Alaska
Fisheries Science
Center

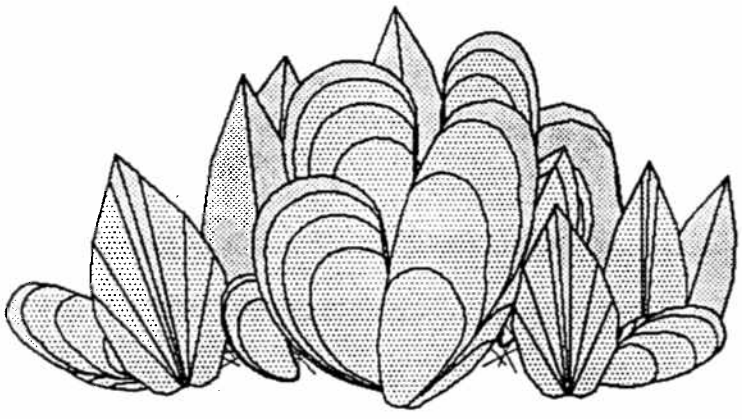
National Marine
Fisheries Service

U.S DEPARTMENT OF COMMERCE

AFSC PROCESSED REPORT 94-02

1991 and 1992 Recovery Monitoring and Restoration of Intertidal Oiled Mussel (*Mytilus trossulus*) Beds in Prince William Sound Impacted by the *Exxon Valdez* Oil Spill

May 1994



ERRATA NOTICE

This document is being made available in .PDF format for the convenience of users; however, the accuracy and correctness of the document can only be certified as was presented in the original hard copy format.

Inaccuracies in the OCR scanning process may influence text searches of the .PDF file. Light or faded ink in the original document may also affect the quality of the scanned document.

1991 and 1992
Recovery Monitoring and Restoration of Intertidal Oiled Mussel (*Mytilus trossulus*) Beds in Prince William Sound Impacted by the *Exxon Valdez* Oil Spill

by

Malin M. Babcock, Patricia M. Rounds, Christine C. Brodersen, and Stanley D. Rice

Auke Bay Laboratory
Alaska Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
11305 Glacier Highway
Juneau, Alaska 99801-8626

May 1994

Contents

List of Tables

List of Figures

EXECUTIVE SUMMARY

♦ The persistence of *Exxon Valdez* crude oil (EVC) in sediments underlying some dense mussel (*Mytilus trossulus*) beds in Prince William Sound (PWS), Alaska, began to cause concern in spring 1991. This crude oil could be a source of chronic hydrocarbon (HC) contamination to the mussels, which could be a source of continuing exposure to higher consumers through ingestion, notably birds and mammals, including humans. Staff from NOAA's Auke Bay Laboratory (ABL) and other Federal and State of Alaska agencies conducted surveys to examine the problem. This work was supported by the *Exxon Valdez* Trustee Council; the portion beginning in 1992 was Restoration Project R103. This report covers the work conducted by ABL that has also been submitted to the Trustee Council as the Interim Status Report of Restoration Project R103A.

♦ In 1992, staff from ABL sampled mussels and sediments from 64 mussel (*Mytilus trossulus*) beds in PWS to establish the presence or absence of EVC; examined within-bed variability of HC distribution in three oiled mussel beds; conducted site manipulations at three mussel beds to increase flushing action in underlying sediments; and measured the physiological health of mussels from oiled and unoiled beds by examining byssal thread production rates.

♦ The distribution of polynuclear aromatic hydrocarbons (PAH) in selected 1991 and 1992 sediments confirmed the presence of EVC underlying mussel beds. Gas chromatography/mass spectroscopy (GC/MS) data from sediments collected in 1992 show only moderate weathering, indicating that the dense mussel layers may provide a barrier to natural environmental dispersion and weathering of EVC.

♦ ABL used two methods for determining petroleum HC in sediments. A fast screening method, ultraviolet fluorescence (UVF), was used to estimate total petroleum hydrocarbons (TPH) in over 500 sediment samples. Selected sediment samples were then analyzed by GC/MS, a more complex, detailed, and costly procedure that provides quantitative profiles of aromatic and aliphatic hydrocarbon analytes. Mussels are still being analyzed for HC by GC/MS, and the UVF sediment data are being used to select mussels for GC/MS analysis from sites of particular interest.

♦ Sediments collected from 64 oiled mussel beds in PWS in 1992 were measured by UVF; 25 (39%) had TPH greater than 10,000 μg/g wet weight. The highest concentrations of oil were in sediments collected from Foul Bay (62,258 ± 1,272 μg/g wet weight TPH). Sampled oiled mussel beds ranged over the entire area of PWS impacted by the spilled oil (except for the extreme southwestern portion of PWS where none were identified by interested agencies as being of concern). Limited GC/MS analyses of mussels showed body burdens of PAHs up to 6.97 ± 0.95 μg/g dry weight.

♦ Sediment TPH, as measured by UVF, varied greatly within a bed; and TPH levels in sediments underlying dense mussel beds were significantly ($P < 0.05$) related to transect. Significant differences were also related to the depth of the sample, with TPH levels in the 0-2 cm layer consistently higher than in the byssal thread layer just above. Limited analytical data returned on GC/MS analyses of mussels confirmed that PAH levels in Chenega Island mussels sampled in May were highly variable within the bed, ranging from 0.09 to 6.02 μg/g dry weight, and trends in mussel concentrations were similar to trends in sediment concentrations. Mussels from the lower and middle transects had significantly higher PAH levels than mussels from the upper transect and bedrock, where concentrations were similar to those at a control site (Barnes Cove).

♦ Minimally intrusive site manipulations (removal of mussels from 30-cm wide vertical strips to promote flushing of oil) were conducted at three heavily oiled mussel beds in PWS. Although the data analyzed to date are insufficient to draw conclusions, petroleum HC levels tended to be reduced within the strip itself after 90 days. Evaluation of this technique and measuring changes in petroleum HC will continue in 1993.

♦ To assess physiological health of mussels, byssal thread production rates were measured on groups of mussels transported from PWS to ABL. We conducted two series of tests: 1) an inter-bed comparison of mussels from known oiled and unoiled beds, and 2) an intra-bed comparison of mussels from areas within two oiled beds with different concentrations of TPH in underlying sediments. Although preliminary analysis indicates that mussels from heavily oiled beds produce fewer threads in a 48-h period, byssal thread data are still being analyzed and companion HC data for mussels still have not been analyzed.

INTRODUCTION

The persistence of EVC underlying some dense mussel (*Mytilus trossulus*) beds in PWS began to cause concern in spring 1991 among scientists from federal and state agencies. The presence of this crude oil could be a source of chronic HC contamination to the overlying mussels, and thus a pathway for continued exposure to HCs through ingestion by higher consumers. Persistent, high concentrations of HC in mussels from oiled mussel beds may be a reason for continued reproductive failure of harlequin ducks in western PWS, damage to black oystercatchers, and higher than normal mortality of juvenile sea otters; all feed to some extent on mussels or other fauna associated with these beds. These contaminated beds are also of concern for human subsistence.

With the encouragement of the *Exxon Valdez* Restoration Team and the Trustee Council, staff from several federal and state agencies conducted a field survey and sampled mussels and underlying sediments from several sites in June 1991. Subsequent sampling of mussels and sediments in 1991 was conducted in conjunction with other NOAA field trips (Babcock 1991). These pilot surveys produced chemical data that confirmed the existence of substantial amounts of residual EVC in sediments immediately underlying dense mussel beds, and also in mussels. Surprisingly, this oil was relatively unweathered[1].

More extensive work to examine the problem of oiled mussel beds was supported by the *Exxon Valdez* Trustee Council beginning in 1992, as Restoration Project R103. This report covers the work conducted by ABL (Project R103A) through November of 1993; a version has also been submitted to the Trustee Council as the Interim Status Report of R103A (*Exxon Valdez* Oil Spill Trustees 1992).

The primary goal of Study R103A was to document the geographical extent of oiled mussel beds and the intensity of oiling of mussels and the underlying sediments/organic mat within PWS (Fig. 1). The National Park Service evaluated and sampled oiled mussel beds along the Kenai and Alaska Peninsulas, and their work is reported elsewhere (under Study R103B). This documentation provides chemical data to assess the possible linkage of oiled mussel beds with continued damage to harlequin ducks and black oystercatchers (R103C), and juvenile river otters (R103D). These data also provide the Trustees with information on the magnitude of the distribution of residual HC in intertidal sediments associated with dense mussel beds in PWS. These baseline data on oiled mussel beds will allow monitoring of natural or assisted recovery in areas with residual HCs from the *Exxon Valdez* oil spill.

Another goal was to intensively sample and conduct minimally intrusive manipulation of selected mussel beds (Fig. 2) to compare the chemical and biological recovery of these oiled beds with and without further treatment. This information is critical in deciding whether cleanup or removal of mussels is appropriate. Oiled mussel beds pose a significant and controversial management problem. Cleaning mussel beds could be labor intensive, and removal would be undesirable to many scientists and managers. Some biologists question the impact of removal of large quantities of mussels on food availability to some species, even if the mussels are oiled. Other biologists fear the impacts of oiled mussels from the oiled beds on sensitive life stages and reproductive events dependent on specialized behaviors. Partial removal of the beds (removal of strips) to enhance water circulation, flushing, and access to the substrate below packed mussel

[1]J. W. Short, National Marine Fisheries Service, Auke Bay Lab., 11305 Glacier Hwy., Juneau, AK 99801-8626. Pers. commun., 1993.

beds may remobilize oil and permit faster biodegradation. The feasibility of this action will be evaluated by the chemical and biological recovery of the mussels and chemical recovery from EVC in underlying sediments.

An additional purpose of this study was to examine the impact of chronic exposure to EVC on the health of the mussels themselves. To minimize costs associated with this goal, all field work was conducted during activities associated with the primary and secondary goals. The biological impacts of oiled sediments underlying these beds on mussels are unknown. Mussels fill too important an ecological niche for researchers to neglect the impacts of chronic exposure to EVC on them. Biological impacts were to be determined from byssal thread production rates, condition and reproductive indices, and histopathological evaluations. Byssal thread production rates should indicate the physiological condition of mussels. Histopathological evaluation should identify any morphological abnormalities and elevated incidence of disease, parasites, and lesions. Condition and reproductive indices should measure the health of a mussel bed. Byssal thread production rates were measured in 1992, and the other measurements will be done on samples collected in 1992. Condition and reproductive indices will be determined at ABL, and the histopathological evaluations will be conducted by a NOAA cooperator in 1993 and 1994.

In this report, we provide a summary of findings from the 1991 surveys and a synopsis of work conducted in 1992 on oiled mussel beds in Prince William Sound, Alaska.

OBJECTIVES

Objective 1. Document the intensity and geographic extent of oiled mussel beds in Prince William Sound, Alaska.

Objective 2. Determine variation in HC concentration in mussels and sediments and the correlation between concentrations in mussels and underlying sediments.

Objective 3. Determine the chemical and biological recovery of mussels and oiled mussel beds without treatment (natural recovery) and with treatment (partial removal of mussels and substrate to enhance natural flushing of HCs from contaminated beds).

STATUS

Findings in 1992, the first formal year of this study, confirm that oiled mussel beds exist in PWS and are widespread in the spill area, but that each site is relatively limited in size.

All sediments sampled for PWS survey purposes in 1992 have been analyzed by UVF, and data have been interpreted. Analysis by GC/MS of selected sediments and mussels is only partially completed, and the available data have not been subjected to principal component analyses (PCA) (Short and Heintz 1993). The same is largely true for sediments and mussels collected under Objectives 2 and 3.

All test mussels have been collected and their byssal thread production rates measured. Data will be examined when all chemical analyses of the mussels are completed. We suspect that the variability of byssal thread extrusion rates will be too great for credible correlations with HC body burdens; further tests are not anticipated. All appropriate associated tissue and sediment samples have been collected and are currently undergoing processing to prepare for HC analysis by GC/MS.

Samples have been collected for the other biological tests (reproductive and condition indices, and histopathological evaluation) of impact or recovery, but analysis has not begun.

METHODS

Objective 1. Intensity and Geographic Extent

Site Identification and Evaluation. In 1991, potential PWS intertidal areas with oiled mussel beds were identified primarily through two sources: 1) Alaska Department of Environmental Conservation's (ADEC) extensive Shoreline Assessment records, and 2) Alaska Department of Fish & Game (ADF&G) researchers on harlequin ducks. Mussel beds were visited, and mussels and underlying sediments were sampled if oil was present. Agency personnel from ADEC, ADF&G, Alaska Department of Natural Resources, U.S. Environmental Protection Agency, and ABL all participated in a June field survey to begin sampling these areas. Subsequent sampling of other oiled mussel beds was conducted later in 1991 in cooperation with other planned field studies by ABL (Babcock 1991). Thirteen oiled mussel beds were sampled in 1991.

We used the same two sources (ADEC and ADF&G) to identify potential oiled mussel beds in spring 1992, plus information provided by field investigators working under other associated studies, R103C and R103D (oystercatchers, river otters) (*Exxon Valdez* Oil Spill Trustees 1992). Actual sampling of sediments and mussels was conducted by ABL, ADF&G, and U.S. Fish & Wildlife Service during extensive field work.

Throughout this report, we use both general PWS location and Segment numbers to identify locations of these beds. Segment # refers to the code assigned to a specific section of shoreline within the EVC impacted area of PWS. This system was generated by the interagency Shoreline Cleanup Assessment Team (SCAT) during 1989 and 1990, and used to survey and evaluate oiling characteristics and status of cleanup[2]. Throughout this report, the term "site" refers to a particular mussel bed, identified by a geographic name or more specifically by its ADEC segment number. Where we sampled multiple oiled mussel beds within one ADEC segment, they are designated with a number following the segment number.

The sampled mussel beds ranged in size from approximately 20 m^2 for a small bed on Disk Island to 700 m^2 for the large bed on the tombolo adjacent to Eleanor Island. Density of mussels ranged from thinly interspersed (288/m^2) at Aguliak Island to multiple layers of mussels (5,000/m^2) at Eleanor Island.

Sampling Procedures. The primary criteria for sampling mussels and sediments were the presence of moderately to densely packed mussel beds on relatively fine sediments (i.e., <2 mm diameter) and the detection of crude oil by visual or olfactory methods. Mussel and sediment sampling was modified from methods developed by ABL in previous years (Babcock 1991; Karinen et al. 1993). A transect line, generally 30 m long and parallel to the water line (as topography allowed), was established through the middle of a mussel bed. The length of the transect lines varied according to size and topography and ranged from 10 m at a Disk Island site to 50 m at Foul Bay. At approximately every 3 m along the transect line, and within 1 m above and below the transect line, a small portion of mussels was overturned. Three pooled subsamples of sediment (0-2 cm deep) were collected by scooping sediment from each exposed location with

[2]W. Lane, Alaska Dep. Environ. Conservation, 4241 B St., Anchorage AK 99503. Pers. commun., September 1993.

a HC-free stainless steel spoon into each of three HC-free glass jars. Similarly, triplicate pooled samples of 20-25 mussels each were collected from the overturned portions and placed in three HC-free jars. All samples were immediately cooled, and frozen within 2-4 h.

Although sediments were sampled at all sites listed, mussels were not collected at some sites during the July and early August 1992 sampling because of lack of freezing capacity (Table 1). The more heavily contaminated beds identified during this period were revisited in late August and sampled for mussels and resampled for sediments.

This sampling procedure was designed to provide a minimum of three sample replicates that would show minimal variability in HC concentrations. Protocol was actively being developed in 1991 and set before field work in 1992 (see sample variability section in Discussion). Although pooled replicate sampling was conducted at most oiled mussel beds in both 1991 and 1992, other types of sampling did occur. "Spot" samples were taken at subsites (specific locations) in mussel beds wherever the within-bed distribution of oil was determined under Objective 2, including ABL stripped sites (Table 1), subsites in mussel beds used by ABL for unstripped comparisons, and at subsites manipulated under another project by ADEC (Bauer et al. 1992). These "spot" samples were not pooled for analyses.

Site information, such as date and time of sampling, location, visual and olfactory observations on oiling, and the presence of birds and mammals, was recorded. Where time permitted, density counts (using a 25 x 25 cm quadrat) of mussels at five or six locations along the transect line were also recorded.

Chemistry. Sediment and mussel samples collected in 1991, mussels collected in 1992, and selected 1992 sediment samples were analyzed by GC/MS (Larsen et al. 1992), and data reported here are sums of all PAHs. All samples analyzed by GC/MS are expressed in units of $\mu g/g$ dry weight; samples were extracted wet, and dry weights were determined afterward.

All sediment samples collected in 1992 were analyzed by UVF as adapted from Krahn et al. (1991, 1993) by Holland et al. (1992). This procedure, established at ABL in 1992 to rapidly and economically screen many samples, provided semi-quantitative data, which were then used to select samples for further analyses by GC/MS for quantitative measurements of HC analytes (Larsen et al. 1992). This screening did not measure individual analytes within a sample, but approximated TPH, allowing comparison of relative oil concentrations among samples.

For UVF screening, wet sediment samples were extracted twice with methylene chloride, then concentrated or diluted to match a calibration curve based on the EVC oil standard. These extracts were read with a high-performance liquid chromatograph equipped with a fluorescence detector. Excitation/emission spectra of the extracts were read at the phenanthrene wavelengths (260 nm/ 380 nm), and values were then calculated to estimate TPH based on the amount of phenanthrene in EVC (Holland et al. 1992). Data are reported as $\mu g/g$ wet weight TPH.

Data Analyses. Standard statistical data (means and standard errors) were calculated for all sediment samples analyzed by UVF. Regression analysis was done to compare samples analyzed by UVF and available data produced by GC/MS on the same samples (n = 10 only) (Fig. 3). There was good agreement (R^2 = 0.94) between the two analytical methods, which confirms the reliability of using UVF for screening purposes.

All GC/MS data for 1991 samples have been examined by PCA according to procedures developed under Natural Resource Damage Assessment (NRDA) Study Subtidal 8 (Short and Heintz 1993).

Objective 2. Within-bed Hydrocarbon Variation

Site Selection. We selected three oiled mussel beds to examine within-bed variability of petroleum HC distribution in mussels and underlying sediments at three depths: byssal layer attached to the mussels, sediments 0-2 cm deep immediately underlying the mussels, and sediments 5-7 cm deep. Potential sites were identified through ADEC's Shoreline Patrol Assessment records, information from other principal investigators, and examination of HC data from contaminated mussel beds sampled in 1991 (Table 2). A reconnaissance trip was conducted in spring 1992 to examine candidate sites for this study and for stripping under Objective 3.

The selected oiled mussel beds—Herring Bay (KN133A-1), Chenega Island (CH010B-2), and Eleanor Island (EL013A-2) (Fig. 2, Tables 1 and 3)—were among the largest, most dense, and most contaminated beds sampled to date under this project. These mussel beds ranged from 50 m^2 to 700 m^2 on gently sloping (<5%) beaches. Sediments beneath the mussels were gravel/granules underlain with sand/silt. Tidal range occupied by the beds was 0.1–1.7 m above mean lower low water. Mussels were a fairly uniform size (30-45 mm shell length) and were often evenly distributed throughout the beds. Mean densities were 1,900/m^2 at both Herring Bay and Chenega Island and 5,000/m^2 at Eleanor Island.

Experimental Design. Data collection from these sites was designed to allow comparison of within-bed HC distribution by sample matrix (mussel or sediment), sample transect (tidal height), sediment depth, mussel density, and sediment grain size.

To examine HC distribution within a particular oiled mussel bed, we sampled mussels and underlying sediments at specific subsites (0.25 m x 0.25 m) along transects parallel to the water (Fig. 4). The location of transects depended on bed size and topography; transects were generally 2–5 m horizontally and 0.1 m vertically from adjacent transects. At each sample subsite, separate samples of mussels, sediment attached to the byssal threads of the mussels, and sediment underlying that byssal thread-sediment mat (0-2 cm deep) were collected for HC analysis. Combined sediment samples (both byssal mat substrate and 0-2 cm sediment) were collected at some Eleanor Island subsites because coarseness of the sediment made collecting discrete byssal mat samples difficult. These same mussel beds were then stripped as described under Objective 3. Byssal layers, surface sediments, and mussels were also collected from Latouche Island, Bay of Isles, and Chenega Island unstripped beds. These beds were generally too small or irregular to sample on transects similar to the stripped beds. Sediments were collected at three or four spots representative of each bed. In all six beds, mussel density at each subsite was estimated by counting mussels in one-half of the subsite area. Additional mussels were collected from adjacent bedrock to compare their HC body burdens to those of mussels on contaminated sediments. This intensive sampling was carried out in May before site manipulations done under Objective 3. Deeper sediments (5-7 cm) were collected in August at all six beds.

Each mussel sample consisted of 20 individuals, and each sediment sample consisted of 8-10 scoops (approximately 200 g). All instruments used in sampling were HC-free. For deeper samples, separate HC-free spoons were used for removing overlying sediment and for taking the samples. Samples were placed in HC-free sampling jars and chilled until frozen—usually within 2-3 h.

Chemical and Physical Analyses. Chemical analyses are described under Objective 1. Grain size was determined for selected sediments using 63 μm, 250 μm, and 1 mm sieves.

Data Analyses. The TPH concentration data from Chenega Island bed (CH010B-2), collected in May, were analyzed initially by three-way ANOVA, treating sample transect, depth, and

distance from the bed's central axis. This analysis indicated that only transect affected TPH concentrations significantly. Differences between the two sediment depths at each subsite, apparent graphically, were masked by this approach. So data from Chenega Island and Herring Bay were analyzed with an unbalanced two-way split-plot analysis (Snedecor and Cochran 1956), where sample transects were treated as blocks, and the sediment depth as treatments.

At Eleanor Island, we did not obtain discrete samples at the two depths at enough subsites to permit split-plot analysis. Therefore, at Eleanor Island the effects of transect and depth were analyzed separately. A paired *T*-test examined the differences between concentrations at the two depths. A separate one-way ANOVA was run where transect was the treatment; TPH concentrations used in this analysis were from composite depth samples or were the mean concentrations of the two depth samples at each subsite.

For the smaller beds at Latouche Island, Bay of Isles, and Chenega Island (CH010B-3), TPH concentrations in the May byssal layer and surface sediments were compared with a one-way ANOVA. Additional one-way ANOVAs examined the relationship of concentrations at varying depths at the same subsite by comparing sediments collected in August at 0-2 cm and 5-7 cm at all six sites.

Available GC/MS data from Chenega Island mussels were analyzed with ANOVAs by transect when comparing within-bed samples to bedrock samples and by transect and distance from the central axis when only samples within the bed were compared. The relationships between mussel density and HC concentrations in underlying sediments at both depths and in mussel tissue were examined with ANOVA. All tests were considered significant at $P \leq 0.05$.

Objective 3. Manipulation and Biological Recovery

Site Selection. See preceding under Objective 2.

Experimental Design. The effects of removing a strip of mussels to facilitate flushing of HCs from a mussel bed were examined at the Chenega Island (CH010B-2), Herring Bay, and Eleanor Island sites. After intensive HC sampling of mussels and sediments was completed (Objective 2), a 30-cm-wide strip of mussels, together with the sediments attached to the byssal threads (to a depth of approximately 1 cm), was removed along each bed's central axis at right angles to the sample transects (Fig. 4). At the Chenega Island and Herring Bay beds, the strip extended completely through the mussel bed; at the large Eleanor Island bed, the strip extended from the seaward edge of the bed to 0.5 m upslope of the upper sample transect.

Surface sediment samples for HC analyses were collected 30 d (June) and 90 d (August) after stripping, and mussels were collected at 90 d. Initial sampling is described under Objective 2. Subsites sampled in June and August were immediately adjacent to the specific May subsites. The TPHs in samples collected after stripping were compared with initial concentrations to evaluate effectiveness of the manipulation.

Over the summer, HC concentrations in stripped beds were compared to concentrations in three unstripped beds to detect general changes not related to stripping. The unstripped beds—Latouche Island, Bay of Isles, and Chenega Island (CH010B-3)—were moderately to heavily oiled (Table 4). Samples were collected in June and August at subsites near those sampled in May. Means of TPHs at subsites in each bed in May were compared with TPH levels in June and August.

We monitored the manipulated beds to determine mussel stability along edges of strips, the movement of adults onto stripped areas, and the settling of juveniles on the strips. Photographs taken 30 d post stripping and at the end of the season recorded sedimentation and movement of mussels onto the strips. Density counts at sampling subsites in the strip provided some indication of reoccupation of the strips. Individual mussels were tagged with colored 0.3 cm x 0.7 cm tags at 0.5-m intervals along the initial margins of the strips, and their positions recorded on the two subsequent sampling trips.

Biological Recovery. To examine biological impacts of 3 years of exposure to elevated levels of petroleum HCs on mussels, we measured byssal thread production in mussels and collected samples for condition and reproductive indices of mussels.

Byssal Thread Production Tests. For the two experiments on byssal thread production (inter-bed comparisons and intra-bed comparisons), mussels were transported in insulated coolers (with *Fucus* spp. and artificial ice) from PWS to ABL the day they were collected. The total time that mussels were out of the water was less than 36 h.

At ABL, mussels were separated from each other by cutting threads with scissors (to prevent damage to byssal organs), cleaned with paper towels, sorted by size, and abraded slightly on one side with a scouring pad. They were glued to glass plates (20 cm x 30 cm), six mussels per plate, by scratching the plates with a diamond glass marker, applying two-part epoxy adhesive to the scratched points, pressing the abraded sides of the mussels gently into the adhesive, and leaving the plates flat for at least 15 min before placing them into water. Plates were held in racks each holding up to seven plates nearly vertically, about 4 cm apart. All mussels were oriented with siphons up. Racks of plates were maintained in fiberglass tanks (55 cm x 200 cm x 45 cm), oriented with plates parallel to water flow. Seawater was pumped continuously from Auke Bay, at approximately 2 l/min, at ambient temperature and salinity: 6-8°C and 30‰. Light was ambient, through large uncovered windows next to the tanks, in addition to normal laboratory fluorescent lighting which was on during standard workdays.

For both parts of this study, 48-h byssal thread production rates were monitored for each mussel. Rates were measured by cutting all existing threads from each mussel and counting new threads 48 h later (i.e., for a day–12 48–h count, byssal threads were actually cut at d 10 and counted at d 12). Threads were cut approximately in half, and the attached portions scraped from the glass. New threads were counted from the back side of each glass plate, where thread attachments were most clearly visible. Racks of mussels were removed from the water only long enough to count and cut byssal threads, and to re-glue any mussels that had come loose.

Mussels for the inter-bed comparisons were collected on 3 May from six PWS mussel beds considered oiled, and three beds considered unoiled (Fig. 2). Mussels and underlying sediments were also taken from each site for HC analysis and confirmation of oiled/unoiled status. Mussels were collected along a horizontal 30-m transect and from 1 m on either side of it and pooled. Sediment samples for HC analyses were collected as described under Objective 1. To avoid bias, mussels from all PWS sites were coded only by number.

For the inter-bed comparisons, 36 mussels (38–40 mm long) from each site were divided into three replicate groups of 12 mussels each and maintained in three replicate tanks. Additional mussels from each site (for periodic HC analyses) were held in plastic baskets in each tank. Counts of the preceding 48-h production of byssal threads were made on days 2, 4, 6, 8, 12, 16, 20, and 24. Mussels from each site were taken for HC analysis just before the mussels were introduced into the experimental holding tanks, and after 4, 8 and 16 d in the tanks. Each sample consisted of seven mussels from each of the three replicate tanks pooled into one HC-free sample

jar and immediately frozen. A terminal 24-d sample for HC analysis from each site was taken by removing all remaining mussels from the glass plates and freezing them in sample jars.

Mussels for the intra-bed comparisons were collected on 14 June from two oiled PWS mussel beds (Herring Bay and Chenega Island) and one unoiled control bed (Olsen Bay). At each oiled site, one of the four collection subsites was on bedrock, and the other three were on sediment in areas judged to have different levels of oil contamination in the underlying sediments. Samples of sediments were also taken from each subsite for analysis of HC content. Seventy mussels were collected from a 0.5 m x 0.25 m area at each subsite, and sediment samples were taken from the same area by lifting patches of mussels and scooping the top 2 cm of sediment directly below the byssal layer. Thirty-six mussels (34–40 mm long) from each subsite were divided into three replicate groups of 12 mussels each and maintained in three replicate tanks. Counts of the preceding 48-h production of byssal threads were made on days 2, 4, 6, 8, 10, 12, 16, 25, and 38. Samples from each site were taken for tissue HC analysis only once, just before the mussels were introduced into the experimental tanks.

Condition Indices and Histopathological Evaluation. Condition indices will be calculated for all mussels analyzed for HCs by methods developed by NRDA studies Subtidal 3 and CH1B (dry tissue weight/shell volume) and recommended by Crosby and Gale (1990). Mussels for reproductive/histopathology evaluation were collected from 16 mussel beds (Table 1; Fig. 2). Most samples were collected at intensively sampled sites in May, June, and August. Additional mussels on bedrock adjacent to intensively sampled beds were collected in August to examine possible differences between mussels on contaminated sediments and bedrock in the same area. Sixty mussels were collected per sample: 30 were frozen in the shell; the remaining 30 were shucked and fixed in buffered 10% formalin. Fixed samples will be examined histologically to determine gonadal developmental stage and the presence of histopathological and reproductive abnormalities; this work will be done by a cooperator in 1993 and 1994. Selected frozen mussels may be used to determine a gonadal index: dry weight of mantle tissue (site of most gonadal material) compared with whole body tissue dry weight (Natl. Res. Council 1980)

Chemical Analysis. Analyses are described under Objective 1.

Data Analysis. The effects of stripping on HC concentration were examined with a complete randomized block ANOVA of UVF surface (0-2 cm deep) sediment data for the three sampling periods in each bed. Data were blocked by transect. Changes in oil concentrations in surface sediment (0-2 cm) in the unstripped beds were examined by ANOVA with time as the independent variable.

Significance of differences between groups of mussels in the experiments on byssal thread production was determined by ANOVA on plate means, and by post-hoc tests.

RESULTS

Objective 1. Intensity and Geographic Extent

Both mussels and sediments from visibly oiled intertidal areas in PWS, 1991 and 1992, have substantial amounts of oil. All HC data from 1991 were analyzed by GC/MS and units are presented in μg/g dry weight of the sum of PAHs. Sediment samples collected in 1992 were screened by UVF and semi-quantitative estimates of TPHs are given in units of μg/g wet weight.

Too few mussel samples from the 1992 survey have been analyzed to date to make inter-year comparisons, and the data are not presented here.

1991 Sediments and Mussels. Sediments from a mussel bed on northeastern Chenega Island had the highest PAH levels found in 1991 (Table 2): 489.14 ± 32.13 μg/g dry weight (mean ± SE; measured by GC/MS), followed by the mussel bed on western Herring Bay (144.45 ± 144.03 μg/g). Concentrations of PAHs in deep sediments (4 - 6 cm) from a site in eastern Herring Bay were 86.20 ± 47.27 μg/g, but surface (0–2 cm) PAHs were only 0.22 ± 0.03 μg/g. Concentrations of PAHs ranging from 11 to 72 μg/g were shown in sediments from Bay of Isles, Eleanor Island, Flemming Island, Foul Bay, and Latouche Island. The remaining sites (Bainbridge Island, Disk Island, Evans Island, Elrington Island) had PAHs in sediments approaching background levels.

In mussels the highest PAH concentrations (Table 2) were from a small islet in Foul Bay on the western mainland (10.34 ± 2.85 μg/g), Bay of Isles (5.96 ± 1.10 μg/g), and northeastern Latouche Island (3.81 ± 1.28 μg/g). Concentrations in mussels from Disk Island and a mussel bed on the eastern side of Herring Bay were intermediate. Concentrations of PAHs approaching background levels were evident at the remainder of the mussel beds sampled in 1991.

The oil in sediments underlying the mussel beds in PWS was consistent with EVC; and the distribution of relative PAH concentrations in the Chenega Island and Herring Bay sediment samples collected during September 1991 (Fig. 5) was consistent with the distribution of corresponding PAHs in EVC.

1992 Sediments and Mussels. Sediments from 25 of 64 mussel beds sampled had TPH, as measured by UVF, >10,000 μg/g wet weight (Table 3; Fig. 6). The highest concentrations of oil were in sediments collected from Foul Bay (62,258 ± 1,272 μg/g), a small islet in Herring Bay that is a site of experimental manipulation and intensive sampling (30,726 ± 7,282 μg/g), a mussel bed on eastern Applegate Island (26,867 ± 1,924 μg/g), a bed on northern Knight Island (26,728 ± 820), and another experimental bed on northern Chenega Island (26,403 ± 3,448 μg/g).

Moderately contaminated sediments, 1,000–10,000 μg/g TPH, were documented at 25 mussel beds (Table 3), and sediments underlying 14 mussel beds showed concentrations <1,000 μg/g. The latter included sites established under the NRDA Coastal Habitat 1B study (Table 3), which were intentionally sampled to provide control data and were sites where data existed from previous years.

The relationship between HC concentrations in mussels and in the underlying sediments was tighter in 1992 than in 1991 (Fig. 7). There was virtually no correlation in HCs between mussels and underlying sediments in 1991.

The oil in sediments underlying the mussel beds in PWS in 1992, as in 1991, was consistent with EVC; and the distribution of relative PAH concentrations in the Chenega Island sediment samples collected during May 1992 (Fig. 5) was consistent with the distribution of corresponding PAHs in EVC.

The 1992 sediment from Chenega Island (a different, more densely settled mussel bed from that sampled in 1991) was relatively high in HCs and unweathered, indicating natural environmental processes were not efficiently removing HCs from underneath mussels. The prominence of the more highly methylated homologues in the 1991 samples compared with the 1992 sample indicates that EVC in the bed sampled in 1992 has undergone less weathering than that from the bed sampled in 1991.

Objective 2. Within-Site Variability

Concentrations of TPH in sediments, measured by UVF, varied greatly within the three intensively sampled beds. In the Chenega Island bed for example, TPH concentration at adjacent subsites along the same sampling transect differed by as much as three orders of magnitude (Fig. 8). This degree of variability was typical of sediments at both the bysal layer and 0–2 cm depths in all three beds.

Concentration variability was related to sample transect, sediment depth, and the interaction between these two factors. Variability was not related to sample distance from a bed's central axis (0 line in Fig. 4). The split-plot ANOVA of Chenega Island and Herring Bay concentration data and the one-way ANOVA of Eleanor Island data indicate that variability in surface sediment concentrations on the same transect was less than variability between transects. At Chenega Island and Herring Bay, concentrations on the lower two sample transects were significantly higher than those on the upper sample transect (Fig. 9). The reverse pattern was observed at Eleanor Island: sediments on the upper transect had a mean concentration more than 10 times higher than the mean for sediments on the lower transect.

There were significant differences in TPH concentrations related to depth at five of the six sites (Table 5). Byssal layer TPH concentrations were generally lower than those in the underlying surface sediments. These differences were significant in the Chenega Island, Herring Bay, and Bay of Isles beds. At Chenega Island and Herring Bay, where data allowed split-plot analysis of the effects of both transect and depth together, byssal layer concentrations were significantly lower than surface sediment concentrations on the middle transect in both beds and also on the lower transect in the Herring Bay bed (Fig. 10). Concentrations in deep sediments (5-7 cm deep) differed from concentrations at the other two depths at the six sites, but there was no consistent pattern (see Fig. 11 for distribution at unstripped sites).

Sediment grain size data have not yet been analyzed. Sediments at the Eleanor Island and Latouche Island beds were visibly coarser than those at Chenega Island, Herring Bay, and Bay of Isles beds. Byssal layer sediments were coarser than surface sediments at all six sites; grain size differences between surface and deep sediments were not apparent.

Concentrations of PAHs in Chenega Island mussels sampled in May were also highly variable within the bed, ranging from 0.09 to 6.02 μg/g dry weight. Although total PAHs in mussels was poorly correlated ($R^2 = 0.30$) with TPH (measured by UVF) in surface sediments at each subsite, trends in mussel concentrations were similar to trends in sediment concentrations (Figs. 12 and 13). Levels of PAHs were significantly higher in mussels from the lower and middle transects than in mussels from the upper transect and bedrock, where concentrations were similar to those at the control site (Barnes Cove).

Congruent samples of surface sediments and mussels have been analyzed by GC/MS at only six Chenega Island subsites to date. Levels of PAHs in sediments were over three orders of magnitude greater than in mussels at the lower sample transect (Fig. 13) and slightly higher at the middle transect. Within the bed, distance of sample subsite from the central axis had no effect on PAHs in mussels. Insufficient numbers of mussels from Herring Bay and Eleanor Island have been analyzed to date to describe mussel HC distribution in those beds.

Mussel density was fairly uniform throughout all three beds and showed no relationship to levels of contamination in sediments or mussels.

Objective 3. Manipulation and Biological Recovery

Chemical Recovery. There appears to be a decline in sediment HC loads after 30 and 90 d in the experimentally placed strips in the Chenega Island and Herring Bay beds but not in the Eleanor Island bed. Sediment TPH concentrations in the June and August samples from the stripped areas at Chenega Island and Herring Bay were lower than at all other subsites in their respective beds (this difference was significant at Chenega Island; Fig. 14). At subsites away from the strips, sampling time (day 0, 30, and 90) was not significant, indicating no change due to stripping. Surface sediment TPH concentrations in each of the three unstripped beds did not differ over the three sampling periods (Fig. 11).

Mussels collected in August have not yet been analyzed. Evaluation of stripping effects on mussel HC body burden is not yet possible.

Photos of the strips in June and August show movement of mussels onto the strip and increasing irregularity of strip edges. Mean mussel densities at strip subsites in June and August were about 33% of densities at other subsites. Movement onto the strip was most apparent at Eleanor Island, where dense mussels, two or three layers deep along the strip margins, sloughed into the strip in clumps. Data on movement of tagged mussels are available for all three beds only for the June sampling. Approximately 33% of the 90 mussels tagged in May moved more than 10 cm along the strip axis or at right angles to the strip. At Chenega Island and Herring Bay, the direction of movement was generally upslope and away from the strip; at Eleanor Island, it was upslope and toward the strip. Only 9% of the tags could not be found. No settlement of juvenile mussels or sediment erosion was observed in the strips.

Biological Recovery: Byssal Thread Extrusion Rates. The rate of byssal thread production varied over time for all groups in both the inter- and intra-bed comparisons. The patterns of increasing and decreasing rates were similar for all groups within a study, but the patterns for the two studies differed considerably from each other (Figs. 15 and 16). Because the rates for the different groups within a study changed little relative to each other over time, the mean rate for each group over the entire study period is used in the comparisons presented below.

In the inter-bed comparisons, mussels from the six oiled sites combined had a lower rate of byssal thread production than mussels from the three unoiled sites (Fig. 15). Individually, only three groups had a rate significantly different from the others ($P < 0.01$): Barnes Cove mussels had the highest rate, Olsen Bay mussels the second-highest, and Latouche Island mussels the lowest; none of the others differed significantly from each other.

Screening UVF measurements of HCs in sediments confirmed the oiled/unoiled status of the sites (Table 3). Barnes Cove and Olsen Bay sediments had extremely low TPH levels, and Chenega Island and Herring Bay had the highest levels. However, the HC concentration in each mussel bed (Table 3) and byssal thread production rates for mussels from those beds were not well correlated ($R^2 = 0.225$). The Latouche Island mussel bed was not among the most contaminated mussel beds. Bligh Island sediment HC measurements were not available for spring 1992; however, previously sampled sediments at this site were consistently typical of unoiled sites.

In the intra-bed tests, mussels from all the Chenega Island subsites produced more threads than mussels from any of the Herring Bay subsites (Fig. 16). This pattern would not be predicted from the TPH levels in sediments at the subsites; the three subsites on sediment at Chenega Island all had higher TPH concentrations than the three subsites on sediment at Herring Bay (Fig. 16). Within each site, rate of byssal thread production was not correlated with TPH concentration. Mussels from unoiled Olsen Bay produced only slightly more threads than mussels

from the most heavily oiled subsites, and fewer threads than the mussels from the Chenega Island bedrock subsite.

Analyses of HC body burdens for mussels from both the inter-bed and intra-bed tests have not yet been completed.

DISCUSSION

Mussels and sediments sampled under this study, in both 1991 and 1992, have produced among the highest concentrations of EVC seen in any mussels and sediments taken by all studies since 1989, the year of the oil spill. In sediments, TPHs over 62,000 μg/g wet weight (by UVF) were found at one site whereas PAH concentrations up to 11 μg/g dry weight (by GC/MS) were documented in mussels.

Based on the importance of dense mussel beds (on finer, unconsolidated substrates) as food for higher consumers and as a community and physically stabilizing influence in the intertidal area, the *Exxon Valdez* oil spill Interagency Shoreline Cleanup Committee intentionally avoided treatment or cleaning of these beds. These beds were not destroyed or cleaned, and, as an unanticipated consequence, they may be a source of chronic exposure to organisms inhabiting the near-surface and surface areas, thus providing a possible pathway for petroleum HCs to enter the food web for higher consumers.

Objective 1. Intensity and Geographic Extent

The geographic distribution (Figs. 1 and 2) of these highly contaminated mussel beds includes almost the entire area of PWS that was impacted by the *Exxon Valdez* oil spill. Sampled oiled mussel beds are bounded by Applegate Island and Foul Bay in the northwest, north Eleanor Island in the northeast, Bay of Isles on the east, and northern Elrington Island in the south. Most of the contaminated mussel beds we have located lie within the Knight Island group, an area particularly impacted by EVC. Extensive surveys were not conducted in the farthest southwestern portion of PWS. This portion of PWS was not identified as containing intertidal areas of concern when reviewing ADEC's Shoreline Assessment Patrol records, nor were any beaches in this area identified by principal investigators of consumer species as being a possible source of chronic contamination.

Weathering patterns of PAHs shown for Chenega Island and Herring Bay samples are consistent with those of EVC[1]. The weathering patterns of the 1991 samples are similar to those shown by Michel and Hayes (1993a) for a surface sediment sample taken in September 1991 (N13/2B—not associated with any mussel bed) from a sheltered, set-aside area in eastern Herring Bay.

Dense mussel beds may provide a protective layer against natural environmental and weathering processes in underlying sediments. Of the two different Chenega Island mussel beds sampled, one (CH010B-2, sampled in May 1992) had a fairly dense, evenly distributed layer of mussels (1,900/m^2) lying over the sediments, whereas the other (CH010B-1, sampled in September 1991) had a sparser, interspersed distribution of mussels. Although the sparser bed was in a more protected location than the denser one and was sampled nearly a year earlier, the prominence of the more highly methylated homologues in the sample indicates that the HCs from the sparser bed had undergone *more* weathering (Fig. 5). Indeed, the 1992 samples from the denser Chenega

Island mussel bed sediment appear to show less weathering than any of the PAH profiles shown by Michel and Hayes (1993a,b). This limited finding indicates that dense mussel beds act as armor, or protection, against weathering of oil-contaminated sediments.

The inherent variability in distribution of residual crude oil was confirmed by our intensive sampling of selected beds (also see results of our work conducted under Objective 2) and by incidental samples collected at depths of 5-10 cm at three mussel beds during regular survey sampling. At two of these mussel beds, oil concentration was significantly higher ($P < 0.01$) at the subsurface depths compared to surface sediment (Bay of Isles, 18,653 ± 3,791 vs. 1,764 ± 827 μg/g TPH; Herring Bay, 13,004 ± 37 vs. 5,473 ± 876 μg/g TPH), whereas at the mussel bed on Squirrel Island, surface sediments had higher PAHs than subsurface sediments (14,467 ± 913 vs. 3,499 μg/g). The patchiness of distribution of EVC is also shown by Michel and Hayes (1993a,b). There were also many references to subsurface "lenses" of oil throughout ADEC's Shoreline Assessment Patrol reports. The presence of subsurface lenses was also documented by Michel and Hayes (1993a,b). These lenses were not necessarily associated with mussel beds. Oil at depth is probably less available as a source of chronic exposure to surface-dwelling organisms than oil only 0-2 cm below the surface.

Although every effort was made to reduce sample variability among replicate samples collected from the same mussel beds, variability was high in many cases as reflected by relatively high standard error values (Tables 2 and 3). We have identified four possible sources of the high variability seen at some sites: 1) The sites identified as being studied intensively by ABL and ADEC were sampled by a "spot" method (i.e., each sample of mussels and sediments was taken from a particular subsite on these beds and samples were not pooled to reduce variability); 2) some mussel bed sediments were sampled at two different periods, and sediments sampled during the second period may not have been collected from exactly the same place on the bed; 3) sampling was conducted by numerous personnel from several agencies, and strict adherence to sampling protocol as outlined previously was not followed in all cases; and finally, 4) inherent variability exists in both horizontal and vertical distribution of residual crude oil within the beds themselves (also see Objective 2).

Objective 2. Within-bed Variability

We have demonstrated that EVC is distributed unevenly in sediments underlying dense mussel beds, both horizontally and by depth in substrate. Elevation had a significant effect on distribution of EVC in the sediments within a mussel bed.

Dynamics of floating EVC in the intertidal (nearshore) areas of PWS over multiple tidal cycles probably accounts for most of the uneven distribution of EVC in intertidal sediments. The semi-diurnal tidal cycle in PWS ranges from -1 m to +4.8 m above mean lower low water. Twice a day, mussel beds are alternately covered with seawater and then exposed to air—each for 5-7 hours. An incoming tide with floating EVC would strand the crude oil on a mussel bed during ebb tide. The elevation of this stranding depends primarily on the height of that particular tide. This EVC would then be vulnerable to surface evaporation and weathering, but more important to this discussion, this oil would infiltrate the mussels and byssal layer to the underlying sediments. The rate of infiltration would be influenced by weather conditions, wave energy, sediment grain size, and viscosity of EVC. Once EVC had penetrated the surface sediment layer, outside physical factors would become less important than gravity, grain size, and other interstitial conditions in further dissemination and/or remobilization of the crude oil. The physical presence

of the mussel layer may also retard remobilization of this infiltrated EVC, especially in areas of low wave energy, ensuring its persistence in sediments below the surface. Oil remaining on the surface would then be repeatedly remobilized during subsequent tidal cycles and redeposited during ebb tide in the same or other locations. The twice-daily remobilization and transport of EVC stranded at the mussel bed elevations allowed a wide area to be vulnerable to stranding and infiltration.

Effects of tides probably account for the significant effect of elevation on distribution of EVC. The intertidal elevations occupied by mussel beds are awash with seawater twice daily, whereas areas higher in the intertidal zone may not be inundated for extended periods. Deposited EVC could remain stranded in the higher intertidal areas up to 14 d if stranding occurred during a series of neap tides. The EVC stranded at higher elevations would be vulnerable to evaporation for a longer time than EVC deposited in the mussel beds, and often weathered to visible surface patches of asphaltene. Aerial exposure within the tidal elevation occupied by these mussel beds varied. For example, mussels in the upper portion of a bed (+2 m above mean lower low water) were exposed 50% of the time during May 1992 compared with 6% for mussels at 0 m. Oil stranded in the higher portion of a bed would have been subject to evaporation and remobilization by wave action more often than oil stranded in the lower part, contributing to higher concentrations of oil at lower elevations within the Chenega Island and Herring Bay beds.

Hydrocarbon levels in the Eleanor Island mussel bed, where the upper sample transect had higher HCs than the lower transect, may reflect the partial cleanup on this beach of the lower portion of the mussel bed.

Other physical factors probably also influence the uneven ("patchy") occurrence of EVC under the mussel beds: vagaries of localized currents, weather, temperature, beach topography, and the length of time floating EVC was present in the nearshore areas. This dynamic process of tidal remobilization and redeposition of oil probably continued for at least 4-6 months after grounding of the *Exxon Valdez* on 24 March 1989.

Discussion of HC distribution related to sample transect and depth must also consider sediment grain size. In beds with coarser sediments (Eleanor and Latouche Islands), the highest concentrations of total oil in the bed were at a depth of 5-7 cm. In finer textured beds (Chenega Island, Herring Bay, and Bay of Isles), highest concentrations were in the surface sediments (0-2 cm). In all intensively sampled beds, byssal layer sediments tended to be coarser and less contaminated than surface sediments. The fine surface sediments at Chenega Island, Herring Bay, and Bay of Isles provided more surface area for oil adsorption than coarser sediments in other beds (Wade and Quinn 1980) and tended to be anoxic, which would retard microbial degradation of the oil (Delaune et al. 1980). We used UVF data from two sampling periods (May and August) in depth comparisons because ANOVA of surface sediment concentrations at all intensive sites showed no change over the summer; sediments at the other depths were assumed to be as consistent.

The generally similar distribution pattern of total PAHs in mussels and in sediments within the Chenega Island bed (Fig. 13), rather than a strong correlation at each subsite, supports findings that filter feeders take up organic contaminants from sediment primarily by an indirect route via the surrounding water (Roesijadi et al. 1978; Pruell et al. 1986). Results from NRDA Project Air/Water 3 suggest that the source may be ingestion of oiled particulates, rather than dissolved HCs (Short and Rounds 1993). The similarities in distribution pattern also suggest that oil released into the water from oiled sediments does not disperse widely and has little impact on mussels in cleaner parts of the bed or on adjacent bedrock. At beds that were less protected

(Eleanor and Latouche Islands), a more diffuse dispersion of oil throughout the water filtered by the mussel bed is probable. Completion of mussel analyses will provide more data related to sediment and mussel HC concentrations.

Objective 3. Manipulation and Biological Recovery

Stripping. Reduction of surface sediment HC concentrations in the Chenega Island strip is likely. Sediments from the strip sampled after 30 and 90 days had significantly lower TPH concentrations than the rest of the bed. More sheen was observed at the bottom of the Chenega Island and Herring Bay strips at 30 and 90 days than was seen before stripping, indicating that buried oil became more mobile in the bed after stripping. More conclusive is the lack of effect at subsites outside the strip, where sediments continued to be insulated by mussels from flushing.

The variability of HC distribution within mussel beds is also relevant to the monitoring of concentration changes in all the stripped beds. Subsites sampled in June and August were intentionally not identical to each other or to the May subsites to prevent influence of prior sampling. Given the high within-bed variability of HC distribution over short distances (Figs. 8 and 9), changes in concentrations due to stripping may be hard to detect.

The effect of stripping on mussel HC body burden is speculative until mussels collected in August have been analyzed. Given that concentrations in sediments outside the strips remained fairly uniform after stripping and that body burdens in May mussels corresponded to sediment concentrations (Objective 2), August body burdens could be expected to be similar to those in May. If any changes in HC body burden are detected, elevated burdens are possible because of increased mobility of oil due to stripping.

The movement of mussels onto strips and only little erosion in the strips indicate that stripping does not destroy mussel bed structure and function. Even at the Chenega Island and Herring Bay beds, where movements of individually tagged mussels suggest that most mussels along strip margins moved away from the strips, enough mussels moved onto the strip to stabilize strip sediments. There is some indication of sediment deposition in the Eleanor Island strip; we found a second layer of mussels 5 cm deep under sediment in the strip when we collected deep sediment samples in August. These sediments may have been deposited by a storm that dislodged mussels along the western and northern margins of the bed. The stability of mussels and sediments in the strips, after subjection to winter storms, will be revaluated in 1993. Few juvenile mussels settled onto the bare strips, probably because juveniles usually recruit to adult byssal threads and because settlement rate is lower on soft sediments than on other substrates (McGrorty and Goss-Custard 1991). Mobile oil in the beds also may have discouraged juvenile settlement (Nelson 1982), or local currents may have been unfavorable.

Final evaluation of the efficacy of stripping must await analysis of 1993 HC samples. Despite moderate mussel density on the strips at 90 d and probable further sloughing of mussels and sediments onto strips, further reduction of sediment HCs could be expected in the strips, as a result of winter storm activity. Present sediment HC data indicate, however, that restoration measures will have to be more intrusive to reduce present levels of contamination throughout a bed. Removal of all contaminated mussels and sediment has been proposed as a restoration measure, but this would, of course, destroy the beds. An alternative that would maintain the bed integrity is the creation of multiple narrow strips or stripped patches and the transplanting of stripped mussels to nearby clean sediments. (Feasibility of transplanting was examined last year on a small scale by ADEC and NOAA.) Transplanted mussels on clean substrates would

depurate, providing a cleaner food source for predators. Mussels remaining in the bed would prevent sediment erosion, would reoccupy stripped areas as HC concentrations in strips decreased, and would provide settlement substrate for juveniles. If HC concentrations remain high in unstripped areas, those areas could be stripped once mussels in areas already manipulated become well established, probably the following year. This strip/transplant approach would be less labor intensive than transplanting a whole bed or replacing contaminated sediments with clean sediments.

Biology, Byssal Thread Extrusion Rates. The overall pattern of lower rates of byssal thread production in mussels from the oiled sites than in mussels from unoiled sites confirmed the observation (Carr and Reish 1978) that oiling inhibits byssal production. Reduced output of byssal threads not only indicates reduced condition of the mussels, it poses a direct risk to a mussel population. Byssal threads are vital to preventing mussels from being washed away. Almost one-half of the oiled Eleanor Island mussel bed was eroded away during winter 1992; the effect of oiling on byssal thread production may have been a contributing factor.

When mussels from four subsites in each of two oiled mussel beds were compared, between-bed differences were greater than within-bed differences, despite the differences in TPH concentrations measured in the sediments from each subsite. This probably indicates that mussels take up HCs from the water around them rather than from the sediments beneath them, and therefore the mussels within a bed carry more uniform HC concentrations than the sediments do.

Several questions remain to be answered about the results of the byssal thread production rate test. We do not know why all tested groups of mussels varied in their production rates so uniformly with time. Temperature affects byssal thread production (Glaus 1968), but temperature does not explain the observed rate changes. An undetermined environmental variable probably caused the fluctuations; experiments to be completed in 1993 with uncontaminated local mussels may determine the cause. There is no obvious explanation for the anomalously low thread production by mussels from the unoiled Bligh Island and moderately oiled Latouche Island mussel beds, or for the low correlation between the measured degree of oiling in specific beds and the thread production rates of mussels from the beds. We do not yet know how closely byssal thread extrusion rates reflect the body burdens of HCs in the mussels. Analyses of mussels from these tests (which are currently being processed) will answer that question and may shed light on the others.

ACKNOWLEDGMENTS

This study was partially funded by the *Exxon Valdez* Oil Spill Trustee Council under Restoration Study 103. We relied on the help of many to fulfill the objectives of this study in 1992. Mark Brodersen and John Bauer, ADEC, assisted in providing both access to ADEC's field notes and transportation during one field trip to PWS. Sam Patten, Dan Gray, and Michael East of ADF&G, and Brad Andres of U.S. Fish and Wildlife Service identified and sampled potential oiled mussel bed sites. ABL personnel who assisted in our field effort were Adam Candeub, Mark Carls, Scott Feldhausen, Dan Fremgen, Debbie Shosteck, and Bruce Wright. Andy Gunther of Applied Marine Sciences also helped in our sampling program. Mark Carls, Adam Moles, and Michael Murphy of ABL and Andy Gunther and Robert Spies of Applied Marine Sciences reviewed and edited the report for submission to the Trustee Council. We are grateful to all.

CITATIONS

Babcock, M. 1991. Hydrocarbon analyses of mussels and substrates/sediments collected from Prince William Sound, 1991: A special survey of oiled mussel beds. Report to the *Exxon Valdez* Oil Spill Trustee Council. U.S. Dep. Commer., Natl. Mar. Fish. Serv., Auke Bay Lab., 11305 Glacier Hwy., Juneau, AK 99801-8626, 3 p. + tables.

Bauer, J., W. Ghormley, and P. Montesano. 1992. Oiled mussel feasibility study interim report. Internal document. Oil Spill Response Center, Alaska Dep. of Environ. Conserv., 4241 B Street, Anchorage, AK 99503, 8 p. + appendices.

Carr, R. S., and D. J. Reish. 1978. Studies on the *Mytilus edulis* community in Alamitos Bay, California: VII. The influence of water-soluble petroleum hydrocarbons on byssal thread formation. Veliger 21:283-287.

Crosby, M. P., and L. D. Gale. 1990. A review and evaluation of bivalve condition index methodologies with a suggested standard method. J. Shellf. Res. 9:233-237.

Delaune, R. D., G. A. Hambrick, III, and W. H. Patrick, Jr. 1980. Degradation of hydrocarbons in oxidized and reduced sediments. Mar. Pollut. Bull. 11:103-106.

Exxon Valdez Oil Spill Trustees. 1992. *Exxon Valdez* oil spill restoration. Vol. II: 1992 draft work plan. *Exxon Valdez* Oil Spill Trustees, 645 G St., Anchorage, AK 99501, 57 p.

Glaus, K. J. 1968. Factors influencing the production of byssus threads in *Mytilus edulis*. Biol. Bull. 135:420.

Holland, L., J. Grosenbeck, M. Larsen, and J. Short. 1992. Standard operating procedures for the fast screening analysis of oil in sediments using HPLC fluorescence detection. Internal document. U.S. Dep. Commer., Natl. Mar. Fish. Serv., Alaska Fish. Sci. Cent., Auke Bay Lab., 11305 Glacier Hwy., Juneau, AK 99801-8626.

Karinen, J. F., M. M. Babcock, D. W. Brown, W. D. Macleod, Jr., L. S. Ramos, and J. W. Short. 1993. Hydrocarbons in intertidal sediments and mussels from Prince William Sound, Alaska, 1977-1980: Characterization and probable sources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-9, 69 p.

Krahn, M. M., G. M. Ylitalo, J. Buzitis, S.-L. Chan, U. Varanasi, T. L. Wade, T. J. Jackson, J. M. Brooks, D. A. Wolfe, and C.-A. Manen. 1993. Comparison of high-performance liquid chromatography/fluorescence screening and gas chromatography/mass spectrometry analysis for aromatic compounds in sediments sampled after the *Exxon Valdez* oil spill. Environ. Sci. Technol. 27:699-708.

Krahn M. M., G. M. Ylitalo, J. Joss, and S.-L. Chan. 1991. Rapid, semi-quantitative screening of sediments for aromatic compounds using sonic extraction and HPLC/fluorescence analysis. Mar. Environ. Res. 31:175-196.

Larsen, M., L. Holland, D. Fremgen, J. Lunasin, M. Wells, and J. Short. 1992. Standard operating procedures for the analysis of petroleum hydrocarbons in seawater, marine sediments, and marine faunal tissue at the Auke Bay Laboratory. Internal document. U.S. Dep. Commer., Natl. Mar. Fish. Serv., Alaska Fish. Sci. Cent., Auke Bay Lab., 11305 Glacier Hwy., Juneau, AK 99801-8626.

McGrorty, S., and J. D. Goss-Custard. 1991. Population dynamics of the mussel *Mytilus edulis*: Spatial variations in age-class densities of an intertidal estuarine population along environmental gradients. Mar. Ecol. Prog. Ser. 73:191-202.

Michel, J., and M. O. Hayes. 1993a. Persistence and weathering of *Exxon Valdez* oil in the intertidal zone—3.5 years later. P. 279-286 *in* Proceedings, 1993 Oil Spill Conference. API publ 4580. Am. Petrol. Inst., 1220 L St. NW, Washington, DC 20005.

Michel, J., and M. O. Hayes. 1993b. Evaluation of the condition of Prince William Sound shorelines following the Exxon Valdez oil spill and subsequent shoreline treatment. Vol. 1. 1991 geomorphological shoreline monitoring survey. U.S. Dep. Commer., NOAA Tech. Memo. NOS ORCA 67. Seattle, WA, 94 p.

National Research Council. 1980. The International Mussel Watch. Natl. Academy Sci., Washington, DC, 248 p.

Nelson, W. G. 1982. Experimental studies of oil pollution on the rocky intertidal community of a Norwegian fjord. J. Exp. Mar. Biol. Ecol. 65:121-138.

Pruell, R. J., J. L. Lake, W. R. Davis, and J. G. Quinn. 1986. Uptake and depuration of organic contaminants by blue mussels (*Mytilus edulis*) exposed to environmentally contaminated sediment. Mar. Biol. 91:497-507.

Roesijadi, G., D. L. Woodruff, and J. W. Anderson. 1978. Bioavailability of naphthalenes from marine sediment artificially contaminated with Prudhoe Bay crude oil. Environ. Pollut. 15:223-229.

Short, J. W., and R. A. Heintz. 1993. Qualitative and quantitative determination of *Exxon Valdez* crude oil in sediment samples using principal component analysis of hydrocarbon data. P. 63 *in Exxon Valdez* Oil Spill Symposium, Abstract book. *Exxon Valdez* Oil Spill Trustee Counc., Anchorage, AK.

Short, J. W., and P. M. Rounds. 1993. Petroleum hydrocarbons in caged mussels deployed in Prince William Sound, Alaska, after the *Exxon Valdez* oil spill. *Exxon Valdez* Oil Spill State/ Federal Natural Resource Damage Assessment Final Reports; Air/Water 3. U.S. Dep. Commer., Natl. Mar. Fish. Serv., Auke Bay Lab., 11305 Glacier Hwy., Juneau, AK 99801-8626.

Snedecor, G. W., and W. G. Cochran. 1956. Statistical methods applied to experiments in agriculture and biology, 5th ed. Iowa State Univ. Press, Ames, 534 p.

Wade, T. L., and J. G. Quinn. 1980. Incorporation, distribution and fate of saturated petroleum hydrocarbons in sediments from a controlled marine ecosystem. Mar. Environ. Res. 3:15-33.

TABLES

Table 1.—Summary of type of sampling on oiled mussel beds, Prince William Sound, Alaska, 1991 and 1992. Legend: HCs = samples for hydrocarbon analyses; St/Un = stripped/unstripped beds; Bys Thr = mussels used in byssal thread production tests; HstoPath = mussels sampled for various indices and histopathology; segment # "1-5" = multiple oiled mussel beds on one segment, and "S or D" = surface (0-2 cm) or deep (>4 cm) sampling on same bed; Sed = sediments; Mus = mussels.

Location	Segment #	Agency/ Comments	—1991— —HCs— Sed	Mus	—1992— —HCs— Sed	Mus	St/ Un	Bys Thr	Hsto Path
Aguliak Island, N	AG001A	ADF&G			x	x			
Aguliak Island, S	AG009	NOAA/ADF&G			x				
Applegate Island	AE005A	ADF&G			x				
Applegate Island	AE005B	NOAA/ADF&G			x	x			
Barnes Cove, Knight Is.	KN575A	NOAA CH1B site		x	x	x		x	x
Bainbridge Island	BA006C	NOAA	x	x					
Bay of Isles	KN136A-1	NOAA	x	x		x			x
Bay of Isles	KN136A-2	NOAA/Un			x	x	x	x	x
Bay of Isles	KN004A-D	NOAA/ADF&G			x				
Bay of Isles	KN004A-S	NOAA/ADF&G			x	x			
Bay of Isles, SE	KN207B	ADF&G			x				
Bay of Isles, W	KN203A	USFWS			x	x			
Bay of Isles, Islet	KN016A	USFWS			x	x			
Bay of Isles, W	KN005A	USFWS			x	x			
Bay of Isles, S. Arm	KN205B	NOAA CH1B site	x	x	x	x			x
Bligh Is., West Bay	none	NOAA CH1B site	x	x		x		x	
Chenega Island	CH009-1	NOAA			x	x			x
Chenega Island	CH009-2	ADF&G			x				
Chenega Island	CH009-3	NOAA/ADF&G			x	x			
Chenega Island	CH010B-1	NOAA	x	x	x	x			x
Chenega Island	CH010B-2	NOAA/Stripped			x	x	x	x	x
Chenega Island	CH010B-3	NOAA/Un			x	x	x	x	x
Chenega Island	CH011A	ADF&G			x				
Crab Bay, Evans Is.	EV500A	NOAA CH1B site		x	x	x			
Crafton Island	CR004A	ADF&G			x				
Crafton Island	CR005A	ADF&G			x				
Disk Island, W	DI066A	NOAA/ADF&G			x	x			
Disk Island, NW	DI067A-1	NOAA			x	x			
Disk Island, NW	DI067A-2	ADEC			x	x			
Disk Island, NW	DI067A-3	ADF&G			x				
Disk Island, NW	DI067A-4	NOAA/ADF&G	x	x	x		x		
Disk Island, NW	DI067A-5	NOAA/ADF&G			x	x			x
Disk Island, NE	DI059A	NOAA/ADF&G			x	x			

Table 1.—(Continued).

Location	Segment #	Agency/ Comments	—1991— —HCs— Sed	Mus	—1992— —HCs— Sed	Mus	St/ Un	Bys Thr	Hsto Path
Eleanor Island, SW	EL015A-1	ADF&G			x				
Eleanor Island, SW	EL015A-2	ADF&G			x				
Eleanor Island, SW	EL015A-3	NOAA/ADF&G			x	x			
Eleanor Island, W	EL013A	NOAA/Stripped	x	x	x	x	x	x	x
Eleanor Island, W	EL011A	USFWS			x	x			
Eleanor Is., NW Bay	EL052A-2	ADF&G			x				
Eleanor Is., NW Bay	EL052A-1	NOAA/ADF&G			x	x			
Eleanor Is., NW Bay	EL052B	ADF&G			x				
Eleanor Is., NW Bay	EL054A	NOAA			x	x			
Elrington Is., Fox Farm	ER007A	NOAA CH1B site		x	x	x			
Elrington Island, NE	ER020B	NOAA	x	x	x	x			
Evans Island, W	EV017	NOAA	x	x					
Evans Island, E	EV900	NOAA	x	x					
Evans Is., Bishop Pt.	EV036A	NOAA			x	x			
Fleming Island, W	FL004A	NOAA	x	x	x	x			
Foul Bay	MA002C	NOAA	x	x	x	x			
Green Island	GR008A	NOAA			x	x			
Herring Bay, E	KN113A	ADF&G			x				
Herring Bay, E	KN113B-1	NOAA/"OMNI" Site	x	x					x
Herring Bay, E	KN113B-2	ADF&G			x				
Herring Bay, E	KN114A	NOAA/ADF&G			x	x			
Herring Bay, E	KN115A	ADF&G			x				
Herring Bay, E	KN119A-D	NOAA/ADF&G			x	x			
Herring Bay, E	KN119A-S	NOAA/ADF&G			x	x			
Herring Bay, E	KN120A	ADF&G			x				
Herring Bay, E Islet	KN121A	ADF&G			x				
Herring Bay, S Islet	KN133A-1	NOAA/Stripped			x	x	x	x	x
Herring Bay, S Islet	KN133A-2	ADF&G			x				
Herring Bay, SE Islet	KN144B	USFWS			x	x			
Herring Bay, E	KN300A	NOAA	x	x	x				x
Ingot Island	IN031B	ADF&G			x				
Knight Island, S	KN500B	ADF&G			x				
Knight Is., Lower Pass.	KN103A	ADF&G			x				
Latouche Island, NE	LA015C	NOAA			x	x			x
Latouche Island, NE	LA015E-1	NOAA	x	x	x				
Latouche Island, NE	LA015E-2	NOAA/Un			x	x	x	x	x
Latouche Island, NE	LA015E-3	NOAA/ADEC			x				
Latouche, Sleepy Bay	LA018A	NOAA CH1B site	x	x	x				

Table 1.—(Continued).

Location	Segment #	Agency/ Comments	—1991— —HCs— Sed	Mus	—1992— —HCs— Sed	Mus	St/ Un	Bys Thr	Hsto Path
Naked Is., Outside Bay	NA026A	NOAA CH1B site		x	x	x			
New Year Island, S	NY001	USFWS			x	x			
Olsen Bay	none	NOAA CH1B site	x	x	x	x		x	x
Squire Island, Islet	SQ004B	USFWS			x	x			
Squirrel Island, E	SL001D-1	ADF&G			x	x			
Squirrel Island, E	SL001D-2S	NOAA/ADF&G			x	x			
Squirrel Island, E	SL001D-2D	NOAA/ADF&G			x				

Table 2.—Sums of polynuclear aromatic hydrocarbons (PAHs) and PAH groups in sediments and mussels sampled from oiled mussel beds in Prince William Sound, Alaska, 1991. Units are in μg/g dry weight. Legend: S = sum; Naphthal. = naphthalenes; Phenanth. = phenanthrenes; Dibenzothio. = dibenzothiophenes; segment # "1-4" = multiple oiled mussel beds on one segment, and "S or D" = surface (0-2 cm) or deep sampling (>4 cm) in same bed; *N* = number of samples; SE = standard error about the mean.

Location	Segment #	Date	N	S PAHs		S Naphthal.		S Fluorenes		S Phenanth.		S Dibenzothio.		S Chrysenes	
				Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
SEDIMENTS															
Bainbridge Is.	BA006C	28-Jun-91	3	0.65	0.63	0.10	0.09	0.06	0.06	0.27	0.27	0.16	0.16	0.04	0.04
Bay of Isles	KN136A	27-Jun-91	3	41.23	15.47	9.12	5.60	2.95	1.37	14.43	4.55	10.07	3.22	3.44	0.99
Chenega Island	CH010B	07-Sep-91	3	489.14	32.13	86.66	7.70	61.56	3.82	185.81	11.89	112.21	7.98	28.96	1.47
Disk Island	D1067A-4	29-Jun-91	3	0.54	0.11	0.02	0.00	0.02	0.00	0.15	0.02	0.08	0.02	0.21	0.06
Eleanor Island	EL013A	27-Jun-91	3	71.22	46.33	16.68	10.94	9.88	8.09	23.32	14.80	13.56	7.24	5.11	3.30
Elrington Is.	ER020B	28-Jun-91	3	0.65	0.12	0.03	0.01	0.03	0.01	0.19	0.07	0.11	0.03	0.21	0.02
Evans Island	EV017A	28-Jun-91	3	0.06	0.02	0.01	0.01	0.00	0.00	0.02	0.01	0.01	0.00	0.02	0.00
Flemming Is.	FL004A	28-Jun-91	3	17.06	8.35	3.71	3.06	2.02	1.06	5.40	2.42	3.19	1.50	2.03	0.26
Foul Bay	MA002C	07-Aug-91	3	11.71	1.18	4.00	0.35	1.03	0.18	3.79	0.38	2.24	0.24	0.38	0.04
Herring Bay	KN113B-1	06-Sep-91	3	144.45	144.03	31.66	31.42	25.86	25.83	48.82	48.79	28.11	28.10	6.28	6.27
Herring Bay	KN300A-D	06-Sep-91	3	86.20	47.27	28.10	14.30	8.76	5.17	26.78	15.73	15.29	9.17	4.72	2.59
Herring Bay	KN300A-S	06-Sep-91	3	0.22	0.03	0.01	0.00	0.01	0.00	0.06	0.01	0.03	0.00	0.09	0.01
Latouche Is.	LA015E-1	29-Jun-91	3	13.71	4.41	3.64	1.24	1.18	0.49	4.99	1.65	2.91	0.86	0.68	0.21
MUSSELS															
Bainbridge Is.	BA006C	28-Jun-91	3	0.24	0.13	0.02	0.01	0.04	0.03	0.09	0.05	0.05	0.03	0.03	0.01
Bay of Isles	KN136A-1	27-Jun-91	3	5.96	1.10	0.23	0.07	0.41	0.12	2.66	0.54	1.47	0.27	0.83	0.08
Chenega Island	CH010B-1	07-Sep-91	3	0.69	0.06	0.03	0.01	0.11	0.03	0.29	0.04	0.12	0.02	0.11	0.00
Disk Island	D1067A-4	29-Jun-91	3	1.00	0.41	0.10	0.07	0.14	0.04	0.41	0.18	0.21	0.10	0.12	0.03
Eleanor Island	EL013A	26-Jun-91	3	0.32	0.07	0.04	0.01	0.03	0.01	0.14	0.04	0.04	0.01	0.05	0.01
Elrington Is.	ER020B	28-Jun-91	3	0.41	0.03	0.02	0.00	0.05	0.01	0.18	0.01	0.07	0.01	0.06	0.01
Evans Island	EV017A	28-Jun-91	2	0.06		0.02		0.01		0.01		0.00		0.01	
Evans Island	EV900A	08-Sep-91	2	0.06		0.01		0.01		0.01		0.00		0.01	
Flemming Is.	FL004A	28-Jun-91	3	0.66	0.18	0.04	0.01	0.08	0.02	0.27	0.09	0.13	0.06	0.11	0.02
Foul Bay	MA002A	07-Aug-91	3	10.34	2.85	1.41	0.35	1.33	0.50	4.23	1.11	2.35	0.70	0.70	0.16
Herring Bay	KN113B-1	06-Sep-91	3	1.43	0.25	0.07	0.03	0.13	0.05	0.64	0.09	0.21	0.04	0.31	0.04
Herring Bay	KN300A	06-Sep-91	3	0.96	0.13	0.09	0.05	0.08	0.01	0.48	0.06	0.14	0.02	0.13	0.01
Latouche Is.	LA015E-1	29-Jun-91	3	3.81	1.28	0.24	0.11	0.31	0.13	1.69	0.57	0.92	0.34	0.50	0.14

Table 3.—Total oil hydrocarbons, as measured by ultraviolet fluorescence, in sediments from mussel beds in Prince William Sound, Alaska, 1992. Units are μg/g wet weight. Legend: *N* = number of samples; SE = standard error; Pooled Rep = pooled replicate samples (usually 3 or 6); CH1B site = site established under Natural Resource Damage Assessment Study CH1B; segment # "1-5" = multiple beds sampled in one segment, and "S or D" = sediments taken at surface (0-2 cm) or a discrete depth (>5 cm) (most undesignated samples were collected at 0-2 cm; some were composited over 0-10 cm).

Location	Segment #	Agency/Notes	Type Sample	*N*	Mean	SE
Aguliak Island, N	AG001A	ADF&G	Pooled Rep	3	9,972.31	906.11
Aguliak Island, S	AG009	NOAA/ADF&G	Pooled Rep	6	11,002.08	1049.42
Applegate Island	AE005A	ADF&G	Pooled Rep	3	8,766.08	1944.02
Applegate Island	AE005B	NOAA/ADF&G	Pooled Rep	6	26,867.32	1923.30
Barnes Cove, Knight Is.	KN575A	NOAA CH1B site	Pooled Rep	3	0.33	0.27
Bay of Isles	KN004A-D	NOAA/ADF&G	Pooled Rep	3	18,652.59	3791.46
Bay of Isles	KN004A-S	NOAA/ADF&G	Pooled Rep	3	1,763.83	827.41
Bay of Isles	KN136A-2	NOAA/Unstripped	Spot	6	17,359.02	3142.62
Bay of Isles, Islet	KN016A	USFWS	Pooled Rep	3	4,698.85	922.68
Bay of Isles, S. Arm	KN205B	NOAA CH1B site	Pooled Rep	3	9.37	0.87
Bay of Isles, SE	KN207B	ADF&G	Pooled Rep	3	21,933.58	1887.03
Bay of Isles, W	KN005A	USFWS	Pooled Rep	3	1,664.16	196.25
Bay of Isles, W	KN203A	USFWS	Pooled Rep	3	6,435.82	670.68
Chenega Island	CH009-1	NOAA	Pooled Rep	3	26.50	2.86
Chenega Island	CH009-2	ADF&G	Pooled Rep	3	11,507.37	1517.35
Chenega Island	CH009-3	NOAA/ADF&G	Pooled Rep	6	20,482.43	1575.84
Chenega Island	CH010B-2	NOAA/Stripped	Spot	6	26,403.42	3447.87
Chenega Island	CH010B-3	NOAA/Unstripped	Spot	6	22,068.63	5399.74
Crab Bay, Evans Is.	CH011A	ADF&G	Pooled Rep	3	7,899.71	780.46
Crafton Island	EV500A	NOAA CH1B site	Pooled Rep	3	0.00	0.00
Crafton Island	CR004A	ADF&G	Pooled Rep	3	3,361.33	867.87
Disk Island, NE	CR005A	ADF&G	Pooled Rep	3	3,066.58	517.59
Disk Island, NW	DI059A	NOAA/ADF&G	Pooled Rep	6	8,248.99	1233.85
Disk Island, NW	DI067A-1	NOAA	Pooled Rep	3	14,019.91	1221.85
Disk Island, NW	DI067A-2	ADEC	Spot	10	15,070.66	2499.00
Disk Island, NW	DI067A-3	ADF&G	Pooled Rep	3	6,324.49	533.32
Disk Island, NW	DI067A-4	ADF&G	Pooled Rep	3	4,979.16	1085.18
Disk Island, NW	DI067A-5	NOAA/ADF&G	Pooled Rep	3	22,599.68	3224.92
Disk Island, W	DI066A	NOAA/ADF&G	Pooled Rep	6	11,941.94	2533.54
Eleanor Is., NW Bay	EL052A-1	NOAA/ADF&G	Pooled Rep	3	197.97	32.93
Eleanor Is., NW Bay	EL052A-2	ADF&G	Pooled Rep	3	3,265.87	844.70
Eleanor Is., NW Bay	EL052B	ADF&G	Pooled Rep	3	9,868.16	1160.41
Eleanor Is., NW Bay	EL054A	NOAA	Pooled Rep	3	307.41	63.39
Eleanor Island, SW	EL015A-1	ADF&G	Pooled Rep	3	11,871.14	1477.22
Eleanor Island, SW	EL015A-2	ADF&G	Pooled Rep	3	17,178.53	399.59
Eleanor Island, SW	EL015A-3	NOAA/ADF&G	Pooled Rep	3	3,149.13	225.93
Eleanor Island, W	EL011A	USFWS	Pooled Rep	3	2,118.16	229.35
Eleanor Island, S	EL013A	NOAA/Stripped	Spot	5	7,370.69	2415.25
Elrington Is., Fox Farm	ER007A	NOAA CH1B site	Pooled Rep	3	37.41	0.71
Elrington Island., NE	ER020B	NOAA	Pooled Rep	3	953.56	112.68
Evans Is., Bishop Pt.	EV036A	NOAA	Pooled Rep	3	10,725.19	1646.00
Fleming Island, W	FL004A	NOAA	Pooled Rep	3	1,787.46	207.79
Foul Bay	MA002C	NOAA	Pooled Rep	3	62,257.90	1272.43
Green Island	GR008A	NOAA	Pooled Rep	3	46.42	8.52
Herring Bay, W	KN113A	ADF&G	Pooled Rep	3	8,106.17	1179.24
Herring Bay, E	KN113B-2	ADF&G	Pooled Rep	3	14,966.76	896.45

Table 3.—(Continued).

Location	Segment #	Agency/Notes	Type Sample	*N*	Mean	SE
Herring Bay, E	KN114A	NOAA/ADF&G	Pooled Rep	6	17,318.12	1001.43
Herring Bay, E	KN103A	ADF&G	Pooled Rep	3	26,728.29	819.51
Herring Bay, E	KN119A-D	NOAA/ADF&G	Pooled Rep	3	13,003.64	36.55
Herring Bay, E	KN119A-S	NOAA/ADF&G	Pooled Rep	6	5,473.01	875.89
Herring Bay, E	KN120A	ADF&G	Pooled Rep	3	7,771.31	1423.75
Herring Bay, E Islet	KN121A	ADF&G	Pooled Rep	3	1,694.94	355.27
Herring Bay, S Islet	KN133A-1	NOAA/Stripped	Spot	5	30,726.02	7281.92
Herring Bay, S Islet	KN133A-2	ADF&G	Pooled Rep	3	23,497.21	412.38
Herring Bay, SE Islet	KN144B	USFWS	Pooled Rep	3	481.31	114.22
Ingot Island	IN031B	ADF&G	Pooled Rep	3	12,515.02	828.32
Knight Island, W	KN500B	ADF&G	Pooled Rep	3	10,704.66	957.65
Latouche Island, NE	LA015E-2	NOAA/Unstripped	Pooled Rep	3	3,951.06	1003.64
Latouche Island, NE	LA015E-3	NOAA/ADEC	Spot	8	11,243.57	4538.46
Louis Bay, Knight Is.	KN115A	ADF&G	Pooled Rep	3	2,813.91	436.39
New Year Island, S	NY001	USFWS	Pooled Rep	3	940.46	352.91
Olsen Bay	none	NOAA CH1B site	Pooled Rep	3	0.90	0.74
Sleepy Bay, Latouche	LA018A	NOAA CH1B site	Pooled Rep	3	279.60	59.20
Squire Island, Islet	SQ004B	USFWS	Pooled Rep	3	18.91	1.10
Squirrel Island, E	SL001D-1	ADF&G	Pooled Rep	3	3,063.23	455.23
Squirrel Island, E	SL001D-2D	NOAA/ADF&G	Pooled Rep	1	3,499.00	
Squirrel Island, E	SL001D-2S	NOAA/ADF&G	Pooled Rep	3	14,466.80	912.56

Table 4.—Polynuclear aromatic hydrocarbon (PAH) groups in mussels sampled from oiled mussel beds in Prince William Sound, Alaska, 1992, as analyzed by gas chromatography/mass spectroscopy. Units are in μg/g dry weight. Legend: S = sums; Naphthal. = naphthalenes; Dibenzothio. = dibenzothiophenes; Phenathr. = phenanthrenes; *N* = number of samples; SE = standard error.

SITE	SEGMENT #	NOTES	SAMPLE DATE	N	S PAHs		S Naphthal.		S Fluorenes		S Dibenzothio.		S Phenanthr.		S Chrysenes	
					MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
Barnes Cove	KN575A	Control	6/92	1	0.06		0.03		0.00		0.00		0.00		0.01	
Foul Bay	MA002C	Survey	6/92	3	6.97	0.95	0.90	0.12	0.70	0.13	1.67	0.24	2.17	0.31	0.71	0.07
Bay of Isles	KN136A-1	Unstrip	5/92	1	2.55		0.87		0.22		0.43		0.57		0.23	
Latouche	LA015E-3	Unstrip	6/92	3	0.57	0.17	0.09	0.01	0.07	0.02	0.12	0.05	0.16	0.06	0.07	0.01
Applegate Is.	AE005B	Survey	8/92	3	1.84	0.30	0.15	0.02	0.19	0.03	0.47	0.08	0.59	0.11	0.23	0.03
Disk Is.	DI067A-5	Islet face	8/92	3	4.22	0.11	0.45	0.09	0.49	0.04	1.07	0.05	1.21	0.05	0.51	0.03
Herring Bay	KN133A-1	Stripped	5/92	3	3.23	1.54	0.18	0.04	0.53	0.28	0.92	0.46	0.88	0.43	0.41	0.18
Herring Bay	KN114A	Survey	8/92	3	1.85	0.05	0.16	0.01	0.19	0.02	0.45	0.09	0.46	0.04	0.28	0.04
Chenega Is.	CH010B-2	Stripped	5/92	6	2.47	0.77	0.32	0.07	0.27	0.09	0.50	0.16	0.91	0.38	0.26	0.08
Chenega Is.	CH010B-3	Unstrip	5/92	3	0.54	0.04	0.13	0.00	0.07	0.00	0.10	0.02	0.11	0.01	0.08	0.01

Table 5.—Relationship of total petroleum hydrocarbon concentrations (measured by ultraviolet fluorescence) in byssal, surface, and deep sediments in six mussel beds in Prince William Sound. Samples were collected in May, June, and August 1992. Asterisks indicate significant difference in concentrations between depths indicated. Level of significance at larger beds may not apply to all sample transects (see p. 12).

		Sediment Depth		
Site	Segment #	0 cm	0-2 cm	5-7 cm
Chenega Is.	CH010B-2	byssal <*	surface >*	deep
Herring Bay	KN133A-1	byssal <*	surface >	deep
Eleanor Is.	EL013A	byssal <*	surface <*	deep
Chenega Is.	CH010B-3	byssal <	surface >	deep
Bay of Isles	KN136A	byssal <*	surface >	deep
Latouche Is.	LA015E	no data	surface <*	deep

FIGURES

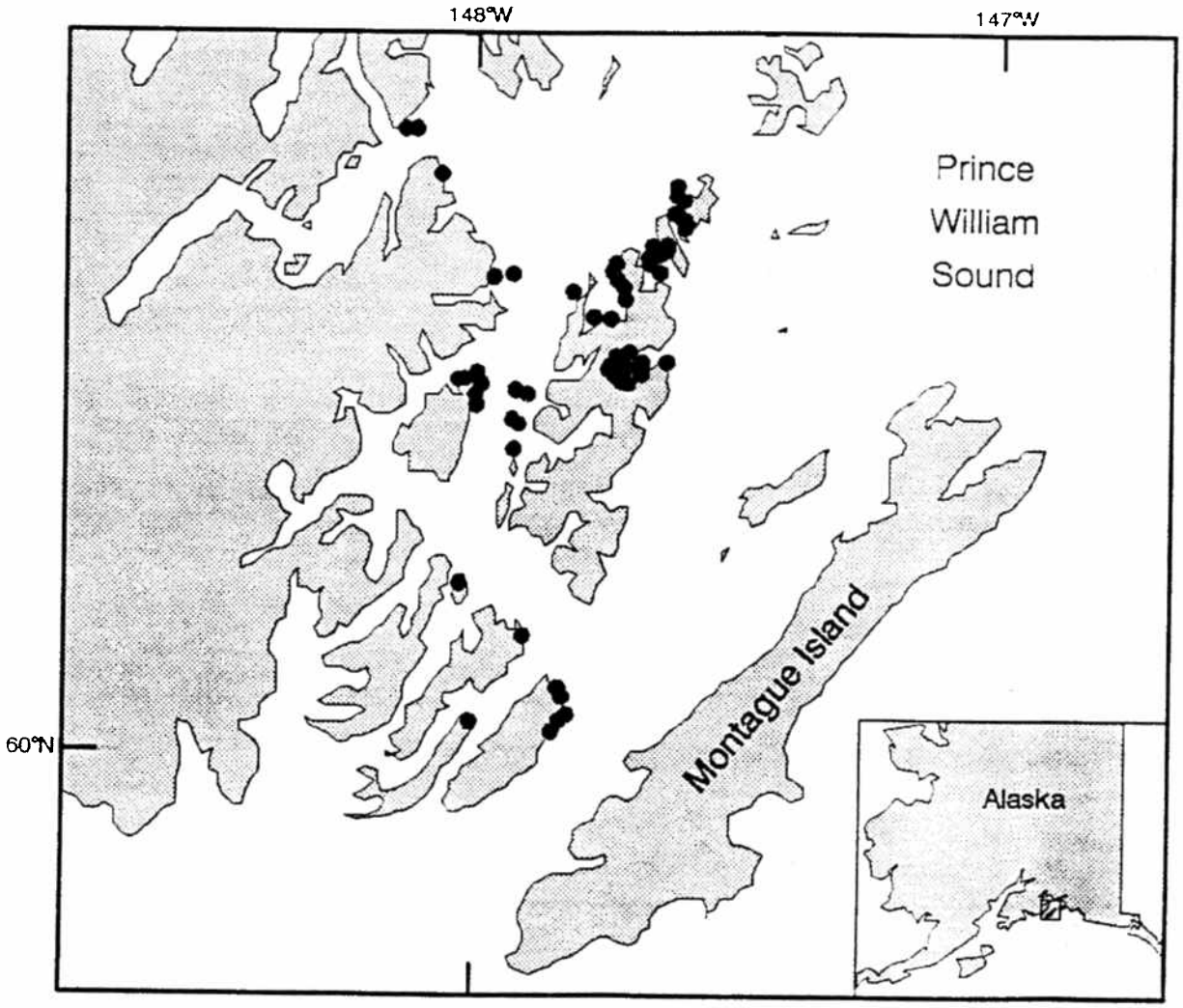


Figure 1.—Map of western Prince William Sound showing locations of 52 mussel beds where total petroleum hydrocarbons in sediments underlying the mussel beds exceeded 1,000 μg/g wet weight as measured by ultraviolet fluorescence. These sites were all sampled in 1992.

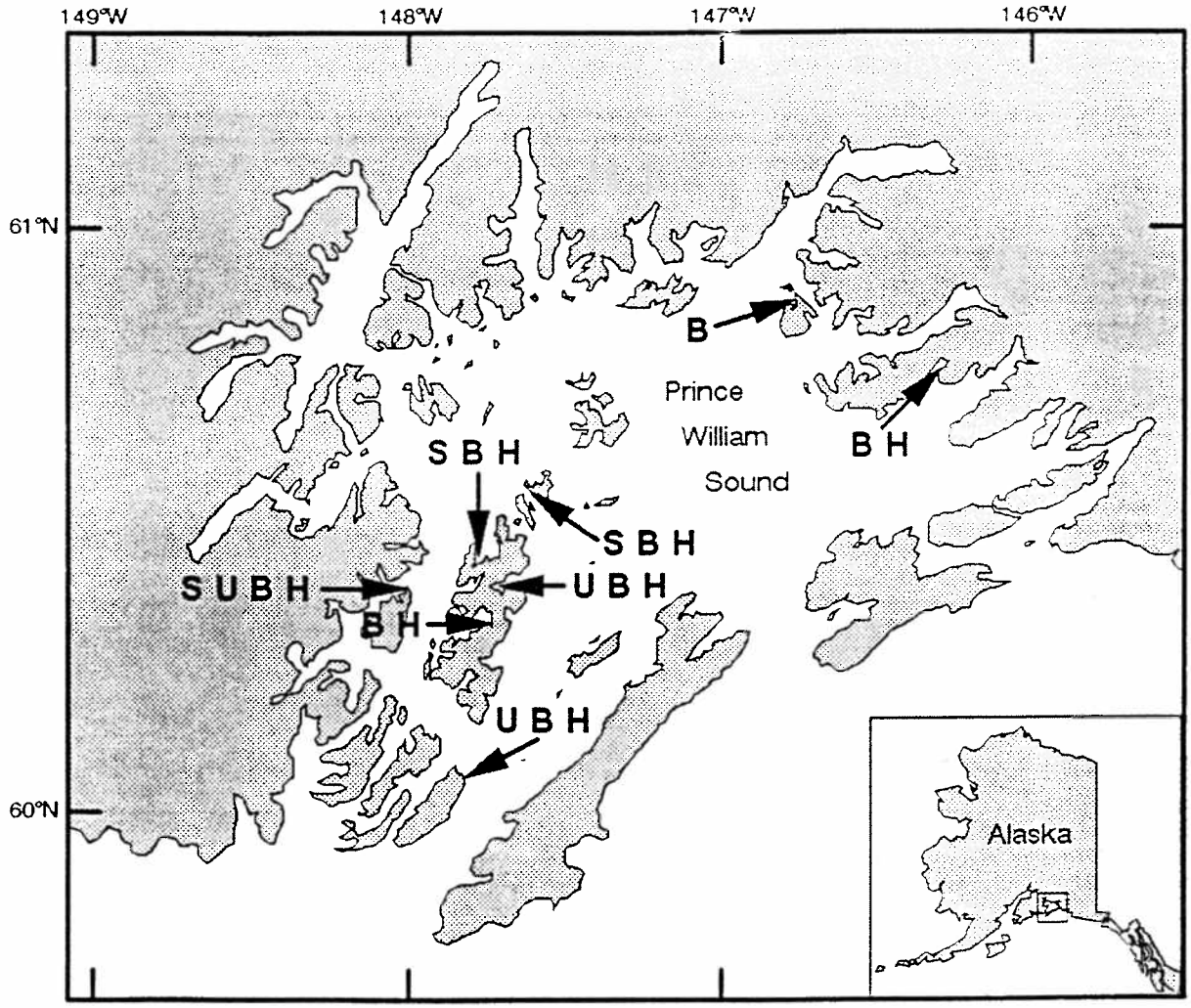


Figure 2.—Map of Prince William Sound showing mussel bed sites where intensive sampling or manipulation occurred and where samples were collected in 1992 for tests of biological recovery. Legend: B = mussels collected for byssal thread extrusion rates; H = mussels collected for histopathological examination and determination of reproductive indices; S = mussel beds that were stripped; U = unstripped beds that were sampled for comparison to stripped beds. At all these sites, additional mussels and sediments were collected for petroleum hydrocarbon analyses.

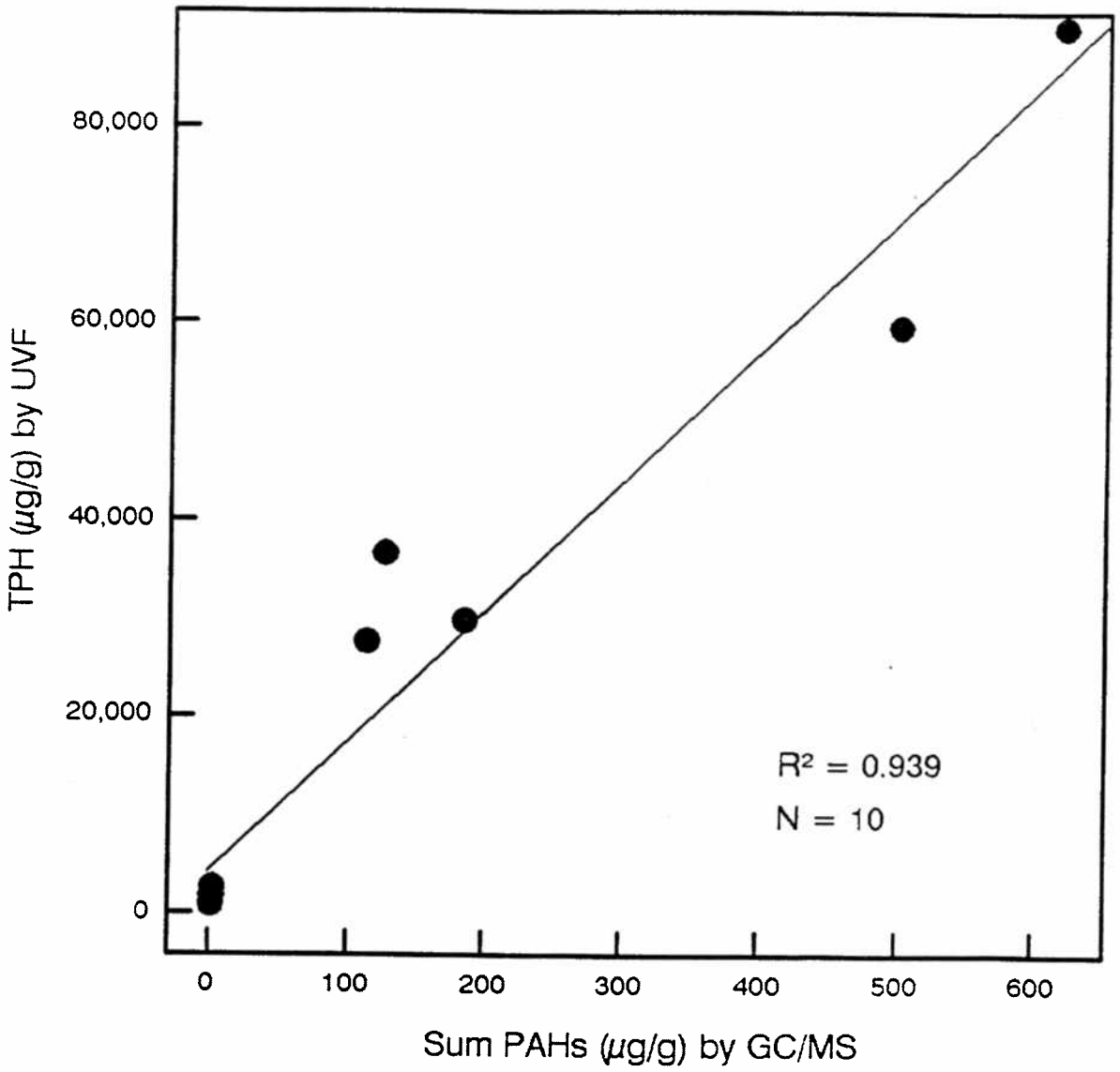


Figure 3.—Correlation of total petroleum hydrocarbons (TPH) in sediments, measured by UVF, with the sum of polynuclear aromatic hydrocarbons (PAHs), measured by GC/MS, in the same sample. Samples were collected in Prince William Sound in 1992.

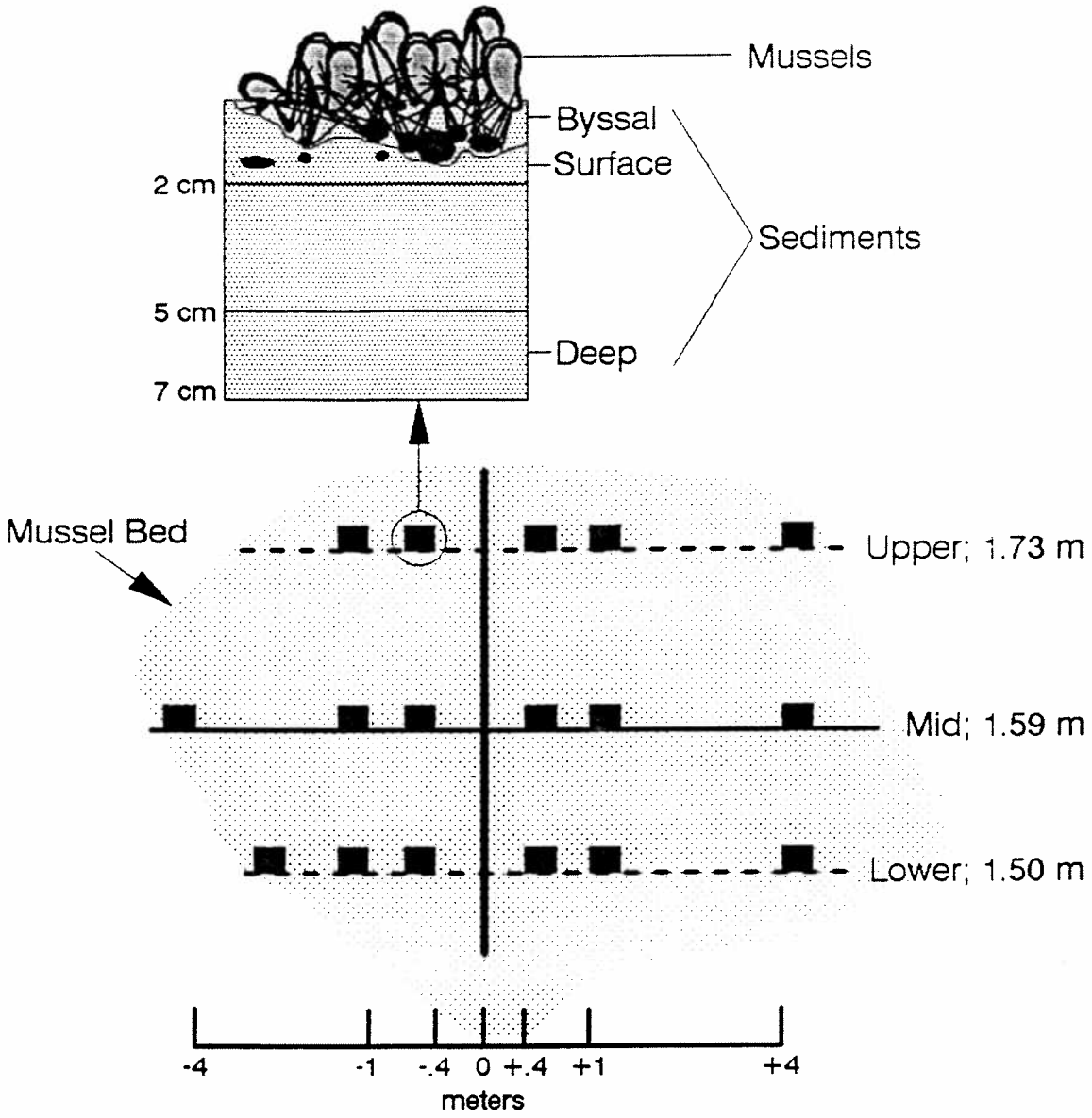


Figure 4.—Hydrocarbon sampling grid on oiled mussel bed, Chenega Island, Prince William Sound, 1992. Sampling patterns at Herring Bay and Eleanor Island beds were similar. Lower, Mid, and Upper refer to sample transects parallel to the water line, lower being lower on the beach. The central axis of the bed is at right angles to the transects; numbers along the bottom of the diagram indicate distance of sample subsites (the black squares) from the central axis. The upper diagram shows the spatial relationship of hydrocarbon samples collected—mussels and sediments at three depths.

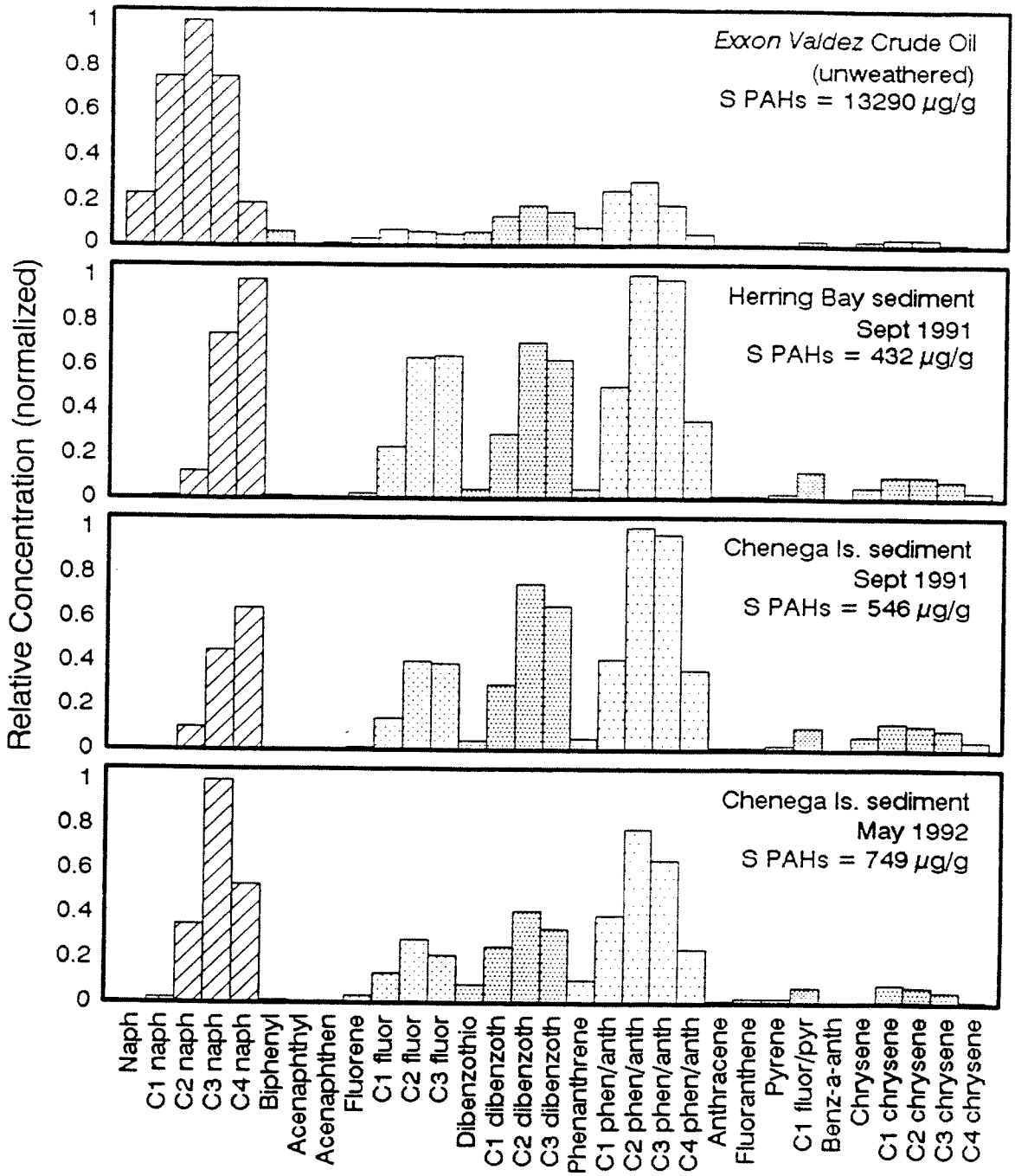


Figure 5.—Distribution of individual polynuclear aromatic hydrocarbons (PAH) in unweathered *Exxon Valdez* crude oil and sediments underlying a mussel bed in Herring Bay and two different mussels beds on north Chenega Island. Concentrations are normalized to the most abundant compound (usually C3 naphthalene) to depict weathering patterns independent of the actual quantities of PAHs present in the samples. S = sum.

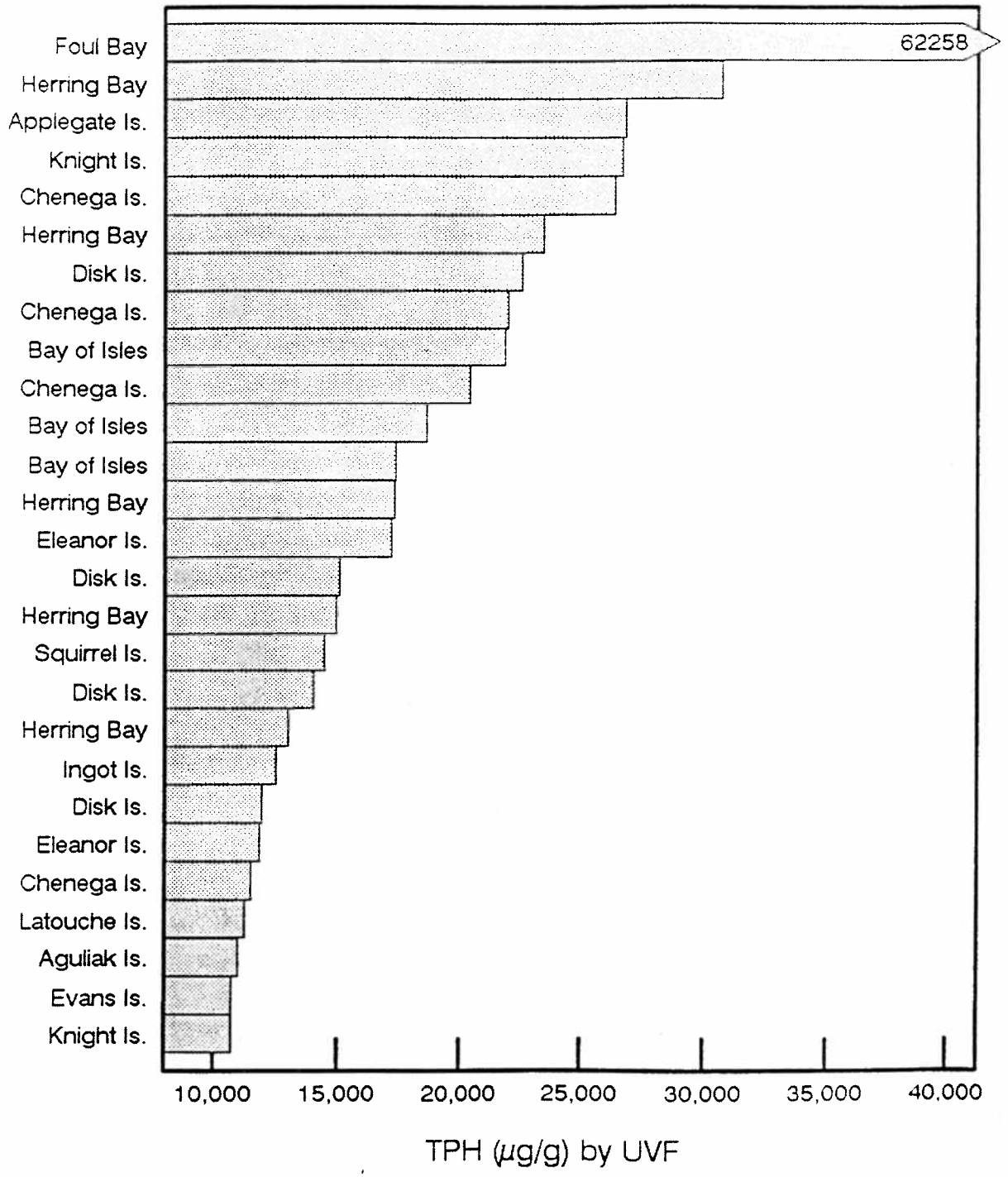


Figure 6.—Prince William Sound mussel beds with underlying sediments exceeding 10,000 µg/g wet weight total petroleum hydrocarbons (TPH) measured by ultraviolet fluorescence (UVF). Additional site information is in Table 3. All samples were collected in 1992.

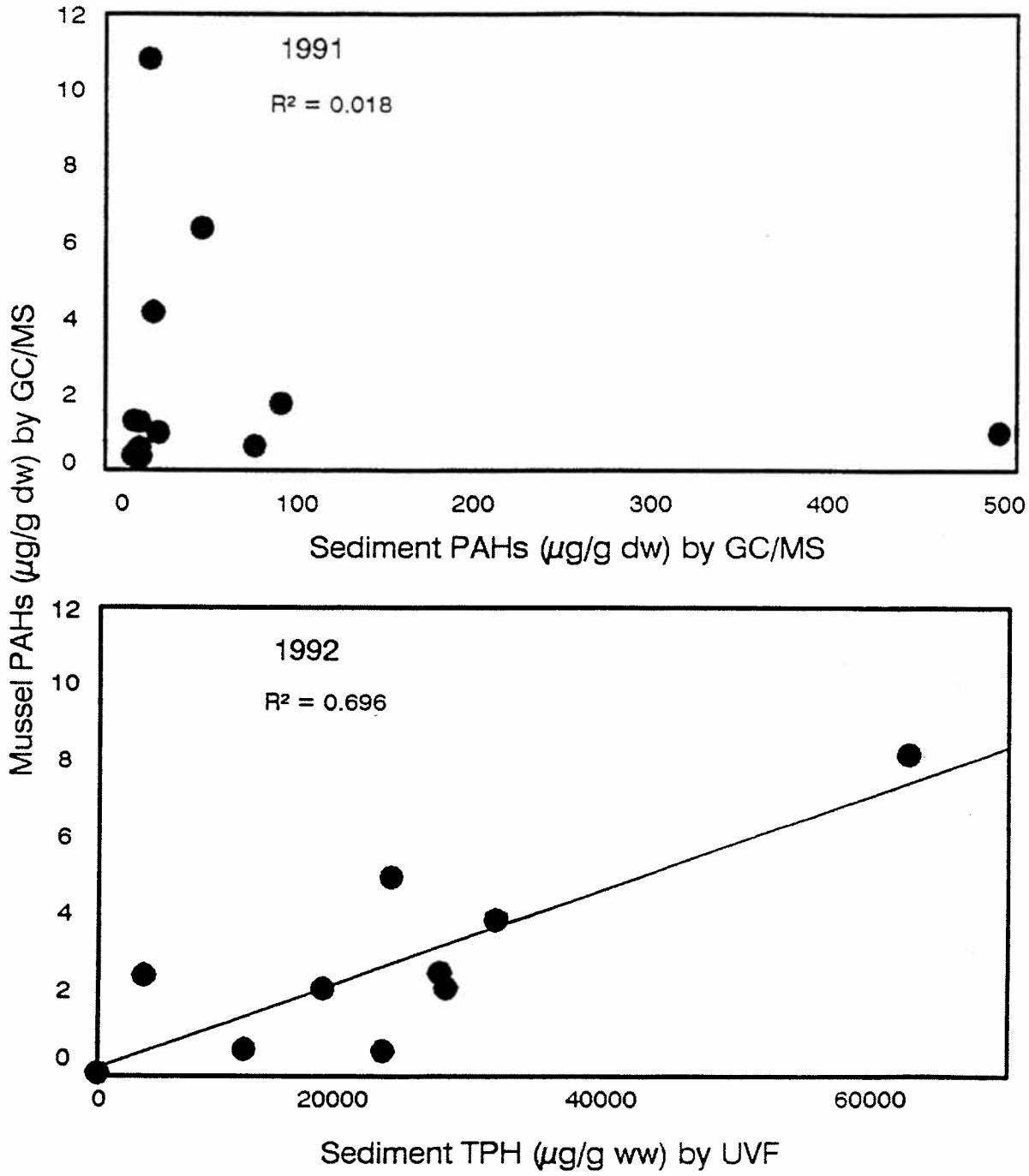


Figure 7.—Relationship of sums of polynuclear aromatic hydrocarbons (PAHs) in mussels to PAHs measured in underlying sediments for oiled mussel beds sampled in 1991 (both measured by gas chromatography/mass spectroscopy—GC/MS); and of PAHs (GC/MS) in mussels related to total petroleum hydrocarbons (TPH), measured by ultraviolet fluorescence (UVF) in underlying sediments in 1992.

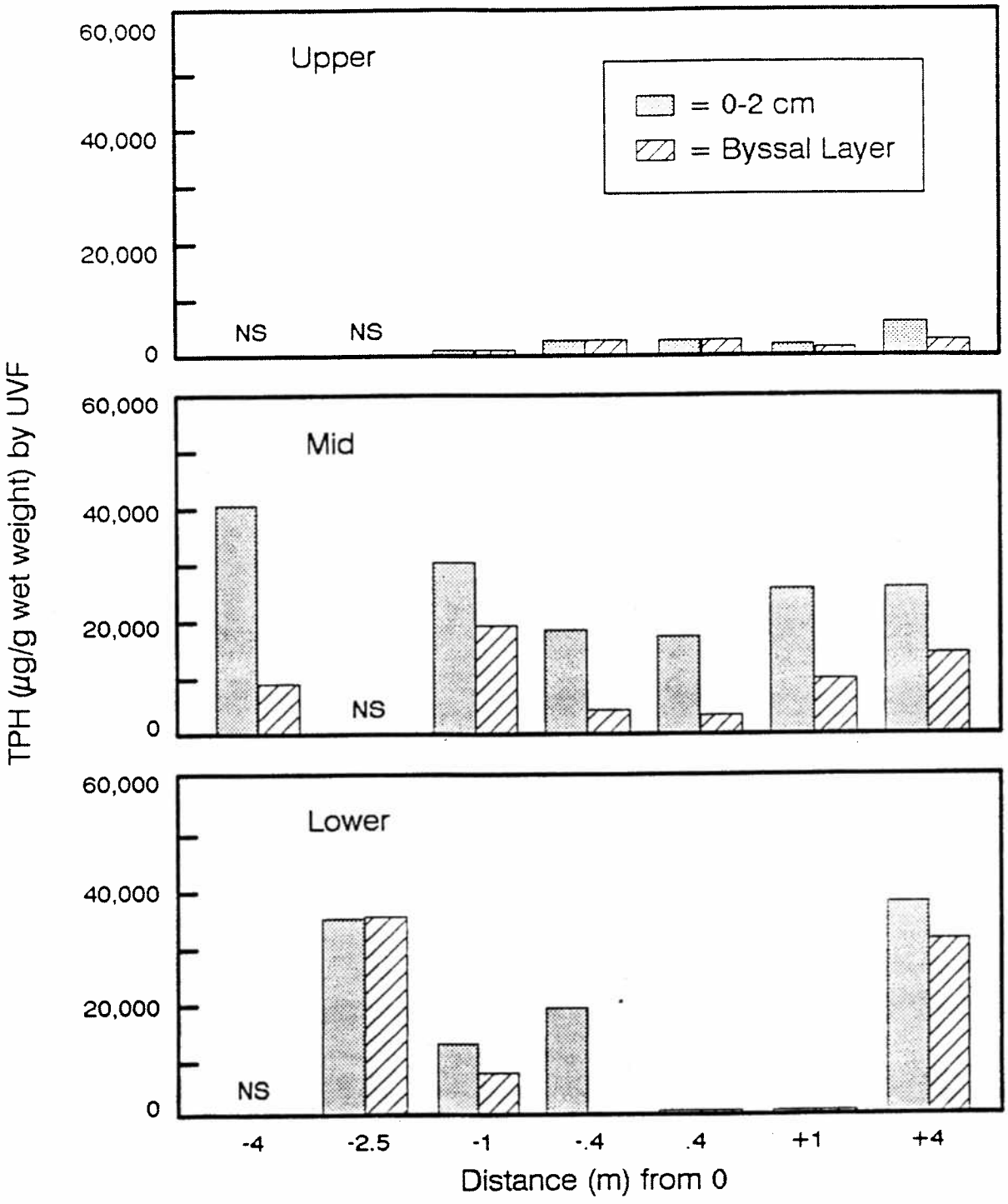


Figure 8.—An example of variability in the distribution of total petroleum hydrocarbons (TPH) determined by ultraviolet fluorescence (UVF) in byssal and surface sediments of the Chenega Island mussel bed, Prince William Sound, May 1992. NS = no sample collected. Lower, Mid, and Upper refer to sample transects; distances of samples from the central axis of the mussel bed are on the *X* axis (see Fig. 4).

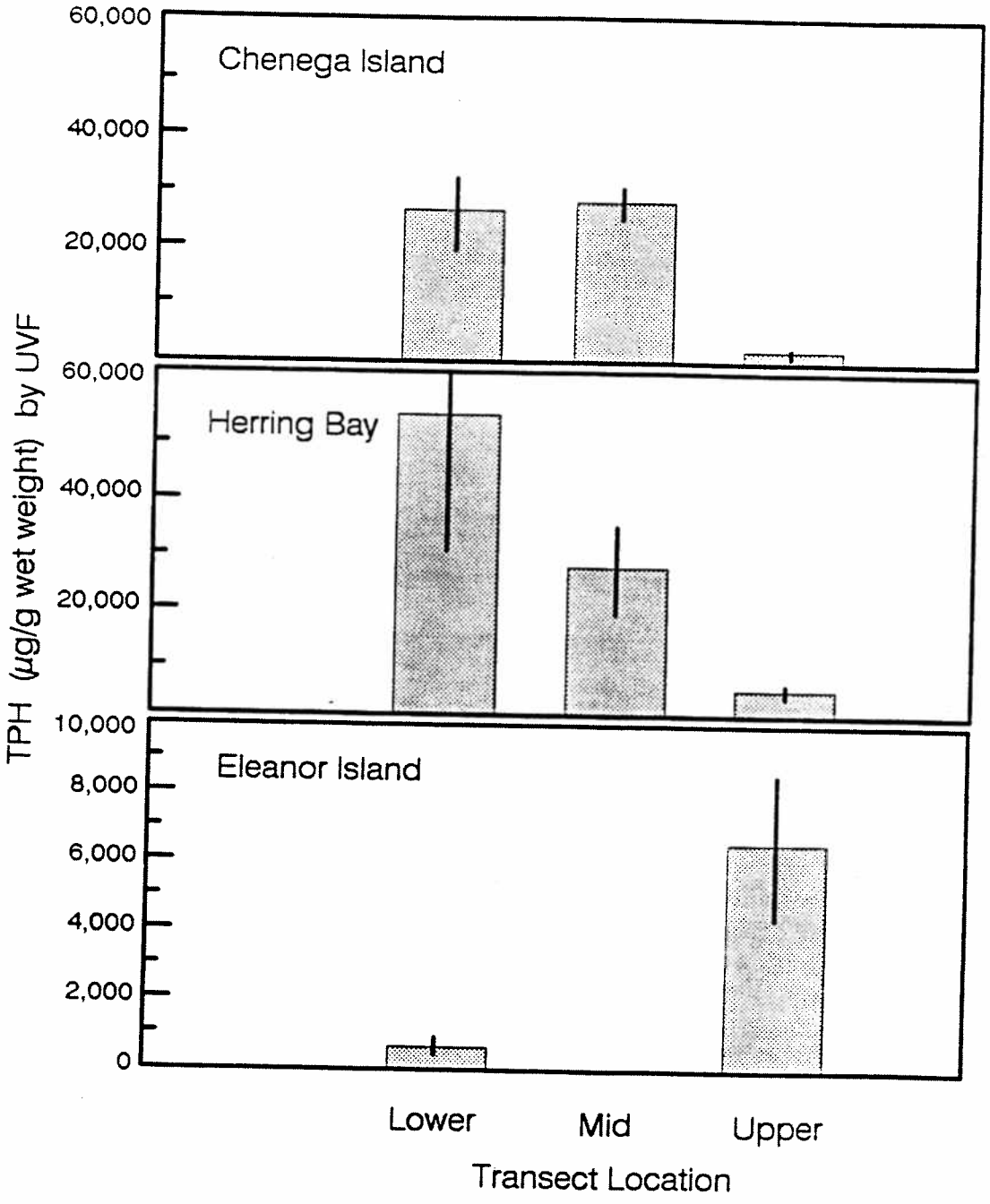


Figure 9.—Total petroleum hydrocarbons (TPH), measured by ultraviolet fluorescence (UVF), in surface sediments in Chenega Island, Herring Bay, and Eleanor Island mussel beds, Prince William Sound, May 1992. Note scale for Eleanor Island TPH differs from the other two beds. Lower = lower sample transect, Mid = middle sample transect, Upper = upper sample transect; vertical bars = standard error; n = 4-6.

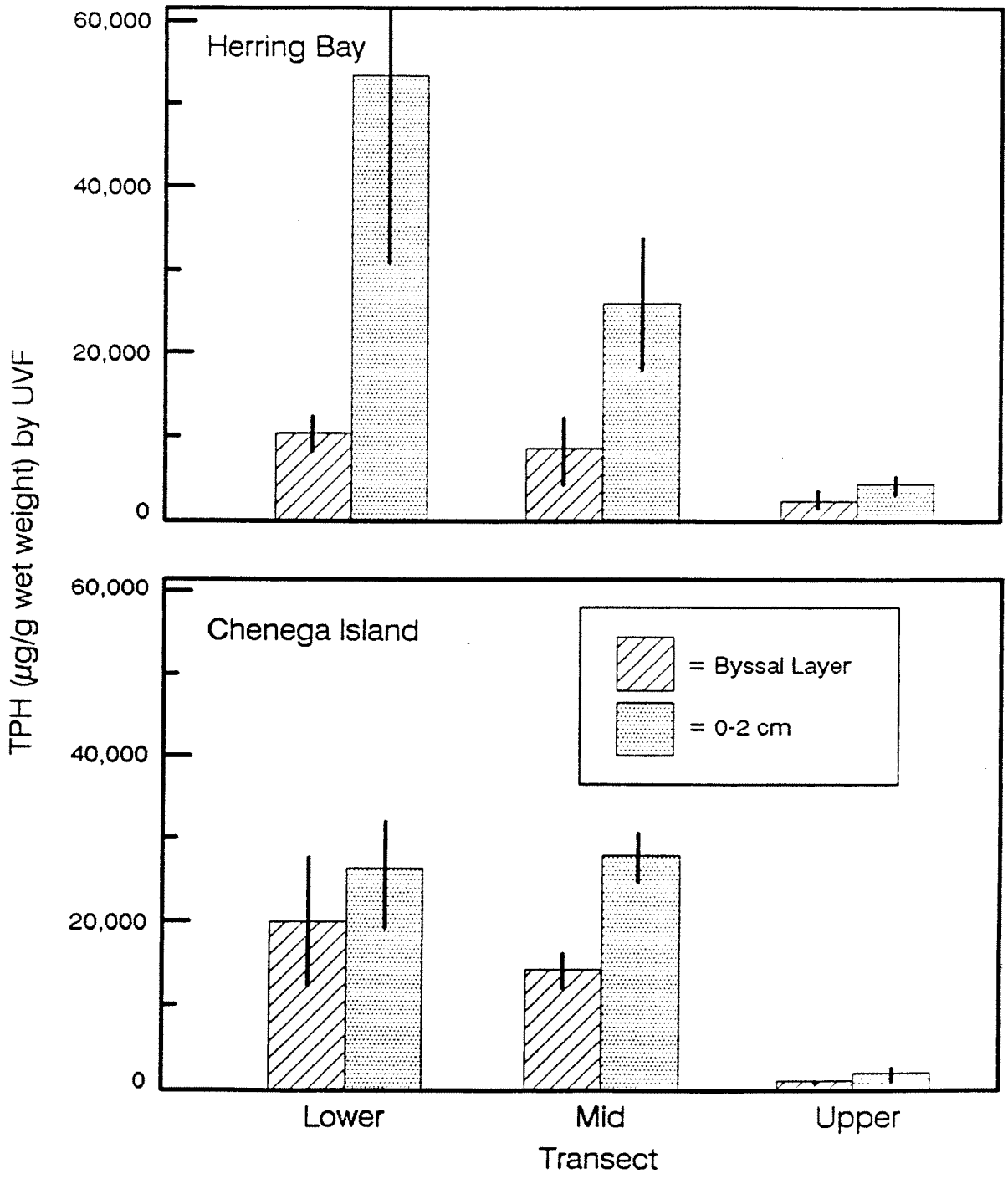


Figure 10.—Total petroleum hydrocarbons (TPH), measured by ultraviolet fluorescence (UVF), in sediments at two depths in the Herring Bay and Chenega Island mussel beds, Prince William Sound, May 1992. Vertical bars = standard error; n = 4-6.

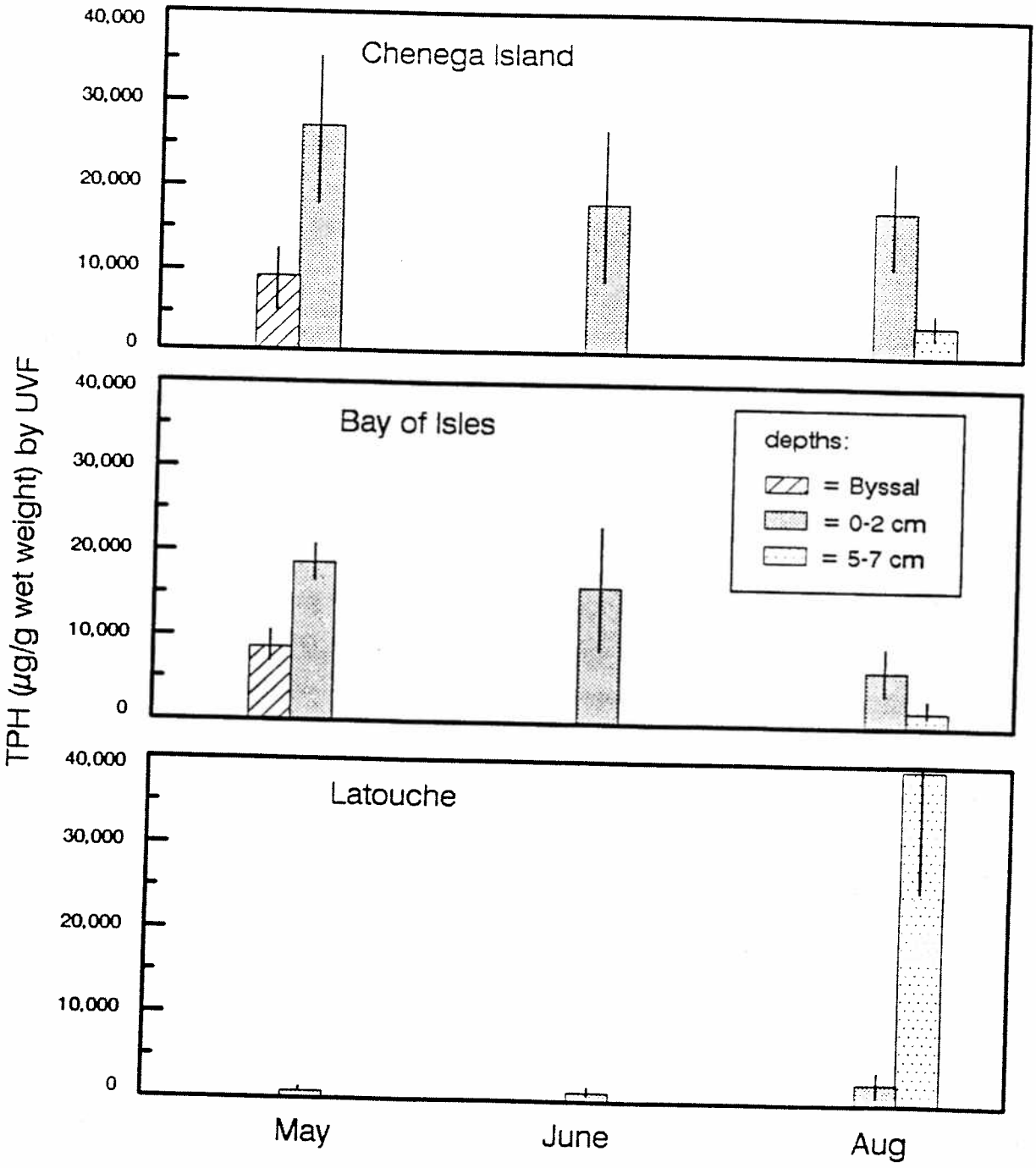


Figure 11.—Total petroleum hydrocarbons (TPH), measured by ultraviolet fluorescence (UVF), in sediments at three unstripped mussel beds at three depths in prince William Sound, May, June, and August 1992. Vertical bars = standard error; n = 3 or 4.

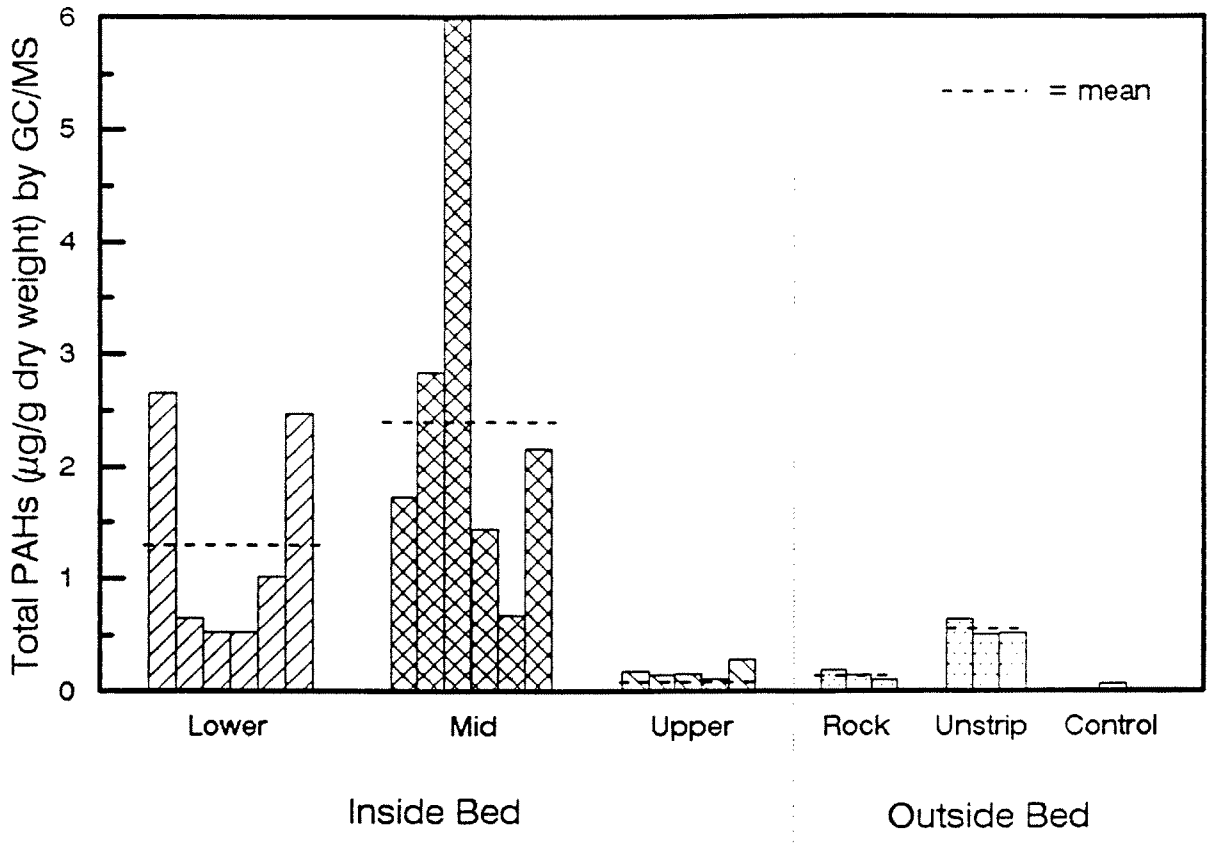


Figure 12.—Distribution of sums of polynuclear aromatic hydrocarbons (PAHs), measured by gas chromatography/mass spectroscopy (GC/MS), in mussels from the Chenega Island bed, grouped across sample transect and compared with mussels on adjacent bedrock, the unstripped site at Chenega Island, and Barnes Cove, a control site. Mean PAH concentrations are significantly higher in mussels from the two lower transects than in mussels from the upper transect and bedrock. $P \leq 0.05$.

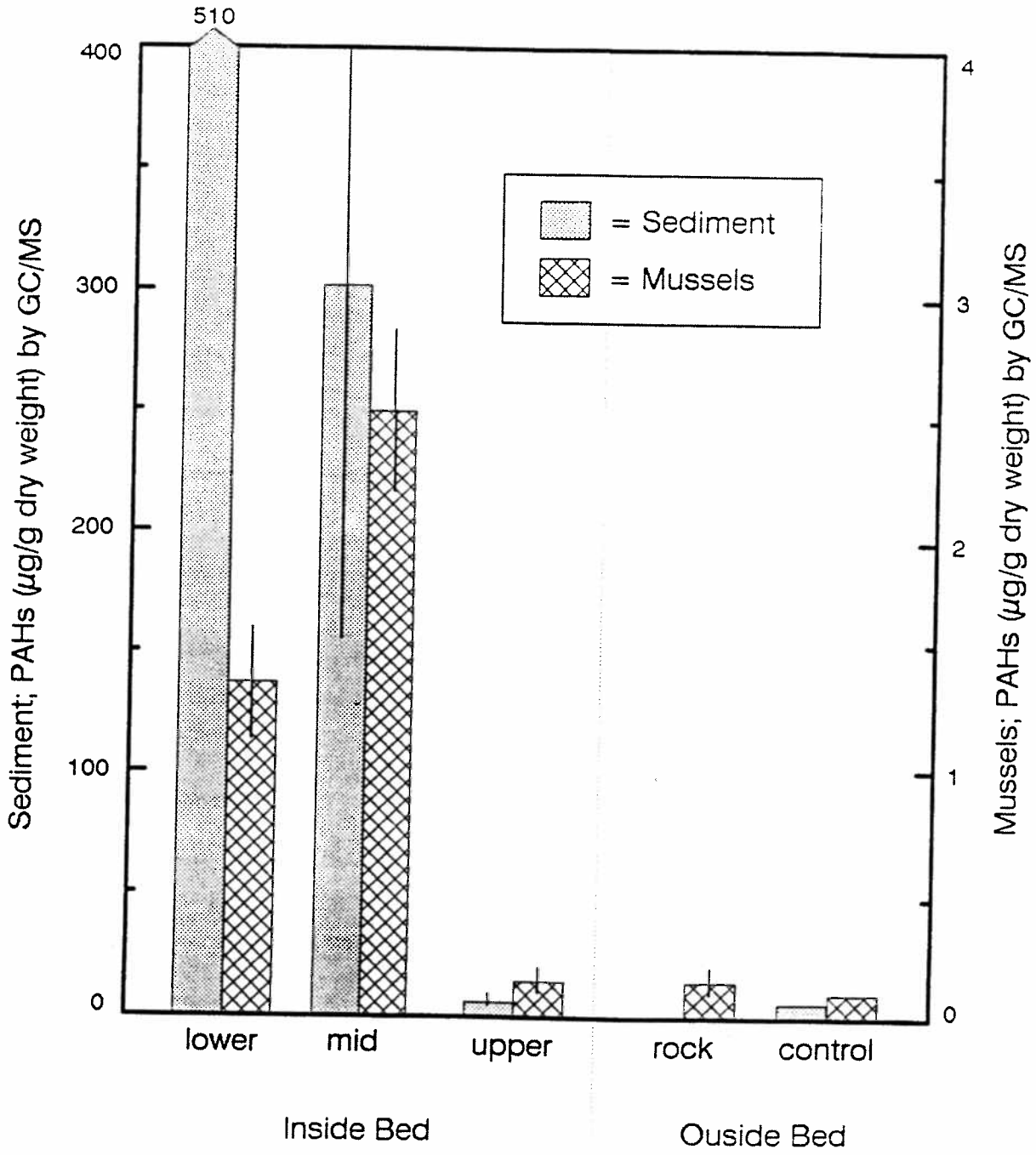


Figure 13.—Mean sums of polynuclear aromatic hydrocarbons (PAHs), measured by gas chromatography/mass spectroscopy (GC/MS), in sediments and mussels from the three sample transects in the Chenega Island mussel bed, adjacent bedrock (May 1992), and control site, Barnes Cove (June 1992). Vertical bars = standard error; n = 2-6.

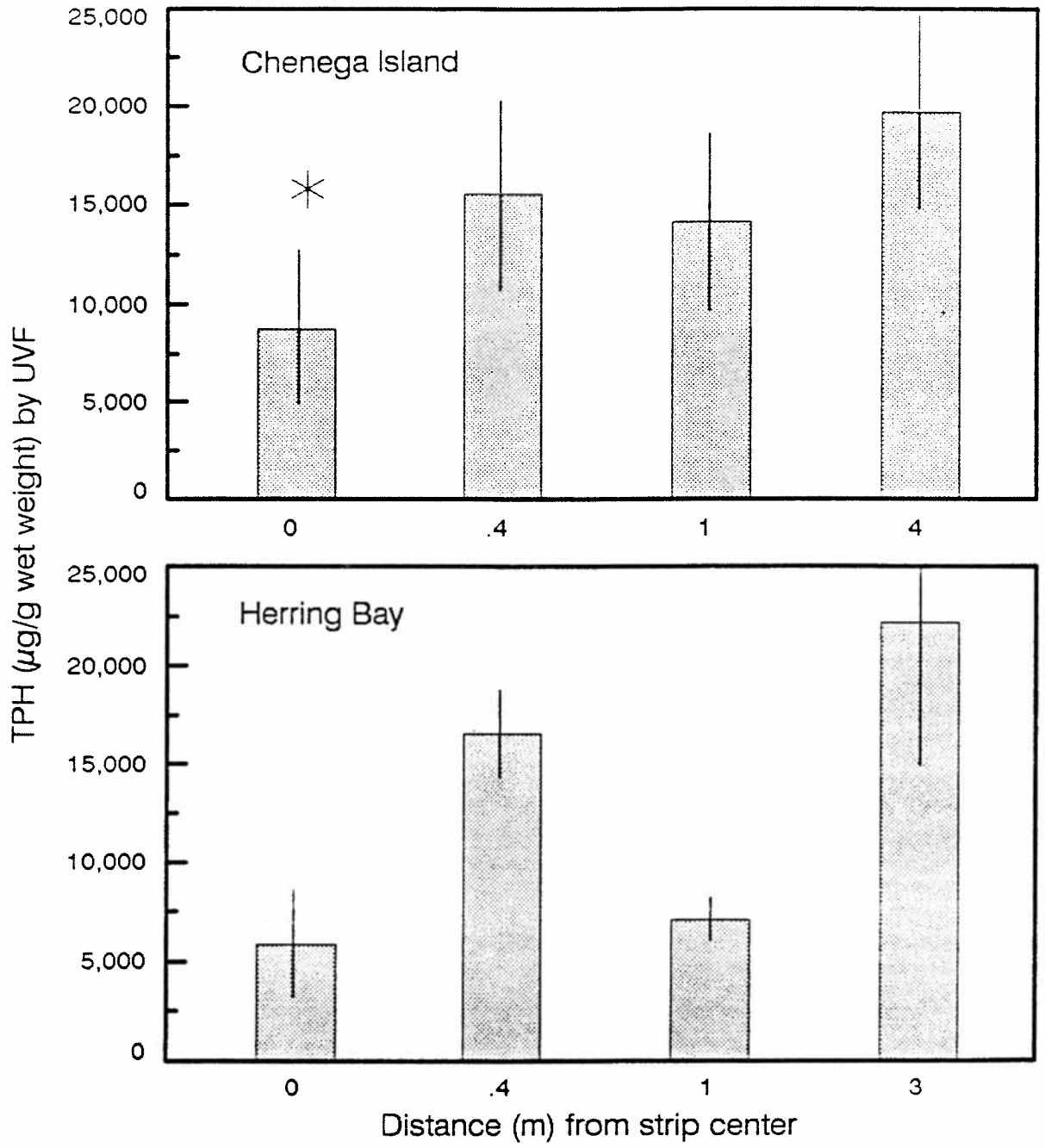


Figure 14.—Mean total petroleum hydrocarbons (TPH), determined by ultraviolet fluorescence (UVF), in surface sediments (0-2 cm deep) at several distances from the strips ("0" on X axis) at Chenega Island and Herring Bay beds in June and August 1992. Vertical bars = standard error; n = 6 for strip subsites, n = 10-12 for subsites outside the strip. An asterisk indicates significant difference between concentrations in the strip versus the rest of the bed. $P \leq 0.05$.

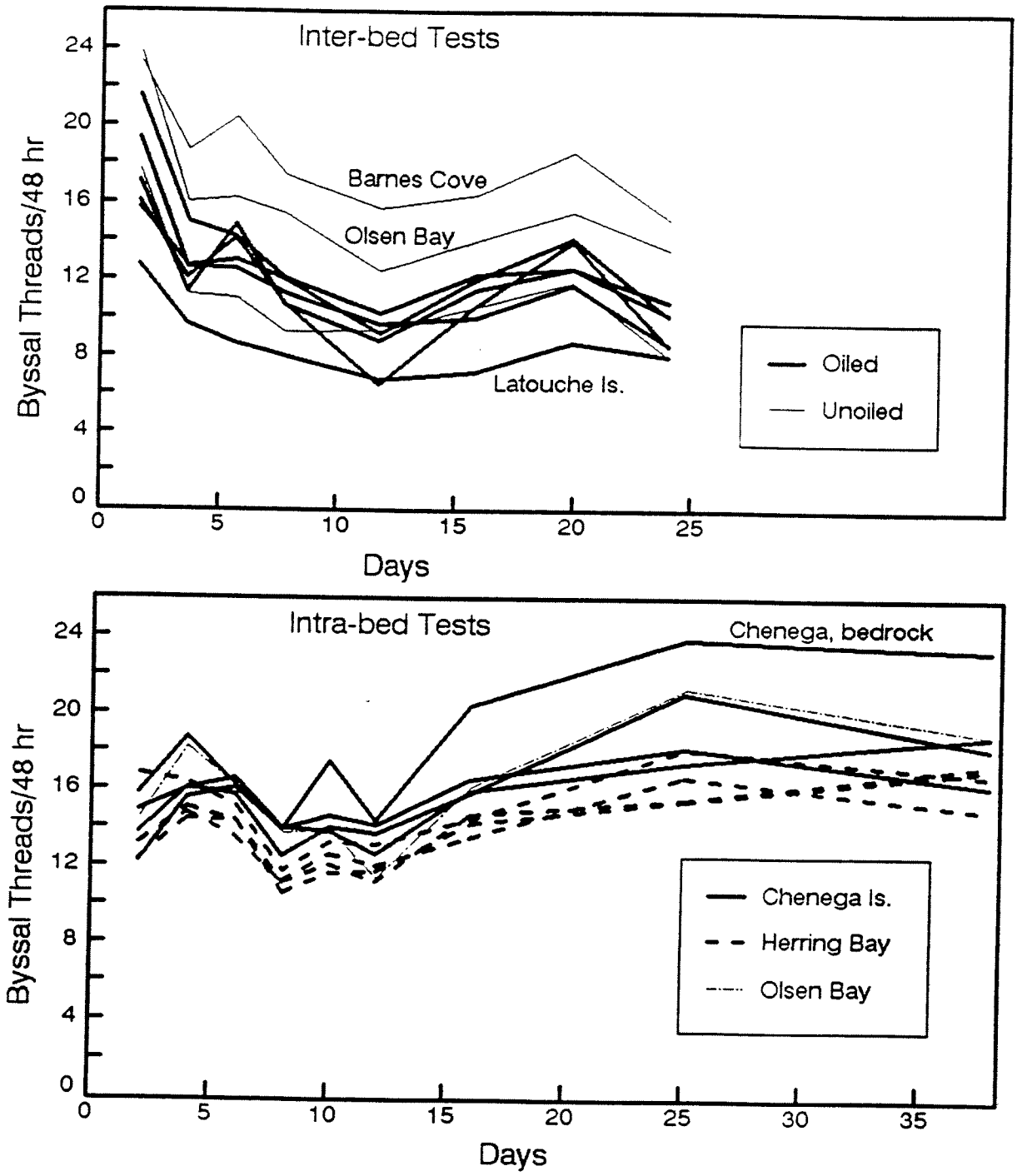


Figure 15.—Mean numbers of byssal threads produced in 48 h by groups of 36 mussels from Prince William Sound. Inter-bed tests show production by mussels from 6 oiled and 3 unoiled mussel beds. Intra-bed tests show production by mussels from 4 locations within an oiled Chenega Island mussel bed, 4 locations within an oiled Herring Bay bed, and from an unoiled Olsen Bay bed.

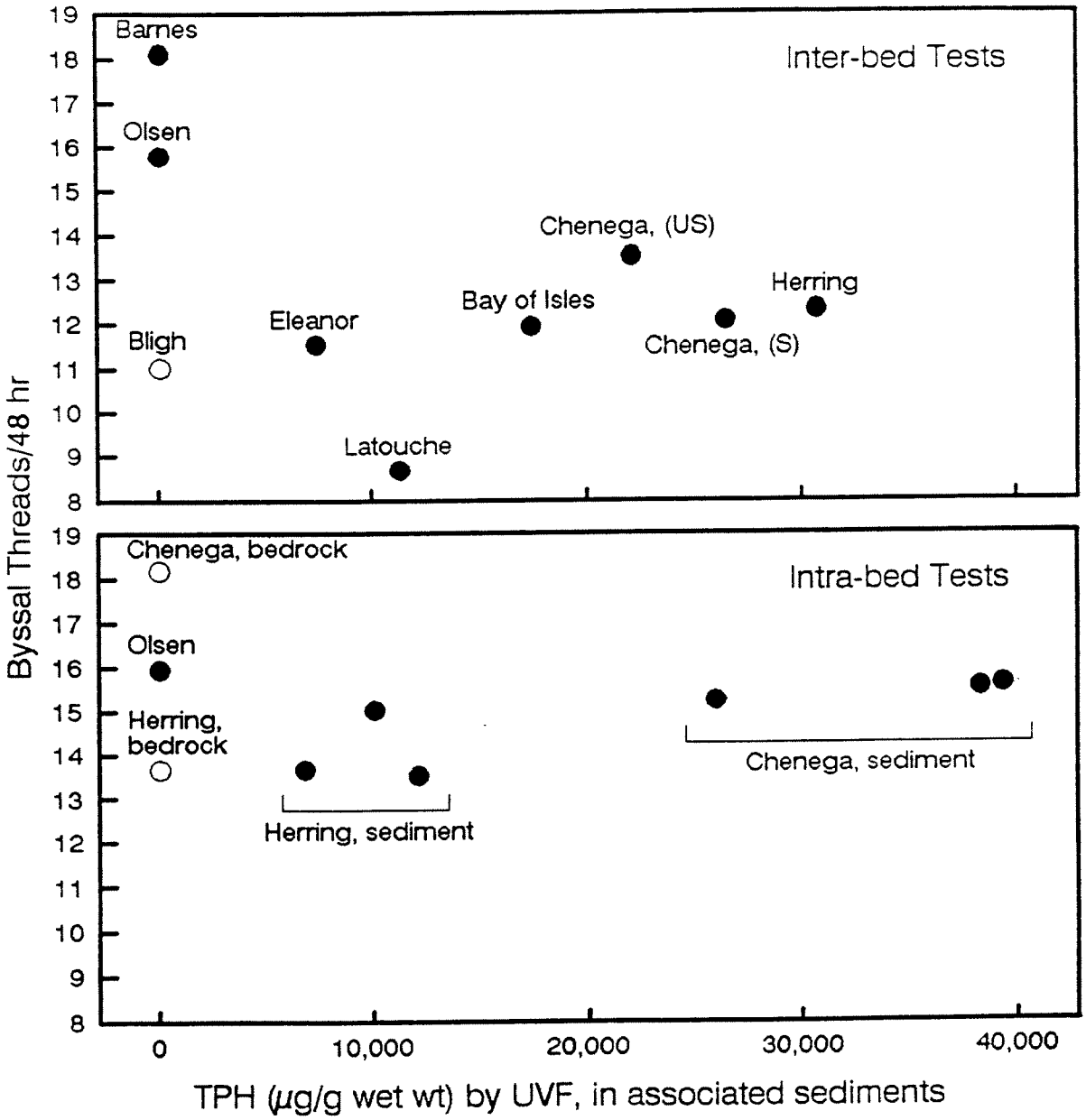


Figure 16.—Mean numbers of byssal threads produced in 48 h throughout the test periods by groups of 36 mussels from Prince William Sound, plotted against ultraviolet fluorescence (UVF) estimations of total petroleum hydrocarbons (TPH) in associated underlying sediments. Hydrocarbon levels indicated by open circles are assumed to be near 0, either because the mussels were collected from bedrock rather than sediment, or because sediment sample data were unavailable (Bligh Island) but previous measurements have been near 0 µg/g TPH. S = mussel beds that were stripped; US = unstripped beds that were sampled for comparison to stripped beds.

finis