IV. Discussion

A. Sediment Conditions

Regionally, average particle grain sizes (Table 4-1) of sediments at sites in the middle of the inlet were coarser while those on the west side of the inlet were finer. The predominance of coarser grains in the middle of the inlet was influenced by the degree of exposure to wave action and currents at the Kalgin Island sites, and by the number of highly exposed shoals examined. In contrast, the sites on the west side of the inlet, especially toward the north, receive heavy loads of fine grained, suspended sediments from the many river systems feeding from glaciers.

Table 4 –1. Summary of upper Cook Inlet regional sediment characteristics.

	West Side	Middle	East Side	Overall
Number of Sites Sampled	11	8	6	25
Average particle grain size (mm)	0.113 ± 0.088	0.22 ± 0.128	0.176 ± 0.143	0.16 ± 0.12
TOC (%)	0.449 ± 0.345	0.155 ± 0.211	0.427 ± 0.337	0.357 ± 0.326
TKN (%)	0.032 ± 0.024	0.01 ± 0.008	0.03 ± 0.022	0.025 ± 0.022
C:N	14.5:1 ± 4.9	11.3:1 ± 6.8	13.5:1 ± 5.5	13.3:1 ± 5.6

While some of the sites examined supported small populations of single-celled or large plants, all sites depend on organic matter produced in or imported from other areas to support the nutritional requirements of the invertebrates living there. Measures of the quantity and quality of this form of nutrition are provided by analyses of Total Organic Carbon (TOC) and Total Kjeldahl Nitrogen (TKN) (Table D-1). Both TOC and TKN are substantially lower at the sites in the middle of the inlet than on either shore. Carbon-nitrogen ratio (C:N) values are slightly lower in the middle of the inlet than on the shores, reflecting the reduced influence of terrestrial inputs of organic matter at the mid-Inlet sites.

Levels for all of these variables are substantially lower in the sites examined during this survey than we have observed in sediments in Prince William Sound (Houghton et al. 1997). The implications are that most of these sites are impoverished in terms of organic nutrients and indicate that Cook Inlet can be considered an oligotrophic estuary, an ecosystem that imports most of its food resources rather than producing its own.

The greatest similarity was with the highly impacted Prince William Sound shorelines that had been treated by high-pressure hot-water washing (Lees et al. MS), which also were characterized by low concentrations of organic carbon and nitrogen. However, C:N ratios appear to be lower in sediments in upper Cook Inlet than in Prince William Sound, indicating that nitrogen concentrations are relatively higher, indicating a stronger marine (or weaker terrestrial) influence in the inlet. Furthermore, C:N ratios this low imply that the organics observed are composed predominantly of microbial or phytoplankton tissue rather than vegetative detritus from kelp or the rivers (Kroer 1994; CSIRO 2000). In view of the extremely low concentrations of organics on the shoals combined with the low C:N ratios, it is likely that the major source of organics on these structures is the bacterial flora adhering to the sediment particles. Considering the high turbidity of the water, it is likely that benthic diatoms or blue-green algae would be the only single-celled algae that might constitute a significant proportion of the organics in the sediments. Nevertheless, the C:N ratio at all of the sites where a diatom film or blue-green algal turf was observed had C:N ratios of greater than 10:1 and averaged 15.5:1. This reinforces the notion that the low C:N ratios observed at these high-energy sites indicate that the bacterial film adhering to the sediment particles was the primary source of organics at these sites.

Bitter Soto (1999) reported that both particle grain size and hydrodynamic activity are negatively correlated with organic matter. Our data supports this finding, both TOC and TKN exhibited a significant negative correlation with median particle size ($p < 0.01$; Figure DCL-1). Based on this correlation and the premise that the organics are predominantly microbial, a strong correlation between TOC and TKN was also expected. The correlation between TOC and TKN was found to be positive and highly significant ($p < 0.001$; Figure 4-1).

Figure 4-1. Relationships among particle grain size, TOC, TKN, and C:N ratios.

Another consequence of low organics is that bioavailability of PAHs in sediment is higher (Weston 1990). This investigator found that the rate of assimilation of PAHs in sediments by the lugworm *Abarenicola pacifica* decreased as concentrations of organic matter increased. This suggests that bioaccumulation of PAHs might be more rapid in Cook Inlet sediments than in Prince William Sound.

B. Physical and Biological Conditions and Sampling Potential

Regarding survey conditions, we found that sediments at most sites were sufficiently firm to permit working and collecting. Caution had to be exercised at some locations to prevent loss of boots, and the sand tended to liquefy in a hazardous manner at some locations on the shoals, but every site examined was sufficiently stable to permit sediment sampling and the activities required for site survey and tissue collections.

C. Most Abundant Species and Potential Sentinels

What about epibiota?

Important criteria in selecting suitable sentinel species, ranked approximately from most to least important, include:

- Proximity to sources of hydrocarbon contamination as well as occurrence in remote reference areas;
- Adequate abundance to support regular collection in a monitoring program;
- Adequate biomass to support requirements of the analytical lab for attaining low levels of detection;
- Feeding mode providing considerable exposure to water-borne (dissolved or particulate) or floating contaminants;
- Ease in collection; and
- Ease in dissecting tissue.

Suitability in feeding modes is generally ranked, from most to least favorable: suspension feeder >> surface deposit feeder >> subsurface deposit feeder >> herbivore >> scavenger/predator.

Potential sentinel species were observed at most of the locations surveyed. Adequate quantities to support a monitoring program were observed at the extreme northern and southern sites on both sides of the inlet. However, adequate quantities were not observed at several sites on the east and west side of the inlet, i.e., Boulder and Moose Points on the east side of the inlet and NW of West Foreland and Drift River on the west side. Adequate stocks to support monitoring were also observed at three of the four sites examined on Kalgin Island. Adequate stocks were lacking at the northwest corner of the north shore of the island but it is likely they occur in the bight south of the northwest corner. Unfortunately, sentinel species were not observed on any of the shoals.

The mud clam *Macoma balthica* was, by far, the most abundant macroinfaunal species and the most widely distributed potential sentinel species. It occurred at densities that could sustain harvest for a monitoring program on the east and west sides of the inlet and on Kalgin Island (all sites except NW Kalgin Is.), and in southern (Kalifornsky Beach, Chisik Island, and North Tuxedni Spit) and northern (Chickaloon Bay and Beluga River So.) ends of the survey area. Because of its small size, collection of sufficient tissue and dissection would require considerable effort. While *M. balthica* can function as a suspension feeder, it is a generally considered to be a facultative surface deposit feeder (Kamermans et al. 1992; Webb 1993). Thus, it normally is feeding primarily on organic particulates and fine inorganic particles at the water-sand interface rather than on water-borne hydrocarbons. *Macoma balthica* appears to be the only species observed living in close proximity to the major potential sources of hydrocarbon contamination in upper Cook Inlet. Shaw (1976) and Myren and Pella (1977) used *M. balthica* as a sentinel organism for hydrocarbon contamination in Port Valdez. The latter investigators reported that its density increased between MLLW and the mid-intertidal. They also found that population density was quite stable seasonally. In contrast, McGreer (1983) reported considerable seasonal variation in density and implied that intense feeding by shorebirds (dunlin) may have caused the observed strong reduction.

Softshell (*Mya arenaria*)s and razor clams (*Siliqua patula*), both true suspension feeders, would be excellent sentinel species because of their size and ease in collection but distribution of both was limited. Harvestable populations of both species were observed only at southern stations and therefore appear to be relatively remote from the likely sources of hydrocarbons. As commercially exploited species, both are easily dissected. *Siliqua* was found at six stations (Clam Gulch on the east side, SE and NW Kalgin Island in the middle, and Harriet Point North, No-name Creek, and Polly Creek on the west side. *Mya* was only observed at three sites (two on Kalgin Island and one on the west side of the inlet south of the West Foreland. Bioaccumulation factors of up to 220,000 have been reported for *Mya* (Kure and Depledge 1994). McDowell et al. (1999) noted that the softshell clam has been commonly used as a sentinel species and that effects of exposure can be seen in the reproductive cycle as a consequence of disruptions to the bioenergetics of feeding. For example, Gilfillan and Vandermeulen (1978) reported changes in growth rates and physiological condition of softshell clams in Nova Scotia following exposure to Bunker C oil.

Distribution of the lugworm, *Abarenicola pacifica,* included the entire range of sites surveyed on the west side of the inlet. Consequently, it is likely that populations could be located on beaches close to sources of hydrocarbon contamination. The lugworm was generally abundant where it was observed and the worms are relatively large so collection of adequate biomass would be easy. However, since the lugworm feeds on subsurface sediments, it acts more as a sampler for longer-term contamination that has become entrained in the sediment column rather than water-borne contaminants.

Although infrequently used previously to assess chronic PAH contamination of the sediment (Kaag et al. 1998), the lugworm, a deposit feeder, would be a good candidate species for assessing chronic contamination of sediments. Augenfeld (1980) examined the effect of Prudhoe Bay crude oil on sediment working rates of *A. pacifica*. Kaag et al. demonstrated the importance of considering its reproductive cycle and Weston (1990) reported that, because the bioaccumulation rate correlates inversely with organic carbon, the concentration of organic carbon in the sediment is also an important consideration. Thus, because many of the sediments observed in upper Cook Inlet have low organics, bioaccumulation rates would be high.

Mussels, true suspension feeders, are used widely as sentinel species for a variety of contaminants (Salazar and Salazar 1990) and are routinely sampled for that purpose at several locations in Prince William Sound (Kinnetic Laboratories 1997; Payne et al. 1998). Moreover, it has been used as a sentinel species since the early 1970s (e.g., Gilfillan 1975). The blue mussel *Mytilus edulis* concentrates contaminants up to 100,000 times (Widdows and Donkin 1992). Unfortunately, however, distribution of mussels in upper Cook Inlet appears very restricted. Mussels were observed at only a single location on each side of the inlet, likely as a result of ice scour and high turbidity conditions. Moreover, both sites were at or toward the southern end of the study area and are thus remote to the major sources of potential hydrocarbon contamination.

In summary, it appears that the mud clam, *M. balthica*, although the smallest and most difficult to collect and deal with, is the most suitable of the organisms observed during this survey, primarily because of its high abundance across a broad geographic range. The lugworm, *A. pacifica*, is the next most suitable. Based on abundance, biomass, ease of collection and dissection, and feeding mode, softshell and razor clams and mussels would be highly effective sentinel organisms. However, because they are relatively uncommon or absent in the upper inlet and do not appear to occur near any of the major sources of hydrocarbons, they do not provide feasible resources.

D. Level of Contamination

In general, the sediment and tissue samples examined in this program were extremely clean. There was no evidence of any petroleum hydrocarbon contamination from either refined products or crude oil sources observed in any of the samples. The TPAH values for the polynuclear aromatic hydrocarbons that were observed in the sediments ranged from <1.3 µg/kg (ppb; the SIM GC/MS limit of detection) to 80 ppb. In most of the samples, the measured PAH could be generally attributed to natural sources including eroding peat and coal. In several sediment samples, including the two with the highest TPAH values, the sources were identified as a combination of combustion products and eroding peat. The TPAH concentrations in the tissue samples ranged from <8 ppb to 1,300 ppb. The most commonly observed PAH in the tissues was naphthalene, which generally made up over 90 percent of the TPAH and was often the only PAH detected. We believe the naphthalene came from digestion of peat fragments that had been ingested by the filter- and detritus-feeding organisms examined in the program. Without exception, however, in the four samples with TPAH concentrations in excess of 250 ppb, the source of the PAH appeared to be from a combination of eroding peat and combustion products. Coal had previously been suggested as a source of aromatic hydrocarbons to subtidal sediments within Cook Inlet (Lees et al. 1999; Payne et al. 2000); however, the importance of peat as a source of PAH to intertidal sediments and organisms had not been recognized before this project. There was no evidence of any PAH being accumulated from coal in any of the tissue samples examined.

1. Coal Samples

Examination of the PAH, aliphatic, and sterane/triterpane data for the coal samples has revealed that no two of the source samples are exactly alike, and the ratios of individual PAH within a homologues group differ widely. The variability observed in the coal signatures demonstrates that the coal composition within Cook Inlet is extremely heterogeneous, and that a variety of sources are suggested. With that as a caveat, however, there were also several similarities noted, and the most significant of these is the commonality of the PAH components observed in nearly all samples. Specifically, parent and alkylated PAHs were observed for the following groups: naphthalenes, phenanthrene/anthracenes, fluoranthene/pyrenes, and (in a few cases) chrysenes. In addition, perylene is prominent in all of the coal samples, and it is the most abundant PAH in many.

The statement that none of the samples were identical comes from variability observed in the ratios of the alkylated PAH groups. In almost all cases there appears to be a water-washed pattern for the naphthalenes with less weathering observed for the other PAH groups. C1-phenanthrenes/anthracenes predominate over the parent phenanthrene (or anthracene, which is absent in most samples). Conversely, in most of the sediments, phenanthrene (derived from eroding peat fragments) predominates over its alkylated homologues (or else it is the only component present).

Interestingly, the weathering of the naphthalenes is similar in the North Foreland and Beluga River SW coal samples regardless of particle size. Naphthalene and C1-naphthalenes were largely removed from chunks of coal 3- to 5-inch in diameter and sand-sized fines from Beluga River SW and the coal extracted from the exposed coal seam on the beach north of North Foreland. Presumably, this weathering occurred during the coal maturation process and is very limited after the coal has formed. If this were not the case, then one might expect more weathering in the smaller particles, on which higher surface-area to volume ratios promote selective leaching of the more water-soluble lower-molecular weight parent components.

The histogram plots for the aliphatic components in coal show an even wider variability among the different sources examined. In general, n-alkanes are not observed with molecular weights below n-C 20. The one exception was for No-name Creek coal, which contained trace level n-alkanes n-C 10 through n-C 13, plus n-C 17, and n-C 19.

The absolute concentrations and relative abundance distributions of steranes and triterpanes in the coal samples are also extremely variable. Nowhere was this more apparent than near Beluga River SW, where S/T 3, S/T 35, and S/T 37 were present in fine and chunk coal, but S/T 37 was absent in North Foreland seam coal. Clam Gulch coal contained many of these S/T constituents, but also a large S/T 22. No-name Creek coal was predominantly S/T 3.

2. Eroding Peat

The significance of the PAH signal from peat eroding from the bluffs, cliffs, and scarps adjacent to the beaches in Cook Inlet has not been recognized up to this time. The analysis of an eroding peat sample collected from Captain Cook State Park has provided a unique and very characteristic PAH pattern (naphthalene and C1- through C3-naphthalene) accompanied by a trace of biphenyl, an isolated phenanthrene, and a very predominate perylene. This unique pattern was observed in all of the peat-containing sediments examined in this program with only the relative amount of perylene varying to a significant extent. We did note, however, that even though the PAH pattern was very consistent, the sterane/triterpane pattern observed in several peat-containing sediment samples varied significantly from the pattern observed in the single peat reference sample collected in the program. That led us to conclude that the PAH profile for peat appears to be much more stable and invariant compared to the S/T pattern. Nevertheless, the subtle changes in the peat PAH and S/T signatures observed at these different sediment sites probably reflects differences in organic source materials from which the peat was derived. As a result of these observations, and the ubiquitous presence of the very characteristic PAH peat signal in many of the intertidal sediment samples, it might be appropriate as part of a future EMP effort to systematically collect a wider range of peat samples from the bluffs and eroding scarps above the intertidal stations where peat was identified in the sediments analyzed in this program. Data from the analysis of those samples could then be used to develop a larger database of PAH and sterane/triterpane profiles for this ubiquitous and important source of aromatic hydrocarbons to the upper and middle Cook Inlet marine environment.

3. Intertidal Sediment Samples

Identifying coal sources in sediment samples was difficult due to the extremely low concentrations of aromatics observed in the sediments in nearly all cases. Likewise, although aliphatic constituents are present in coal at concentrations equivalent to or in some cases up to 100 times greater than the PAH concentrations, the aliphatic constituents were generally below the method detection limits for the sediment samples analyzed in the program. Method detection limits for the aliphatic constituents are based on flame ionization detector gas chromatography (FID GC), whereas method detection limits for the corresponding PAH in a given sample are based on selected ion monitoring (SIM) GC/MS. Thus, the method detection limits for PAH in sediments generally ranged between 1-2 ppb, whereas method detection limits for the aliphatics (AHC) are generally around 100-200 ppb.

Another factor that confounded identification of coal PAH patterns in the intertidal sediment samples came from the fact that all of the intertidal sediments were sampled by hand, and only the finest-grained sediments were generally collected and placed directly into the sample jars. When isolated coal fragments were observed lying on the beach or in more concentrated accumulations in the troughs of sand- and mud-waves, they generally manifest themselves as larger coffee-ground-sized particles or flakes and chunks up to several inches in diameter. As a result, when coal was visually observed, we collected it separately, and in collecting the sediment samples, we specifically avoided including the larger coal particles in the sample, knowing they would overwhelm any other PAH signal present. This would not necessarily be the case for subtidal sediments collected by grab samplers. When sampling subtidal sediments from a boat, there is no opportunity to direct the placement of the grab sampler to avoid larger coal fragments. As a result, they would be included in the "grab" sample, and thereby be a major contributor of PAH when present. This, in fact, appears to be the case in the offshore subtidal sediment samples collected in the EMP to date, and would be consistent with the observation by Lees et al. (1999), that the TPAH content in the subtidal sediments actually increased as the particle grain size (PGS) distribution increased.

The one station where there was definite evidence of particulate coal mixed into the intertidal sediments was at No-name Creek (see Figure 3-76), where the intertidal sediments were relatively coarse, containing 73 percent medium sand. In this instance, the coal signal in the sediment was primarily identified by the just-above-detection-limit concentrations of phenanthrene/anthracene and fluoranthene/pyrene homologues that were also identified in the coal particulates collected from the upper intertidal shoreline at this site. The possibility of any of the observed PAH being from either Cook Inlet or Alaska North Slope (ANS) crude oil can be eliminated by the nearly equal abundance of the fluoranthene/pyrene group compared to be phenanthrene/anthracene group in the sediment sample. Fluoranthene/pyrene homologues are six times less abundant than phenanthrene/anthracene homologues in both Cook Inlet and ANS crude oils, and these higher molecular weight components would not be present in refined products such as diesel or fuel oil. Absolute confirmation of the presence of coal in the sediment sample under consideration was confounded by the S/T pattern of the coal particles isolated further up the beach compared to the S/T pattern for replicate 1, which more closely matched the S/T pattern observed at Polly Creek (see Figure 3-75). Unfortunately, S/T analyses were arbitrarily completed only on all replicate 1 samples, so there are no S/T data for the replicate 2 sample containing the PAH profile most similar to that of the No-name Creek coal sample. As mentioned previously, it is also significant that the PAH profiles observed in the tissue samples from the razor clams collected at both Polly Creek and No-name Creek looked nothing like the PAH patterns observed in the sediments. Likewise, had there been crude oil contamination at No-name Creek, it would have shown up in the tissue analyses. Instead, the data suggest that the PAH present in coal are not bioavailable, and that they are not accumulated by filter- or deposit-feeding organisms.

The highest TOC and TKN values were consistently observed in the finer-grained sediment stations where the classic PAH pattern derived from eroding peat was noted. This is not surprising given the exceptionally high values for TOC (>100,000 ppm) and TKN (6,500 ppm) measured in the eroding peat sample. The sum of just those PAH observed in peat (naphthalene plus the C1- through C3-alkylated naphthalenes, biphenyl, and phenanthrene, but not perylene because it was also characteristic of coal) correlated significantly with TOC ($r^2 = 0.76$) and TKN ($r^2 = 0.64$). Figures 4-2 and 4-3 show the linear regression plots for these two statistical analyses. Similar analyses of TOC and

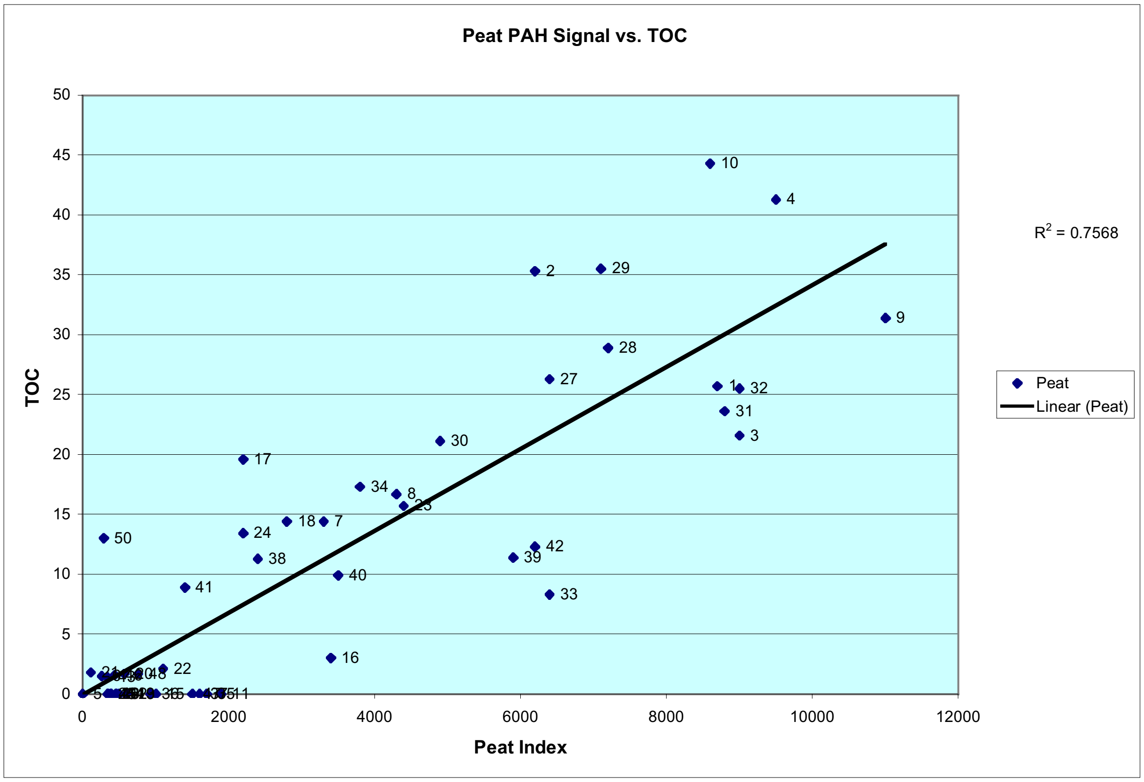
TKN versus perylene alone (as a surrogate for coal) failed to yield a statistically significant correlation. TPAH (which would include PAH from all sources, including combustion products, peat, coal, crude oil, refined products, etc.) correlated less significantly with TOC (r^2 = 0.58) and TKN (r^2 = 0.47).

4. Intertidal Tissues

Combustion products have fine enough PGS distributions that they can be ingested and ultimately incorporated into the tissues of filter- and detritus-feeding intertidal organisms, but larger coal particles and fragments are apparently excluded. The results of the intertidal sediment analyses suggest that coal particles smaller than the medium- to fine-sand range are either not present or they are not incorporated into intertidal sediments. Given their lighter densities, any finer-grained coal particles are apparently winnowed out of the intertidal sediments by the waves and currents with each flood tide. Coal particles were observed on top of sand and mud within the intertidal zone at numerous locations, but we never saw a significant coal PAH pattern in any of the finer-grained intertidal sediment samples examined in the program. Alternatively, if finer-grained coal particles were present and were ingested by filter-and detritus-feeding organisms, there does not appear to be any transfer of particulate-phase PAH associated with the coal particles into the tissues themselves. Peat fragments, on the other hand, appear to be intermediate in behavior with evidence of peat ingestion observed in several tissue samples and possible bioaccumulation of naphthalene, which would otherwise be below the method detection limit if it were simply associated with peat fragments still present in the gut.

The TAlk patterns from many of the tissue samples suggest the presence of higher molecular weight n-alkanes (n-C 29, n-C 30, n-C 31, and n-C 32) associated with the peat signal, but other than naphthalene, none of the other PAH associated with eroding peat were observed. The n-alkanes could be detected because of their significantly (three order-of-magnitude) higher relative concentrations compared to the PAH in the peat sample (for example, see Figure 3-55), and the PAHs if simply present as ingested peat fragments would be at such a low concentrations that they would be below the MDL of 8-32 ppb obtained for the tissue analyses. Nevertheless, naphthalene was observed at significantly elevated concentrations as the sole PAH component in 10 tissue samples from stations where high concentrations of eroded peat were observed in the surrounding sediments. As a result, we believe that the measured naphthalene concentrations accurately represent true tissue burdens, and that the source can be attributed to dissolution and bioaccumulation of naphthalene during digestion of the decaying peat fragments. Although naphthalene was also observed in several of the Field Blanks, its source in those Field Blanks was traced to contamination of the distilled/deionized water supplied by the Woods Hole Group Laboratory. Additional factors adding to the veracity of the observed naphthalene truly being in the tissue samples and not occurring as the result of a sampling or laboratory artifact include the following: 1) All of the smaller organisms (*Macoma balthica*, , lugworms, etc.) were placed directly into the I-Chem® glass jars supplied by the laboratory; 2) the I-Chem® glass jar blank (not

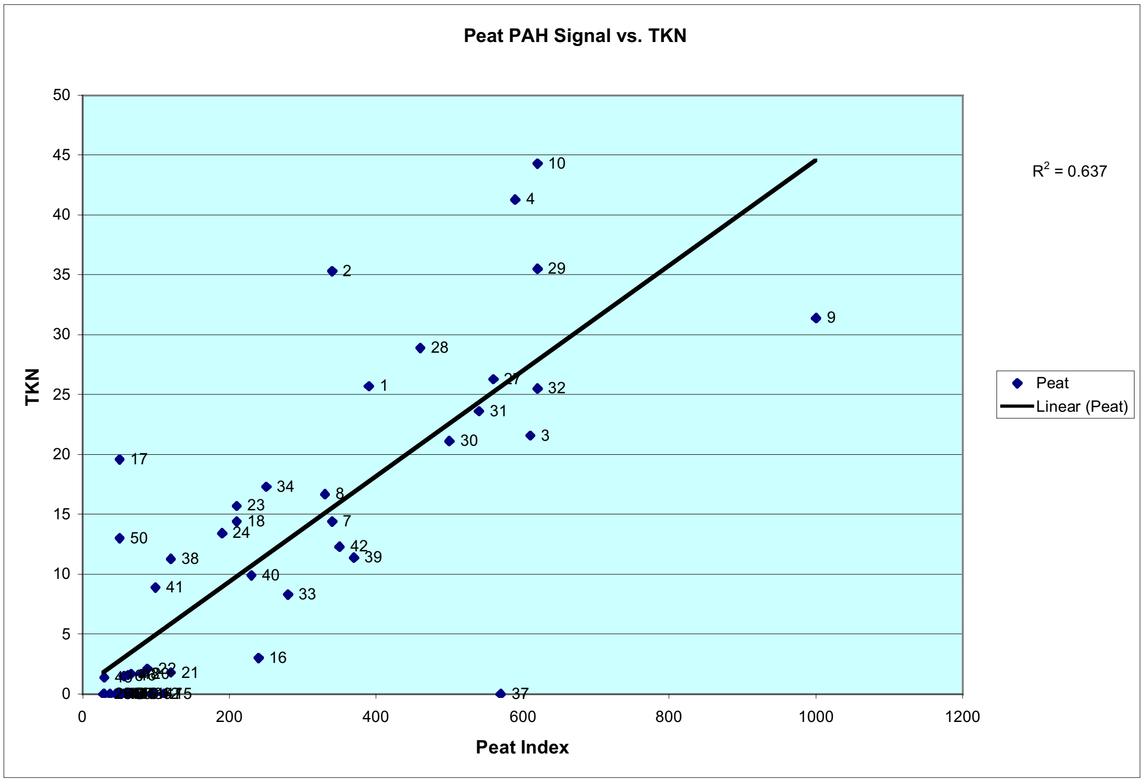
Figure 4-2. Comparison of PAH signal in peat (Peat Index) and Total Organic Carbon (TOC).



containing any of the laboratory-supplied distilled water) showed no PAH contamination at a method detection limit of 20 parts per trillion; 3) larger organisms such as razor clams and mussels were wrapped in aluminum foil and then placed in Zip-Lock® bags for transport to the laboratory; and 4) naphthalene was not observed in any of the Laboratory Methods Blanks run in parallel with the analyses of the tissue and sediment samples collected in this program.

Given the limited water solubility of the higher-molecular weight n-C 29 through n-C 32 alkanes, it is most likely that this signal observed in numerous tissue samples represents

Figure 4-3. Peat PAH Signal vs. Total Kjeldahl Nitrogen.



peat particles in the gut rather than dissolved constituents that partitioned into other tissues. What is also suggested by the data is that naphthalene from eroded peat can dissolve to a limited extent in the gut (naphthalene has the highest water solubility of any of the PAH), and thereby become available for bioaccumulation in the tissues of exposed organisms. Figure 4-4 shows the PAH profiles for eroded peat and *Macoma balthica* and *M. arenaria* samples from Oldmans Bay and West Forelands South stations. Clearly, the only PAH observed at significant concentrations in any of these tissue samples is naphthalene. Figure 4-5 compares the AHC histogram plots for these same samples, and the presence of peat-derived n-alkanes is clearly demonstrated in two of the tissues and suggested in the others. Another reason we believe that the naphthalene signal has to be associated with the digestion of peat comes from the fact that there were no significant concentrations of naphthalene in any of the other source samples examined in the program. That is, with the exception of eroded peat, naphthalene is generally the least abundant PAH in any of the coal samples, and it is significantly depleted compared to its C1-C4 alkyl-substituted homologues in both Cook Inlet and ANS crude oils. Furthermore, when naphthalene is present in a liquid state (dissolved in crude oil and

Figure 4-4. PAH histograms for eroding peat and selected tissues from Oldmans Bay and West Foreland South.

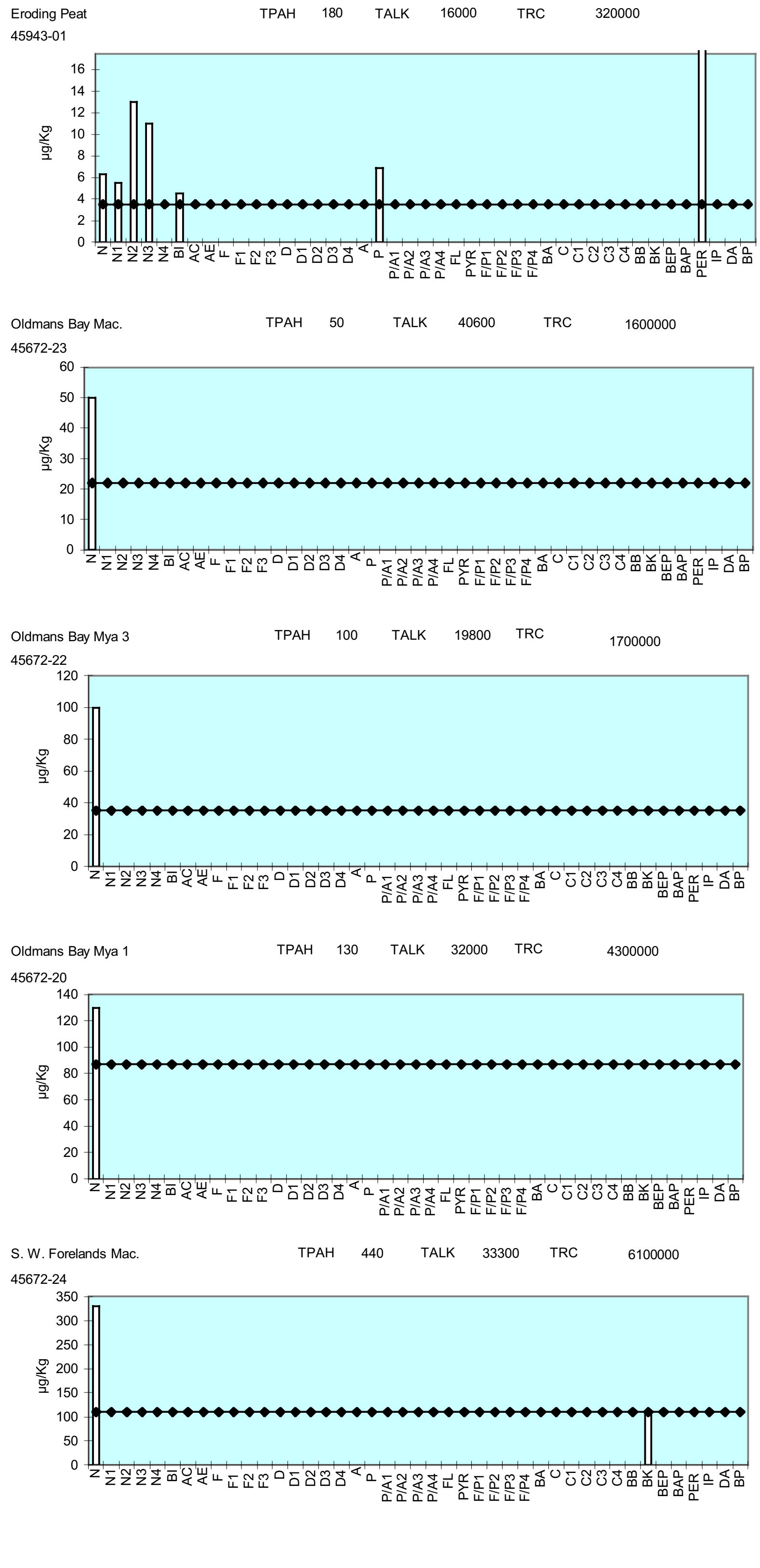
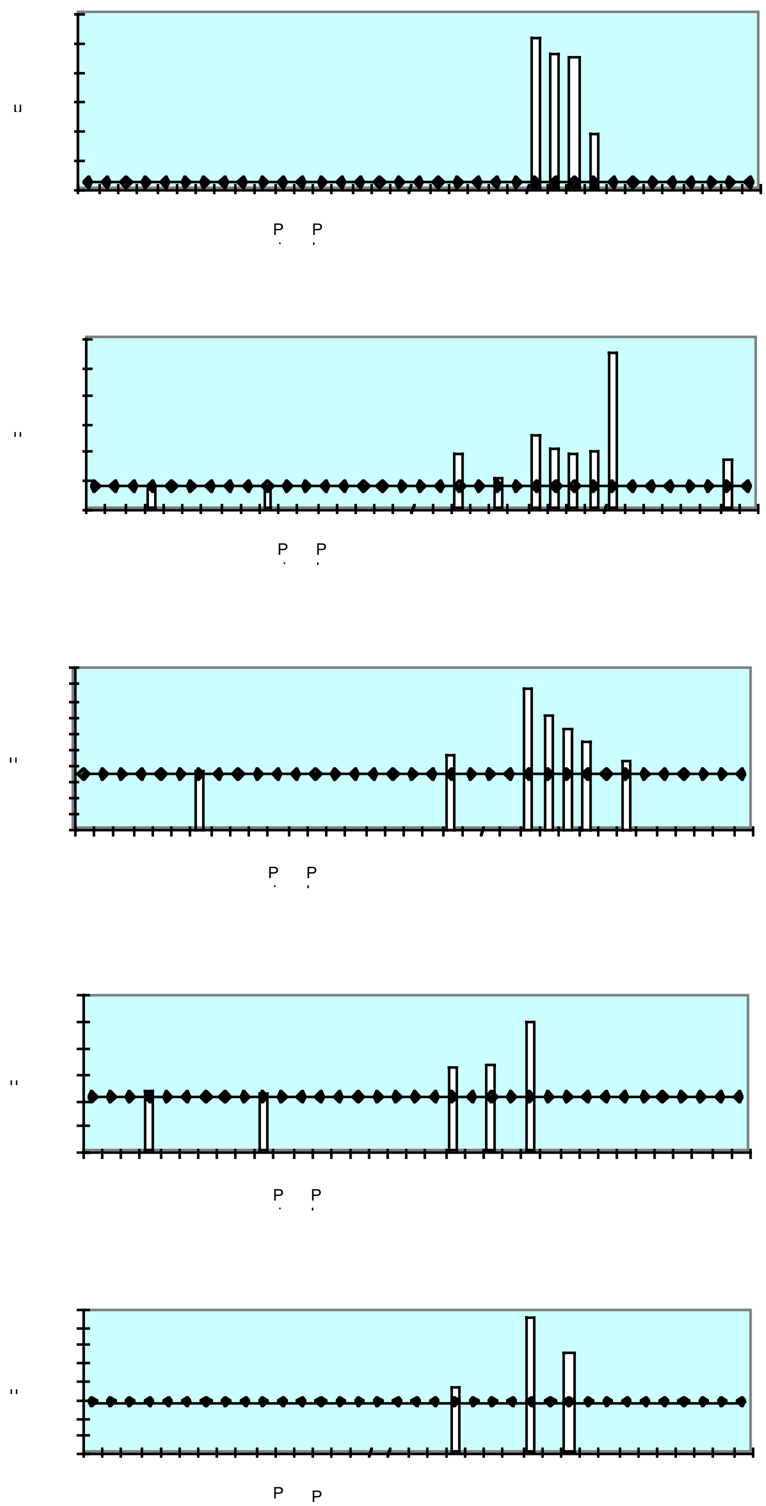


Figure 4-5. AHC histograms for eroding peat and selected tissues from Oldmans Bay and West Foreland South.



petroleum products), it is readily bioaccumulated along with each of its alkylated homologues and most of the other higher molecular weight PAH when oil droplets are ingested by filter- and deposit-feeding organisms. Nevertheless, only naphthalene was observed in most of the tissues examined in the program, and it was present at the highest concentrations in organisms collected from beaches such as the West Foreland South where eroding peat scarps were a significant geomorphological feature. Because the clams were not purged of gut contents, we only conclude that the naphthalene was found in whole animals including gut contents. We cannot conclude that it was being assimilated into tissues following digestion from eroded peat particles.

E. Factors Influencing Distribution of Long-lived Infaunal Organisms

Sites were examined on the basis of four abiotic characteristics (substrate type, upper elevation of a significant infaunal abundance, and intensity of wave and current action) and several biological characteristics (Table 4-2). Only seven types of organisms were sufficiently abundant during the surveys at the various sites to use in attempting to understand the factors that are influencing the distribution of macroinfaunal organisms. These "characterizing" taxa include: blue-green algal of or diatom films on the surface of the sediment; two large worms (the lugworm *Abarenicola pacifica* and the errant nereid polychaete *Laonnates* sp.), and three bivalves (the mud clam *Macoma balthica*, the softshell clam *Mya arenaria*, and the razor clam *Siliqua patula*). All but the algae are relatively long-lived and it is believed that the algal conditions are relatively persistent, or least recurrent during the spring and summer. Some other less commonly encountered species that are included in the discussion are the echiurid *Echiurus echiurus alaskensis*, the sipunculid *Phascolosoma agassizii*, and the surf clam *Mactromeris* (=*Spisula*) *polynyma*. These taxa are also relatively long-lived.

1. Upper Elevation of Significant Infauna Abundance

The upper elevation at which significant infaunal abundance was observed varied considerably among the sites examined during this survey (Table 4-2), ranging from approx. +21 feet MLLW at Chickaloon Bay to approx. MLLW at Clam Gulch and Polly Creek (Pentec Environmental 1996). Generally, populations with high biomass (e.g., razor clam beds) were at the lower elevations. However, *Macoma balthica* and the nereid worm, *Laonnates* sp. were abundant near the upper edge of two of the higher flats (Chickaloon Bay and Nikolai Creek; Table 4-2).

Table 4-2. Summary of selected sediment characteristics, elevation of macrobiotic assemblages, tidal and wave intensities, and selected biotic features.

Table 4-2. Summary of selected sediment characteristics, elevation of macrobiotic assemblages, tidal and wave intensities, and selected biotic features.

2. Substrate Type

The five sediment texture categories used to classify the sediments observed during this survey, ranging from very fine (silt/clay) to fine to medium sand, reflect a broad spectrum of hydrodynamic energy regimes. Typically, silt/clay is found in areas that are depositional or are eroding high intertidal flats whereas, at the other end of the spectrum, the fine to moderate sand is found in areas that are scoured by considerable wave action, strong tidal currents, or both.

For example, some of the silt/clay areas are also still responding to recent change in sea level caused by the 1964 Good Friday Earthquake. Typically in Cook Inlet, the ground level "dropped" from slightly to several feet. In many areas, previously marshy areas became intertidal and were subsequently exposed to tidal and wave action. Many of

these areas continue to erode and are still unstable, thus likely discouraging colonization by long-lived animals such as the softshell clam (*Mya* spp.)

The two types of sediment typically not supporting long-lived macroinfauna were unstable mud and fine to fine/medium sand without silt (Table 4-2). Unstable mud, usually in areas inshore of offshore sand bars (e.g., Bishops Beach Creek, Moose Point, Redoubt Creek) usually were uninhabited by infaunal organisms. It appears the mud in these locations is actively depositional, relatively mobile, and has been deposited rapidly; consequently it is likely that macroinfaunal organisms cannot become established or persist long enough to attain maturity. Furthermore, the fine to fine/medium sands observed on the shoals, at Boulder Point, and on the sand spit extending southwest from Moose Point, were generally uninhabited (Table 4-2). All of these sites are exposed to fast currents during both the ebb and flood stages of the tide.

Exceptions to the generality of this condition were observed at lower tidal elevations at several sites. These include: 1) at –3.4 feet MLLW on the outer edge of the sand spit extending southwest from the southeastern point on Kalgin Island; 2) below MLLW on the north side of Harriet Point; 3) at MLLW on the NW corner of Kalgin Island; and 4) at +4 feet MLLW at West Foreland North. Impoverished assemblages including sparse populations one or more of following species (*M. balthica*, *A. pacifica*, the sand dollar *Echinarachnius parma*, and juvenile *S. patula* and *M. polynyma*) were observed at these sites. Two of these species (*E. parma* and *M. polynyma*) are common (Lees and Houghton 1978) in similar sediments (median grain size ~ 0.28 mm) in the middle of lower Cook Inlet at depths around 55-60 m where maximum tidal currents are moderate (~1 kt) but there is no wave action (Dames & Moore 1978).

3. Hydrodynamic Intensity

a) Currents

Maximum current velocity ranges from over 7 kts during ebbing spring tides near Middle Ground Shoal and the East Foreland (Anonymous 1995) to probably somewhat less than

0.5 kt along relatively protected shores during flooding neap tides (e.g., Tuxedni Channel). Similarly high velocities probably occur on all of the shoals whereas lower velocities probably occur in protected areas such as Bishop's Creek Beach or south of West Foreland. Thus, variation in current intensity is great among the sites observed during this study.

We characterized current intensity of each site based primarily on shoreline topography and sediment features such as sand waves. Thus, exposed sites such as shoals or on points were judged to have high intensity currents during flood and ebb tidal stages whereas sites that were protected by a point or inshore of a wide flat were judged to have low intensity currents. To the degree possible, we checked these assumptions using Shio, NOAA's tide and current program.

We characterized current intensity as high for both flood and ebb tides at five sites. No macroinfauna and very limited infauna was observed at these sites. At all sites where the abundance of at least one macroinfaunal organism was characterized as common or abundant, current intensity was characterized as moderate or below at least part of the time. All sites where blue-green algal or diatom films were observed had low or moderate current intensities (Table 4-2).

Levin et al. (1994) reported that substrate mobility "exerts primary control over infaunal community structure at two high-energy sites". At sites experiencing daily tidal flows of about 0.7 kts, differences in sediment composition and density exhibited substantially different mobility. Tubicolous and epifaunal animals were more abundant in the more stable substrate whereas subsurface burrowers were more common in the shifting substrate. Considering that currents in some of the areas were an order of magnitude higher than those reported by Levin et al. (1994), and that sediment stability varied to a greater degree, the wide variation in the development of infaunal assemblages is understandable.

b) Waves

Wave intensity was characterized on the basis of beach orientation relative to wind patterns at Kenai Airport and maximum fetch. Adjustments were made in cases where fetch was interrupted by islands or shoals. Beach orientation and wide flats offshore of a beach were also important considerations. Strongest predominant winds are from the northeast in fall and winter and so beaches facing northeast have greatest exposure. Predominant winds in the spring and summer, generally considerably milder than winter winds, are from the southwest. Thus, beaches with a southwesterly exposure are substantially less exposed than those with the northeasterly exposure.

Wave intensity was designated as strong for eight sites (Table 4-3). It is clear from the abundance patterns of the macroinfaunal organisms that strong wave intensity is less important than currents; several sites with strong or moderate to strong wave action supported sparse or abundant infaunal populations. Some sites with weak wave action but high current intensity did not support macroinfaunal organisms. Nevertheless, wave intensity is obviously an important factor. None of the sites with strong wave action supported infaunal populations with greater than sparse abundance. All of the sites where macroinfauna was characterized as abundant or common were characterized as having moderate to strong wave intensity or less. Algal films were observed only as sites characterized as having weak or weak to moderate wave intensity.

Three of the five sites characterized as having high wave intensity but only moderately strong currents supported only sparse, mainly juvenile, macroinfaunal organisms typified by bivalves. However, two of the sites (NE corner of Chisik Island and so. of Beluga River) supported abundant *Macoma*. The Chisik site also supported a variety of other large macroinfauna and long-lived epifaunal organisms on the boulders on the flat. Three of the five sites characterized as having moderate wave intensity supported abundant or common bivalve resources, including razor clams at Polly Creek. Eight of thirteen assemblages containing abundant or common populations of one or more species occurred at sites characterized as having weak wave intensity (14 sites total).

The distribution patterns observed suggest that strong currents on both flood and ebb tides stringently depress the ability of macroinfauna to establish and survive in sediments. The effect of periodic episodes of strong wave events of the intensity occurring in Cook Inlet is probably not as important as that of the strong tidal currents which occur four times daily. However, if boulders are present in the low intertidal zone, populations of some epifaunal organisms (e.g., the sea anemone ?*Urticina crassicornis* at Boulder Point and SE corner of Kalgin Island) can become established in areas exposed to both strong currents and wave action.

4. Characterizing Biota

Seven types of organisms were designated as characteristic, based on their size and abundance, in the case of the invertebrates, or aerial coverage, in the case of the algal films (see Tables 3-3 and 3-4). These included: algal films (benthic diatoms) or turf (blue-green algae); three bivalves (*Macoma balthica*, *Mya arenaria*, and *Siliqua patula*), and two polychaete worms (*Abarenicola pacifica* and *Laonnates* sp.)

a) Algal Films

The algal films were restricted to muddy areas with weak to moderate wave action and low or moderate current intensity. Blue-green algal turfs were observed at higher elevations on muddy flats whereas diatom films occurred at mid to lower elevations (Table 4-2).

b) *Macoma balthica*

The most abundant and widespread (13 of 25 sites) animal observed was the mud clam *M. balthica* (Table 4-2). With estimated densities of over 2,000 per sq. m. at two locations (Light Point, Kalgin Is.; and Chickaloon Bay), it was designated as abundant at five sites and common at an additional three. It occurred at all but one site where silt/clay was a significant component in the substrate. At the exception (Moose Point), the silt/clay deposit was very soft, unconsolidated, and probably ephemeral. Factors cited as important in regulating density of *M. balthica* include tidal height (Myren and Pella 1977; Vassallo 1969), sediment grain size, carbon and nitrogen content of the sediment (Newell 1965), and sediment bacteria (Tunnicliffe and Risk 1977).

Two types of surficial sign indicate the presence and, to a degree, the abundance of this clam. A starburst (stellate) pattern shows the tracks of the incurrent (feeding) siphon where an individual has been feeding. A commonly observed meandering furrow is also associated with the clam. This track apparently is a response of the clam to a trematode parasite (Swennen 1969; Swennen and Ching 1974) and not associated with feeding.

c) *Abarenicola pacifica*

The lugworm *Abarenicola pacifica* also occurred widely throughout the surveyed area (Table 4-2). Based on the abundance of its fecal castes, it was characterized as abundant or common at seven of the nine sites at which it was observed. The lugworm and *Macoma* co-occurred at seven sites. Sediments at all seven sites were some variant of sandy silt or silty sand. Although populations were observed at a few sites deemed to have high to moderate current intensity and moderate to strong wave action, the densest populations were observed at sites with moderate or weaker current intensity and moderate to weak wave action.

d) *Mya arenaria*

Mya is found only at relatively protected sites (especially inside embayments) in the lower inlet. It also was observed only at protected locations in the southern quarter of the upper inlet, i.e., at the Tuxedni site, at the northeast corner of Kalgin Island, and in the bight at the north end of Oldmans Bay (Kalgin Island; Table 4-2). Most other sites in the upper inlet, in which Tuxedni Bay is the only well-defined embayment, are exposed to the degree that they are somewhat scoured by ice and are not depositional. Snelgrove et al. (1999) found that settlement of *M. arenaria* was highest in sheltered areas, especially where adults were present in the sediments. Dunn et al. (1999) has shown that post-larval *M. arenaria* can be resuspended by relatively low velocity currents (~0.3 kts) and disturbance by activities of other large macroinfaunal organisms. Resuspension of post-larvae in areas of higher current velocities would result in removal of the post-larvae from the settlement area. It is likely that only protected areas are not routinely exposed to currents exceeding 0.3 kts in upper Cook Inlet. Thus, protection may be one of the important factors influencing the occurrence of *Mya*.

However, otherwise acceptable sites probably do exist in the upper inlet, e.g., the southern side of the West Foreland, and so it is likely that other factors are operating as well. These could include high turbidity, low water temperature, and reduced salinity, which are physical factors that could impose limits on survival and distribution of larval and adult stages. Thus, a model describing the distribution of infaunal (and epibiotic) organisms in the inlet also needs to incorporate tolerances to these physical factors as well as larval and adult longevity, behavior, and the potential effects of species interactions (esp. predation and bioturbation).

e) *Siliqua patula*

The razor clam, *Siliqua patula*, was only observed at near or below MLLW in fine sand or silty sand at 6 locations. Typically, in sediments where adults were observed (only Clam Gulch and Polly Creek), other species of bivalve were uncommon or absent (Table 4-2). Generally, only juvenile surf clams, *Mactromeris polynyma*, co-occurred with juvenile razor clams. The absence of adults at the four sites where juveniles were observed suggests that these locations are too unstable to support adult populations.

f) Burrowing Worms

The large burrowing nereid polychaete *Laonnates* sp. was observed in the mid (+13 feet MLLW) to upper intertidal (~+21 feet MLLW) zone at three sites characterized as erosional mud flats composed mainly of silt/clay. These sites have probably been slowly eroding since the 1964 Good Friday Earthquake. Populations of this worm construct abundant burrows along channels draining the mud flats (Figure 3-30c). These sediments are highly non-porous and retain water well. Thus it is likely the burrows are water-filled within a few cm of the surface.

5. General Patterns in Macroinfauna

Generally, sites on the east side of the upper inlet supported fewer taxa and lower standing stocks of macroinfauna than those on the west side or on Kalgin Island. Dominant macroinfaunal species were similar (the razor clam, *Siliqua patula*, the mud clam, *Macoma balthica*, and the lugworm, *Abarenicola pacifica*), but several species were observed on the west side of the inlet (the softshell clam, *Mya arenaria*, the tongueworm, *Echiurus echiurus alaskensis*, and the peanut worm, *Phascolosoma agassizii*).

This distinction between sites on the east and west sides suggests differences in some physical and/or biological resources, e. g, avenues of dispersion, recruitment constraints, physical disturbance, or nutrient availability. The clustering by exposure gradients within the west side sites suggests the natural selection of species responding to habitat pressures.

No macroinfaunal organisms were observed on the intertidal portions of any of the four shoals examined and the infaunal samples were extremely impoverished or empty. This condition agrees with that described by Morsell et al. (1983) for studies in Knik Arm. Based on their study, however, it is likely that mobile epibenthic crustaceans such as crangonid shrimp, mysids, and gammarid amphipods move into this habitat when it becomes immersed during higher tides.

Similarly to the sediment types, the distribution of averages for species richness and abundance (based on measured density estimates or conversions of qualitative abundance estimates) of the macroinfaunal assemblage at various locations appear strongly influenced by the hydrodynamic energy regime. Thus, species richness and macroinfaunal density are lower in sediments reflecting the extremes in hydrodynamic energy and higher in the more moderate areas (Table 4-3). Thus, diversity and density are lower in areas exposed to high or low (silty depositional areas) energy but higher in areas of moderate energy (correspondingly with coarser sediments). Similarly Bachelet and Dauvin (1993) reported that biomass was higher in sheltered beaches than on semi-exposed beaches. This pattern agrees generally with intermediate disturbance hypothesis described by Austen et al. (1998) and tested by Huxham et al. (2000). Because the sediment grades are driven primarily by hydrodynamic factors such as wave energy and current intensity, our findings support Huxham et al.'s contention that this pattern is driven more by physical rather than biological factors, at least in these mostly physically influenced habitats. However, although these organisms do appear to respond to the sediment type, this relationship is, to a degree, confounded or additionally influenced by other major environmental factors and, possibly, by biological factors.

Table 4-3. Relationship of numbers of target and total macroinfaunal taxa and estimated macroinfaunal density to sediment types.

ENERGY LEVEL
LOW → **HIGH**

Number of Taxa/ Sediment Type	Silt/Clay	Sandy Silt/Clay	Silty Fine Sand	Fine Sand	Fine/ Medium Sand
Target Macroinfauna	0.8	2.6	1.8	1.2	0.7
Total Macroinfauna	1.8	3.4	3.0	1.3	0.7
Estimated Overall Macroinfaunal Density	330	580	130	70	0.1

These distribution patterns suggest that strong currents on both flood and ebb tides stringently depress the ability of macroinfauna to establish and survive in sediments. The effect of periodic episodes of strong wave events of the intensity occurring in Cook Inlet is not as important as that of the strong tidal currents which occur four times daily. The consistency of the tidal currents, which, in areas such as the shoals, mix the sediment down to a depth of over 15 cm, makes it impossible for larvae to become established after settlement. Moreover, the low concentrations of organics and the high C:N ratio indicate that the upper few centimeters of sediments are systematically purged of detrital material making them poor sources of nutrition for deposit feeders. However, if boulders are present in the low intertidal zone, populations of some epifaunal organisms (e.g., the sea anemone ?*Urticina crassicornis* at Boulder Point and SE corner of Kalgin Island) can become established.

Ice scour and gouging are other episodic factors affecting the survival and distribution of macrofauna in Cook Inlet. They are probably only important in the upper inlet north of the East Foreland on the east side but, along the west side of the inlet, probably as far south as Cape Douglas (Lees and Houghton 1977; Lees et al. 1980). Ice effects are probably most important at sites where ice floes carried by tidal currents plow and bulldoze the intertidal and shallow sediments on each tide change. Strongly affected sites probably include all of the shoals, Beluga River SW, Moose and Boulder Points, the north side of West Foreland, the north side of Harriet Point, the NW and SE corners of Kalgin Island, and the NE corner of Chisik Island.

The contrast in the macroinfauna between the Chisik and Tuxedni sites may be quite revealing, especially with regard to the softshell clam, *Mya*. An understanding of the reasons why softshell clams are absent at the Chisik site but common 2.5 nm across the channel at the Tuxedni site would probably be enlightening. Moreover, the dense population of the burrowing spoonworm *Echiurus* observed at the Chisik site is replaced at the Tuxedni site by a burrowing sipunculid worm (*Phascolosome agassizii*). These were the only sites at which either *Echiurus* or *Phascolosoma* was observed in the upper inlet. The fact that *Echiurus*, which is normally found living with *Mya* in the lower inlet from Chinitna Bay south, did not occur at any other site suggests that conditions in the upper inlet are not suitable to one or more of its life stages.

In terms of sediment, morphology, and hydrodynamics, the two areas are quite different. The mud flat is somewhat lower at Chisik than at the Tuxedni spit (+2 to +4 feet vs. +7 to +8 feet); based on the reported vertical distribution of *M. arenaria* in lower Cook Inlet (Lees et al. 1980), however, it is not likely this difference is important. The substrate at Chisik has a large component of pebbles mixed into the mud and scattered patches of gravel and boulders. Both sites have a relatively thin (1 to 3 inches thick) layer of soft mud over well-compacted mud. At the Chisik site, the lack of conspicuous berm development indicates the beachface is either stable or slowly retreating. Because of its orientation, the Chisik site is directly exposed to storm waves from winter storms. Also it probably acts as a "catcher" beach and ice being driven by the northeasterly winds is carried onto the flats on outflowing ebb tides from of the north. It is likely this area amasses considerable quantities of ice from the upper inlet. This suggests that ice scour and plowing could be substantial in this area during the low stage of ebb tides in the winter.

These differences suggest that geomorphological processes differ considerably between the two sites. The lower elevation and the predominance of gravel in the sediment on the flat at Chisik suggest that it is not a depositional site. In contrast, the absence of gravel at Tuxedni spit and the fact that the mud flat is 4 to 5 feet higher suggest that substantial deposition occurs there. Moreover, it appears that sediments at the Chisik site are disturbed more frequently and intensely than at Tuxedni spit. From the viewpoint of succession, the infaunal differences suggest that *Mya*, which probably requires long undisturbed periods and represents the climax assemblage, cannot become established if the sediment is disturbed on an annual basis. In contrast, *M. balthica*, *Abarenicola*, and *Echiurus* appear to be able to deal with periodic disturbance.

6. Organic Particulates for Nutrition

The relationship between deposited organics and abundance of infaunal organisms has been recognized for decades (e.g., Pearson and Rosenberg 1978). Recently, Edgar (1999) and Hagberg and Tunberg (2000) observed a positive correlation between macrobenthic abundance and deposited organic detritus. Olabarria et al. (1998) reported that, next to grain size, organic matter is among the most important factor governing distribution and abundance of subtidal infaunal assemblages. Consequently, the paucity of organics in the sediments in upper Cook Inlet is an important consideration in explaining the distribution and abundance of infaunal organisms in intertidal sediments. In this regard, Bitter Soto (1999) reported that the C:N ratio was the second most important abiotic component determining species diversity (species richness and abundance) of infaunal assemblages in Costa Rica. This study also reported an inverse relationship between hydrodynamic rigor and organic matter and carbon.

7. Turbidity

Total Suspended Solids (TSS) loading is probably a significant problem for planktonic larvae as well as adult stages of macroinvertebrates in upper Cook Inlet. Moreover, the associated reduction in light transmittance is a limiting factor for most algae. Even on the west side of lower Cook Inlet, kelps are not found below –3 feet below MLLW and coralline algae extend only to about –10 feet below MLLW. It is likely that TSS clogs the gills of many suspension feeders, thus limiting their ability to grow or survive. Mortality and poor condition reported for *Mytilus trossulus* suspended for a month in Mussel Watch arrays during CIRCAC's early Environmental Monitoring Program (A. D. Little 1995). These observations support the hypothesis that the absence of mussels in most of upper Cook Inlet is at least partially due to the high TSS concentrations in the upper inlet. In contrast, the distribution of *Macoma balthica*, a deposit feeder, is apparently not limited by high concentrations of TSS.

8. Water and Air Temperature

Based on the distribution patterns for both *Macoma balthica* and *Mya*, low water temperatures in upper Cook Inlet are not important limiting factors. For example, MacGinitie (1955) reported finding both *M. balthica* and two species of *Mya* in sediments collected at Pt. Barrow.

Freezing during low tide in winter may be a problem for some of the macroinfaunal taxa but possibly not for *Mytilus trossulus*. *Mytilus edulis* has been reported to be capable of surviving freezing for a considerable period of time. Bourget (1983) reported that *M. edulis* from the St. Lawrence Estuary could survive temperatures of –20° C for 16 hours, i.e., considerably longer than a tidal exposure.

9. Reduced Salinity

If it is important at all, reduced salinity probably only affects the survival of planktonic larval stages of some of the macroinfaunal taxa (Thorson 1946). Low salinity is known to limit the distribution of many adult echinoderms (Boolootian 1966). Low salinity probably also limits the distribution of some of the worms and may reduce survival of worm larvae (e.g., Greenwald and Hurlbert 1993).

10. Life History and Longevity

Information on the larval and adult longevity of the macroinfaunal taxa observed in this region is sparse. Lees et al. (1980) suggested that *M. balthica* in lower Cook Inlet probably live up to 10 years. *Mya* is reported to live somewhat longer (7-12 years in New England (MacKenzie and McLaughlin (2000) and 7-17 years (Newcombe 1935)). The specimens of *Mya* observed during this survey were primarily older, larger specimens. Juvenile *Mya* were uncommon in either the visual surveys or in the infaunal samples. In light of Beukema (1992) observations on the effects of climatic variation on recruitment success for *Mya*, it is likely that recruitment varies considerably among years in upper Cook Inlet. These observations are consistent with those of Strasser et al. (1999), who reported that just a few year classes dominated the adult populations in the Wadden Sea. *Siliqua patula* has been reported to live at least 13 years (Weymouth et al. 1931).

We definitely had more than one year-class of *Macoma* so at least some of the mud is remaining there for a couple of years. However, *Macoma* is a relatively mobile clam compared to *Mya* and can probably tolerate plowing by ice as long as it is not crushed (Armonies and Hellwig-Armonies 1992). *Macoma* is often found buried several centimeters deep in sediments (e.g., Myren and Pella 1977) and is an active burrower in unconsolidated sediments. McGreer (1983) found specimens buried up to 25 cm in the sediment but indicated that most were in the upper 5 cm.

The various large worms (*Abarenicola*, *Echiurus*, and the sipunculid *Phascolosoma*, may live more than 5 years. For example, *Arenicola marina* has been reported to live at least 6 years in the Baltic Sea (Thorson 1957). Unfortunately, we didn't collect information that would reveal whether we were seeing only one, or more than one, year-class of the various large worms.

11. Settlement and Recruitment Success

Based on research by and several investigators, it appears that *Macoma balthica* is a very good colonizer. vander Veer et al. (1998) reported peak settlement densities of about 4300 per sq. m. in June in the Dutch Wadden Sea. We observed densities of up to 3,600 per sq. m. and over 1,000 per sq. m. at 4 sites during this study. The behavior of this bivalve after settlement may contribute considerably to its recruitment success (Beukema 1993). In the Wadden Sea, a large proportion of the new recruits redistributes twice during their first year. Initially they move shoreward but during the subsequent winter, they move to lower tidal levels. This strategy tends to allow the species to optimize available space over a broad range of tidal elevation and specialize on favorable elevations during different life stage.

Mya, with high fecundity, planktonic dispersal stages and life stages that lend well to unintentional transport by humans, a broad spectrum of habitat and food preference, tolerance of a wide range of environmental conditions such as salinity and temperature, longevity, and perhaps relatively large size, is also considered a good colonizer (Strasser 1998). Nevertheless, vander Veer et al. (1998) reported peak settlement for *Mya arenaria* was about an order of magnitude lower than in *Macoma* in the Wadden Sea. Considering the paucity of sites at which we observed juvenile and adult *Mya* (1 and 3, respectively) in the upper inlet, it seems plausible to suggest that this region is environmentally marginal for the softshell clam and that one or more physical factors approach or exceed the tolerance levels of one or more life stages. Alternatively, its infrequency of occurrence may be the result of the limited number of areas that provide suitable shelter from the hydrodynamic stresses that characterize most of the areas in the upper inlet.

12. Predation

Predation by crustaceans, bivalves, shorebirds, and some fishes can be an important limiting factor in distribution of infaunal species. vander Veer et al. (1998) found that juveniles and adults of a sand shrimp (*Crangon crangon*) consumed considerable quantities of post-larval bivalves but did not regulate bivalve recruitment. Based on beach seine and trawl sampling in Knik Arm, two species of the genus *Crangon* are known to be abundant in intertidal and subtidal sediments in upper Cook Inlet (Morsell et al. 1983). Moreover, the large isopod, *Saduria entomon*, for which we commonly observed tracks intertidally in the upper inlet, has been reported to prey on both newly settled and adult *Macoma balthica* (Ejdung and Bonsdorff 1992). Shorebirds also feed heavily on *M. balthica* during low tides in the upper inlet year-round (Robert Gill, US Fish & Wildlife Service, pers. comm.). During studies in 1998, he found extensive populations of the clam as far north as the Lowry River and analysis of shorebird gut contents indicated that *M. balthica* comprised >95 percent of the diet of Rock Sandpipers. Zwarts and Blomert (1992) reported that another shorebird (the knot *Calidris canutus* feeds heavily on *M. balthica* in the Wadden Sea in Europe year-round.

Dunn et al. (1999) have reported that in areas where *Macoma* density is high, its feeding and feeding activities may restrict successful recruitment by *Mya*. Brey (1991) further reported that, in areas of high density, the sum of the potential feeding area for the individuals of *M. balthica* in a population may exceed the available surface area by a factor of up to 3.2, implying that the intensity of predation on all recruiting species is intense, as well as between members of the population (intraspecific competition) and other species (interspecific competition). Densities of *M. balthica* in upper Cook Inlet are often as high as that reported in the Wadden Sea, suggesting that such competition is probably prevalent in this region as well.

13. Bioturbation

Several of the macroinfaunal species actively disturb and move through sediments. These types of bioturbation have varied effects (Widdicombe and Austen 1999). In addition to the effects noted above for *Macoma*, in areas where it moves to feed or in response to a parasite (Swennen 1969; Swennen and Ching 1974), it also functions as a sediment destabilizer (Widdows et al. 2000). Due to its burrowing and feeding activities, the lugworm *Abarenicola* acts as an "ecosystem engineer" (Riisgård and Banta 1998). Moreover, its feeding and burrowing activities are reported to cause declines in abundance of juvenile *Macoma* and *Mya* (Flach 1992).

14. Conclusions on Important Factors

Assemblages and populations in intertidal habitats are frequently driven primarily by physical factors such as temperature, emersion, or desiccation. The distribution and abundance of macroinfauna in upper Cook Inlet is apparently driven by a variety of physical, chemical, and biological factors, many of which are interrelated. These have been discussed in some detail above. A summary of these factors and the relationships between them is depicted in Figure 4-6.

Currents appear to be the most important, affecting physical and chemical properties of sediment as well as the ability of larvae to recruit or adults to survive. At sites that are exposed to strong tidal currents during both the ebb and flood stages (e.g., all of the shoals or Boulder and Moose Points), the fine particles comprising TSS are not able to remain settled on the bottom. They therefore pass through to less dynamic areas before becoming deposited on the sea floor. As a consequence of these currents, the intertidal sediment is intensely mixed, possibly to a depth of about a foot on the shoals.

Typically, these areas are also exposed seasonally to strong wave action associated with seasonal storms from the northeast, southwest, or both (e.g., shoals south of Kalgin Island). However, wave action is of secondary importance in this regard because it is sporadic. It can be catastrophic periodically but for deep burrowing organisms, is probably not important once they become established. Consider, for example, the dense populations of large burrowing Pismo and razor clams on the beaches of California and Washington, respectively, which are both exposed to much stronger wave action than any beaches in Cook Inlet.

As a consequence of the severe hydrodynamic conditions, it appears that organic particulates and post-larvae of infaunal organisms are largely swept out of these areas. The result is the severe impoverishment or absence of infauna that was observed on the shoals and at Boulder and Moose Points.

High deposition or erosion rates are important but are secondary effects of low or high current velocity. The occurrence of muddy or sandy substrate depends on the balance between the rate of input of material, the type of material (silt/clay or sand), and the intensity and frequency of physical disturbance. All locations are exposed to moderate or high TSS loads and thus have the potential, through deposition, to become muddy habitats (Sharma and Burrell 1970). Some areas are also exposed to considerable loads of coarser material, either from rivers or from erosion of bluffs, and thus have the potential to become sandy through deposition (e.g., Old Cannery Creek).

Sediment stability is important but, again, is a secondary effect of current velocity and/or wave action, as well as ice gouging. The mud in many locations appears to be a relatively constant habitat unless it gets plowed routinely by ice. Plowing, combined with some deposition, may be what accounts for the layer of poorly consolidated mud

Figure 4-6. Factor likely to play a role in the distribution and abundance of macroinfauna in upper Cook Inlet and suspected interrelationships.

over the well-consolidated mud. The more frequently it gets plowed, the deeper and less consolidated it is.

At the other extreme, at sites where currents or wave action are so mild that the suspended particulates become deposited at a rapid rate, sediments are too unconsolidated and unstable to support burrowing infaunal organisms. It is likely that such sediments (e.g., behind the sand spit at Moose Point) are too ephemeral for the development of assemblages of organisms that can tolerate such fine, unconsolidated sediment (e.g., *Nuculana* or *Yoldia*).

Availability of food is a critical issue. Upper Cook Inlet is an oligotrophic environment, i.e., it has low concentrations of organic matter in the sediment and probably in the water column. Nearly all of the organic matter is probably imported from other systems, either from terrestrial and riverine sources or from lower Cook Inlet. The combination of low concentrations of organic matter and high turbidity is probably one of the major reasons why suspension feeders such as the softshell clams and mussels do not occur in the upper inlet. It is likely that abrasion and gill clogging resulting from high TSS combined with the lack of phytoplankton for nutrition lead to very high mortality in most planktonic larvae and many adult suspension feeders. Other than *M. balthica* and *A. pacifica*, which are predominantly deposit feeders, most of the invertebrates in the upper inlet are mobile crustaceans that brood their eggs and release competent juveniles rather than planktonic larvae. Moreover, they are scavengers or detritivores rather than filter feeders.

Areas exposed to less extreme combinations of currents and wave action appear to offer better opportunities for infauna. The most abundant macroinfaunal organism, *M. balthica*, occurred equally well at sites exposed to both moderate or low ebb and flood currents and moderate or weak wave action but did not occur commonly at sites with strong currents or wave action. This pattern seems to apply well to the lugworm and the remaining taxa.

In the lower portion of the upper inlet, it is likely that *Mya* is an indicator of the climax assemblage in stable substrate (the redwood of the mud flats) and areas where it is absent are probably too disturbed to allow it to get started. On the sand flats, *Siliqua* and *Mactromeris*, both active diggers requiring sediments that can easily be liquefied in order to dig or rebury, appear to represent the climax community.

Farther north, where conditions appear to exclude these large bivalves, *M. balthica* and *A. pacifica* appear to represent the climax community. *Macoma balthica* typically lives a stationary life also moves around a mud flat when infected by a parasitic trematode. In the stationary mode, it feeds from a stationary position, and the feeding activities of the incurrent siphon create a stellate pattern in the mud surrounding its burrow. In the digging mode, it burrows laterally, leaving meandering tracks in the surface of the sediment. The lugworm feeds by ingesting sediment for the microbial flora and organic matter contained therein. It is therefore necessary that the sediment be somewhat unconsolidated rather than stiff and plastic like the underlying consolidated clay at most sites visited.

Migratory predators such as rock sandpipers, crangonid shrimp, and the large isopod *Saduria entomon* probably play a role in the recruitment success of the macroinfauna as well as in the survival of adults of species such as *M. balthica* and *A. pacifica*. In many of these substrates, once adult populations become established, they also exert a role in the ability of recruiting larvae to become established. *Mya*, *Siliqua*, and *Mactromeris* filter quantities of the larvae out of the water column. *Macoma balthica* vacuums recently settled post-larvae of many species from the surface of the sediment.

Most of the mud flats occur in the upper inlet, near the river sources. However, local deposits of mud occur south (in the lee) of promontories such as the West Foreland, Harriet Point, and Redoubt Point, or at the mouth of rivers/creeks such as the Kasilof River or Bishop Creek. In most of these muddy locations, *Macoma balthica* thrives. From our data, *M. balthica* was found only at sites where silt comprised from 66 to 98 percent of the sediments. One exception (where silt was only 24.5 percent) was Kalifornsky Beach; however, sediment sampling there occurred in a sandy creek delta surrounded by pure silt.

The rest of the inlet is categorized as current- or wave-swept cobble, pure sand, muddy sand, or a mix of all. The station cluster based on macroinfaunal presence/absence data (Figure 3-35) shows a simple breakdown of sites based on the presence of either the mud clam (*Macoma balthica*) or the razor clam (*Siliqua patula*); essentially a dichotomy of muddy versus sandy sites. The muddy sites then break down into subgroupings based on the presence or absence of various accompanying species such as lugworms (*Abarenicola pacifica*), softshell clams (*Mya arenaria*), or three rarer burrowing species (spoonworms (*Echiurus*), sipunculids (?*Phascolosoma agassizii*), or nereid polychaete worms (*Laonnates*)).

V. Summary and Conclusions

A. Sediment Conditions

The reasons for measuring particle grain size of the sediments is that the textures provide insight into the hydrodynamic regime and the types of animals that one might expect at a site. A broad, diverse range of sediment textures was observed, including silt/clay (at 5 sites), sandy silt/clay (5), silty fine sand (6), fine sand (6), and fine to medium sand (3). Textures are typically driven largely by the level of hydrodynamic energy impinging on each site. Thus, the sites examined represent a broad range of hydrodynamic conditions ranging from extremely harsh (daily currents up to 7 knots and periodic heavy wave action) to quite benign (allowing deposition of clay particles). Coarsest sediments were observed on the shoals and exposed beaches such as NW Kalgin, West Forelands North, Boulder Point, and Moose Point. Finest sediments were observed at the most protected sites, e.g., inside the sand or gravel spit at Moose Point or NE Kalgin Island, or at Bishop's Beach, Nikolai Creek, or West Foreland South. Typically, except at the exposed sites, sediments at most sites contained a large fraction of fine or very fine particles and even many of the sites with coarse sediments also had less rigorous areas where silt and clay predominated, either at lower elevations or behind a spit of some kind. On average, sites in the middle of the inlet (the shoals and Kalgin Island) generally had more coarse and less fine material than sites on the east or west sides.

Concentration of organic matter (Total Organic Carbon (TOC)and Total Kjeldahl Nitrogen) was typically low in sediments at the sites examined. Where an expected value for TOC in coastal sediments would range around 1percent the average in these sediments was 0.36 percent. At eight sites, TOC concentrations were depressed below 0.1 percent. The low levels of organics in the sediment indicate that the upper inlet is quite oligotrophic, i.e., does not produce its own food but instead relies on imported resources, and as a result, it is relatively starved for organic nutrients that feed many suspension feeders and deposit feeders. The average Carbon:Nitrogen ratio, which is both a measure of food quality and provides insight into the nature of the organics present, was relatively low (13.3:1) with several sites below 10:1. These values suggest that the organics are primarily in the form of bacterial films on sediment particles.

Concentrations of organics and the magnitude of C:N ratios are highly influential in the development of infaunal assemblages. The low concentrations of organics in the sediments and the low C:N ratios undoubtedly exert a strong influence on the nature of these assemblages and the abundance of the populations of organisms living in these habitats. Another consequence of the low concentrations of organics is that PAHs in the sediments would be more bioavailable to the organisms living in and on the sediments.

B. Sampling Potential and Biological Conditions

It appears to be generally true that, within the surveyed regions and intertidal limits, sampling is feasible. Sediments were firm enough (with the possible exception of the shoal west of Kalgin Island) and access practicable at all of the locations surveyed to permit at least limited sampling. Below the elevations at which we sampled, it is possible that sediments may become too unstable to sample.

At several locations, the intertidal shelf was so broad that practical sampling was restricted to the upper intertidal zone, adjacent to the point accessible by aircraft or wheeled vehicle. Nevertheless, most of these sites had adequate populations of a suitable sentinel species to support a monitoring program. Surveys on the Susitna Flats by Robert Gill (National Biological Survey, pers. comm.) for *Macoma balthica* extended as far north as the Lewis River and up to at least a kilometer offshore from the top of the beachface at several locations. While such a program is of high interest to CIRCAC's monitoring goals, the intensity of the sampling effort is impractical for CIRCAC's needs.

Sampling at some locations did not appear to be worthwhile because of the paucity of potential sentinel species or the ability of the sediments to hold potential hydrocarbon contaminants. Sampling worthiness of the sites that we examined, as based on the occurrence of adequate populations of potential sentinel species and organics in the sediment, is indicated in Table 5-1. Future sampling does not appear to be worthwhile at any of the locations where current intensity or wave action is high. The only site at which our data indicated it was not worthwhile to sample was Old Cannery Creek. Based on discussions with Robert Gill, however, it is likely that the populations of the mud clam (*M. balthica*) are richer at a lower tidal elevation (farther offshore) and therefore worthy of sampling. In view of this site's proximity to the Drift River loading terminal, however, the effort to sample that site at a lower elevation would probably be worthwhile.

Table 5-1. Sampling worthiness of the sites examined during CIRCAC reconnaissance survey in August-September 2000 based on occurrence of sentinel species.

WORTHWHILE	NOT WORTHWHILE
EAST SIDE OF INLET	
Clam Gulch	Boulder Point
Kalifornsky Beach	Bishop Beach
Chickaloon Bay	Moose Point
MIDDLE OF INLET	
SE Corner of Kalgin Is.	Shoal South of Kalgin Is.

Oldmans Bay, Kalgin Is.	Shoal West of Kalgin Is.
NE Kalgin Island	NW Kalgin Island
	Shoal North of Kalgin Island
	Middle Ground Shoal
WEST SIDE OF INLET	
NE Chisik Island	
No. Tuxedni Bay	
Polly Creek	
No-name Creek Beach	
Redoubt Creek	
Harriet Point North	Old Cannery Creek
West Foreland South	
West Foreland North	
Nikolai Creek	
Beluga River SW	

C. Potential Sentinel Species

The criteria used to identify the potential sentinel species were:

- proximity of populations to sources of hydrocarbon contamination as well as occurrence in remote reference areas;
- adequate abundance and biomass to support regular collection and to achieve low levels of detection in chemical analysis;
- a feeding mode providing considerable exposure to water-borne (dissolved or particulate) or floating contaminants; and
- ease in collection and dissection of tissues.

Species observed during the survey considered to be potential sentinel species included:

- the lugworm *Abarenicola pacifica*;
- the mud clam *Macoma balthica*;

- the softshell clam *Mya arenaria*;
- the mussel *Mytilus trossulus*;
- the razor clam *Siliqua patula*; and
- the surf clam *Mactromeris polynyma*.

The most suitable among these were the mud clam *Macoma balthica* and the lugworm *Abarenicola pacifica*, largely because both species are widely distributed in the upper inlet and common to abundant at sites near to oil production facilities. Neither, however, is a suspension feeder and so they are less sensitive monitors of hydrocarbon contamination than mussels or razor clams. Unfortunately, suspension-feeding sentinel species were not observed north of Kalgin Island.

D. Levels of Contamination

Sediments and tissues of three bivalves were subjected to intense hydrocarbon analyses. In general, the intertidal sediments were extremely clean, with TPAH values ranging from 0 in one of the replicates from the South Shoal (no PAH detected at a selected ion monitoring GC/MS MDL of 1.5 ppb) to 80 ppb in one of the replicates from Moose Point. Evidence of any petroleum hydrocarbon contamination in any of the intertidal sediments examined was absent, although occasionally PAH associated with combustion products were detected. Aliphatic hydrocarbons, as measured by total n-alkanes (TAlk) and total resolved constituents (TRC) at low method detection limits and were generally believed to be of biogenic origin. Traces of PAH derived from eroding peat were frequently encountered, and occasionally evidence of coal was detected.

In general, the intertidal organisms were extremely clean, with TPAH values ranging from no PAH detected in a mussel sample from Clam Gulch to 1,300 ppb in a *Macoma* sample from Redoubt Creek. Aliphatic hydrocarbons, as measured by total n-alkanes (TAlk) and total resolved constituents (TRC) were consistently higher in the tissue samples than the corresponding sediments. The majority of the constituents making up the TRC values were biogenic components that were ingested by the organisms or polar lipid-like materials that were not completely separated from the tissue extracts during fractionation and chromatographic cleanup prior to analysis. The TAlk appeared in many cases to include n-C 29, n-C 30, n-C31, and n-C32, which could be attributed to eroded peat that was apparently still present in the gut of the organisms in the sample. Interestingly, the tissue and surrounding sediment samples consistently produced completely different PAH and AHC profiles, indicating that, for the most part, we were not just looking at ingested sediment in the tissue samples and that the species are capable of particle selection. The intertidal tissue samples examined showed no signals of petroleum hydrocarbon contamination, although occasionally PAHs associated with combustion products were detected. Traces of PAH presumably derived from eroding peat were frequently encountered at those sites where higher levels of peat were observed in the sediments. However, no evidence of PAH derived from particulate coal was detected in any of the tissue samples.

By any measure, it is clear that the sediments contain only very low concentrations of hydrocarbons and the bivalve populations from which the tissues were collected have not been exposed to detectable concentrations of petroleum hydrocarbon contaminants. The major sources of the hydrocarbons detected in sediments and tissues appear to be eroded peat. A very slight signal of pyrogenic hydrocarbons (combustion products) was observed at a few locations. No evidence of Cook Inlet crude oil was observed in either sediments or tissues.

E. Factors Influencing Distribution of Long-lived Infaunal Organisms

The distribution and abundance of macroinfauna in upper Cook Inlet is apparently driven by a variety of physical, chemical, and biological factors, many of which are interrelated. The more important of these include:

- Intensity of currents and wave action;
- Turbidity;
- Suspended and deposited nutrition (phytoplankton, detrital matter, bacteria);
- Sediment texture and stability;
- Settlement and recruitment success; and
- Predation.

Currents, affecting physical and chemical properties of sediment as well as the ability of larvae to recruit or adults to survive appear to be the most important of these. At sites that are exposed to strong tidal currents during both the ebb and flood stages, neither the fine particles comprising TSS and organic particulates, nor larvae ready to recruit into the sediment are able to remain settled on the bottom. They therefore are transported on to less dynamic areas before becoming deposited on the sea floor. Moreover, this highly mixed sediment is too abrasive and nutrient-starved to support mature infaunal populations or assemblages. Typically, many of these high-energy areas are also exposed seasonally to strong wave action associated with seasonal storms from the northeast, southwest, or both, but, because this type of energy is sporadic, it is only of secondary importance. At the opposite end of the hydrodynamic energy spectrum, areas with little exposure to currents of wave action are depositional. In depositional areas with high sediment loads of glacial flour, the material is so fine and the deposition rates so great that few organisms can survive.

Areas exposed to less extreme combinations of currents and wave action appear to offer better opportunities for infauna. The most abundant macroinfaunal organisms occurred equally well at sites exposed to both moderate or low ebb and flood currents and moderate or weak wave action but did not occur commonly at sites with strong currents or wave action.

Availability of food is another critical issue. Upper Cook Inlet has low concentrations of organic matter in the sediment and probably in the water column. Nearly all of the organic matter is probably imported from other systems, either from terrestrial and riverine sources or from lower Cook Inlet. The combination of low concentrations of organic matter and high turbidity is probably one of the major reasons why suspension feeders such as the softshell clams and mussels do not occur in the upper inlet. It is likely that abrasion and gill clogging and a paucity of phytoplankton for nutrition lead to very high mortality in most planktonic larvae and many adult suspension feeders. Other than *M. balthica* and *A. pacifica*, which are predominantly deposit feeders, most of the invertebrates in the upper inlet are mobile crustaceans that brood their eggs and release competent juveniles rather than planktonic larvae. Moreover, they are scavengers or detritivores rather than filter feeders.

Migratory predators such as rock sandpipers, crangonid shrimp, and the large isopod *Saduria entomon* probably play a role in the recruitment success of the macroinfauna as well as in the survival of adults of species such as *M. balthica* and *A. pacifica*. In many of these substrates, once adult populations of most of the macroinfaunal organisms become established, their feeding and burrowing activities also exert control over the ability of recruiting larvae of all potential settlers to become established.

In summary, it appears the two primary factors affecting the distribution of intertidal infauna in Cook Inlet are the massive loads of silt being dumped from the northern river systems and the extreme tidal currents caused by the large tidal flux and the shape of the basin. Without the currents, Cook Inlet would be rapidly on its way to becoming the world's largest mud flat. *Macoma balthica* would flourish from Anchorage to Kodiak. And without the silt, Cook Inlet would be populated with razor and surf clams across the same range. Instead, we find an extreme range of habitats and a combination of animals appropriate to each.

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