.66
Elson Lagoon	-26.37	1.90
Elson Lagoon	-25.90	2.78
Elson Lagoon	-26.56	2.49
Smith Bay	-26.59	1.08
Smith Bay	-26.93	0.33
Smith Bay	-26.52	1.60
Smith Bay	-26.48	1.56
Smith Bay	-26.33	1.94
Offshore	-24.17	7.95
Offshore	-24.69	7.91
Offshore	-24.09	9.27
Offshore	-25.66	3.85
Offshore	-26.18	3.86
Offshore	-25.65	4.35

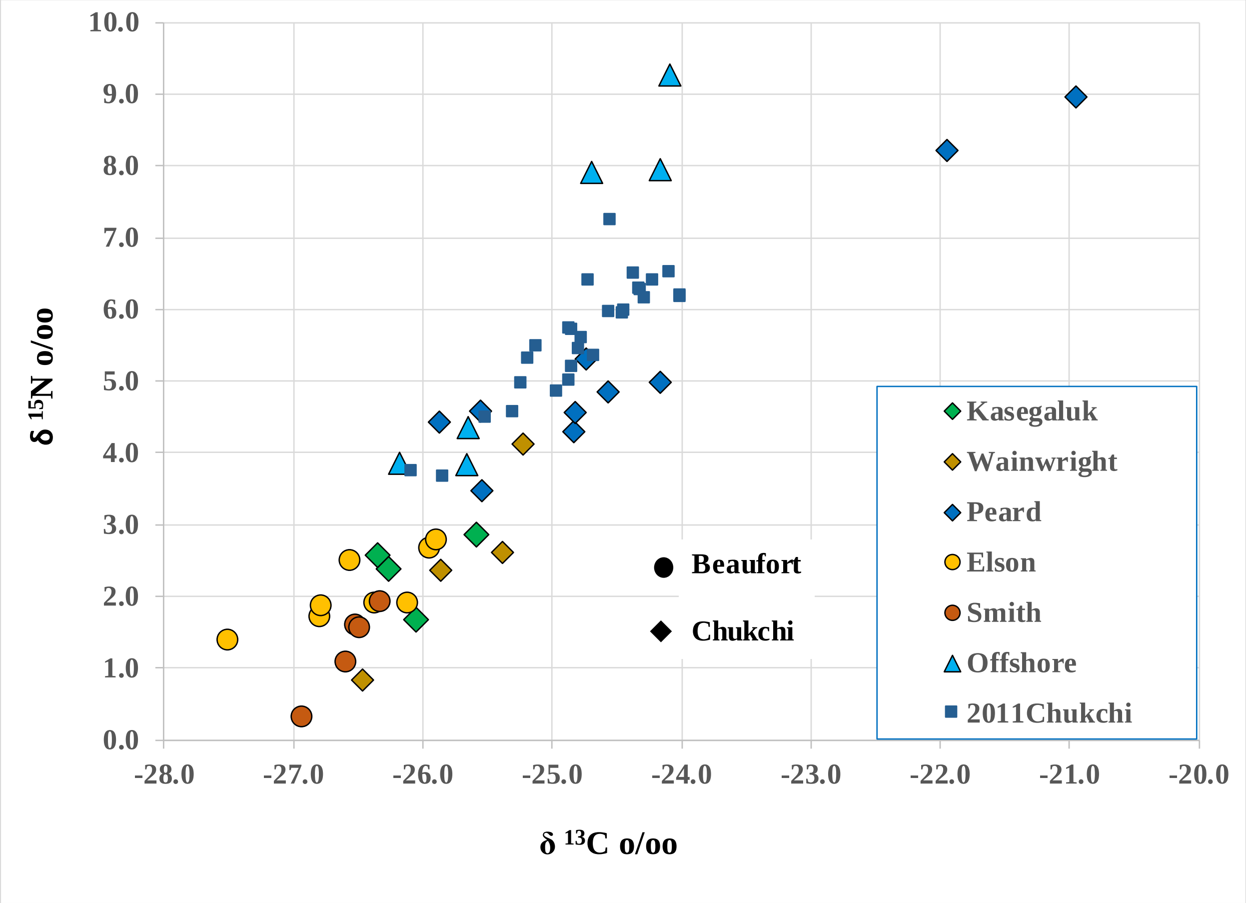

Figure 23. Biplot of $\delta_{o/oo}$ for isotopes of carbon (^{13}C) and nitrogen (^{15}N) in estuaries and lagoons in the Chukchi and Beaufort Seas. Also plotted are the Wainwright offshore transect and isotope data from the coastal Chukchi Sea collected in 2011 (Dasher *et al.* 2016).

Tissue concentrations of PCBs were relatively low and did not demonstrate any pattern (Table 10). Some fish contained low chlorinated congeners, while others had higher level congeners, but there was no consistent spatial or species pattern. The concentrations were lower than seen in starry flounder (*Platichtys stellatus*) from Naknek and Dillingham (mean 22.7 ng/g) but higher than levels seen in fish from open water in Nushagak and Kvichak Bays (4.8 ng/g) (Hartwell *et al.*, 2016a). Most of the chlorinated pesticides listed in Table 4 were below detection limits. The exceptions are listed in Table 10. No samples had detectable DDT or its metabolites. Conversely, all samples had detectable hexachlorobenzene. Hexachlorobenzene is banned for use as a pesticide, but is still released in small quantities from other chemical manufacturing, industrial processes, incineration and residuals from when it was used. It is highly persistent in the environment and highly bioaccumulative in lipids and biomagnifies in the food chain. It is distributed around the globe by a process termed ‘global distillation’ (Wania and Mackay 1995) whereby it circulates from warm areas and collects in colder areas, such as the poles, where it has never been used. Cyclodienes (chlordane and related compounds) and HCH (hexachlorohexanes) were seen at low levels in some fish but not all samples. These compounds are also subject to global distillation. Butyltins were below detection in all fish. Buyltins were below detection in all fish.

Metals concentrations in the fish did not exhibit any pattern (Table 11). There were individual spikes for mercury, copper, lead and chromium, but there was no spatial or species-specific pattern. Arsenic was elevated reflecting the elevated concentrations in sediment. Whole body concentrations of As were higher relative to average values in the Alaska Fish Monitoring Program, but nickel was not. Arsenic will accumulate in organisms (UK Marine SACS, 2001), but neither tend to biomagnify up the food chain (UK Marine SACS, 2001; WHO, 1991). The values seen in the Arctic estuaries are comparable to average tissue levels seen in Bristol Bay starry flounder (*P. stellatus*) and rainbow smelt (*Osmerus mordax*) from Nushagak and Kvichak Bays (6.68 and 3.35 ug/g, respectively) (Hartwell *et al*, 2016a). Whole-body arsenic body burdens in fish from Chrome Bay on the Kenai Peninsula averaged 1.33 ug/g (Hartwell *et al*. 2016b). Although not strictly comparable, liver and muscle tissue in salmon returning to Kachemak Bay contained and average of 1.14 ug/g arsenic (Apeti *et al.* 2013). These were fish returning from years in the open north Pacific ocean. The US EPA does not have consumption thresholds for arsenic or nickel.

Table 10. Organic contaminants detected in Arctic estuary fish. (ng/g dry)

*below method reporting limit

Species	**Slender eelblenny** ***Lumpenus fabricii***	**Arctic flounder** ***Pleuronectidae glacialis***	**Fourhorn sculpin** ***Myoxocephalus quadricornis***	**Arctic cod** ***Boreogadus saida***	**Fourhorn sculpin** ***Myoxocephalus quadricornis***	**Arctic cod** ***Boreogadus saida***	**Arctic sculpin** ***Myoxocephalus scorpioides***
Location	**Peard**	**Peard**	**Elson**	**Elson**	**Elson**	**Smith**	**Smith**
#	30	1	2	4	4	3	6
wt (gm)	11.3	50.7	27	51.7	155.3	26.2	11
% Lipid (dry)	6.57	13.55	6.79	18.22	9.95	27.08	11.08
Total PCBs	3.23	0	16.03	14.38	1.06	14.18	0
Cyclodienes	0	0	0	1.11	0.97	3.88	0
Total HCH	0	1.46	1.53	0	0	1.62	1.83
Hexachlorobenzene	0.89*	1.56	1.14	8.44	1.66	5.62	1.43

3.4 Benthic Community Characterization

A total of 18,246 organisms, representing 114 taxa were enumerated in the estuarine samples, excluding epiphytic species (hydroids, barnacles etc.). Following elimination of the ‘artificial’ species (see methods), there were 78 taxa and 18,143 organisms. Of these, 17 were rare or unique taxa: occurring in only one or two stations. Thus, the final assemblage was comprised of 61 taxa and 18,077 animals distributed over 21 sampling stations.

The most numerous taxa were polychaetes, ostracods, oligochaetes, and nematodes. However, the distribution of the latter three was very spotty. They were numerically dominant at only a few stations where there were 1,000 or more individuals, but present at much lower numbers elsewhere. The dominant taxa in terms of diversity were polychaetes and arthropod malacostracans, together comprising 47 taxa. Echinoderms (starfish, sea urchins etc.) were completely absent.

The offshore transect stations had 59 taxa, comprised of 1,969 individuals excluding epiphytic and artificial taxa. Not surprisingly, the offshore stations had a distinctly different species assemblage than the estuarine stations. Thirty eight taxa were found only in offshore stations. Twenty were found in both offshore and estuarine habitats, but of them, nine were rare or unique taxa in the estuaries (found only at 1 or 2 stations). Unlike the estuarine stations, the most numerous taxa were bivalves, foraminifera, and arthropod malacostracans. However, one species of bivalve (*Rochefortia tumida*, aka *Kurtiella tumida*) accounted for 98% of all bivalve individuals. There were 21 malacostracan taxa, 22 polychaetes and 12 bivalves. Ostracods, oligochaetes, and nematodes only accounted for 93 animals, or 4.7 % of the total. Again, echinoderms were completely absent.

The nodal analysis was run with the estuarine data and with both estuarine and the offshore data together. The offshore stations were completely separate from the estuarine stations. The estuarine stations sorted into the same set of groups with or without the offshore set in the matrix (Figure 24). Based on species composition each estuary was distinct with three exceptions.

Station 82 in Admiralty Bay is unique. It has low salinity, TOC, abundance and number of taxa. Unlike the rest of Elson Lagoon/Dease Inlet, it is all sand. The only taxon with any significant abundance was Oligochaetes. Station 5 and its duplicate in Peard Bay are also unique. It was also located by the shore and shallow, all sand unlike the rest of Peard Bay, with low TOC, abundance and number of taxa. Kugrua Bay, (three stations in the right half of the Peard Bay cluster), while part of the Peard Bay stratum, lacks a subset of species found in the deeper bay. Station 67 in Elson Lagoon lies in the Smith Bay cluster (denoted with * in Figure 24).

It is the only station in Elson that is not behind barrier islands (Figure 4). It is mostly sand, unlike the rest of Elson Lagoon stations. Like Smith Bay, it is open to the influence of the Beaufort Sea.

As a group, Elson Lagoon stations have the greatest number of species by far, followed by Peard Bay. There is a group of 16 species found in Smith Bay and Elson Lagoon that are virtually absent from the Chukchi estuaries. Peard Bay sites (including #5) have a group of 9 species that are virtually absent from the other estuaries, plus a group of 7 taxa found in sandier locations, that are rarely found elsewhere.

Table 11. Whole body concentrations of trace elements detected in Arctic estuary fish. (ug/g dry). Selected DEC Alaska Fish Monitoring Program average concentrations (adjusted to dry weight, 75% increase) are included.

Species		**Ag**	**As**	**Ba**	**Cd**	**Cr**	**Cu**	**Hg**	**Li**	**Mn**	**Ni**	**Pb**	**Se**	**Sn**	**Zn**
Slender eelblenny	Peard	0.08	6.13	5.48	0.22	1.69	4.71	0.058	1.07	22.1	1.47	0.46	2.32	0.09	124.0
Arctic flounder	Peard	0.06	11.50	1.57	0.16	0.52	2.94	0.114	0.37	13.1	0.93	0.10	3.08	0.04	94.3
Shorthorn sculpin	Peard	0.07	4.57	7.64	0.41	13.40	6.04	0.049	1.42	29.8	2.55	0.73	2.01	0.04	107.0
Arctic cod	Elson	0.02	2.55	13.90	0.59	0.54	2.39	0.038	0.79	14.4	0.60	0.60	2.27	0.04	122.0
Fourhorn sculpin	Elson	0.13	5.05	7.47	0.12	1.20	14.10	0.084	0.91	20.9	1.44	0.27	3.81	0.09	71.5
Arctic cod	Elson	0.07	10.70	7.93	0.26	1.48	5.00	0.030	1.18	18.9	1.62	0.43	3.45	0.21	81.3
Fourhorn sculpin	Elson	0.13	6.02	10.30	0.23	1.03	101.00	0.258	1.01	18.2	7.58	3.12	2.79	0.27	132.0
Slender eelblenny	Elson	0.12	4.98	4.33	0.37	1.07	7.81	1.190	0.64	15.2	1.01	0.37	3.27	0.08	65.7
Arctic cod	Smith	0.07	8.74	3.52	0.47	0.51	7.64	0.069	0.42	11.6	0.97	0.12	3.28	0.00	82.0
Arctic sculpin	Smith	0.09	4.30	8.44	0.15	2.86	8.41	0.049	1.02	29.0	1.53	0.52	2.98	0.08	82.8
DEC AFMP															
Arctic flounder			6.40		0.00	1.24	2.23	0.080			1.75	0.00			
Fourhorn sculpin			3.64		0.00	4.80	3.90	0.204			2.84	0.00			
Arctic sculpin			3.40		0.07	1.20	4.00	0.092			2.56	0.00			

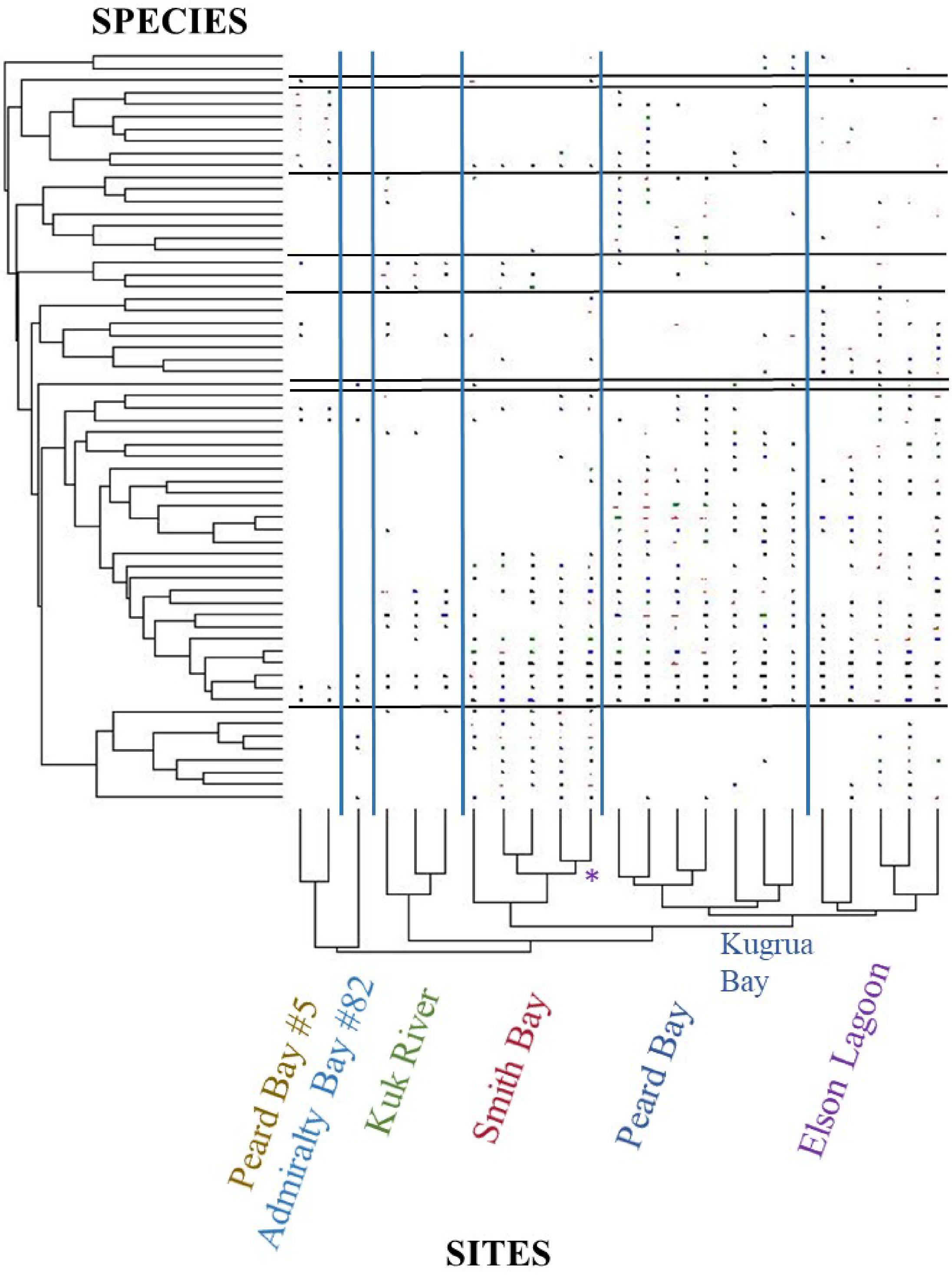

Figure 24. Nodal plot of site vs. species clusters showing the distribution of species among sites. Dots indicate that a species on the Y axis was present at the corresponding site on the X axis.

The MDS analysis is consistent with the nodal analysis interpretation. Figure 25 illustrates the MDS ordination plot for all estuarine sites and includes physical habitat variables. The four estuaries each sort out into separate groups, the relationships between the fauna and physical variables are obvious. Elson Lagoon and Smith Bay are more alike than they are to Peard Bay and Wainwright Inlet (Kuk R.). They are slightly colder and thus have slightly higher bottom dissolved oxygen concentrations. Stations 5 (Peard) and 82 (Elson) are outliers in this analysis also, probably because they were all coarse sand and almost on shore.

One concern in evaluating changes in benthic macroinvertebrate populations is in the sieve size used to screen the animals out of the sediments. The NCCA program through 2010 had used a 1.0 mm sieve screen size on the US West Coast and Alaska surveys. Since 2010 the NCCA sieve mesh size has been reduced to 0.5 mm. As any change is sieve mesh size would impact future NCCA sampling and analysis and break a long-term trend line based on 1.0 mm sieve mesh it was important to evaluate the relevance of sieve size mesh in this survey. Multiple authors have shown the influence of using different sieve mesh sizes in benthic parameters (Barba *et al*. 2010; Couto *et al*. 2010; Hammerstrom *et al*. 2010; Hartwell and Fukuyama 2015; Thompson *et al*. 2003). In all these cases the 1.0 mm screen missed a substantial number of taxa and individuals. Authors do not universally agree on the magnitude of the impact of differences in sieving efficiency depending on whether analyses are based on such parameters as abundance, or biomass, or diversity etc., and the statistical approach. Some of the reasons for the use of different sieve sizes are due to: 1) costs of processing samples and identifying organism to the lowest possible taxonomic level 2) the question that each study is addressing, and 3) historical use of sieve size to allow comparisons of data between areas. EMAP studies on the east and Gulf coasts, and all of the nation-wide NOAA NS&T Bioeffects studies use a 0.5 mm sieve.

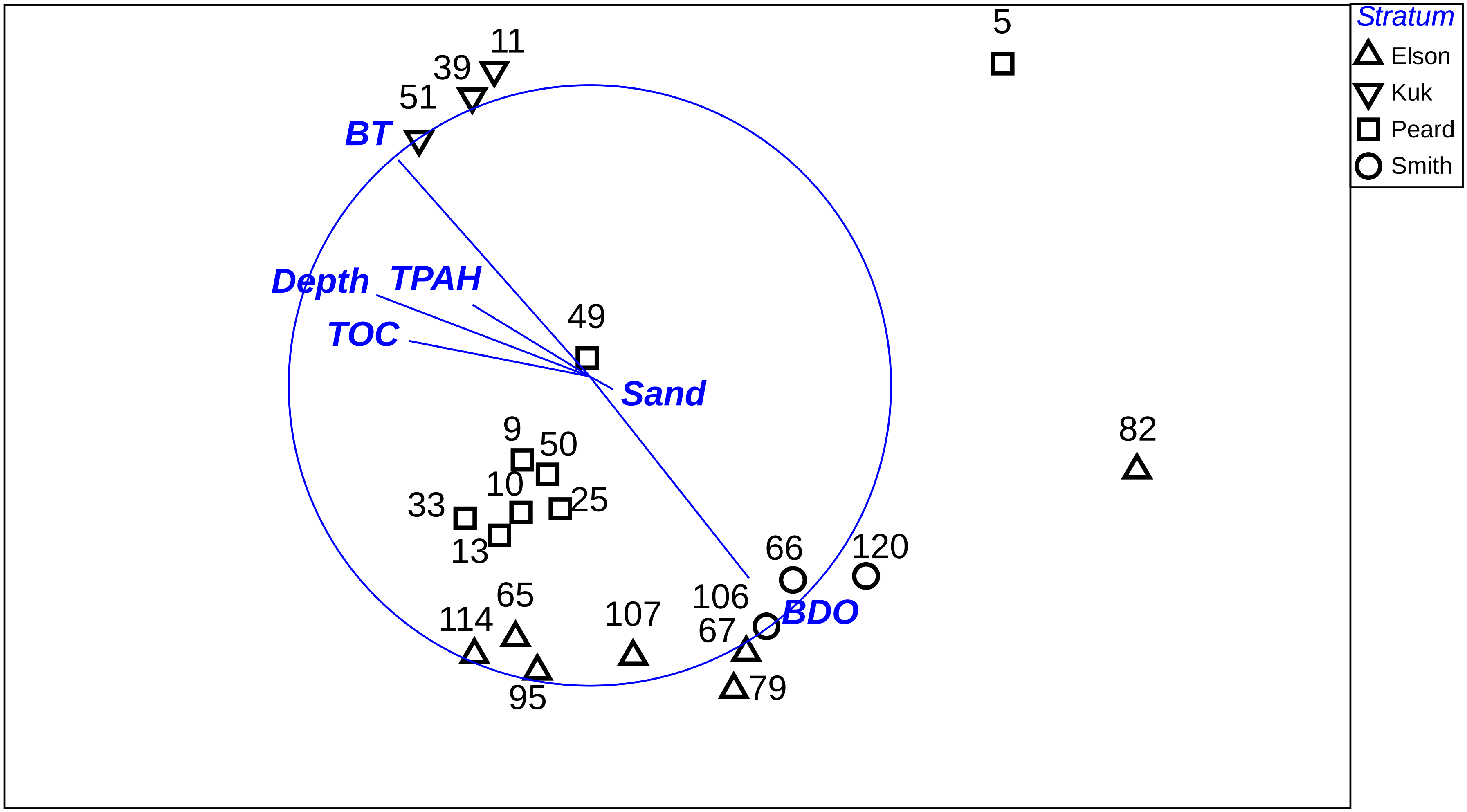

Figure 25. MDS ordination plot of Arctic estuaries based on biological community present at each station. Data includes both 1.0 mm and 0.5 mm sieve results. BT = bottom temperature, BDO = bottom dissolved oxygen, TOC = total organic carbon, TPAH = total PAHs

Because of the smaller size of the organisms captured in the 0.5 mm sieve, in general, fewer can be identified to species than in the 1.0 mm collection. This is a consequence of both the difficulty of identifying species-specific traits in small specimens, and a larger proportion of the animals are likely to be juveniles, which may not yet possess adult stage characteristics. Sampling late in the growing season will tend to capture the benthic community at peak seasonal development, but some species spawn late in the season, and some species spawn repeatedly throughout the season so juveniles of some species are always present. It has been noted that sieving efficiency varied seasonally due to settlement pulses, and differed by phyla and between species within a phylum.

In the Arctic estuaries, there were twice the number of taxa on average in the 0.5 mm sieve than in the 1.0 mm sieve collections (Table 12). There was an almost order of magnitude difference in abundance numbers, but this was due in part to high numbers of specific taxa at selected sampling sites (e.g. ostracods, oligochaetes). Diversity values were usually higher in the smaller mesh size. However, the difference in biomass was only 15%. These changes may bias interpretation of parameters such as feeding guilds, taxonomic composition of the community, organisms with or without hard parts (shells, carapace), diversity, biomass, dominance, and indicator species. Different multivariate statistical techniques applied to the data illustrate that the smaller sieve size produces a clearer distinction between community traits and the physical habitat drivers that influence them. Paired t-tests demonstrated significant differences in the population metrics sampled. Biomass was lower in the 0.5-mm-mesh sieve component (difference = 1.39, t = -2.74, p = 0.0127, df = 20) and density was higher (difference = 630, t = 4.15, p = 0.0005, df = 20). The number of taxon categories found in each sieve component was significant at a higher level of significance ($\alpha = 0.10$) with the 0.5-mm-mesh sieve components having greater numbers of categories identified (difference = 2.3, t = 1.81, p = 0.0859, df = 20).

Table 12. Benthos parameters after sieving through different size mesh.

	1.0 + 0.5mm Sieve				**1.0 mm Sieve**		
Estuary	# Taxa	Abund./m^2	Diversity		# Taxa	Abund./m^2	Diversity
Wainwright Inlet	15	4125	1.35		9	1075	1.35
Wainwright Inlet	15	2175	1.95		7	1350	1.05
Wainwright Inlet	24	4950	2.09		14	2900	1.49
Peard Bay	20	2175	2.20		11	1675	1.54
Peard Bay	29	11700	2.19		14	1150	2.10
Peard Bay	55	29475	2.35		27	2425	2.40
Peard Bay	53	47050	2.32		22	4150	1.81
Peard Bay	35	27300	2.18		9	700	1.78
Peard Bay	35	14425	2.26		16	2675	1.69
Peard Bay	33	3875	2.92		21	2000	2.39
Peard Bay	45	74850	1.52		21	3200	2.46
Elson Lagoon	45	27200	2.49		26	3950	2.37
Elson Lagoon	42	15400	2.17		19	1775	2.14
Elson Lagoon	55	28450	2.39		28	7050	2.33
Elson Lagoon	10	2450	0.71		3	175	1.08
Elson Lagoon	34	13900	2.03		11	900	1.98
Elson Lagoon	52	33675	1.87		28	5250	2.29
Elson Lagoon	24	6950	1.96		9	550	2.01
Smith Bay	30	11325	2.12		12	1775	1.14
Smith Bay	32	16875	1.82		13	1875	1.19
Smith Bay	29	49600	0.80		11	2775	1.13
Wainwright Offshore Deep	40	1880	2.90		21	710	2.67
Wainwright Offshore Deep	26	1830	1.99		12	410	2.14
Wainwright Offshore Deep	18	3280	1.35		12	1130	1.60
Wainwright Offshore Deep	20	560	2.22		6	110	1.67
Wainwright Offshore Deep	31	8830	1.17		16	2200	1.27
Wainwright Offshore Shallow	15	240	2.50		1	10	0.00
Average	31.9	16464.6	2.0		14.8	1998.0	1.7
Total		444545				53945	

MDS analysis demonstrated that the community structure differed by sieve size. The 0.5 mm mesh sieve component demonstrated clear separation of stations strongly correlated with depth and bottom-water dissolved oxygen. Community structure in the 1.0 mm mesh sieve component was less clear without distinct groupings. The MDS of all fauna together was like the 0.5 mm mesh sieve component in that the plot demonstrated clear groupings. The groupings were also evident in the MDS ordination plot for the physical variables (Figure 26). Correlation analysis of the MDS distance matrices demonstrated that the MDS analyses of the 0.5 mm mesh sieve component was highly correlated with the plot of all fauna together and both of those were closely correlated with the physical MDS. Physical characteristics correlate well with community structure suggesting that all together, the data have captured the physical/biological interactions well. Faunal communities appear to be associated largely with bottom-water dissolved oxygen (reflecting colder temperatures in Elson Lagoon and Smith Bay) and water depth (Peard Bay). The MDS plot of the 1.0 mm mesh sieve component was moderately correlated with the analysis of all fauna together and less so with the 0.5 mm mesh sieve component. These results demonstrate that the community structure patterns captured were largely reflected in the 0.5 mm mesh sieve component with the 1.0 mm mesh sieve component more weakly reflecting those patterns. The higher density of the 0.5 mm mesh sieve component resulted in fewer zero values and a more reliable pattern for these estuaries than the 1.0 mm mesh sieve component. Disturbance due to freezing limits populations and thus, organisms present are likely migrants that enter the estuaries as larvae or juveniles. The higher number of zeros in the 1.0 mm mesh sieve component makes that data set less reliable for the present purpose (too little data and too many zeros for MDS to be reliable). To quantitatively assess the differences between mesh sizes, the unreliability of the 1.0 mm mesh makes inferences untenable in this highly disturbed environment. In terms of assessing habitats and categorizing them it seems the 1.0 + 0.5 mm data together are superior

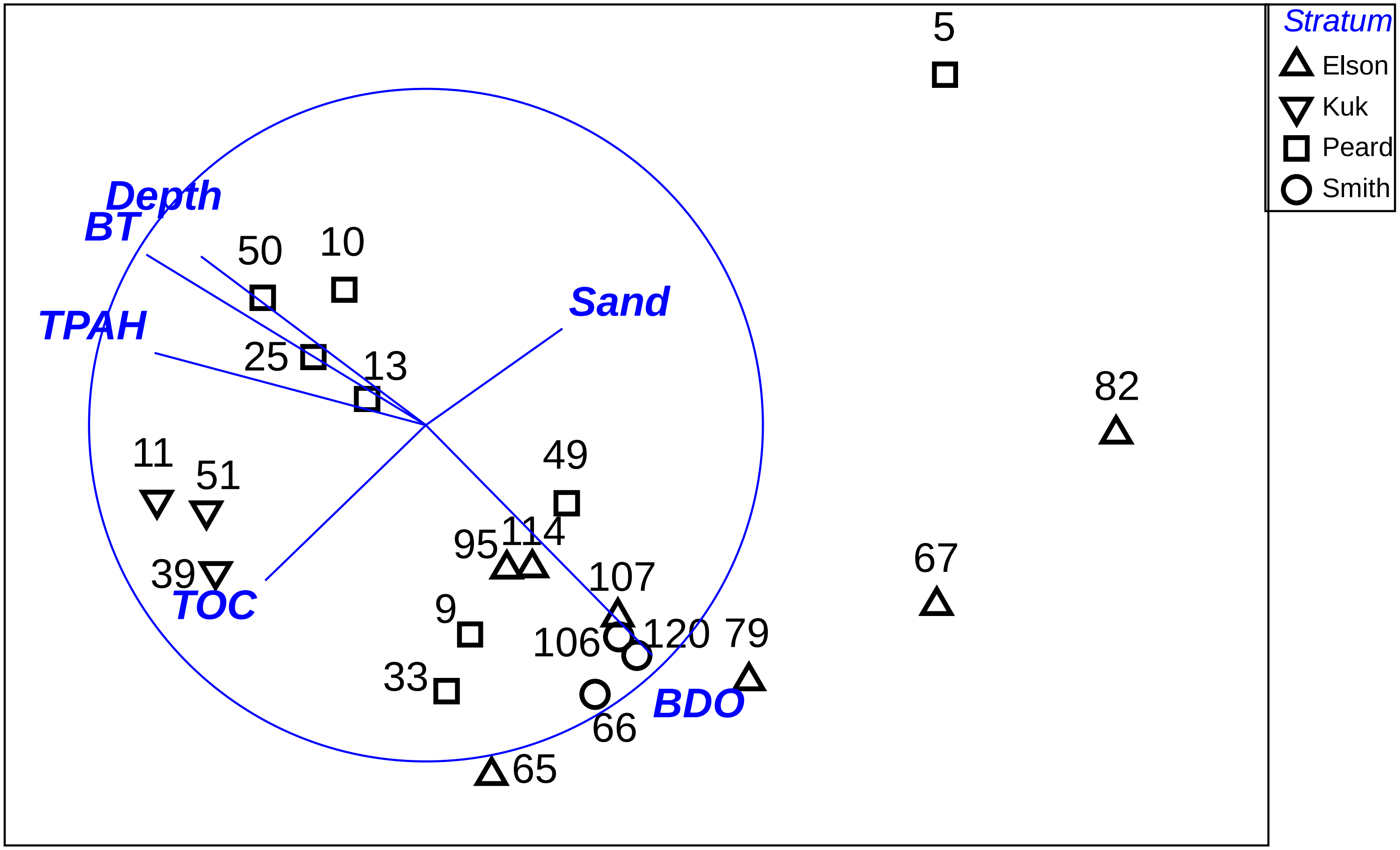

Figure 26. MDS ordination plot of Arctic estuaries based on physical variables at each station. (BT = bottom temperature, BDO = bottom dissolved oxygen, TOC = total organic carbon, TPAH = total PAHs).

4. CONCLUSIONS

The estuaries in the northeast Chukchi and western Beaufort Seas are in pristine condition relative to chemical contaminants. However, resident benthic communities are highly stressed due to harsh physical conditions resulting from shallow water and annual land-fast ice. Resident organisms are dominated by species that migrate into the estuaries after spring break up. Sediment types are dominated by silt, with sandy sediment close to shorelines. Clay and gravel are largely absent. The water columns were not stratified and are uniformly turbid with suspended silt. Salinities were generally above 20 ppt, but sampling locations were not far up the estuaries due to depth considerations.

Organic carbon and PAHs were relatively high for uncontaminated locations, but reflect the input of peat and coal deposits in the watersheds. Petroleum hydrocarbons were not evident as no sampling sites were in the vicinity of known oil seeps. Arsenic and nickel concentrations were uniformly elevated, indicating naturally derived soil releases from the watersheds. Stable isotope ratios of carbon and nitrogen indicate that all the estuaries except Peard Bay are strongly dominated by terrestrial inputs. Peard Bay has a very limited watershed and is subject to unrestricted open-ocean water input. The Beaufort Sea estuaries also may have less influence of ice algae than the Chukchi estuaries due to earlier freeze-up and later spring thaw.

Resident populations of fish were very limited, and were primarily made up of juveniles. Body burdens of chlorinated organic contaminants were low, but trace levels were present. Presumably, older offshore fish would contain higher levels of bioaccumulative compounds, but the present data set cannot confirm that. Fish did reflect elevated arsenic levels compared to fish in other regions of the state.

Resident benthic infaunal communities overlapped in terms of species makeup, but each estuary contained a distinct assemblage. Peard Bay and Elson Lagoon were the most diverse estuaries of the group. The Beaufort Sea estuaries contained species not seen in the Chukchi Sea estuaries, and vice versa. Sieving the benthos samples through 0.5 mm and 1.0 mm mesh yielded very different results. The 1.0 mm results revealed significantly fewer taxa and abundance values. Definitive multivariate statistical contrasts between sieve sizes are hampered by lack of data in the 1.0 mm data set.

The offshore transects sampled off Wainwright had primarily sandy sediments, with well mixed water column and slightly below full strength seawater salinity (ave. 31 ppt), typical of the Alaska Coastal Current. Organic carbon content was very low except in pockets of silty sand sediments. There was little overlap between benthic species communities in the offshore stations and the estuaries. Half of the benthic species present were not seen in the estuaries, and those that were found offshore were found in very low numbers. Chlorinated organic compounds were not analyzed based on earlier findings. Stable isotope ratios of ^{13}C and ^{15}N were less depleted than the estuarine values, but still exhibited the influence of terrestrial input, relative to open-ocean values.

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APPENDIX A

Chemicals and chemical groups for which ERLs and ERMs have been derived (organics ppb, metals ppm, dry weight).

	ERL	**ERM**
Total DDT	1.58	46.1
pp'-DDE	2.2	27
Total PCBs	22.7	180
Total PAHs	4022	44792
High weight PAHs ($\geq$ 4 rings)	1700	9600
Low weight PAHs ($\leq$ 3 rings)	552	3160
Acenaphthene	16	500
Acenaphthylene	44	640
Anthracene	85.3	1100
Flourene	19	540
2-Methyl Naphthalene	70	670
Naphthalene	160	2100
Phenanthrene	240	1500
Benzo-a-anthracene	261	1600
Benzo-a-pyrene	430	1600
Chrysene	384	2800
Dibenzo(a,h)anthracene	63.4	260
Fluoranthene	600	5100
Pyrene	665	2600
Ag	1.0	3.7
As	8.2	70
Cd	1.2	9.6
Cr	81	370
Cu	34	270
Hg	0.15	0.71
Pb	46.7	218
Ni	20.9	51.6
Zn	150	410

APPENDIX B

Station locations.

Station	Site No.	Lat.	Long.	Stratum
AK-NCCA-15-016	16	70.2928	-161.6485	Kasegaluk Lagoon
AK-NCCA-15-024	24	70.2879	-161.3814	Kasegaluk Lagoon
AK-NCCA-15-028	28	70.2658	-161.5266	Kasegaluk Lagoon
AK-NCCA-15-044	44	70.2660	-161.4981	Kasegaluk Lagoon
AK-NCCA-15-011	11	70.5101	-159.7809	Wainwright Inlet
AK-NCCA-15-015	15	70.6001	-159.9874	Wainwright Inlet
AK-NCCA-15-039	39	70.4670	-159.8293	Wainwright Inlet
AK-NCCA-15-047	47	70.4456	-159.8809	Wainwright Inlet
AK-NCCA-15-051	51	70.5538	-159.8718	Wainwright Inlet
AK-NCCA-15-005	5	70.7967	-158.8176	Peard Bay
AK-NCCA-15-009	9	70.7761	-159.1602	Peard Bay
AK-NCCA-15-010	10	70.8377	-158.7633	Peard Bay
AK-NCCA-15-013	13	70.8265	-158.5646	Peard Bay
AK-NCCA-15-018	18	70.8530	-158.9502	Peard Bay
AK-NCCA-15-025	25	70.8162	-158.6560	Peard Bay
AK-NCCA-15-033	33	70.7970	-159.1691	Peard Bay
AK-NCCA-15-037	37	70.7952	-158.6182	Peard Bay
AK-NCCA-15-049	49	70.7915	-159.2127	Peard Bay
AK-NCCA-15-050	50	70.8762	-158.8707	Peard Bay
AK-NCCA-15-065	65	71.3666	-156.4656	Elson Lagoon
AK-NCCA-15-067	67	71.2042	-155.8128	Elson Lagoon
AK-NCCA-15-079	79	71.2772	-156.0189	Elson Lagoon
AK-NCCA-15-095	95	71.3081	-156.2501	Elson Lagoon
AK-NCCA-15-107	107	71.2984	-155.9920	Elson Lagoon
AK-NCCA-15-114	114	71.3265	-156.4286	Elson Lagoon
AK-NCCA-15-069	69	71.1263	-155.5366	Elson Lagoon
AK-NCCA-15-082	82	71.0373	-155.5879	Elson Lagoon
AK-NCCA-15-066	66	70.8662	-154.2514	Smith Bay
AK-NCCA-15-073	73	70.9114	-154.1342	Smith Bay
AK-NCCA-15-106	106	70.8965	-154.5171	Smith Bay
AK-NCCA-15-113	113	70.9093	-154.4716	Smith Bay
AK-NCCA-15-120	120	70.8197	-154.0758	Smith Bay
AK-NCCA-15-D1B	D1B	70.7055	-160.0202	Offshore Deep
AK-NCCA-15-D2B	D2B	70.7124	-159.9766	Offshore Deep
AK-NCCA-15-D3B	D3B	70.7726	-159.8520	Offshore Deep
AK-NCCA-15-D4B	D4B	70.7416	-159.8512	Offshore Deep
AK-NCCA-15-D5B	D5B	70.7912	-159.7519	Offshore Deep
AK-NCCA-15-S10B	10B	70.7050	-159.8932	Offshore Shallow
AK-NCCA-15-S9B	S9B	70.6728	-159.9894	Offshore Shallow

APPENDIX C Sample site activities.

Site ID	site no.	Stratum	Date	Secchi Depth (m)	CTD profile	Nutrient Sample	TSS Sample	Chlorophyll Sample	Underwater Video	Benthos Collection	Sediment Collection	Air PAH	Trawl Conducted	Fish
AK-NCCA15-024	24	Kasegaluk Lagoon	08/14/15	X	X	X	X	X	X					
AK-NCCA15-044	44	Kasegaluk Lagoon	08/14/15	X	X	X	X	X	X					
AK-NCCA15-028	28	Kasegaluk Lagoon	08/14/15	X	X	X	X	X	X					
AK-NCCA15-016	16	Kasegaluk Lagoon	08/14/15	X	X	X	X	X	X			X	X	
AK-NCCA15-011	11	Wainwright Inlet	08/15/15	X	X	X	X	X		X	X			
AK-NCCA15-039	39	Wainwright Inlet	08/15/15	X	X	X	X	X		X	X			
AK-NCCA15-047	47	Wainwright Inlet	08/15/15	X	X	X	X	X						
AK-NCCA15-051	51	Wainwright Inlet	08/15/15	X	X	X	X	X		X	X	X	X	
AK-NCCA15-015	15	Wainwright Inlet	08/15/15	X	X	X	X	X			X			
AK-NCCA15-013	13	Peard Bay	08/18/15	X	X	X	X	X	X	X	X			
AK-NCCA15-037	37	Peard Bay	08/18/15	X	X	X	X	X	X					
AK-NCCA15-005	5	Peard Bay	08/18/15	X	X	X	X	X	X	X	X	X		
AK-NCCA15-005Dup	5 dup	Peard Bay	08/18/15			X	X	X		X	X			
AK-NCCA15-025	25	Peard Bay	08/18/15	X	X	X	X	X	X					
AK-NCCA15-033	33	Peard Bay	08/19/15	X	X	X	X	X	X	X	X			
AK-NCCA15-009	9	Peard Bay	08/19/15	X	X	X	X	X	X	X	X			
AK-NCCA15-049	49	Peard Bay	08/19/15	X	X	X	X	X	X	X	X			
AK-NCCA15-018	18	Peard Bay	08/19/15	X	X	X	X	X			X		X	X
AK-NCCA15-050	50	Peard Bay	08/19/15	X	X	X	X	X	X	X	X			
AK-NCCA15-010	10	Peard Bay	08/19/15	X	X	X	X	X	X	X	X			
AK-NCCA15-065	65	Elson Lagoon	08/20/15	X	X	X	X	X	X	X	X			
AK-NCCA15-114	114	Elson Lagoon	08/20/15	X	X	X	X	X	X	X	X			
AK-NCCA15-095	95	Elson Lagoon	08/20/15	X	X	X	X	X	X	X	X	X		
AK-NCCA15-107	107	Elson Lagoon	08/20/15	X	X	X	X	X	X	X	X			
AK-NCCA15-079	79	Elson Lagoon	08/20/15	X	X	X	X	X	X	X	X			
AK-NCCA15-067	67	Elson Lagoon	08/20/15	X	X	X	X	X	X	X	X			
AK-NCCA15-069	69	Elson Lagoon	08/21/15	X	X	X	X	X	X		X			
AK-NCCA15-082	82	Elson Lagoon	08/21/15	X	X	X	X	X	X	X	X			
AK-NCCA15-066	66	Smith Bay	08/23/15	X	X	X	X	X	X	X	X			
AK-NCCA15-106	106	Smith Bay	08/23/15	X	X	X	X	X	X	X	X	X		
AK-NCCA15-106Dup	106 dup	Smith Bay	08/23/15		X	X	X	X		X	X			
AK-NCCA15-113	113	Smith Bay	08/23/15	X	X	X	X	X	X		X			
AK-NCCA15-101	101	Smith Bay	08/24/15	X	X	X	X	X	X					
AK-NCCA15-073	73	Smith Bay	08/24/15	X	X	X	X	X	X		X			
AK-NCCA15-120	120	Smith Bay	08/24/15	X	X	X	X	X	X		X		X	X
D1B	D1B	Deep Offshore	08/15/15		X									
D2B	D2B	Deep Offshore	08/15/15		X					X	X			
D4B	D4B	Deep Offshore	08/15/15		X					X	X			
D3B	D3B	Deep Offshore	08/15/15		X					X	X			
D5B	D5B	Deep Offshore	08/15/15		X					X	X			
S10B	S10B	Shallow Offshore	08/16/15		X					X	X			
S9B	S9B	Shallow Offshore	08/16/15		X						LS			
LS= limited samples.														

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