NOAA Technical Memorandum NOS ORCA 114

Integrating Physical and Biological Studies of Recovery from the *Exxon Valdez* Oil Spill

Case Studies of Four Sites in Prince William Sound, 1989-1994

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National Oceanic and Atmospheric Administration
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NOTICE

Contents

Figures

Figures continued

Figures continued

Figures continued

Figures continued

Figures continued

Tables

Tables continued

Tables continued

INTRODUCTION

On March 24, 1989, the tanker *Exxon Valdez* grounded on Bligh Reef in Alaska's Prince William Sound, rupturing its hull and spilling nearly eleven million gallons of Prudhoe Bay crude oil into a remote, scenic, and biologically productive body of water. It was the largest oil spill in U.S. waters. In the weeks and months that followed, the oil spread over a wide area in Prince William Sound and beyond, resulting in an unprecedented response and cleanup.

The Hazardous Materials Response Branch (HAZMAT, now the Hazardous Materials Response and Assessment Division) of the National Oceanic and Atmospheric Administration (NOAA) was among the many local, state, Federal, and private agencies and groups to provide immediate operational and scientific support during the assessment, response, and cleanup phases. In their role as science advisors to the Federal On-Scene Coordinator (FOSC), HAZMAT representatives provided spill trajectory, resources at risk, and early spill impact information during the initial stages of the spill. Once the focus shifted from response to cleanup, HAZMAT addressed issues related to the effectiveness and environmental effects of cleanup technologies.

While there is no question that the *Exxon Valdez* spill was an unfortunate, and in some ways, tragic incident, it is also clear that it provided a necessary impetus to reexamine the state of oil spill prevention, response, and cleanup. One result was the passage of the Oil Pollution Act of 1990 by the U.S. Congress. Many states responded in similar fashion by tightening or completely restructuring oversight of oil production and transportation. For NOAA/HAZMAT, the *Exxon Valdez* spill was by far the largest (and longest-term; scientists on-scene worked nearly round-the-clock for the six months following the spill) incident response ever mustered. In addition, it was a unique opportunity to learn about the long-term effects of oil and cleanup activities in a relatively pristine setting, and to gain a greater level of understanding that would facilitate a more effective and lower impact response in future incidents.

To that end, NOAA/HAZMAT has sponsored and administered shoreline monitoring activities in Prince William Sound to study both the physical and biological changes at sites that were oiled and subsequently treated during the cleanup. These studies have differed from other spill-related investigations that have taken place since 1989 in at least two important ways:

1. The primary purpose for the monitoring was to evaluate the effects of both oil and cleanup on the physical and biological recovery of shorelines, with the ultimate goal of improving future response and cleanup actions. This was a distinctly different approach from many of the other studies, sponsored by state or Federal trustees or the Exxon Corporation, which sought to either demonstrate or refute claims of damage for litigation purposes. One consequence of this has been the freely available data and interpretive reports from the NOAA/HAZMAT studies since their inception.

2. It was recognized very early during the *Exxon Valdez* experience that understanding the effects of oil and shoreline treatment required a multidisciplinary approach rather than a series of isolated studies. For example, it became apparent that recovery of biological communities could not begin until the physical substrate was stable or other habitat characteristics were appropriate. Thus, estimates of recovery time had to take into account both the stabilization of the habitat and a sufficient reduction in chemical toxicity attributable to oil. Chemical sampling has been an integral part of the geomorphological and biological studies that constitute the major components of the NOAA/HAZMAT monitoring effort; and furthermore, there has been increasingly substantial overlap between those two major components over the course of the monitoring program. One result of the integrated approach is this report, which brings together and links research findings from three disciplines.

The primary components of the NOAA/HAZMAT monitoring program, geomorphological and biological studies, had separate origins in 1989. Geomorphological studies in Prince William Sound formally began in September 1989 at the request of the U.S. Coast Guard. The objective of these studies was essentially operational in nature: to provide the scientific information necessary for making recommendations on shoreline treatment strategies for 1990 and beyond. Specifically, the studies were designed to monitor the persistence of oil on Prince William Sound shorelines over the first fall and winter after the spill, to characterize the chemical composition of oil residues, and to provide information for forecasting the degree and distribution of shoreline contamination. The field work was initially contracted to Applied Technology, Inc., with managerial oversight provided by Research Planning, Inc. (RPI) and NOAA/HAZMAT. In 1990, NOAA/HAZMAT contracted with RPI to continue and expand the studies.

The biological studies that represent the other major component of the monitoring program had their beginnings in the early days of the spill, in Spring 1989. The principal investigators for the biological assessment were initially employed by Dames and Moore, Inc., under contract to Exxon Co. USA, to establish fixed intertidal monitoring sites in Prince William Sound. By 1990, the principal investigators had moved to other companies (Pentec Environmental, Inc., and ERC Environmental and Energy Services Co., Inc) and were no longer associated with the Exxon monitoring program. By that time, NOAA/HAZMAT had identified a need for focused biological studies to complement the geomorphological studies and to guide shoreline cleanup decisionmaking, and in mid-1990 contracted with Pentec and ERC to continue the work.

Both geomorphological and biological studies (with their integral components of chemical analysis, provided by the Institute for Environmental Studies at Louisiana State University) have continued since their beginnings in 1989. In some years, researchers have made several field sampling trips in order to characterize within-year or seasonal changes occurring at the study sites. More important has been the opportunity to make field visits over the longer-term, to observe changes with time measured in units of years rather than weeks or months. The NOAA/HAZMAT program is one of the few that can provide information and trend data from immediately following the spill (and in some cases, before oil came ashore at study sites) to the present. Current plans are to continue the monitoring effort through the end of the decade.

That different shoreline types are affected differently by oil spills has long been recognized, and is the basis for NOAA/HAZMAT's approach to defining resources at risk during a spill, and for the ongoing effort to classify the environmental sensitivity of shorelines around the country. Experiences with previous spills have provided a number of lessons about the behavior and persistence of oil in the environment. Yet when the *Exxon Valdez* spill occurred, the gravel beaches that are common in much of Prince William Sound presented a special problem because of their unique setting compared with gravel beaches at spills studied earlier, such as the *Amoco Cadiz*. The Prince William Sound beaches are more sheltered from wave action and they were highly modified by uplift during the Good Friday earthquake of 1964, almost exactly 25 years before the spill. Basic questions arose whose answers would shape the nature of both response and cleanup. These included questions such as:

- How long will the oil that penetrated into the gravel beaches persist in the environment?
- What are the best options for response and cleanup, given the physical characteristics of the beach?

- How long will it take shorelines highly modified by heavy washing or berm relocation to return to their original physical configurations?
- What improvements can be made in our understanding concerning which shorelines are most sensitive to oiling and/or treatment effects?

The type of oil spilled greatly affects its physical behavior, persistence, fate, and effects on biological resources. As a result, chemical analysis of oil residues is critical to understanding both the fate and the effects of spilled petroleum in the environment. It is also important to track how the oil changes as it weathers over space and time. For example, the emulsified oil that stranded onshore in the Gulf of Alaska had very different physical properties, and thus behavior, compared to the fresh liquid oil that affected much of Prince William Sound. Detailed chemical analysis is essential in order to provide answers to questions that arise during a spill such as:

- What is the source of stranded oil?
- How toxic is it?
- How long will the oil persist in the environment?
- How long will toxic effects persist?
- What are the best options for response, given the physical and chemical characteristics of the product?

Similarly, spilled oil can have highly variable biological effects depending on the relative sensitivity of resources and habitats to oil exposure. In the approach embodied by environmental senstivity indices that are often used as references for contingency planning and response, exposed rocky shorelines are classified as least sensitive to oiling, and sheltered marsh habitats as most sensitive (Hayes et al. 1981). Although the obvious priority during the initial stages of a spill is preventing exposure to oil, as time passes the emphasis will shift to clean up of stranded product. Understanding how communities will recover from oil exposure and cleanup activities is an important input in structuring a treatment strategy.

In Prince William Sound, there is an abundance of gravel beaches and rocky shorelines. These shoreline types rank relatively high in environmental sensitivity assessments, and the subtleties of oil behavior and the biological resources that can be found on the shoreline defined a range of effects from both oiling and cleanup activities. Relevant questions from a biological perspective include:

- What kind of biological communities can be found in the affected area?
- Is any information known about biological resources that existed before the spill?
- What was the nature of initial oiling?
- Will toxicity of the oil change with time?
- How have the biological communities changed with time?
- What changes can be attributed to the spill?
- How long before biological communities ~~to~~ recover from the spill and cleanup?

Ultimately, we probably would like to know:

- What cleanup activities/methods will speed natural recovery?
- What will cause more harm than leaving the oil alone?

Although the physical, chemical, and biological characteristics of an oil-impacted area are evaluated discretely, interpretation of results from each component study should not take place independent of the others. Consideration of just one piece of the picture conveys an unrealistically isolated system. Sammarco (1994), introducing a book on the biophysics of marine larval dispersal, makes an allegorical reference that is most appropriate for the science related to oil spill assessment:

> The Ryoan-ji Buddhist Temple is the home of one of the most famous rock-and-sand seki-taki gardens in Japan. It was constructed in Kyoto in the 1470's by an anonymous designer. It is simple in form, with a bed of white and grey gravel serving as a base for 15 rocks placed within the garden in what would appear to be no particular order. It is surrounded on three sides by a high wall and can only be viewed from one side adjoining the temple. Despite its initial appearance, however, there would appear to be some order to the placement of the rocks, because in no position from the viewing area can one see all 15 rocks at the same time. From any single perspective, one can see only a portion of the rocks. In order to understand the full design of the garden, and obtain a full count of the rocks, one must change one's vantage point or perspective while remembering the results of the previous view or views, until all of the information can be assembled to reveal the true nature of the garden.
>
> The message here is that a single perspective cannot provide all of the answers to a question, despite the intensity of our attempts to see the whole pattern. Many things will remain hidden from our view.
>
> Thus, the approach to a given problem by one scientist will most likely be different from that of someone else within the same discipline but with different training and experience. Complex scientific problems often need to be approached from two or more disciplinary perspectives.
>
> Sammarco (1994)

This is precisely the situation that became apparent in the NOAA/HAZMAT monitoring program: the natural interaction among physical, chemical, and biological environments requires an integrated assessment approach if we are to understand the effects and recovery from this spill. The degree of physical exposure to waves and light not only defines the character of a preexisting biological community, but also significantly affects the persistence—and weathering—of oil, and hence, the degree of biological effect. For example, dense mussel beds or plant cover can stabilize a beach and inhibit the normal processes that degrade residual oil. Oil beneath such biological layers may be "fresher" relative to that in similar substrates without the plant or animal cover. The oil may also be more biologically available because of its less weathered status, particularly to the mussels that have provided cover. However, if cleanup personnel disrupt the bed to clean the oil from the substrate, the beach may become physically destabilized, resulting in broader local effects. Moreover, the net environmental benefit of disrupting the mussels and their associated epibiotic community may not justify such a severe oil removal activity.

Complicating assessment of the physical and biological effects of the oil spill is the fact that the Prince William Sound region has experienced a major disruptive event in the relatively recent past. Almost exactly 25 years before the *Exxon Valdez* grounding, an 8.4-Richter scale earthquake occurred, with its epicenter at the edge of the Sound, about 50 km from the grounding site (Plafker 1969). Much of the Prince William Sound study area was uplifted by a meter or much more, significantly changing the physical and biological character of the nearshore environment. Effects of the earthquake are still evident in the Sound, with dead vegetation visible along the shore in some areas, and uplifted subtidal features now found in the intertidal zone.

There are other events unrelated to the spill that make investigation of impacts more difficult. For example, large-scale oceanic events such as the El Niño warming of the Pacific Ocean can adversely affect populations of both migratory and sessile biological organisms. Similarly, the winter of 1988-1989 was an anomalously cold period in Prince William Sound. It is likely that this stressed or killed many exposed intertidal plants and animals. Shortly thereafter, the oil spill occurred. These facts reinforce the need to carefully consider reference and control comparisons in order to account—to the extent possible—for these extraneous events.

The intent of this report is to bring together, in a structured way, information on four sites in Prince William Sound that were affected by the *Exxon Valdez* spill. Although other NOAA/HAZMAT documents have reported results of geomorphological, chemical, or biological studies, the goal here is to portray the processes of impact and recovery in a broader, and more multidisciplinary fashion by linking changes in physical processes and chemical weathering to those in biological community structure. We believe that it is only through this explicit consideration of linkage that we can begin to understand the effects of the *Exxon Valdez* spill and cleanup. Realistically, it may not be possible or practical to approach all monitoring efforts in such a multidisciplinary fashion. But we hope that, at a minimum, the role of the physical in defining the biological—and vice-versa—is considered and acknowledged. We believe that this can only improve the overall effectiveness of environmental assessment.

ACKNOWLEDGMENTS

As might be expected with a program of this temporal length and complexity, there have been many direct and indirect participants and benefactors—unfortunately, too many to individually acknowledge here. However, we would like to recognize certain key players. These include former NOAA Administrator John Knauss; former HAZMAT chief John Robinson; HAZMAT managers David Kennedy, Robert Pavia, and Jean Snider; U.S. Environmental Protection Agency environmental scientists Susan McMullin and John Armstrong; and NOAA attorney Craig O'Connor. Support for the program in the first three years was provided by NOAA, the U.S. Coast Guard, the U.S. Environmental Protection Agency, the Minerals Management Service, the American Petroleum Institute, and the Marine Spill Response Corporation. More recently, total funding has been provided through the *Exxon Valdez* Restitution Program.

Editorial review for this manuscript was provided by Lori Harris and Charlene Swartzell of HAZMAT. Jill Petersen of HAZMAT provided map files for production of site maps.

SITE SELECTION and REPORT ORGANIZATION

SITE SELECTION

The sites selected for discussion in this report were chosen primarily on the basis of their physical characteristics and the availability of information from the NOAA/HAZMAT monitoring program. We are not suggesting that all Prince William Sound shoreline types resemble the four discussed here, nor that the behavior and persistence of oil at other locations can be entirely explained by the processes proposed and discussed for the selected sites. However, we hope to show how basic elements of the physical environment can influence the fate and effects of an oil spill. By selecting qualitatively different kinds of oiled shorelines, we will demonstrate a range of physical, chemical, and biological effects.

The four sites selected represent a range of shoreline types found in Prince William Sound. Table 1 lists general information for the sites, and Figure 1 shows their location in Prince William Sound. Different treatment approaches were used at the sites, from no treatment (Snug Harbor) to high-pressure, hot -water wash augmented with chemical shoreline cleaner (Smith Island). All four sites have biological communities in common, but each also has unique features. Consequently, each has been affected by oil and cleanup in different ways, and the nature of recovery has varied as well.

Table 1. General characteristics of sites selected for this report.

Study Site	Shoreline Segment #*	Position	Shoreline Classification	Oil/Cleanup Category (see text)	Exposure Index
Block Island	EL-11A	60° 31' 48" N 147° 36' 24" W	Pebble beach/tidal flat	3/2	10
Northwest Bay	EL-52B	60° 32' 37" N 147° 36' 13" W	Bayhead gravel beach	3	64
Smith Island	SM-06B	60° 31' 40" N 147° 23' 05" W	Cobble-boulder platform	3	730
Snug Harbor	KN-401A	60° 15' 51" N 147° 45' 35" W	Rocky rubble slope	2	14

*Shoreline segment designations are included here for reference to the delineations used by agencies and Exxon between 1989 and 1992 during assessment and cleanup activities.

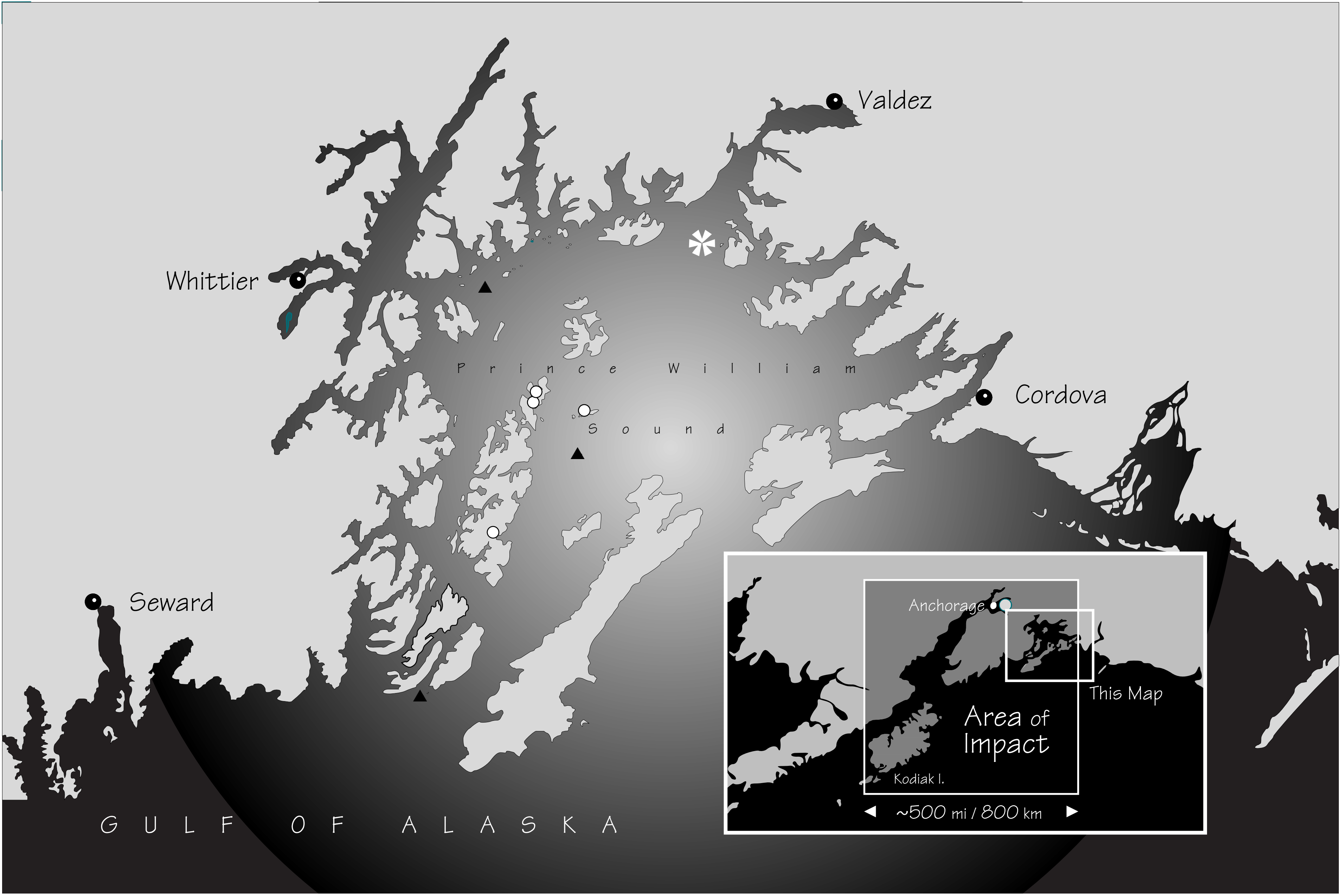

Figure 1. Prince William Sound study area with sampling sites for this report denoted by circles (○), meteorological station s established by NOAA in 1989 shown as (s). Grounding site marked by asterisk.

The study site designation gives the general area in which the shoreline of interest is as a rule less than 50 m long, site names by themselves do not provide enough information for the uninitiated to pinpoint the shorelines in the Sound. The shoreline segment and position using Global Positioning System (GPS) information permit much higher resolution for this determination. The shoreline segment and subdivision designations are the delineations defined by interagency (state, Federal, and Exxon) shoreline assessment teams beginning in 1989. These designations were refined in 1990 to permit consistent designations for the hundreds of kilometers of coastline surveyed and treated after the spill. GPS positions collected during various visits by the biological survey teams provide latitude-longitude information nominally accurate to about 100 m.

Table 2 shows tidal elevations measured at biological study areas within each of the four sites. These were calculated either by noting when the incoming tide reached a fixed marker for a station (such as a permanent stake or transplant frame), or by using a standard survey transit and rod to measure the elevational difference between a site marker and the water level at a recorded time. Although in special instances (e.g., a 1992 mussel transplant experiment at Smith Island), stations were carefully sited according to tidal elevation, most of the transects and stations were established in the early days of the spill in relation to locations of the dominant intertidal biota such as rockweed or red algae. As a result, there is some variability for a given tidal elevation designation ("lower," "middle," or "upper"). Among the four sites, for example, the actual elevation of low transects varied from 0.14 m to 1.05 m.

Shoreline classifications are the geomorphology team's category definitions for the sites. These will be discussed in much greater detail in each chapter. Oiling and cleanup categories are the biology survey team's classifications for defining whether sites were oiled and treated with high-pressure washing. Three general categories were used: Category 1, unoiled; Category 2, oiled, but not high-pressure, hot-water washed; and Category 3, oiled and washed with high-pressure hot water. These also will be discussed in each chapter and in Appendix A. The exposure index—to be defined in the next chapter—represents the geologists' assessment of the relative degree to which study sites are exposed to wave action. The range of index values in Table 1 reflects degrees of exposure from very sheltered to very exposed. As we will see, this is an important factor in evaluating the physical framework of the sites.

Table 2. Tidal elevations of selected biological study sites/stations as determined by standard survey methods. Referenced to mean lower low water.

Site	Station, Level	Transect Location	Elevation, m
Block Island	Gravel low transect	Midpoint	1.048
Block Island	Gravel mid -transect	Midpoint	1.927
Block Island	Rocky mid-transect	Origin	1.164
Block Island	Rocky upper transect	Origin	2.519
Block Island	1992 transplant transect	Plot 11	1.226
NW Bay W. Arm	Gravel low transect	Midpoint	0.142
NW Bay W. Arm	Gravel mid-transect	Midpoint	1.906
Smith Island	Boulder/cobble low transect	Origin	0.582
Smith Island	Boulder/cobble mid -transect	Origin	1.887
Smith Island	1992 transplant transect	Midpoint	2.316
Snug Harbor	Rocky low transect	Origin	0.369
Snug Harbor	Rocky mid-transect	Origin	1.945
Snug Harbor	Rocky upper transect	Origin	2.579

Even without fully understanding what each of the values in Table 1 actually mean, it is apparent that the sites we have chosen to discuss in this report are physically different from each other. This was intentional, to provide the reader with a range of site types to consider. The four sites are more similar in their oiling histories, since we are most interested in effects from the spill. Reference sites (i.e., unoiled or oiled and not cleaned) used in the NOAA/HAZMAT monitoring program have been important for identifying changes that may not be attributable to either oiling or cleanup.

Table 3 shows the frequency and timing of the geomorphology and biology study teams‘ visits to the four sites. Although laboratory chemistry support has been an integral part of both programs since their inception, chemists were not included on the field teams until 1992.

ORGANIZATION OF THIS REPORT

A tremendous amount of information has been collected and analyzed for each of the four sites. Each chapter will focus on one of the sites, summarizing that information in discrete sections as discussed below.

General location

The discussion under general location will introduce the general physical location and characteristics of each site. It will set the stage for the conditions, activities, and study results to follow.

Table 3. **Listing of the survey dates and stations visited during the NOAA geomorphological/chemical monitoring program.**

	1989				1990						1991		1992	1994
Station Number	16-20 Sept.	17-23 Oct.	3-9 Nov.	3-8 Dec.	1-6 Jan.	30 Jan.-3 Feb.	28 Feb.-5 Mar.	23-31 May	22-23 June	1-8 Sept.	19-25 Jan.	25-29 Aug.	10-16 Aug.	21-26 July
N-3	X	X		X	X	X	X	X		X	X	X	X	X
N-5	X	X		X	X	X		X		X		X		X
N-9	X	X	X		X	X	X		X	X	X		X	X
N-14	X	X		X		X		X		X	X		X	X

Oiling and treatment history

As a key part of the overall monitoring study, both the oiling and treatment histories for the sites were extensively researched. Each site chapter will briefly summarize the known information on degree of oiling and the nature of cleanup. Appendix A includes comprehensive histories for the sites.

Written documentation in interagency survey records, and summaries provided by State of Alaska and Exxon personnel were relied upon heavily, but generally did not provide the level of detail necessary to identify conditions and activities at specific study sites. In some cases, this was the best information available and thus served as the basis for the site oiling and treatment classifications. For the target sites for this report, however, better additional information was available, including direct observations and documentation by members of the study teams; dated photographic documentation of conditions and activities at study sites; field notes by Alaska Department of Environmental Conservation monitors; and detailed treatment histories prepared as part of Exxon or agency cleanup monitoring studies.

Geomorphology

The physical characteristics of a shoreline, combined with those of a spilled oil product, will determine the fate of the oil once it strands in the intertidal zone. However, at the time of the *Exxon Valdez* spill, the dynamics of coarse gravel beaches[9] and how they might influence the

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[9] The sediments of the beaches studied are composed primarily of gravel, which means the sediments have an average diameter greater than 2 mm. Gravel is subdivided into four classes on the basis of size:

class	**Size range**
granule	2-4 mm
pebble	4-64 mm
cobble	64-256 mm
boulder	>256 mm

behavior and persistence of oil were poorly understood relative to sand beaches and other habitats. The geomorphology section describes the physical nature of the study site and the changes that have occurred over the course of the monitoring program. Some of these changes can be considered as physical recovery from oiling and treatment, whereas others represent the natural dynamics of the Prince William Sound system. The gemorphology team also documented the occurrence of both surface and subsurface oil at the sites over time.

Chemistry

Chemistry has been an important component of NOAA/HAZMAT activities related to the *Exxon Valdez* spill, from the initial encounters with the oil slick to the latest monitoring visits in Prince William Sound. Chemical analyses give a basic measurement of substrate contamination levels at all sites chosen for the monitoring program. Moreover, these analyses have also permitted insights into the biological availability of aromatic hydrocarbons, the course of weathering of residual oil, and the occurrence of non-*Exxon Valdez* oil contamination.

Chemistry results are generally reported in this document in two different ways, as total petroleum hydrocarbons (TPH), and as summed concentrations of selected polynuclear aromatic hydrocarbons (PAHs). The reasons for this dichotomy in reporting methods are both technical and practical:

- The measurement of TPH gives an estimate of all hydrocarbon compounds that might comprise residual oil, although it can also include material that is not petrogenic in origin. TPH values are simple gravimetric determinations of the solvent-soluble fraction of sediment samples. They are useful as estimates of the bulk oil concentrations in moderately to heavily contaminated samples; at low concentrations, however, the results may overestimate the true value because of the co-extraction of natural background lipophilic compounds such as plant lipid material and waxes. The geomorphology team relied on TPH as a relatively simple way to quantify and verify visual assessments of substrate oiling.

- PAHs are often singled out as a class of compounds of concern, primarily because they have been linked to a range of acute and chronic toxicological effects. The relative distribution of individual PAH compounds gives insight into oil weathering or biologically mediated transformations. Quantitative measurement of PAHs is performed by gas chromatography and mass spectrometry (GC/MS), a much more accurate, precise, and compound-specific method of chemical analysis than TPH determinations. However,

> GC/MS requires sophisticated electronic equipment, and is also much more time-consuming, labor-intensive, and hence, costly (not an insignificant consideration in determining programmatic priorities). The geomorphology team used GC/MS analysis of PAHs to track changes in oil residues, while the biology team relied exclusively on GC/MS analysis for both sediment and tissue samples since program inception. As we will explain later, GC/MS results provided the level of detail necessary for analysis of weathering and source fingerprinting.

All TPH values presented in this study, as well as all sediment results, were calculated on a wet weight basis. For Prince William Sound sediments, which contain few fines, very little difference would be expected between wet weight and dry weight values. Analytical values presented are valid to only two significant figures.

The next chapter discusses chemical approaches in more detail.

Biology

The biological effect of the spill and its associated activities is one of the ultimate concerns for response and shoreline cleanup personnel, resource managers, and residents of an oil-contaminated area. The early toll of the *Exxon Valdez* spill—heavily oiled birds and otters—was graphically communicated in media accounts worldwide. Once the oil began stranding along hundreds of miles of shoreline between Bligh Reef and the far end of Kodiak Island, however, the biological effects became more subtle, certainly less mediagenic, and potentially longer-term in nature. Much of the oil washed ashore in the upper half of the intertidal zone at affected shorelines. What was it doing to the intertidal communities of those habitats? A substantial amount of effort had been invested in determining the *effectiveness* of remedial techniques, but little was known about the environmental *effect*. Were cleanup techniques damaging plants and animals living in the intertidal zone? What were the ecological tradeoffs involved in removing the oil from the environment quickly but intrusively? Answers to these questions were not available in 1989, neither for an ecosystem as remote and relatively pristine as Prince William Sound nor for the scale and methods of shoreline cleanup.

The biology discussions in this manuscript are based on the results of the NOAA/HAZMAT monitoring program between 1989 and 1994. These include results of special studies implemented in addition to the so-called core monitoring activities, and often are framed within results reported in the relevant scientific literature. By drawing on all available information resources we hope to answer some of the questions posed above.

Discussion

Within this section there will be a broader interpretation of mechanism and process, including suggesting the role of physical conditions in determining the makeup of biological communities, and vice-versa. Much of this will be speculative in nature, since there has been no explicit hypothesis testing for most of these physico-biotic interactions. We will present potential explanations for observed conditions and trends, based on the evidence to date, and infer response-related considerations for future incidents in similar circumstances. This analysis will represent the current state of the lessons learned for the site and, as such, will necessarily change with incorporation and consideration of more data and interpretation.

APPROACHES, METHODS, AND DEFINITIONS

The basic approaches and methods used in the NOAA/HAZMAT program have been described elsewhere (see, for example, Houghton et al. 1993, and Michel and Hayes 1993). However, we provide an overview below, and detail other concepts important for understanding the implications of our results.

BIOLOGY APPROACH AND METHODS

General Approach

We used a stratified random sampling design to assess important intertidal assemblage and population (individual taxa) characteristics for this study. Sampling was structured following Zeh et al. (1981) to obtain statistically reliable estimates of density or cover of macrobiota inhabiting the surface (epibiota) and, where possible, the subsurface (infauna), within important zones and habitats.

The biological sampling effort for the NOAA/HAZMAT program was initially stratified according to three habitat types in Prince William Sound: rocky, boulder/cobble, and “mixed-soft.” These categories can be generally defined as follows:

1. Rocky habitats—Intertidal substrate composed primarily of bedrock or very large boulders (50 cm or larger). Because these sites were all sheltered from significant wave energy, the boulders tended to be angular (see explanation of exposure index at the end of this chapter for a detailed discussion related to the study sites).

2. Boulder/cobble habitats—Exposed beaches with nearly 100-percent coverage by rounded cobbles and boulders ranging in size from about 10 to 50 cm. Some larger materials and/or bedrock outcroppings were occasionally present.

3. Mixed-soft habitats—Typically a mixture of silt, sand, granules, and pebbles with a varying proportion of cobbles (5 to 25 cm) or boulders (25 to 50 cm).

Among the four sites targeted for this report, two are considered mixed-soft (Northwest Bay and Block Island), one rocky (Snug Harbor), and one boulder/cobble (Smith Island).

To represent important biological zones and to further stratify the sampling, three tidal elevations were typically sampled at each site: upper, middle, and lower. These are defined in biological terms as follows:

1) Upper—Near the upper limit of attached macrobiota;

2) Middle—The upper portion of the broad rockweed-dominated zone; and

3) Lower—Extending from the lower edge of the rockweed zone to the lower margin of the intertidal.

Finally, sites within each habitat type were assigned to one of three categories to represent the range of oiling and shoreline cleanup stresses experienced in 1989. Stations were classified as Category 1, 2, or 3 based upon available information regarding disturbance from oiling and hot-water hydraulic treatment. We define the categories as:

- Category 1: Unoiled—No significant oiling or treatment reported; considered reference stations.
- Category 2: Oiled/untreated—Completely untreated (setaside site) or not documented as treated with high-pressure, hot water in 1989.
- Category 3: Oiled/treated—Known to have been washed with high-pressure, hot water.

Even though many of the biology sites in the NOAA/HAZMAT program were sampled in 1989 under Exxon sponsorship, the field work was performed by members of the current NOAA scientific team. Thus, the methods and results are consistent and comparable over the entire study period. The original sites were not initially selected through a systematic randomization process, because the movement of the oil and physical characteristics of the sites (e.g., substrate and orientation) precluded true randomization. Within the constraints imposed by the nature of the spill, however, our goal was to select comparable sites within representative geomorphological habitat types, to include oiled as well as unoiled sites within the habitat types.

In the first NOAA/HAZMAT efforts to integrate biology and geomorphology, several stations without 1989 biological data were sampled by the biology team beginning in 1990 because of their inclusion in the then-separate NOAA geomorphological monitoring program. Similarly, in 1990, the geomorphology team began visits to what had previously been exclusively biology sites.

The sample design for the core biology monitoring program was established to monitor long-term recovery trends at sites with known oiling and treatment histories. It is well-suited (by the number of replicate subsamples at each elevation) to compare transects in similar habitats but with different oiling and/or treatment histories. Only a limited number of stations could be sampled in each habitat/oiling/treatment category. Thus, the design is less well-suited for statistical inference regarding the generalized impacts of oiling and treatment over all habitats in Prince William Sound with similar oiling and treatment histories.

Epibiota

Biological variables measured or estimated for epibiota (plants and animals living on or attached to the substrate) included algal cover (percent by taxon) and numbers or percent cover of major epibenthic fauna. Relative cover estimates for biota, substrate types, and oiling were based on visual examination of the tops, sides, and overhangs within a quadrat, but boulders and cobbles were not overturned. A subjective description of oiling in each quadrat was recorded along with the percentage of oil cover found within the quadrat. Individual observers cross-checked each other at frequent intervals to ensure correct identification of biota and consistent estimation of percent cover.

Infauna

Infauna (i.e., the animals living within the sediment) were sampled at middle and lower elevations in mixed gravel, sand, and/or mud (mixed-soft) sites. Smaller infauna were sampled with randomly located 0.009 m^2 by 15 cm-deep cores. Cores were taken next to the randomly located 0.25-m^2 quadrats used to sample epibiota. A different position relative to the quadrat was sampled in each successive sampling trip to avoid recollecting in the same location. Cores were sieved through 1.0-mm screens in the field to remove large non-biological material, then preserved in 10-percent buffered formalin. Detailed sorting and taxonomic analysis took place in the laboratory.

Laboratory staff washed infaunal samples field-sieved on 1.0-mm screens to remove formalin and transferred them to 70-percent ethanol. All animals were sorted from debris and identified to the lowest practicable taxon under a dissecting microscope. All sorting and taxonomy took place in the laboratory, including re-sorting ten percent of the samples for quality control. Regional specialists identified problematic species.

Chemistry Collections During Biology Surveys

Sediments. Personnel wearing disposable surgical gloves sampled biology site sediments for chemistry. They used wooden or plastic spatulas to place sediment samples in pre-cleaned glass jars with Teflon®-lined lids. All equipment was changed between samples. At most stations, the sediment sample was composited from surface sediments from the upper 5 cm of substrate at five randomly chosen locations along the beach contour. Sampling points were located coincident with the locations of the five infaunal cores along established transects. At some stations, a separate sediment sample was collected at each of the five infaunal coring locations for direct correlation with infaunal variables. Hydrocarbon samples were collected primarily from the same tidal levels as the biological samples. All samples were frozen on board the vessels and shipped frozen to the laboratory.

Tissues. Field personnel wore surgical gloves during collection of organisms to be analyzed for tissue levels of hydrocarbons to minimize the potential for contamination through handling. The number of organisms sampled varied according to the animals' sizes, but a minimum of 10 g of wet tissue was collected to allow for duplicate chemical analyses. Sample sizes for mussels and clams usually ranged between 15 and 35 individuals. The entire sample of whole individuals for each species was carefully double-wrapped in aluminum foil. The samples were then placed in labeled polyethylene bags and frozen for transport to the laboratory.

Other Site Characterization Measurements

Field-preserved, whole sediment samples were used to provide grain size distribution information following the procedures of McNeil and Ahnell (1964). Sediments were wet-sieved through a standard sequence of nine screen sizes (12.5 mm to silt-clay < 63 microns). Each fraction was then placed into displacement cylinders, with the volume of water displaced measured in a graduated cylinder.

We measured water temperature and salinity at sites with a YSI-33 field meter. The probe was gently lowered to about 0.3 m below the surface of the water, and water temperature (±1˚C) and salinity (parts per thousand) were read directly off the meter.

GEOMORPHOLOGY APPROACH AND METHODS

A detailed description of the geomorphology methods used on this project is given in Michel and Hayes (1991). The Prince William Sound area was visited for geomorphology study 13 times between September 1989 and July 1994. Table 3 lists the sites monitored during each survey.

Field visits to the study sites were planned to coincide with maximum spring low tides. All field surveys were conducted within the window of 2.5 hours on either side of low tide.

During each site visit, a topographic profile was run perpendicular to the beach, and details of the morphology, sediments, and surface oil-distribution patterns were noted at each survey interval. The station was photographed and sketched in detail, highlighting the distribution of oil, if present, and the effects of cleanup. Trenches were dug at intervals along the profile to determine the depth of oil penetration. Each trench was described and photographed in detail.

Samples were collected of both surface and subsurface oil contamination, usually oiled sediments. Surface oiled sediment samples (upper two centimeters) were collected only for detailed characterization and analysis of weathering trends. Subsurface oiled sediment samples were collected from discrete intervals, frequently from the bottom of the oiled sediments in the trench. Other intervals were collected as appropriate. No samples were composited; all samples were grab samples.

To date, over 820 samples collected as part of the geomorphology studies have been analyzed for TPH. Over 120 samples have been chemically characterized by GC/MS to track weathering patterns in the persistence of PAHs. Chemical analyses were carried out by Louisiana State University's Institute for Environmental Studies.

Throughout this report, we use the terminology and definitions established during the 1991 interagency shoreline surveys of the oiled regions. Surface oil was described using the following terms:

Asphalt pavement (AP): Heavily oiled sediments held cohesively together.

Coat (CT): Oil that ranges between 0.1 and 1.0 mm thick (can be easily scratched off with a fingernail).

Stain (ST): Oil less than 0.1 mm thick (cannot be easily scratched off with a fingernail).

Film (FL): Transparent or translucent film or sheen.

Subsurface oil was described using the following terms:

Heavy oil residue (HOR): Pore spaces partially filled with oil; oil is usually not flowing out of sediments.

Medium oil residue (MOR): Sediments heavily coated with oil; pore spaces are not filled with oil; pore spaces may be filled with water.

Light oil residue (LOR): Sediments lightly coated with oil.

Oil film (OF): Continuous layer of sheen or film on sediments; water may bead on sediments.

The sediments of the beaches studied were composed primarily of gravel, which means the sediments have an average diameter greater than 2 mm. Gravel is subdivided into four classes on the basis of size:

class		**size range**
granule	—	2-4 mm
pebble	—	4-64 mm
cobble	—	64-256 mm
boulder	—	greater than 256 mm

On the figures showing trench descriptions throughout this report, histograms are used to represent field estimates of grain-size distributions in the various sedimentary units. Abbreviations used in these histograms are boulders (B), cobbles (C), pebbles (P), granules (G), and sand (S).

CHEMISTRY APPROACH AND METHODS SUMMARY

Sediment Hydrocarbons

Laboratory sediment hydrocarbon analyses were performed at the Institute for Environmental Studies at Louisiana State University, Baton Rouge, Louisiana. Methods were modified from procedures of Krahn et al. (1988). Sediment samples were weighed into 600-ml beakers for extraction. Approximately 100 cc of material was extracted for each sample. The samples were dried before extraction by adding anhydrous sodium sulfate (Na_2SO_4). Sodium sulfate not only removed any water as an extraction interference, but also enhanced the extraction of weathered oil residue from the pebbles and gravel by acting as an abrasive. Surrogate standards *d*-10-acenaphthalene, *d*-10-phenanthrene, and *d*-14-terphenyl were added. Samples were extracted three times using nanograde hexane solvent and a bath sonication technique. The extracts were combined and then reduced in volume by a combination of rotary-evaporation and solvent reduction under a gentle stream of high-purity nitrogen (nitrogen blow-down). The final concentration varied between 1 ml and 150 ml, depending upon the degree of contamination. The extracts were analyzed by GC/MS using a Hewlett Packard 5890™ GC equipped with a DB-5 high-resolution capillary column directly interfaced to a Hewlett Packard 5970B™ MS. The GC was optimized to provide the required degree of separation (i.e., baseline resolution between nC-17 and pristane). The GC was operated in the temperature program mode with an initial column temperature of 55˚C for three minutes, then increased to 290˚C at a rate of 6˚C/minute, and held at the upper temperature for 17 minutes. The MS was operated in the selective ion mode to enhance quantitative analyses. The injection temperature was held constant at 250˚C, and only high-temperature, low-thermal bleed septa were used. The interface to the MS was maintained at 280˚C.

At the beginning of each analysis period, the MS was tuned to perfluorotributylamine. Quantitative analysis was by an internal standard technique using authentic standards for the non-alkylated PAHs with the exception of naphthobenzothiophene, which was estimated using the response of dibenzothiophene. The alkylated homologs were calculated using the non-alkylated parent. The following internal standards were co-injected: *d*-8-naphthalene, *d*-10-anthracene, *d*-12-chrysene, and *d*-12-perylene.

Tissue Hydrocarbons

Tissue aromatic hydrocarbon analyses were also performed at Louisiana State University. Methods were modified from the procedures of Krahn et al. (1988). Tissues from a given site were removed from their shells, thoroughly rinsed with deionized water, and composited. The composite samples were homogenized in a Tissuemizer (blender) and refrigerated in solvent-rinsed jars with Teflon®-lined caps before further sample preparation. If delay of more than two days was anticipated, the samples were frozen. For analysis, a small aliquot, 3 to 5 g, of the homogenized tissue was added to 40-ml precleaned and solvent-rinsed vials. The samples were digested overnight by adding a single pellet of potassium hydroxide. To enhance the digestion, the samples were sonicated and swirled periodically. The samples were then spiked with the same surrogate standard suite used for sediment analyses. The samples were dried with anhydrous sodium sulfate until they had achieved the consistency of dry sand and extracted three times with dichloromethane. The extracts were combined into a single rotary-evaporation flask and reduced to less than 4-ml volume. At this time, the sample extract was transferred into 4-ml vials and reduced in volume further by nitrogen blow-down. The solvent was exchanged into hexane and reduced to 100 µl.

Sample fractionation, or cleanup, was required to enrich the target analytes while at the same time excluding matrix interferences. Sample fractionation was performed using silica-gel/alumina columns. The columns were calibrated to elute the desired analytes from the column in the aromatic fraction. This fraction was eluted into conical 4-ml volumetric vials and reduced to a final extract volume of 0.1 ml before instrumental analysis. The target analytes were quantified by an internal standard method and corrected for recovery using surrogate standards.

The target analytes were either single compounds or isomers quantified as a single group. The list of target aromatic hydrocarbons detailed in Table 4 exceeds the U.S. Environmental Protection Agency priority pollutant list. Many of the target analytes are not single compounds, but are isomer groups such as the C-2 naphthalene homologues (i.e., the naphthalenes with two alkylated groups). Quantification of the non-alkylated PAH and the saturated alkanes was based on authentic standards. The alkylated homologues were generally quantified by response factors generated by the unalkylated parent, e.g., the response factor for naphthalene (C-0) was used to calculate the C-1 through C-4 naphthalene homologues. Surrogate standards injected with each sample were quantified for extraction efficiency; the surrogates included acenaphthene-*d*10, phenanthrene-*d*10, and terphenyl-*d*14. Results for all analytical methods were reported as a function of wet weight, with dry weight values provided for tissue correction.

Lipid weights were determined by preparing the sample as above except for the digestion step and fractionation. The weight of the solvent extract was determined by a gravimetric analysis (oil/grease analysis). However, the results from these analyses are crude and subject to a variety of interferences that may overestimate the true lipid weight.

Dry weights were determined by weighing a small amount of the homogenized tissue on a preconditioned, prenumbered, and preweighed tin. The tin was placed into a drying oven at 90˚C for 24 hours, then reweighed.

TPH was determined gravimetrically after solvent extraction with freon (Standard Method 503). Selected extracts were also analyzed by GC/MS, targeting 37 PAHs used to characterize petroleum hydrocarbons.

Interpretive Approach for Chemistry

The NOAA/HAZMAT program selectively quantified specific compounds for chemical characterization and source fingerprinting. The most useful group of target analytes in oil for these purposes is the two- to six-ring aromatic and sulfur heterocyclic hydrocarbons, and their respective alkyl-substituted homologues. Although the target aromatic hydrocarbons typically represent less than 5 percent of the bulk composition of most oils, they are essential to characterize petroleum source, identify potential biological effects, determine exposure pathways, and monitor weathering trends and degradation of the oil (Sauer and Boehm 1991). Since hydrocarbons are naturally present in the environment, detailed chemical analyses are required to confirm the presence of oil and differentiate among the types of hydrocarbons detected in a monitoring study. Aromatic hydrocarbons are extremely useful in differentiating petroleum from, for example, byproducts of combustion. That is, oil is characterized by PAHs composed primarily of 1-, 2-, and 3- ring aromatic compounds, with a preference for alkyl-substituted homologues. PAHs resulting from incomplete combustion are characterized by 3-, 4-, and 5- ring aromatic compounds, with few substituted alkyl homologues. Distinguishing between background aromatic hydrocarbons derived from natural events, such as forest fires, and residual oil pollution is a key element in this study.

GC/MS results are generally presented as total target polynuclear aromatic hydrocarbons values (TPAH) and histogram plots of the specific target aromatic hydrocarbons (also called PAH profiles). The TPAH value sums the specific compounds quantified (a complete list is shown in Table 4). TPAH values were presented as ng/mg on either a wet or dry weight basis (one ng/mg is equivalent to one part per million, or ppm). The tissue data were quantified on a dry weight basis to reduce intrasample variability. All analytical values presented are valid to only two significant figures.

TPAH values were useful in comparing gross compositional changes in the concentration of aromatic hydrocarbons—such as to evaluate the accumulation of PAHs in clams transplanted from "clean" sites to contaminated sites. The PAHs analyzed are not specific to oil derived from the *Exxon Valdez* spill, and are not necessarily even petroleum-specific, but the relationships among different target PAH compounds can characterize a given PAH as being derived from petroleum pollution and may characterize the type of oil as well as degree of change caused by weathering. As such, PAH profile plots are valuable tools in assessing the type of PAH pollution, weathering or biodegradation changes in stranded oil, and characterizing bioaccumulation in living organisms.

Table 4. Target compounds assessed by GC/MS in the NOAA monitoring program. Sum of these compounds, excluding those identified with *, is the TPAH value.

Compound	Abbreviation in Text & Figures	Ion Mass
alkanes* (nC-10 through nC-31)		85
decalin*		138
C-1 decalin*		152
C-2 decalin*		166
C-3 decalin*		180
naphthalene	N	128
C-1 naphthalenes	C1N	142
C-2 naphthalenes	C2N	156
C-3 naphthalenes	C3N	170
C-4 naphthalenes	C4N	184
fluorene	F	166
C-1 fluorenes	C1F	180
C-2 fluorenes	C2F	194
C-3 fluorenes	C3F	208
dibenzothiophene	D	184
C-1 dibenzothiophenes	C1D	198
C-2 dibenzothiophenes	C2D	212
C-3 dibenzothiophenes	C3D	226
phenanthrene	P	178
C-1 phenanthrenes	C1P	192
C-2 phenanthrenes	C2P	206
C-3 phenanthrenes	C3P	220
naphthobenzothiophene	NB	234
C-1 naphthobenzothiophenes	C1NB	248
C-2 naphthobenzothiophenes	C2NB	262
C-3 naphthobenzothiophenes	C3NB	276
fluoranthrene/pyrene	FA	202
C-1 pyrenes	C1PY	216
C-2 pyrenes	C2PY	230
chrysene	CH	228
C-1 chrysenes	C1CH	242
C-2 chrysenes	C2CH	256
benzo(b)fluoranthene	BF	252
benzo(k)fluoranthene		252
benzo(e)pyrene	BeP	252
benzo(a)pyrene	BaP	252
perylene	PER	252
indeno(1,2,3-cd)pyrene	IPY	276
dibenzo(a,h)anthracene	DIB	278
benzo(g,h,i)perylene	BNZ	276
hopanes (191 family)*		191
sterenes (217 family)*		217

* Used primarily for source-fingerprinting and not quantified.

Figure 2 is a series of PAH profiles typical of the data presented in this study. The y-axis lists concentration and is generally reported as ng/mg in scientific notation, e.g., 1E+0 is equal to 1, 1E+3 is equal to 1000, and 1E-3 is 0.001. The x-axis lists the specific target compounds identified in Table 4. Table 4 also provides a key for the abbreviations used. The x-axis always shows the same compounds in the same order. By convention (and we recognize that there is no completely satisfactory way to do this), compounds below the method detection limit are represented as zero (0) values in computations. Unless otherwise specified, the error bars represent the standard deviation for field replicates analyzed separately. Analytical variance as measured by splitting field samples at the laboratory into duplicates was usually less than 20 percent.

The series of PAH profiles shown in Figure 2 emphasizes that different oils and pollution sources have compositionally different PAH distribution patterns. In this study, hydrocarbon residues found at most sites were dominated by pollution derived from the *Exxon Valdez* incident. Changes in the PAH profiles were used to characterize loss or uptake of the target compounds.

IMPORTANT DEFINITIONS AND CONCEPTS IN THIS STUDY

Oil Weathering

We define the term “weathering” to encompass the physical and chemical changes that crude oils undergo as a result of interaction with the environment. The fate of oil in an environment, as determined by weathering, is governed by the cumulative physical and chemical properties of the individual constituents in the bulk oil (Payne and McNabb 1984) as well as the influence of environmental factors such as temperature, sea state, and habitat ecology. Processes which affect the fate of oil released into an aquatic environment include evaporation, dissolution, emulsification, absorption, and photochemical and microbial degradation. The rate at which these processes occur is controlled by the physical properties and chemical composition of the oil, exposure to physical processes, abiotic environmental factors, and the existence or absence of hydrocarbon-degrading microorganisms (bacteria, mold, yeast, and fungus) and essential nutrients.

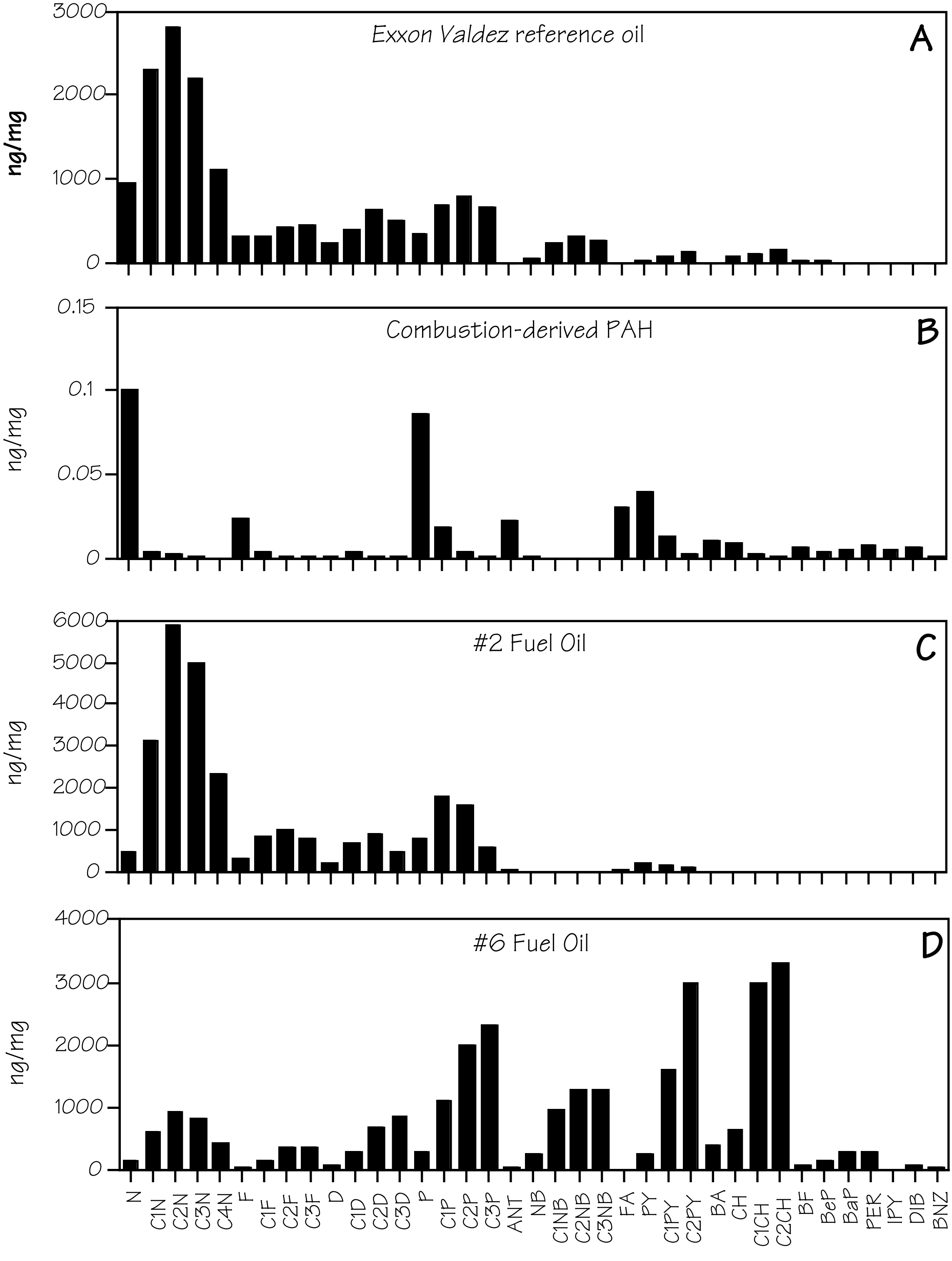

Figure 2. Comparison of the PAH profiles for Exxon Valdez reference oil (A), combustion by-products derived from burning oil (B), diesel (#2) fuel (C), and a heavy #6 fuel oi (D).

Changes in the PAH profiles from samples collected in the NOAA/HAZMAT program were often directly the result of weathering, primarily evaporation and biodegradation. For this study, we use a simple characterization scheme to define weathering state: samples were classified as relatively unweathered, and slightly, moderately, or heavily weathered, as reflected by the change in the PAH distribution pattern between the unweathered *Exxon Valdez* reference oil and the sample of interest. The classifications were defined as follows:

> *Relatively unweathered*—No apparent change in the PAH profile. Loss of compounds more volatile than naphthalene may have occurred.
>
> *Slightly weathered*—No major change has occurred in the relative order or abundance of aromatic homologues. The alkylated naphthalenes are still the most abundant constituents, but may have been slightly reduced. Alkanes generally still present.
>
> *Moderately weathered*—The total naphthalenes are significantly depleted from the bulk oil and the total alkylated dibenzothiophenes and phenanthrenes dominate the histogram plot. The alkane fraction is highly degraded.
>
> *Heavily weathered*—The dibenzothiophenes and phenanthrenes are significantly depleted from the bulk oil and the dominant constituents are the alkylated napthobenzothiophenes, pyrenes, and chrysenes.

Various researchers have described petroleum weathering classifications to document oil degradation in the environment. Early classifications were based primarily on alkanes (Boehm et al. 1981). More recently, classification schemes based on PAHs have been published (Sauer et al. 1993). Weathering classifications are most useful when describing a specific oil type. The descriptions above provide basic chemical information related to compositional changes in the PAH profile of the *Exxon Valdez* reference oil with respect to weathering, and are useful to describe changes observed in the chemistry data.

Standard EPA methodologies for aromatic hydrocarbon analysis are inadequate for assessing petroleum pollution since they do not include some of the key target compounds characteristic of oil. While there is no standardized methodology, there is general acceptance by the research community and regulatory agencies for GC/MS petroleum analysis in oil spill response and monitoring studies. GC/MS provides a very powerful means for separating oil constituents, and is a sensitive and highly selective tool for characterizing spilled oil samples. GC/MS procedures are widely accepted for oil spill response activities, oil fate and effects studies, and baseline pollution monitoring (Overton et al. 1981; Boehm and Farrington 1984; Sauer and

Boehm 1991; Sauer et al.1993). GC/MS provides highly selective source-fingerprinting information as well as compound-specific quantitative results for target aromatic and aliphatic hydrocarbons. Analytical methods are described in detail separately (Henry and Overton 1993; Roques et al. 1994). The analytical approach targets specific compounds selected by the following criteria:

- Hydrocarbon constituents common to crude oils;
- Specific compounds generally associated with chronic oil toxicity; and,
- Oil constituents that have value in differentiating between petroleum and other sources of hydrocarbon pollution, both natural and anthropogenic (e.g., terrestrial plant waxes and combustion by-products).

Figure 3 shows the changes in the PAH profile as a result of weathering, using the preceding definitions. The subsurface sediment (B) would be classified as slightly weathered, the marsh core (C) as moderately weathered, and the surface sediment (D) as highly weathered.

Factors affecting weathering

Chemical actions affecting whole oil in aquatic systems include biodegradation and photolytic degradation, and occur at the oil/water interface; therefore, the amount of surface area affects the rate of oil degradation. Often, the rate and extent of degradation are related to oil concentration since there is a relationship between oil concentration per unit volume and the surface area exposed. The grain size of sediment particles may skew such a relationship. Fusey and Oudot (1984) observed a direct relationship between oil concentration and observable biodegradation during intertidal oil biodegradation studies near Normandy, France. As a result of these experiments, the authors postulated that physical transport processes dominate oil weathering and removal until the concentration of oil drops below some “threshold value” after which biodegradation is the dominant process. Similar trends appear in the Prince William Sound monitoring data.

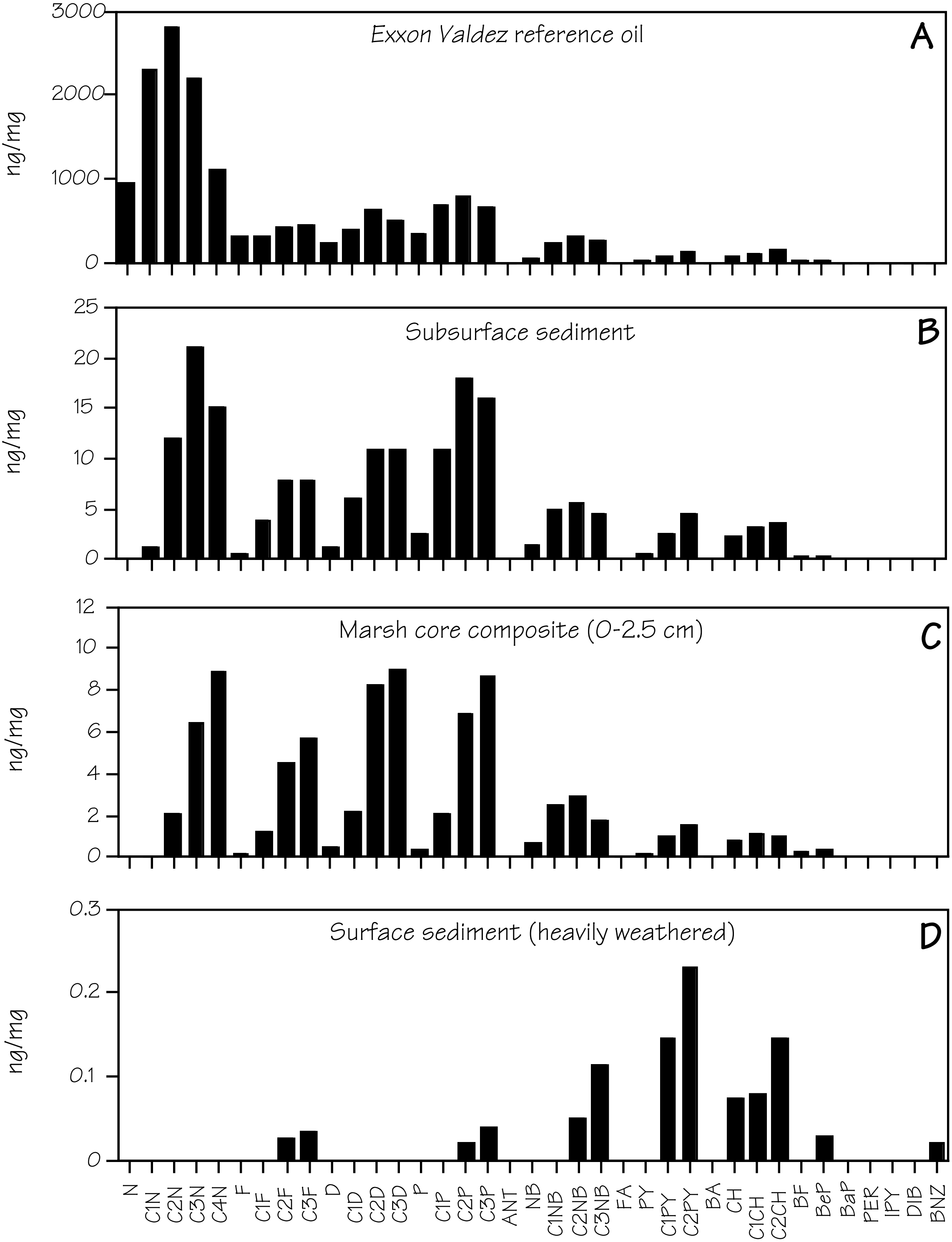

Figure 3. **Comparison of the PAH distribution for the *Exxon Valdez* reference oil (A), subsurface sediment from a gravel beach (B), intertidal sediment samples collected at a marsh (C), and surface sediment from a gravel beach (D).**

Microbes use oil as a carbon source that is ultimately converted to energy, biomass, carbon dioxide, and water. Physical processes, such as high-energy storms, rework oiled sediments and increase the dispersion of oil, thus increasing surface areas and generally reducing the persistence of oil spilled in the environment. Many factors can affect microbial degradation, including the existence of microbial colonies adapted to the degradation of petroleum hydrocarbons. Other factors include the presence of nutrients, oxygen, and a mechanism for exposing the microbes to the oil. Exposing the microbes to oil implies significant surface contact between the oil and microbe-bearing aerated waters. In most marine systems, significant colonies of microbes have adapted to degrade the hydrocarbons associated with terrestrial inputs (such as spruce needles). Studies shortly after the 1989 spill identified high concentrations of naturally occurring hydrocarbon-degrading bacteria in Prince William Sound (Lindstrom et al. 1991).

Certain factors can hinder biodegradation. One such factor is emulsification, which slows biodegradation because the stable mousse formed has a smaller surface area. Samples of mousse collected during the study consistently reflected less degradation than that typical of oiled sediments at the same station. We believe that the presence of a tiny amount of mousse collected during field sampling and compositing can result in a highly biased degradation profile in the GC/MS data. The mousse significantly contributed to the high degree of variability observed in the chemistry data. Another factor, cool weather, often causes slower rates of microbial activity, resulting in less consumption or degradation of the oil (Malins 1981, 1987). The cooler, subarctic climate in Prince William Sound is considered a major factor in the predicted persistence of stranded *Exxon Valdez* oil.

Slightly weathered crude oil can be distinguished from fresh or unweathered crude oil by the loss of the low-molecular-weight constituents such as the normal hydrocarbons less than n-C_{12}, the alkylbenzenes and, to some extent, naphthalene and its alkyl homologues. These initial changes are primarily due to evaporative losses and, to a lesser degree, dissolution. For example, less than 5 percent of benzene is lost to dissolution, while more than 95 percent is generally lost to evaporation. The low-molecular-weight constituents are more volatile and more water-soluble than the high-molecular-weight constituents. The rate and extent at which the components evaporate and undergo dissolution, sedimentation, and degradation affect the persistence and environmental toxicity of different oils. North Slope Crude (NSC) is characteristically a medium-weight crude oil. When compared to a wide range of crude oils and refined oil products, its overall environmental persistence is generally classified as moderate. Microbial degradation is selective and attacks the straight-chain hydrocarbons and more water-soluble oil constituents at faster rates than more complex branched hydrocarbons and compact aromatic hydrocarbons.

The natural environment is adapted to degrade many hydrocarbons, such as the waxes associated with marsh grasses. When exposed to oil pollution, the established microbial community easily degrades the saturated hydrocarbons (a substrate similar to the dominant natural source of carbon), but the naturally occurring microbes are often not able to degrade the aromatics. This is especially true for intertidal marshes, which are enriched with plenty of biomass containing easily degraded saturated hydrocarbons from natural biogenic sources. Microbial communities in these habitats do not develop the species mix necessary to degrade the aromatic components of spilled oil.

Preferential biodegradation of the saturated vs. aromatic hydrocarbons has been commonly reported (Leahy and Colwell 1991), and chemistry results from the NOAA/HAZMAT program are consistent with this. For example, Figure 4 shows saturated hydrocarbons in the *Exxon Valdez* reference oil compared to the oil extracted from a sample collected at an intertidal marsh five years after the *Exxon Valdez* spill. The sample is a composite of the 0-2.5 cm upper sections of four cores. The saturates are heavily degraded with only the isoprenoid hydrocarbons remaining as resolvable peaks. Figure 3, on the other hand, shows data on the aromatic hydrocarbon composition from the same sample, in addition to a surface and subsurface sediment sample collected in Prince William Sound. Microbial degradation has removed the less complex aromatic hydrocarbons but significant quantities of the more highly substituted aromatics remained. Even the relatively volatile naphthalenes and fluorenes were still found in the near surface oiled sediment five years after the spill. In contrast, gravel beach sediments, which contained little or sporadic levels of background biogenic hydrocarbons, were highly dissimilar between surface and subsurface sediments. The surface sample contained a residue that was heavily degraded in both its saturated and aromatic hydrocarbon content, but the subsurface sediment was only moderately degraded (similar to the marsh sample) in its PAH distribution (Figure 3).

High-energy beaches, which provide abundant mixing energy for oil and aerated water contact, are environments where all fractions of the exposed oil are readily degraded. This degradation pattern contrasts sharply to the selective degradation pattern seen in the subsurface gravel beach sediment and muddy marsh sample.

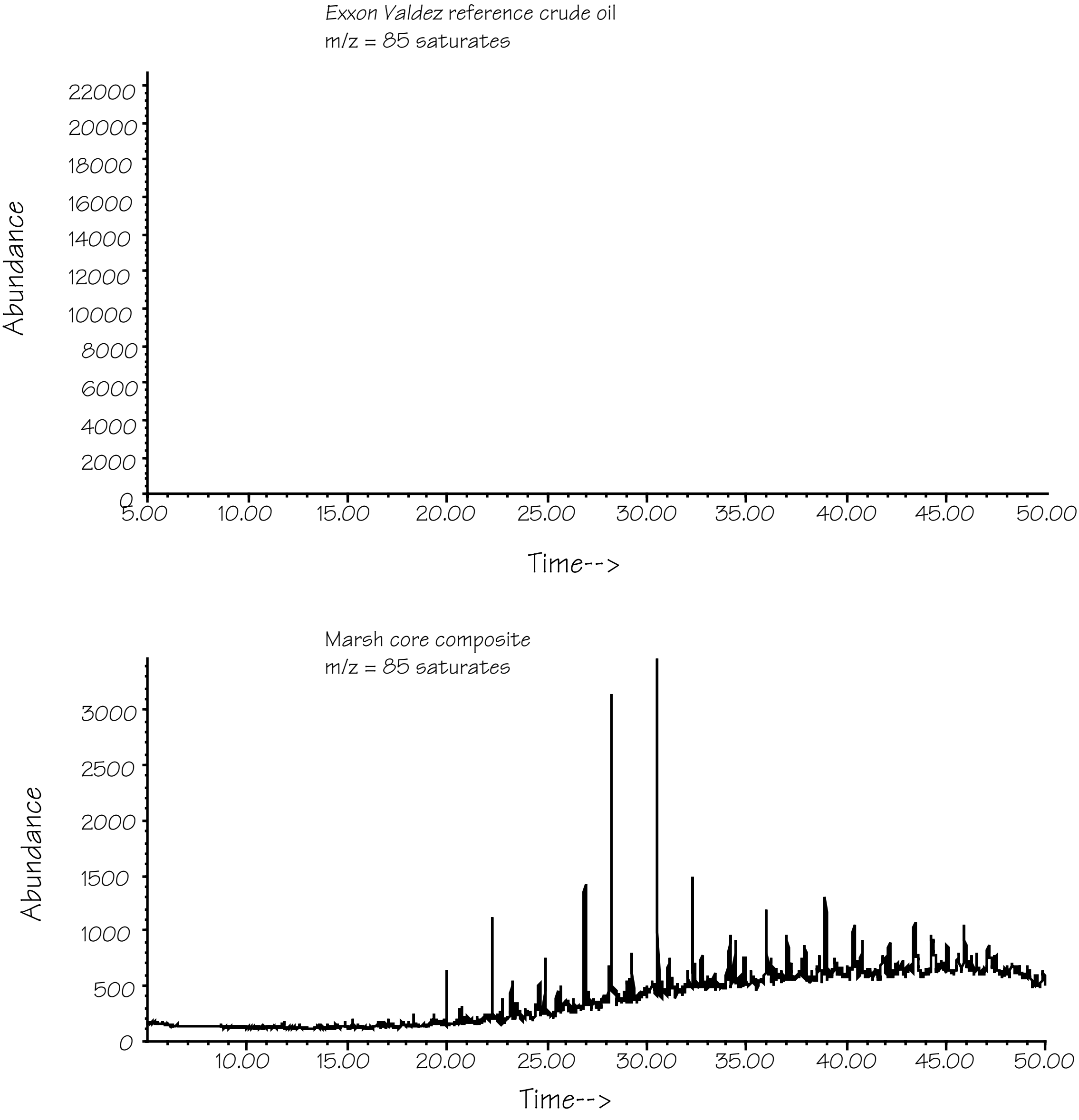

Figure 4. Chromatographic comparison of the alkane profile for the Exxon Valdez reference oil (top) and oil extracted from marsh sediments five years after the spill (bottom). The marsh sediment sample was a composite of the upper 2.5 cm from four separate cores.

The subsurface gravel beach sample represents a case where the oil was trapped in a zone removed from vigorous aerobic microbial degradation. This was due partly to reduced oil-surface area exposure (the threshold effect) and partly to ecological factors such as a lack of essential ingredients (such as oxygen).

What is "Recovery"?

Throughout this report, we refer to the concept of "recovery," particularly with respect to biological communities studied. This word has been defined in many ways and can have very different meanings. Recovery, by all definitions, is a natural process that has been occurring in intertidal habitats in Prince William Sound since the oil first washed ashore in 1989—and in fact, has been taking place since the last major disruption of shoreline communities, the 1964 earthquake. But, although most studies conducted on post-spill intertidal and shallow subtidal biota have recorded observations of the changes that have occurred in one manner or another, recovery is an elusive concept. It is a challenge both to define it and to determine when various assemblages have progressed to a point where they can be classified as recovered.

Intertidal assemblages on both rocky and soft substrates are dynamic. In many cases, they exhibit considerable natural seasonal and long-term temporal variation. Such variation can include changes in abundance, number of species, species diversity, species composition, biomass, productivity, age, trophic structure, or various other measures of biological interest. Ganning et al. (1984) provide a useful graphic portrayal of the manner in which various assemblages or populations of component species can vary both before and during a disturbance and also present a practical definition of recovery. In essence, recovery is the return of an ecosystem to a point within the limits of the natural variability of the system's original functional and structural conditions. Although the definition refers to an ecosystem, the mechanisms and effects are the same on the smaller spatial scales of a geographic region or even a single beach.

The "natural variability" in this definition suggests that an ecosystem, as measured by appropriate biological indices, can fluctuate around some central value and still be considered healthy or stable. The fluctuations will have a short-term variability component created by seasonal and transient events (e.g., storms) superimposed over long-term fluctuations resulting from large-scale events (e.g., El Niño or earthquake damage). The combined range of the short- and long-term fluctuations defines the limits of natural variability.

Following a major disturbance, an assemblage may be displaced from its normal central tendency. Recovery can be considered to be the process of re-establishment or returning to the abundance levels and functional relationships held before the disturbance. Since it is highly unlikely that conditions would ever be identical to those that caused the conditions extant immediately before the disturbance, it is also unlikely that an identical assemblage would ever develop. However, since the recovery concept implies a range of variation, it is reasonable to expect a community or population to return to conditions contained within that range.

In this discussion, another useful term to define is “disturbance,” as recovery is usually discussed in terms of recovery from a disturbance. Hall (1994) references a definition of disturbance as “any discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment.” Obviously, there are degrees of disturbance and not all are strictly comparable. On the other hand, major large-scale disruptions, such as extreme cold weather, ice-scour, and oil spills, can result in similar net effects on the intertidal environment.

Aspects of chaos theory (Gleick 1987) can be applied to assessments of biological recovery from oil spills and other major disturbances. A given biological index graphed over time will appear to endlessly circle some central focus, possibly never repeating its previous series of values but never departing from unmarked limits of the system. In chaos theory, our recovery definition can be stated simply as the return of the system to a comparable circling of the central attractor. A permanently impaired system that could not recover would fail to circle or would cycle into another pattern (e.g., as a result of a chronic pollution source). However, on the beaches in Prince William Sound, the oil is expected to eventually weather away and the biological communities will eventually reestablish themselves from local or immigrant stocks. But as noted above, the cycling pattern will likely never repeat itself in precisely the same manner.

The specification of original functional and structural conditions for complete recovery as suggested by Ganning et al. (1984) implies a requirement for similarities in biomass, species composition, age, and trophic structure. We accept this definition; these requirements probably exist for the infaunal assemblages in mixed-soft substrates or the epibiota on rocky substrates in Prince William Sound.

Feder and Jewett (1988) give an example of such recovery for Prince William Sound for some infaunal bivalves in Port Valdez (i.e., *Nuculana fossa* and *Axinopsida viridis*), for which abundance increased about an order of magnitude between 1971 and 1976-77 and then stabilized until 1985. It is likely that these changes in abundance reflect recovery from disturbance caused by the Good Friday Earthquake of 1964. Many mixed-soft intertidal sites in the Sound that were historically dominated by dense populations of mature clams (*Macoma*, *Mya*, *Saxidomus*, and *Protothaca*) were strongly disturbed by the 1964 earthquake (Baxter

1971). Moreover, the expansion of sea otter range in the Sound before and after the quake (Johnson and Garshelis 1995) adds confusion when interpreting recovery, since feeding activities probably have significantly affected the clam beds. Even before the *Exxon Valdez* oil spill, it was unlikely that the clam beds would return to the exact status that existed before the earthquake. The earthquake, sea otter population growth, and the oil spill all represent major disturbances to the Prince William Sound intertidal and subtidal ecosystems that have shifted the chaotic central focus of recovery discussed above.

An Exposure Index for Prince William Sound

The importance of the level of exposure of a field site to hydrodynamic forces is one of the time-honored concepts in both ecological studies and oil spill response. Heavy wave action is the single most effective natural process for removing stranded oil from shorelines. The degree of physical exposure can also represent the dominant factor structuring the biological communities that live there. Other researchers have recognized the importance of the link between hydrodynamic conditions and biological communities. For example, Denny (1988) detailed the physical mechanics of the nearshore environment and how they affect the organisms living there. Thomas (1986) derived an exposure index for marine sites that he tested as a predictor of littoral zonation in both Bermuda and Canada.

In the NOAA/HAZMAT program, the exposure level of a site was an important consideration in the project design and execution of both the geomorphological and biological studies. Using geomorphic indicators such as size and roundness of sediments, size of beach berms, and presence of storm berms, the geomorphology sites are believed to have the following ranking with regard to exposure to wave action (highest to lowest):

Cobble/boulder platforms with berms
↓
(coarse-grained gravel beaches)
↓
bayhead gravel beaches
↓
pebble beach/tidal flats
↓
rocky rubble slopes and sheltered rocky shores

Also using general geomorphological criteria, plus well-understood and biological adaptations, such as mode of attachment and feeding patterns, the biological sites were noted to be exposed or sheltered. The sites designated as *exposed boulder/cobble* were thought to be subject to considerable wave action, while those termed *sheltered rock* and *sheltered mixed-soft* were not.

As questions pertaining to natural cleanup of the *Exxon Valdez* oil evolved, it became important to summarize a best estimate of the exposure levels of the oiled shorelines in Prince William Sound. This work had to be done without the benefit of detailed wave-gauge records or mathematical model studies. It was finally decided that a good approximation of the relative wave-energy flux at the specific study sites in Prince William Sound could be obtained by relating wind duration and velocity to the effective fetches (straight-line distance over which wind blows to create waves) at each site. Three years of field studies in Prince William Sound had shown that wind conditions are highly variable throughout the Sound on an hourly basis. No specific, long-term wind data were available for the different locations in the Sound. However, NOAA established wind recorders on Lonetree, Seal, and Danger islands (Figure 1) for the period November 22, 1989 to March 6, 1990. These are the best and, in fact, the only, data available on the details of wind conditions in the Sound after the spill.

We calculated an Exposure Index (EI) for all of the geomorphology and biology study sites using wind data from the appropriate wind gauge correlated with three effective fetch distances measured perpendicular to and at 45 degrees to the shoreline. The result is a dimensionless number which, when compared with readings from the other stations in the Sound, is a predictor of the relative exposure of each site to wave action. Both biological and geomorphological criteria for exposure to waves were consistent with the values calculated for the index. Surface oil on the exposed shorelines was removed quickly during the first storm season. Sheltered coasts were cleaned more slowly. Details of these calculations can be found in Michel and Hayes (1995).

As shown in Table 1, the EI for the station at Smith Island was 730 (highly exposed), at Northwest Bay 64 (moderately sheltered), at Snug Harbor 14 (highly sheltered), and at Block Island 10 (highly sheltered). Thus, sites with a wide range of wave conditions are discussed in detail in this report.

Having discussed the basic characteristics of the NOAA/HAZMAT program and the subset of sites chosen for this report, we are now ready to proceed to the details of research results from the monitoring program. The next four chapters will present geomorphology, biology, and chemistry results for the sites we have designated as Block Island, Northwest Bay West Arm, Smith Island, and Snug Harbor.

BLOCK ISLAND (SEGMENT EL-11A)

BACKGROUND AND SITE DESCRIPTION

The Block Island study site is located at the northern end of the Knight Island group, southwest of Eleanor Island, on the northwestern shore of Block Island. Figure 5 is a 1:10,000-scale map of the area that includes the Block Island study area. The site is characterized by a broad tidal flat over much of the intertidal zone, portions of which are underlain by a layer of peat or peat-like material. Bedrock outcrops are common in the lower margin of this site, as well as offshore from it. The shoreline of the study area generally faces to the west and is one of the more sheltered of the areas sampled in the NOAA/HAZMAT monitoring program. This station has the second lowest exposure index (EI=10) of all the geomorphology study locations studied in the NOAA/HAZMAT program.

The geomorphology transect runs from east to west over the tidal flat and is approximately 100 m long. It extends from the supratidal zone into the lower intertidal zone. Four biology transects have been established at the site: at upper and middle elevations on a large bedrock outcrop that borders the site to the south, and at middle and lower elevations on the pebble/granule/sand tidal flat. Figure 6 is a detail map of the site at 1:1,000 scale, showing the approximate location and orientation of the study transects. All biological study stations, with the exception of the station located at the lower tidal flat, are considered to have been oiled and treated with high-pressure, hot water (directives issued to cleanup crews indicated that the lower flat was spared from the direct effects of pressure-washing).

OILING AND TREATMENT HISTORY

The shorelines in the Block Island area were heavily oiled in 1989 and received extensive treatment, particularly during the first cleanup year. The Appendix describes shoreline oiling and the nature of the cleanup.

Shortly after the spill, oiling at the Block Island site was described as continuous and heavy. Conditions there are clearly shown in Figure 7, an aerial overview of the site taken on April 14, 1989. The photograph illustrates a continuous band of oiling in the upper intertidal zone and across portions of the middle and lower intertidal flat. Only the uppermost reaches of the beach and the highest portion of one of the large bedrock outcrops had escaped visible oiling at the time this photograph was taken. Note also that oil sheen was still clearly visible in the adjacent water.

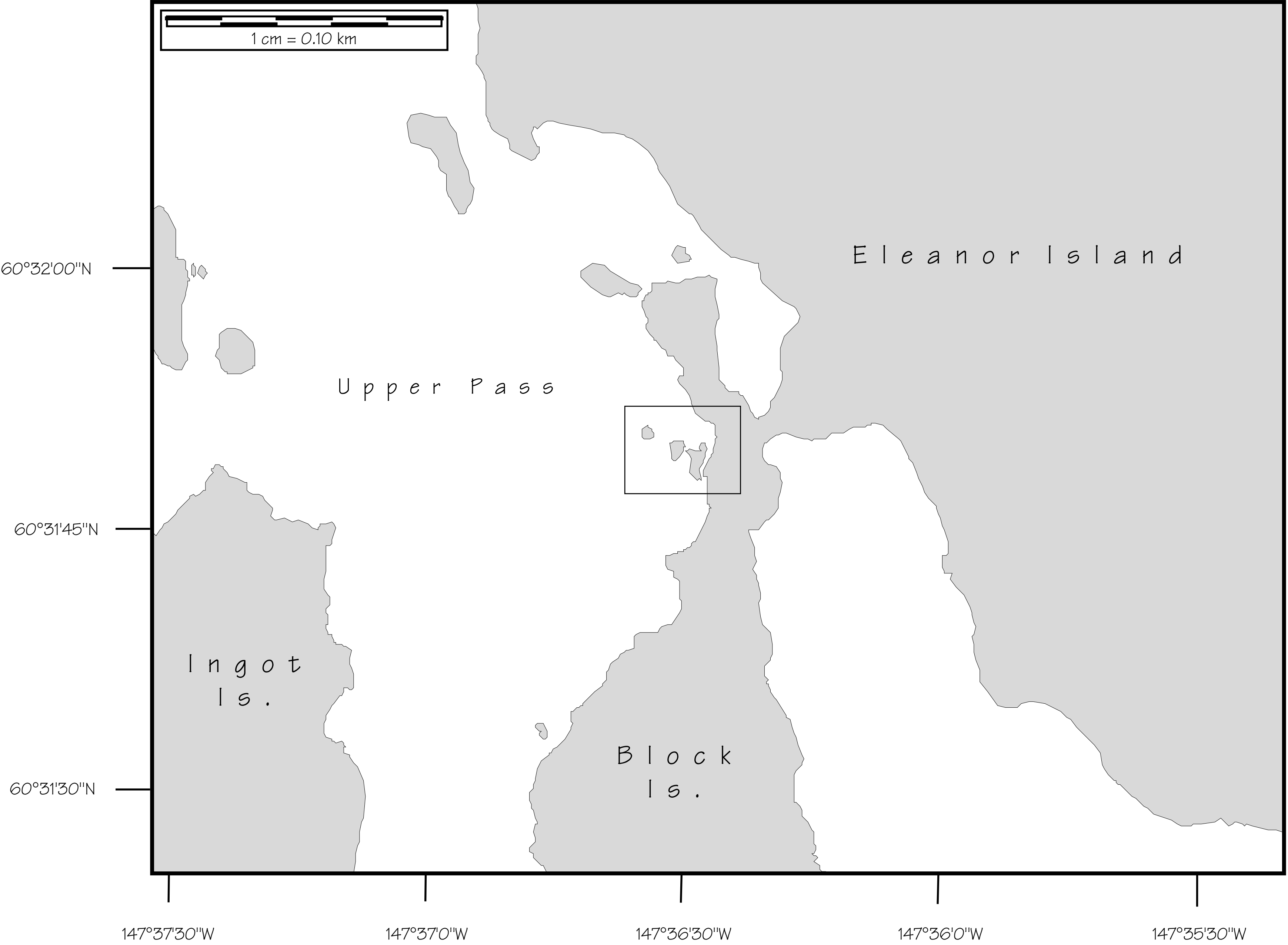

Figure 5. Map of Block Island vicinity, 1:10,000 scale. Rectangle denotes area shown in greater detail as Figure 6.

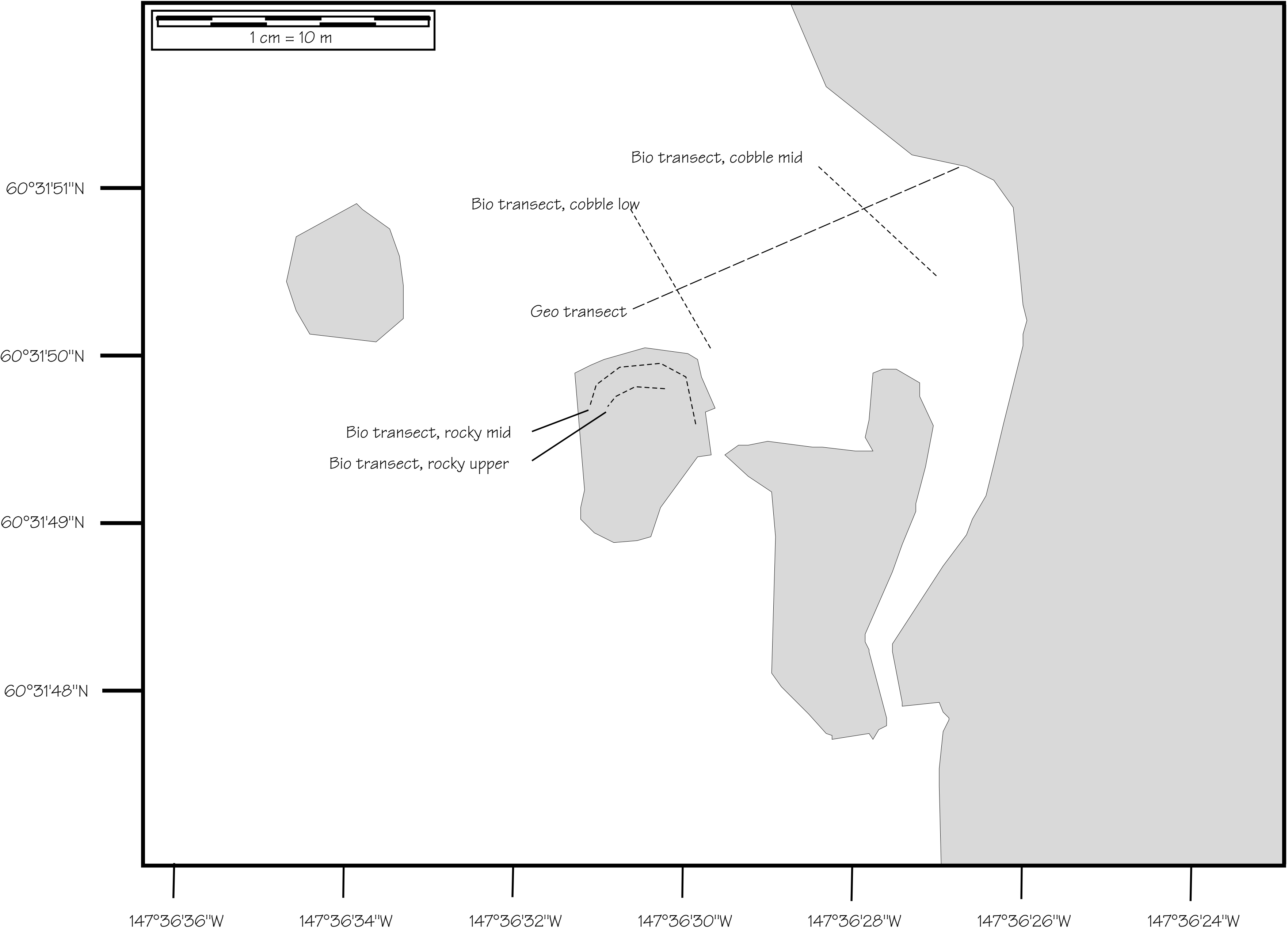

Figure 6. Detail map of Block Island site, 1:1,000 scale, showing approximate location of study transects.

Figure 7. Aerial photograph of Block Island study site on April 14, 1989, three weeks after the *Exxon Valdez* grounded and prior to any cleanup activities. Note sheen on water and areas of heaviest oiling on tide flat. NOAA/HAZMAT photo.

The field notes of monitors from the Alaska Department of Environmental Conservation (Appendix) indicate that the site was treated with steam and both low- and high-pressure flushing in 1989. Figure 8 is another aerial photograph of the Block Island site, taken on July 16, 1989. The stage of the tide was much higher and the lowest of the three bedrock outcrops shown in Figure 7 was submerged and just barely visible in Figure 8. In Figure 8, nearly 20 workers can be seen on the beach herding oil off the flat and into the water, where it apparently was contained by a boom.

Figure 9 is another aerial photograph of the site taken by the geomorphology team on October 22, 1989. Residual oiling is clearly visible on much of the exposed tidal flat.

Observations by field monitors confirmed that this area, with its wide tidal flat surrounded by rocky outcrops, caused a number of problems for cleanup crews. Treatment records show that the most extensive cleanup operations at this site took place in 1989. With a notable exception, there is no documentation of treatment more involved than manual pickup of asphalt pavement patches in the lee of boulder outcrops in 1990 and bioremediation in subsequent years. In 1994, however, mussel beds were temporarily displaced in order to remove underlying oiled sediment at the site at Block Island, as well as at other sites in Prince William Sound.

GEOMORPHOLOGY

Introduction

Located on a roughly north-south shore of Block Island, this station is basically a raised tidal flat surrounded by major rock outcrops with a simple pebble/granule/sand berm on its landward side. The profile is long and flat, extending nearly 100 m on low spring tides. It is one of the very few wide tidal flats in Prince William Sound. The shore faces directly across the channel of Upper Passage, a distance of around 1 km. There are rock outcrops for several meters on either side of the geomorphology profile, and the surface sediments coarsen to cobbles and boulders near both outcrops. There is an open fetch distance of 17 km in a northeasterly direction (45-degree angle to shoreline). However, waves generated by winds blowing along that fetch would have to pass 3.5 km down the 1 km-wide Upper Passage, as well as over and around numerous rock outcrops, before reaching this beach. The 1964 earthquake uplifted the area about 1.2 m.

Figure 8. Aerial photograph of Block Island study site on July 16, 1989, in the midst of shoreline cleanup activities. Note work crew on tide flat and silt plume resulting from shoreline washing. NOAA/HAZMAT photo.

Figure 9. Aerial photograph of Block Island study site on October 22, 1989. Note areas of heavier oiling still visible in lower left portion of figure. Photo by D. Hall, Research Planning, Inc.

Morphology and Beach Dynamics

The geomorphology study team surveyed the Block Island site eleven times between 1989 and 1994. They divided this station into four morphological units:

1. Beachface
   This zone was a simple single berm at the spring/storm berm level. The upper beachface was covered with over 70 percent sand and granule, but the lower beachface, which sloped offshore at an angle of 7 degrees, contained abundant pebbles and cobbles.

2. Upper flat
   This rather flat surface, which sloped offshore at 2 degrees, had a cover of more than 60 percent pebbles on the average. A layer of peat underlaid the oil-bearing surface sediments at depths of 10 cm or so. Throughout the survey period, a litter of clam shells was scattered over the surface. Groundwater drainage rills were common over the upper third of the flat.

3. Lower flat
   The surface of this unit was virtually horizontal. It also had a predominantly pebble surface, mixed with scattered cobbles, boulders, and broken clam shells. The subsurface peat layer continued under this part of the profile as well.

4. Bedrock
   Several major outcrops were clustered around the end of the profile, which was run over a 40-cm high notch in the bedrock ledge. The rock had an abundant cover of biota, including mussels, barnacles, rockweed, and several species of brown and red algae. The extreme end of the profile passed over a sediment deposit populated by a dense growth of eelgrass.

There were no significant changes detected on this profile throughout the study period. During the November 7, 1989 survey, “multiple very small berms” were noted near the high tide line. On March 3, 1990, a “poorly developed spring berm” occurred near high water, but it was so small that it could not be detected on the profile plot. Obviously, no vertical sediment envelope developed on this beach during the study period. The finer materials on the surface of the beachface clearly move around some, as evidenced by the covering and uncovering of the peat layer near the profile. Surface peat exposures were observed on the upper flat during the September 17 and October 22, 1989 surveys.

Sediments

The sediments at this station are derived from erosion of the local bedrock outcrops and soil horizons. The bedrock is composed mostly of metamorphosed basaltic lavas and intrusive mafic rock (Moffit 1954). The distribution of surface sediments along the profile on June 22, 1990 was as follows:

1. The upper beachface was covered by over 70 percent sand and granule.
2. The lower beachface and landward part of the upper flat had the highest percentage of cobbles and boulders (20-30 percent) of any part of the profile.
3. The rest of the profile was rather uniform, containing roughly 10 percent sand, 10 percent granules, 10 percent cobbles, 5 percent boulders, and 65 percent pebbles throughout.

A total of 29 trenches were dug in 1989 and 1990 on this profile. The sediments were fairly uniform in depth, without any armoring of the surface. In most of the trenches, we encountered a substance referred to as “peat” within a few centimeters of the surface. In the field notes for the November 7, 1989 survey, the peaty material in a trench at the 15-m mark on the profile was referred to as “fibric eelgrass peat,” meaning that the source plant material in the peat had not decomposed beyond recognition. It is possible that this raised platform could have been an eelgrass flat before the 1964 earthquake.

Oil Distribution Patterns

Surface oil. Very little surface oil was observed along any part of the geomorphological profile during the surveys, despite the fact that it was initially heavily oiled. In fact, in September 1989, the entire beach and flat looked clean, although sediment samples of the top 5 cm contained 210-220 ppm TPH. In October 1989, the cobbles on the beachface and upper flat were 50 percent covered by an oil stain and those on the lower flat were thickly coated with oil on the undersides. This site was obviously reoiled during the October high tides, and it continued to receive spotty deposits of oil throughout the fall and winter. As a result, the surface sediment chemistry analyses varied widely. March 1990 was an extreme example where scattered mousse patties sampled on the low tidal flat contained over 20,000 ppm TPH.

Low levels of oil were detected in surface samples from the beachface, where those samples averaged 100 ppm TPH. The maximum surface oil cover observed along the profile line during the June 1990 survey was a one-percent coat on some cobbles in the middle intertidal zone. No surface oil was observed during either the August 1992 or July 1994 surveys. However, a search in the surrounding area in 1992 revealed some surface oil in various sheltered microhabitats and pockets in the adjacent rocky areas, indicating the low level of wave reworking that occurs along this sheltered tidal flat.

Subsurface oil. The levels of subsurface oil (defined as deeper than 5 cm) in the tidal flat sediments were highly variable. TPH concentrations have varied by more than an order of magnitude (from 10 to 680 ppm), with no clear spatial or temporal trends. In some areas, heavy black oil would form slicks on the water table, whereas a few meters away only the slightest dull sheen was detectable. Visually the highest contamination tended to be in the lee of major rock outcrops. During the August 1992 survey, oil was detected as dull sheen to black oil droplets on the water table in all five trenches dug into the tidal flat. A sample of 0 to 10 cm in a trench located on the seaward edge of the flat with a dull sheen on the water table contained 430 ppm TPH. Oil penetration has never been very deep; the peat layer occurs 20 to 25 cm deep, and the water table is always just a few centimeters below the surface. In fact, it has always been puzzling as to how these water-saturated tidal-flat sediments became so heavily oiled. Usually, each high tide lifts even heavy slicks off tidal flats. However, this tidal flat has several features that may have contributed to its retaining oil in the subsurface sediments:

1. The surface layer is predominantly pebbles (±80 percent), rather than sand. Oil could have been trapped under or adhered to the pebbles. All of the larger clasts are subangular, so there is very little reworking of these sediments. Once trapped, oil would remain.

2. There are numerous shallow depressions on the flat, presumably from sea otters digging for clams. Oil and/or oiled sediments could have accumulated preferentially in these depressions, although they are usually water-filled.

3. The adjacent mixed sand and gravel beach was treated in 1989 by extensive hot-water flushing, which could have provided the source of contaminated sand.

4. There are abundant infauna, so bioturbation could be a mechanism for mixing the oil deeper.

Whatever the mechanism, once contaminated, oil removal rates have been slow despite the presence of active groundwater drainage across and through the flat. However, by the time of the July 1994 survey, only small stringers of silver sheen were visible on the water filling the two trenches dug in the middle of the flat. A sample from one of the trenches at 2-10 cm contained 80 mg/kg TPH and only 0.2 mg/kg PAH, reflecting the very low levels of oil remaining in the middle of the tidal flat. It should be noted, however, that much higher levels of contamination have typically been present lower on the flat away from the geomorphology profile line and near the biology transect. We will discuss these conditions below.

SEDIMENT CHEMISTRY: TOTAL TARGET PAHs

A large number of samples from the Block Island site were collected and analyzed between 1989 and 1994 for both geomorphology and biology studies. We discussed the results for the gravimetrically determined TPH measurements above. The discussion to follow is based on GC/MS analyses performed in support of the biological studies.

Sediment collected at Block Island has shown a high degree of variability in summed target PAHs. Field-composited samples and mean values for replicate samples across a given transect have shown little definitive trend, either with elevation or with time. It is likely that differences in degree of within-site oiling, discussed in greater detail below, reduce the utility and interpretability of such summarized chemistry results. Table 5 summarizes chemistry results for summed sediment concentrations of PAHs found at the lower intertidal transect of Block Island between 1990 and 1993.

Table 5. Summed target PAH concentrations measured in sediment samples from the lower intertidal biological transect at Block Island site, 1990-1993. Results in parts per million, wet weight.

Sample Date	TPAH	Sample Type
July 1990	0.48	Single composite along transect
September 1990	6.4 ± 12.7	Discrete replicates (5)
May 1991	0.15	Single composite along transect
July 1991	0.64 ± 0.88	Discrete replicates (5)
June 1992	0.78	Single composite along transect
July 1993	0.94 ± 2.0	Discrete replicates (5)

The limited chemistry results available for the middle intertidal transect indicate that measured sediment concentrations were highest in July 1990 (2.5 ppm target PAH), but declined by transects for infaunal collections. As a result, in September of that year to 0.31 ppm. The June 1992 composite result of 0.42 ppm indicates little change between Fall 1990 and Summer 1992.

During the biological team's first visit to the site in July 1990, the variability in sediment oiling was visually apparent, particularly when excavations were made along the lower intertidal transects for infaunal collections. As a result, in September 1990, more detailed discrete chemical collections were initiated, in which samples were collected at each of five locations along the lower transect (instead of the standard single sample composited from the five spots). The results of this, and a similar series of collections made in July 1991 and July 1993, confirmed the high degree of variability within the same tidal elevation at the site and are shown below in Table 6.

Table 6. Summed target PAH concentrations measured in discrete sediment samples from the lower intertidal biological transect at Block Island site, 1990, 1991, and 1993. Results in parts per million, wet weight.

Date	Sta. 1	Sta. 2	Sta. 3	Sta. 4	Sta. 5	Mean
9/90	1.1	1.6	0.07	0.19	29	6.4 ± 12.7
7/91	0.40	0.33	0.06	0.19	2.2	0.64 ± 0.88
7/93	0.02	0.01	0.04	0.14	4.5	0.94 ± 2.0

In May 1991, an experiment was initiated in which littleneck clams (*Protothaca staminea)* were transplanted from a remote, unoiled donor location to the Block Island site. Five plots of transplanted clams were established in the lower intertidal portion of the tidal flat. We will discuss results for tissue concentrations from this experiment later in this chapter. Before the transplanted clams were placed in the plots, we collected sediments at each location. When the clams were collected in September 1991, the sediments were again sampled. The results for these GC/MS analyses are shown below in Table 7 (no result is given for station 2 in September because that plot could not be found).

Table 7. Summed target PAH concentrations measured in sediment samples collected from lower intertidal clam transplant plots at the Block Island site in 1991. Results in parts per million, wet weight.

Date	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
5/91	*0.40*	*0.33*	*0.62*	12	25
9/91	0.31	---	1.1	*0.77*	1.4

Biology results will be discussed later in this document. With respect to sediment chemistry in the lower intertidal zone, the experiment confirmed that the highest concentrations of PAHs were on the southern side of the study site. The overall level of contamination measured in the two most heavily oiled clam plots was substantially lower in September than in May.

In 1992, the clam transplant experiment was repeated and expanded. Fifteen plots were established in three transects on the lower tidal flat (Figure 10). Note that the numbering for these plots was in the reverse direction than it had been in the past (e.g., in 1990 and 1991, plot 1 was located on the north side of the site, while in 1992, plot 1 was south). Sediment chemistry samples were again collected at the beginning of the experiment (July 1992). Figure 11 shows concentrations found in individual plots.

Sediment results from the 1992 transplant collection varied, but the consistent result of highest concentrations being found on the southern side of the site again held true. However, this was the case only for the middle transect line of transplants and reflected a very wide range of concentrations even among adjacent stations (plots), suggesting a relatively narrow band of sediment contamination.

The 1990-1992 sediment chemistry results summarized above illustrate the substantial within-site variability that has characterized the Block Island site over the study period. Some general consistencies, however, have emerged from these data.

- The highest levels of observed and measured sediment contamination have been found in each collection along the south side of the study site, in the lee of a large bedrock outcrop. This is consistent with the site conditions shown in Figure 8, where a particularly heavy area of oiling can be seen on this part of the tidal flat before treatment in April 1989.

- The most consistent sediment chemistry collections between 1990 and 1993 have been those along the lower transect and associated with infaunal cores (Table 5). These results do not show distinct temporal trends, and are most likely dominated by the high within-site variability in contamination.

- The highest Block Island sediment concentrations, all measured in the lee of the large bedrock outcrop on the southern side of the site, remained at about the same level from 1990 to 1992: between 25 and 29 ppm. However, following the mussel bed cleanup activity at Block Island by the state and Federal trustees in 1994, this relatively high level of contamination may not be encountered in future collections.

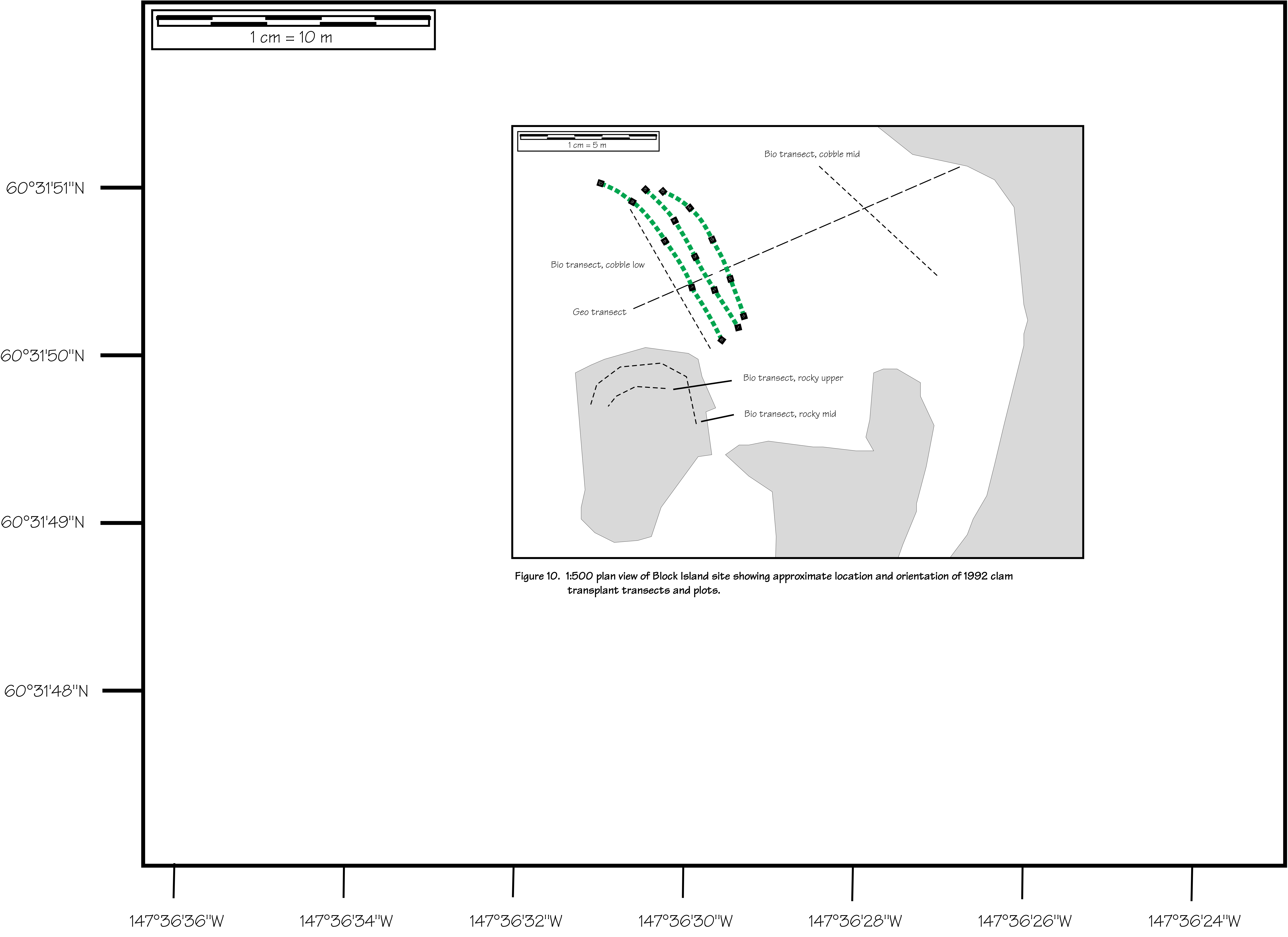

Figure 10. 1:500 plan view of Block Island site showing approximate location and orientation of 1992 clam transplant transects and plots.

Figure 3. Detail map of Block Island site, 1:1,000 scale, showing approximate location of study transects.

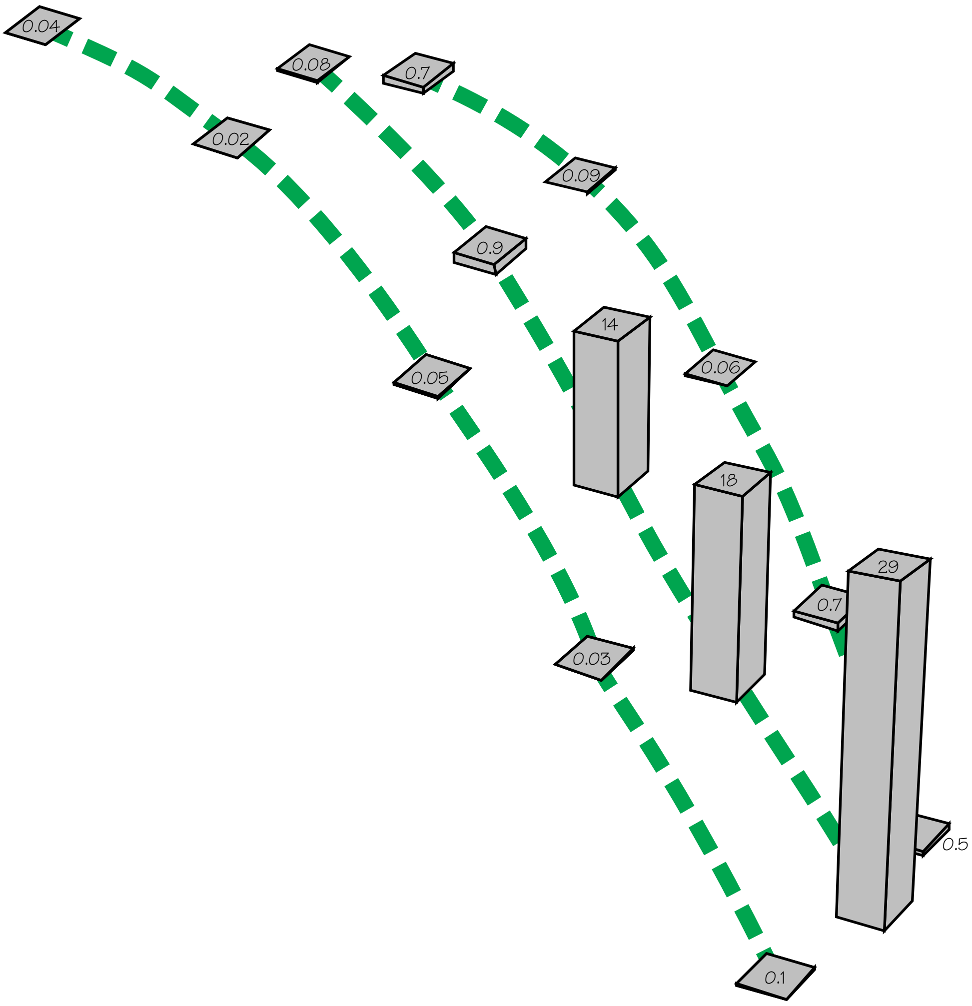

Figure 11. TPAH results for sediments from Block Island clam transplant plots in 1992. Values in ppm wet weight. Refer to Figure 10 for orientation within site.

SEDIMENT CHEMISTRY: PAH DISTRIBUTION AND WEATHERING PATTERNS

In addition to analyzing trends in total PAHs, the sediment chemistry at the Block Island site was also investigated by detailed examination of the PAH distribution patterns. Individual PAH compounds summed in Table 5 were graphed as histogram plots and compared to a sample of unweathered *Exxon Valdez* oil to assess specific changes in the PAH distribution relative to temporal trends in the oil degradation. Figure 12 compares the mean PAH distribution pattern for the lower transect at Block Island in the summers of 1990, 1991, and 1993. All three plots exhibit clear patterns of weathering with respect to the *Exxon Valdez* reference oil (shown in Figure 12A). The most apparent change is the relative decrease in the naphthalene constituents. The pattern reflected in the PAH distribution for 1990 (Figure 12B) can be characterized as only slightly weathered, whereas the 1991 data (Figure 12C) exhibit a moderately weathered oil distribution pattern. While changes among the reference oil, the 1990, and the 1991 profile indicate that degradation was occurring and progressing in a predictable (classical) manner, the expected degradative pattern of change appears broken by the 1993 sediment data. As shown in Figure 12D, the PAH distribution for 1993 resembles that for 1990 more than it does that for 1991. This can be attributed to the contribution of relatively fresh oil present in one of the five stations. Exclusion of this station from the July 1993 PAH profile (Figure 12E) results in a PAH profile typical of heavily weathered oil, in which all of the two- and three-ring PAH compounds have been depleted. The overall concentration of the remaining constituents were found at concentrations significantly below the 1990 levels. Although a high degree of variance was observed in the summed PAH concentrations (as reflected by the error bars around the mean values), consistent patterns of oil weathering and biodegradation were evident from the changes in PAH distribution in the samples.

In the initial clam transplant study in 1991, samples of the native clam stock were removed in May and replaced with uncontaminated clams and exposed in situ until September of the same year. Sediment samples were also collected as a part of this experiment. Figure 13 compares the PAH profiles for the sediment samples removed from the study plots and shows mean results for the standard monitoring program lower intertidal transect. The transplant plot sediments exhibited no significant degradation changes between May (Figure 13B) and September 1991 (Figure 13C). Overall, the clam plots contained less degraded (i.e., fresher) oil relative to the lower transect sediment samples (Figure 13D). The differences, however, were subtle. On the basis of PAH distributions, sediment contamination in both the clam plot area and the lower intertidal transect would be classified as resembling moderately degraded oil.

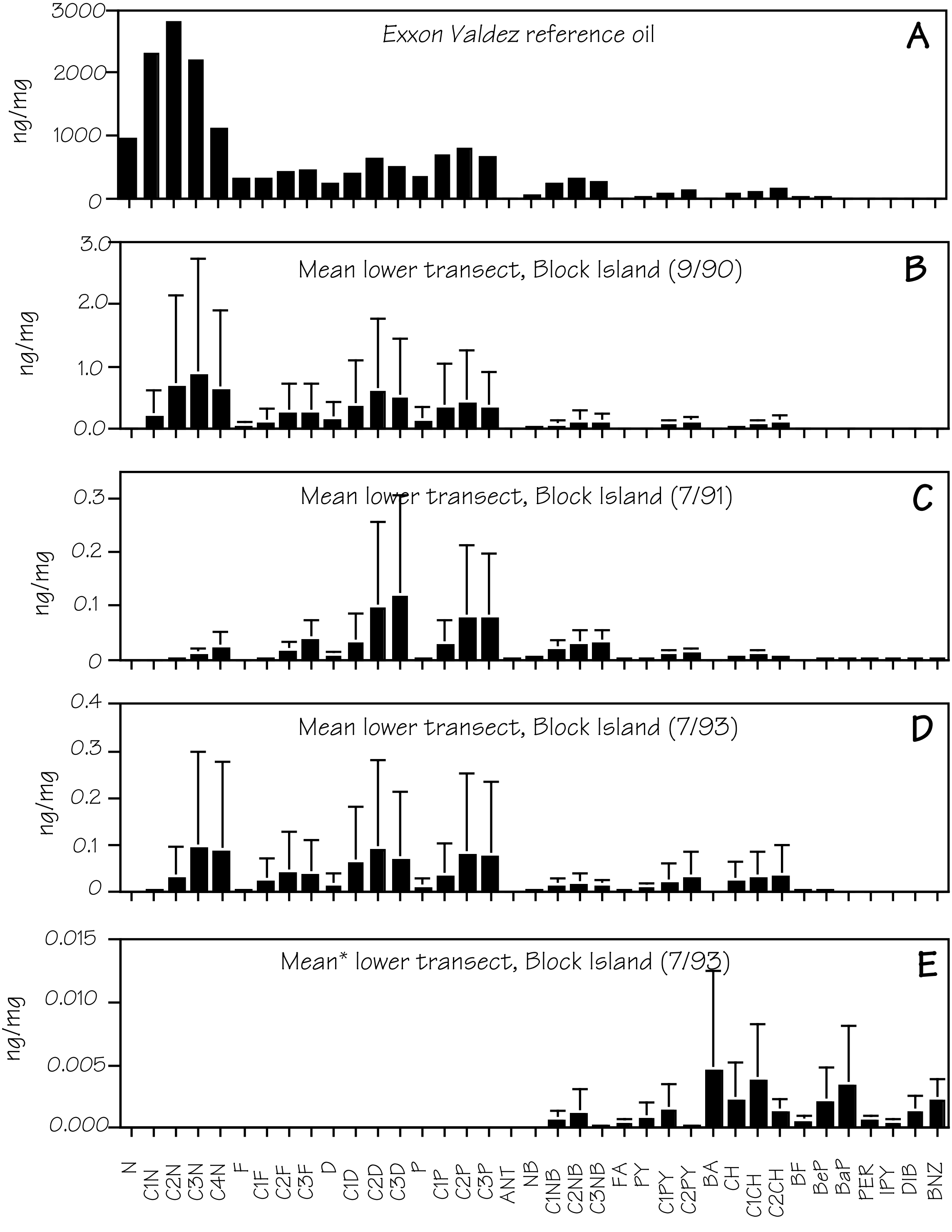

Figure 12. Histogram plot comparison of the PAH profile for the Exxon Valdez reference oil and the mean PAH concentration of sediment samples collected along the lower intertidal transect at Block Island. Each plotted value is the mean of five , replicates except for plot E. *Plot E shows results for the same sample set as plot D, with an anomalous high concentration replicate excluded (see text).

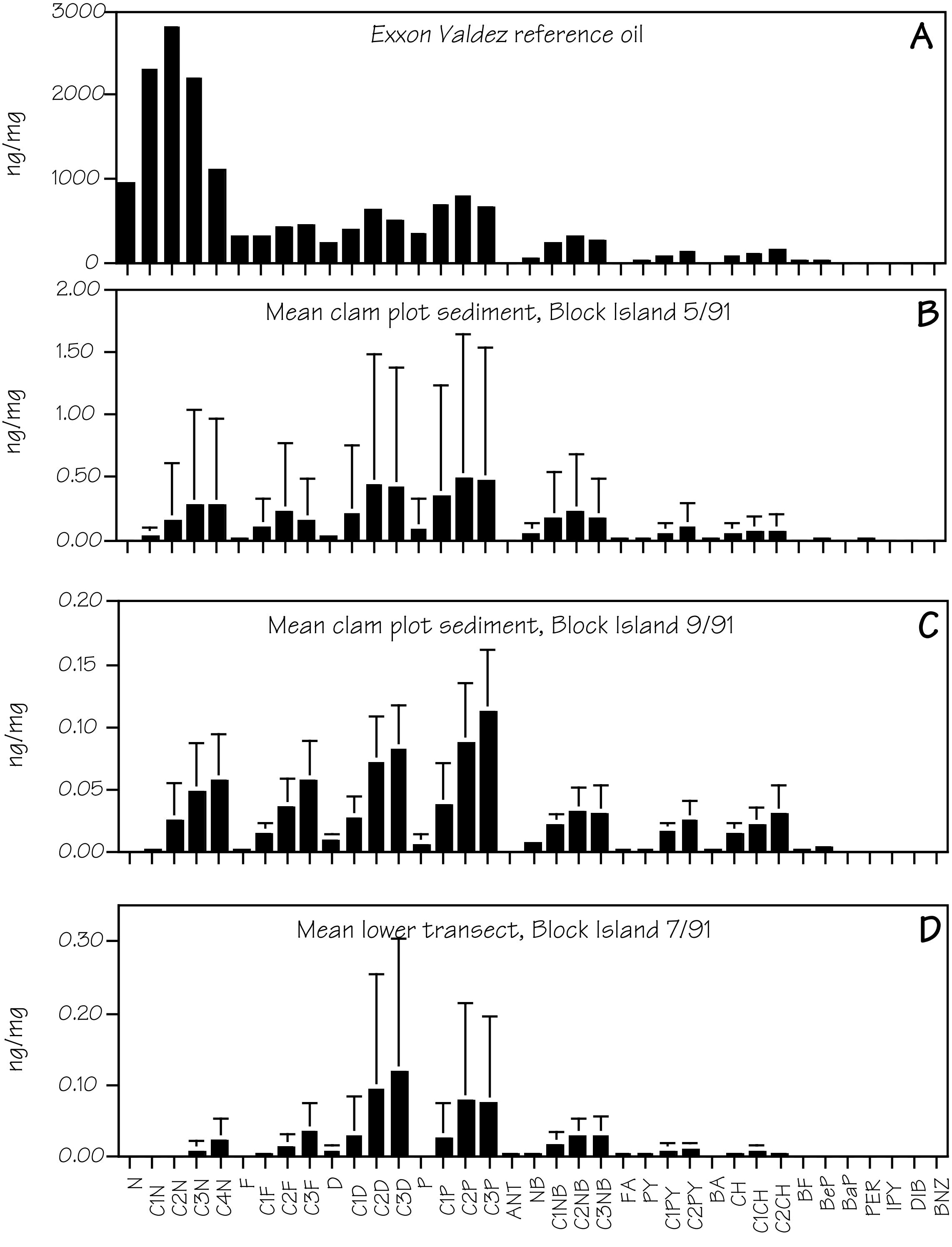

Figure 13. Histogram plot comparison of the mean PAH profile for *Exxon Valdez* reference oil (A), the clam transplant plot sediment samples collected in March (B) and September (C) 1991, and the lower intertidal transect (D) at Block Island.

The degradative differences in oil appear to correlate with oil concentration for most of the data at the Block Island site, and support the concept of a threshold concentration level similar to that observed by Fusey and Oudot (1984). By this argument, physical degradation processes dominate changes in oil chemistry until the oil concentration has been reduced to a point where biological degradation processes can dominate. All of the high concentration samples analyzed in the intertidal zone of Block Island were composed of relatively unweathered oil even as late as 1993. Apparently, the sites of persistent high oil contamination are sheltered from physical reworking and flushing. Therefore, the hydrocarbon concentrations never drop below a threshold level where observable biodegradative changes in the oil chemistry are detectable. The results from Block Island and from the larger NOAA monitoring program suggest that the threshold concentration separating physically and biologically dominated processes of oil degradation falls in the range of 10-100 ppm TPAH on the gravel beaches common in Prince William Sound. Figure 14 is a representation of the trend noted in the 1994 data for all sites sampled. According to this graphic, at 100 ng/mg TPAH, the equivalent TPH concentration was approximately 1.5 percent with a standard deviation of 1.1 percent. Note that the lower TPH values were excluded since they tend to be biased by other biogenic hydrocarbons unrelated to oil.

As the equivalent threshold value of 1.5 percent TPH is derived from the 1994 NOAA data set only, it probably would not be appropriate to assume it is an appropriate figure for other years. However, other data can be analyzed in the same way to yield estimates for a given data set. In general, we believe that the threshold value will depend on aspects of climate, substrate, system energy, etc. Once calculated for a specific situation, the threshold could provide a level of general guidance for shoreline cleanup.

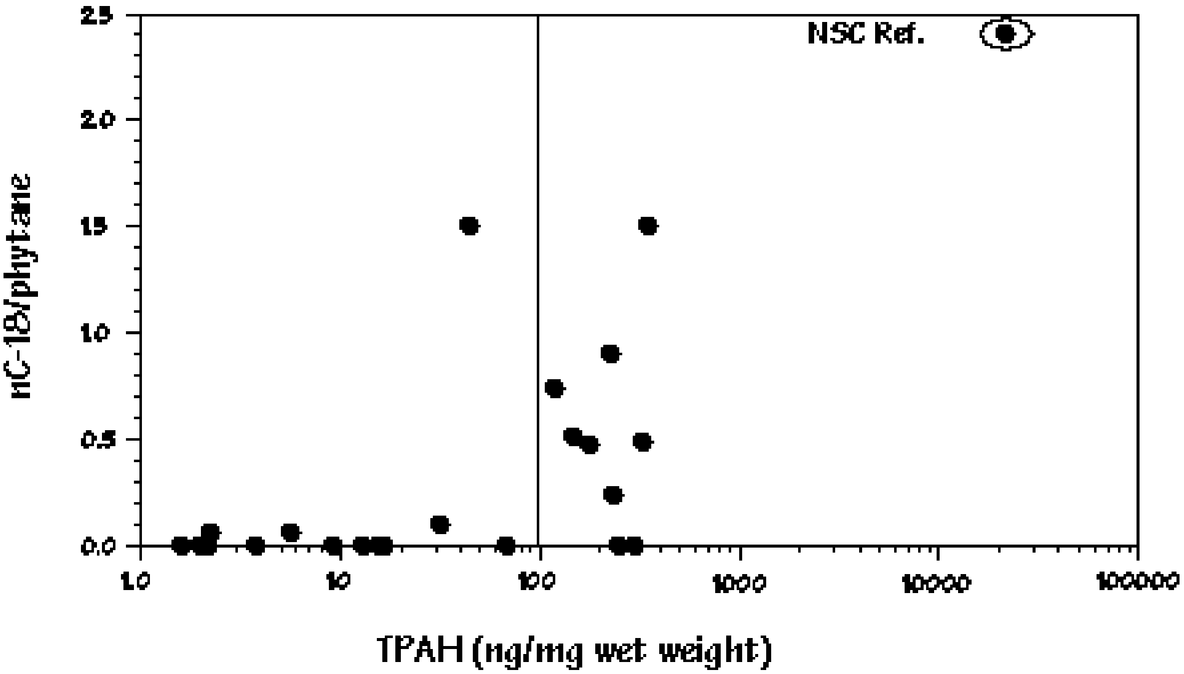

Figure 14. The concentration "threshold" is depicted from the Prince William Sound 1994 oiled sediment samples greater than 1.0 ng/mg TPAH. Data less than 1.0 ng/mg were not included due to biological interferences commonly found in TPH data.

TISSUE CHEMISTRY: PAH DISTRIBUTION PATTERNS IN CLAMS

Figure 15 compares the PAH distribution for native clams removed from the initial transplant plots in May 1991, the transplanted stock after five months exposure, and sediments removed from the same clam plots when the transplant stock was harvested in September 1991. After only five months, the transplant stock apparently accumulated PAHs to a concentration and relative composition consistent with the native stock. The PAH distribution patterns for transplanted clams and the sediments from the same plots are also quite similar, suggesting that the main route of exposure may be related to transport of whole oil rather than dissolved fractions of the oil.

The initial clam transplant study was expanded in 1992 to include 15 stations. Consistent with previous observations at the site, the degree of oiling at the 15 stations was highly variable. Clam tissue chemistry results for three stations in particular were grouped separately from the others because they contained significantly higher PAH concentrations. The oil contamination observed in these “high-concentration” samples at Block Island (Figure 16B) was significantly less degraded than that observed at the other 12 stations, which were classified as “low concentration” (Figure 16C). In Figure 16D, the concentration scale for the analytes has been expanded to permit comparison of PAH distributions between the high-concentration and low-concentration groupings. The oil in the highly contaminated samples exhibited only a slightly weathered pattern, while that in the less contaminated samples was more consistent with a moderately weathered oil.

Figure 17 compares the mean PAH profile for all native clams collected in 1992, with the transplanted clams after one-year exposure and with the mean sediment PAH profile from samples collected with the native clams in 1992. The transplanted stock reached the same level and general PAH distribution, but none of the clams contained the relatively unweathered PAH distribution reflected in the sediment profile. That is, the prominence of the naphthalenes in the sediments was not as apparent in the clam tissues. The clams may have more readily metabolized and excreted the two-ring naphthalenes because of their relative water solubility compared with the three-ring and larger PAH constituents. In addition, the difference between the clam results and the sediment profile shown in Figure 17D is biased by the high concentration of relatively fresh oil detected in sediments at two of the stations during 1992. Clams removed from the highly contaminated areas did show a less degraded profile more similar to that for sediments removed from the more contaminated plots. (See Figure 16, and compare the high concentration clam profile shown as Figure 16B to the sediment profile in Figure 16D.)

Summary Points

- Overall, we observed a consistent temporal trend of oil degradation. By 1993, most of the lower intertidal zone contained only low concentrations of highly degraded oil residues, although selected “hot spots” still contained relatively high concentrations of relatively undegraded oil.

- The sediment chemistry data from Block Island are consistent with the notion of a threshold concentration for domination by physical or biological degradation processes in weathering.

- The PAH distribution pattern detected in clams resembles that for the adjacent sediments, suggesting that they are exposed primarily by processes that transport whole oil—such as fine sediments to which oil has adsorbed. Further, the body burden PAH composition of the clams appears to remain at an equilibrium very similar to that observed in the oiled sediments, with the exception of the more water-soluble and less persistent two-ring PAH constituents.

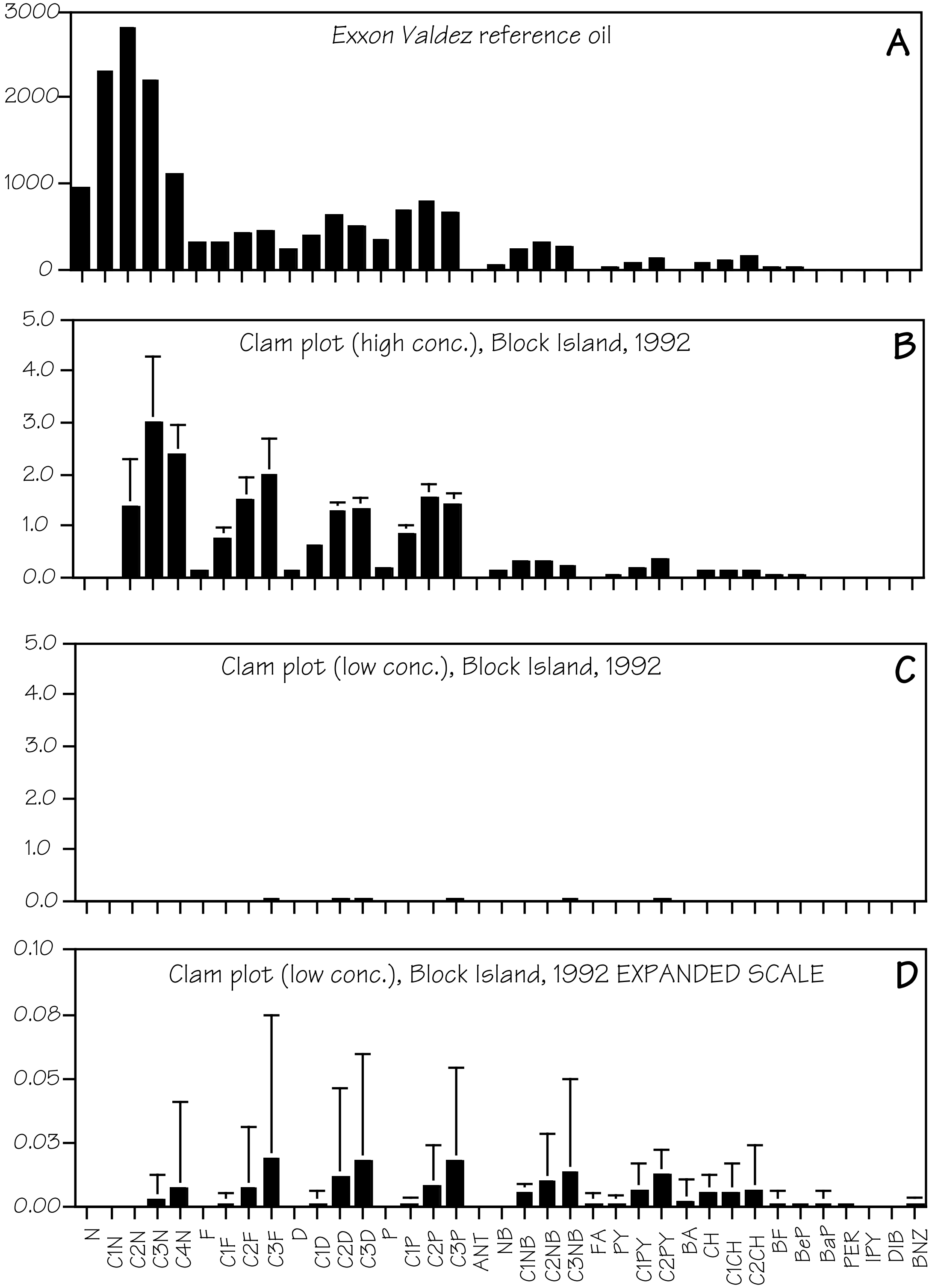

Figure 15. PAH distributions for *Exxon Valdez* reference oil (A), the May 1991 native clams removed from Block Island clam plots (B), transplanted clams after four months' exposure (C), and the mean clam plot sediment values in September (D).

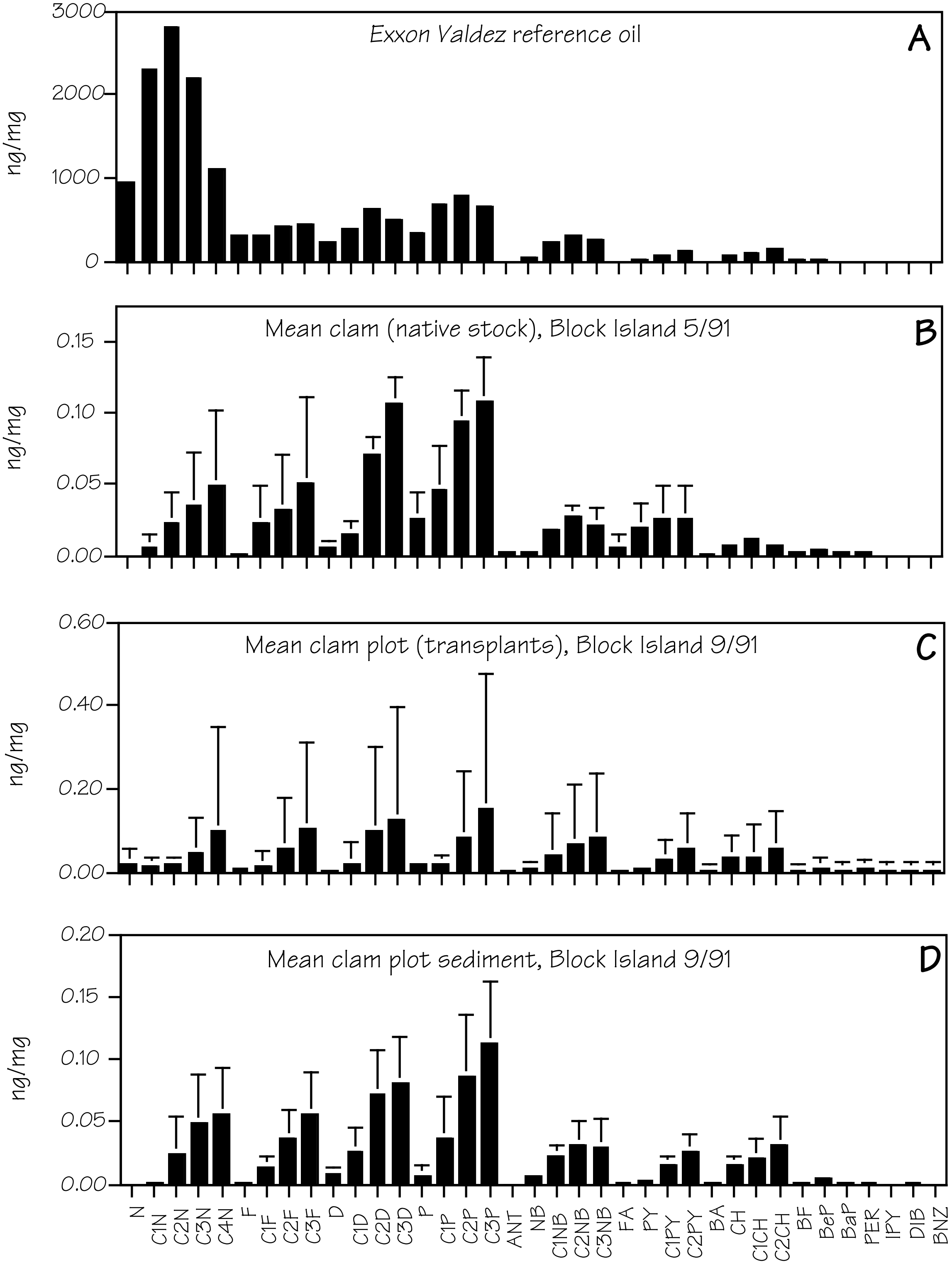

Figure 16. Mean PAH profile for *Exxon Valdez* reference oil and sediments collected in 1992 from the Block Island clam transplant experiment. The lower-concentration sediment samples are shown in a scale equivalent to that for high-concentration samples (15B) for total PAH comparison (15C) , and in expanded scale for PAH distribution comparison (15 D).

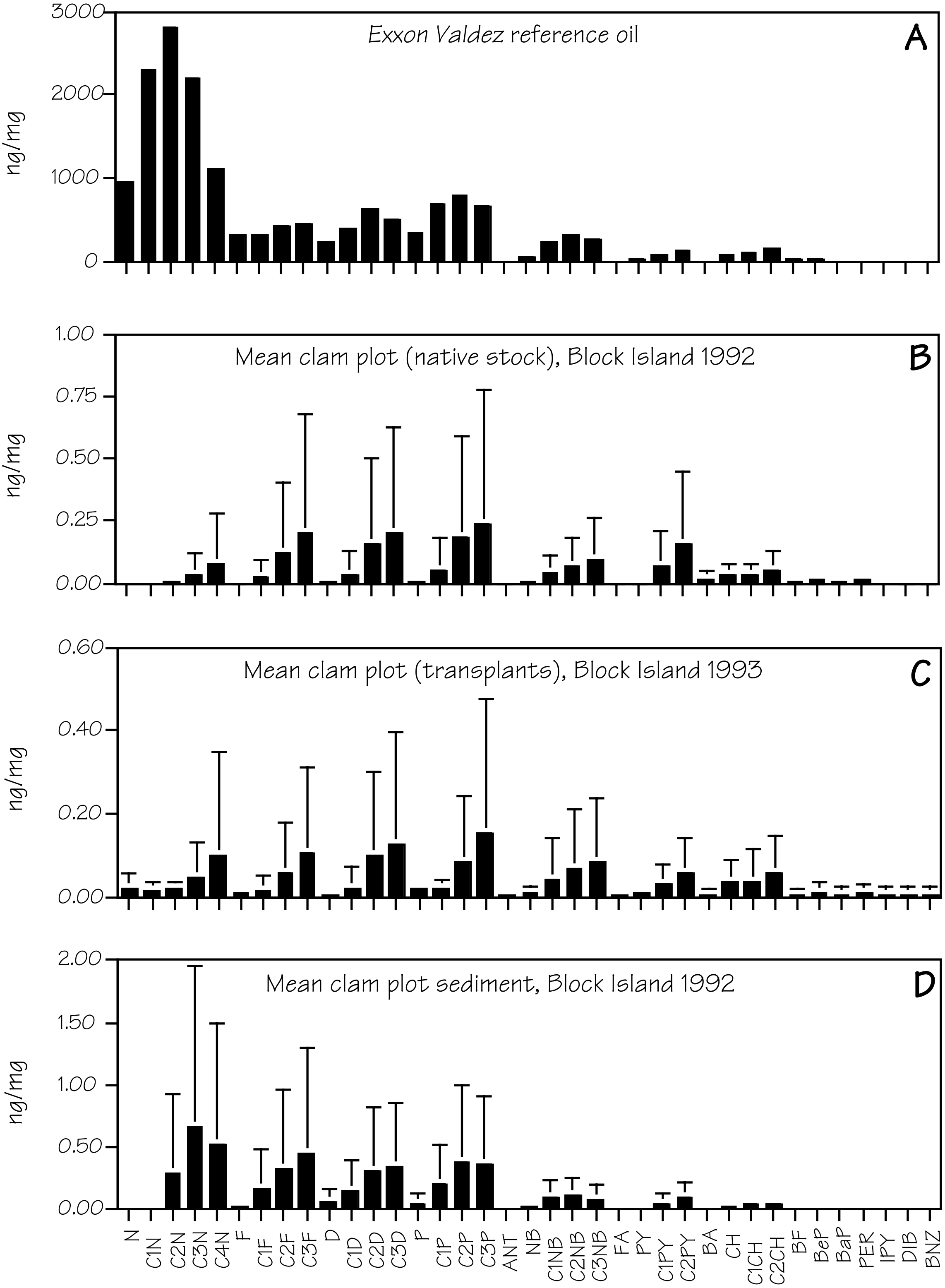

Figure 17. Histogram plot comparison of the PAH profile for *Exxon Valdez* reference oil (A), the 1992 native clams removed from the clam plots (B), the transplanted clams after one-year exposure (C), and the mean sediment values resulting from the 1992 sampling (D).

OTHER PHYSICAL SITE CONDITIONS

We have tracked other physical parameters at the Block Island site since 1991, including nearshore water temperature and salinity, and sediment grain size. Beginning in 1992, we added sediment total organic carbon content, and sediment total Kjeldahl nitrogen (TKN) were added.

Table 8 summarizes water temperature and salinity measurements at the Block Island site. Three of the four available sets of measurements were collected at around the same time of the year and are generally comparable. The results from April 1991 appear to reflect the seasonal changes in temperature and, to a lesser degree salinity, at this site.

Table 8. **Nearshore surface-water measurements at the Block Island site, 1991-1994. Temperatures in degrees Celsius, salinity in parts per thousand.**

Date	Surface Temperature	Surface Salinity
4/91	4.8	31.0
7/91	17.0	25.8
7/92	12.5	23.0
6/93	13.6	26.2
6/94	12.4	25.2

We have collected samples for grain-size analysis at the lower intertidal elevation of Block Island since 1991. In addition, in 1992 we began collecting samples for total organic carbon (TOC) and TKN. Grain-size results for the site are summarized below in Table 9; TOC and TKN results are in Table 10.

Table 9. **1991-1994 sediment grain size analysis results for lower elevation of Block Island site. Values are percent of total displacement volume for each size fraction.**

			SAMPLE YEAR	
SIZE FRACTION	1991	1992	1993	1994
12.5 mm	22.28	42.72	15.66	28.11
6.3 mm	6.69	16.5	13.78	13.58
2.0 mm	10.17	12.43	25.06	26.32
1.0 mm	8.50	7.38	14.41	18.95
500 µ	7.24	5.83	9.65	3.89
250 µ	9.75	9.32	7.27	5.68
125 µ	6.27	3.50	6.39	1.16
63µ	2.65	0.78	2.13	0.53
Silt/clay	26.46	1.55	5.64	1.79

It is important to note that only a single sample has been collected in each year since 1991. Strictly speaking, then, each year's grain size distribution cannot be considered representative of the site and is intended only to reflect general conditions or show gross changes. However, as Table 9 shows, the grain size sample collected in 1991 was very different from any collected since then, in that the smallest size fraction (silt/clay) dominated the sample. This is consistent with the notion that finer-grain sediment fractions were washed from upper to lower portions of the tidal flat during the 1989 cleanup, although it could also simply reflect within-site or between-year variability.

Table 10. **1992-1994 sediment TOC and TKN from Block Island lower intertidal station, with summary results for all sites sampled (1992 n=13; 1993 n=10; 1994 n=11). Results in parts per million.**

Date	Block Is.	Mean, All	Std. Dev., All	Median, All	Range, All
TOC					
7/92	21,300	22,217	14,969	16,600	6,120 - 47,929
6/93	14,000	18,584	13,748	11,500	7,330 - 46,200
6/94	21,400	14,879	4,524	16,100	7,380 - 21,400
TKN					
7/92	403	415	548	282	56 - 2,190
6/93	324	802	1,035	450	122 - 3,410
6/94	513	332	155	315	99 - 518

Measurements of TOC and TKN at Block Island have been fairly consistent over the three years in which they were collected, approximating the midrange of the values from all sites sampled. The small set of values does not indicate trends of either increase or decrease.

BIOLOGICAL CONDITIONS AND PROCESSES

Middle Intertidal Elevation

Five cores were collected and analyzed in 1990 for infauna at the middle elevation station at Block Island. Table 11 shows results from these cores. Taxa considered to be primarily meiofauna (e.g., oligochaetes, harpacticoid copepods, and nematodes) were abundant at the station. However, the processing method for infaunal cores does not provide a quantitative result for meiofaunal taxa due to the screen size used in sieving. The major infaunal taxa present at this station were polychaetes (4.6/core) and bivalves (2.4/core), with the polychaete, *Capitella capitata,* and the bivalve *Macoma* the most abundant species. *Capitella capitata* is considered an opportunistic species and is found in areas of organic enrichment, pollution, or disturbance. However, there is evidence that *Capitella capitata* is represented by a complex of at least four sibling species that vary in their degree of tolerance to environmental parameters (Gallagher and Grassle 1985; Cognetti 1993). *Macoma balthica* has been used to monitor pollution from the oil terminal operation in Port Valdez, Alaska (Shaw et al. 1986), and is a common bioindicator for a wide range of contaminants in many different coastal areas (e.g., Foster et al. 1987; Foster and Wright 1988; Wilson 1994).

Lower Intertidal Elevation

Results are available from infaunal samples collected at the Block Island lower elevation transect between 1990 and 1994. Despite the high residual PAH concentrations in some sediments at this station, it has been one of the richest (in terms of abundance, number of taxa, and diversity of infauna) relative to other sites in the overall NOAA monitoring program. As shown in Table 12, values for diversity and number of taxa found at Block Island were lowest in 1990, the first year that the biological team visited the site, but subsequently increased and have since remained relatively constant. The mean abundance of infauna was also at a minimum in 1990, increased greatly in 1991 and has declined in subsequent years. These fluctuations and the apparent return to more stable conditions may reflect the effects of the initial oiling and then adjustments of the infaunal community as the process of recovery progresses.

Excluding the meiofaunal taxa as described above, the most abundant major individual species or taxa through the five years were primarily bivalve molluscs or polychaete worms (Table 13). Bivalves such as *Macoma*, *Protothaca staminea* and *Mysella tumida* steadily increased in

Table 11. Infaunal data from intertidal cores, Block Island, July 1990.

Taxon	Quad 1	Quad 2	Quad 3	Quad 4	Quad 5	Mean	SD
Turbellaria	0	0	0	0	0	0.00	0.00
Nemertea	1	1	0	1	0	0.60	0.55
Nematoda	2	2	0	11	2	3.40	4.34
Oligochaeta	0	1	0	29	0	6.00	12.86
Harpacticoida	0	0	0	24	0	4.80	10.73
Pholoe minuta	0	0	0	0	0	0.00	0.00
Nereidae	0	1	2	4	2	1.80	1.48
Nereis	0	0	0	0	0	0.00	0.00
Nereis vexillosa	0	0	0	0	0	0.00	0.00
Spionidae	0	0	0	0	0	0.00	0.00
Scolelepis squamatus	0	1	0	0	0	0.20	0.45
Opheliidae	0	0	0	1	0	0.20	0.45
Armandia brevis	0	1	0	0	0	0.20	0.45

Table 11 continued

Taxon	Quad 1	Quad 2	Quad 3	Quad 4	Quad 5	Mean	SD
Capitella capitata	3	0	2	4	0	1.80	1.79
Barantolla americana	0	1	0	0	0	0.20	0.45
Pectinaria	0	0	0	1	0	0.20	0.45
Gastropoda	0	0	0	0	0	0.00	0.00
Bivalvia	0	2	0	2	0	0.80	1.10
Macoma	0	0	0	1	4	1.00	1.73
Macoma balthica	0	0	2	0	0	0.40	0.89
Protothaca staminea	0	0	0	1	0	0.20	0.45
Hiatella arctica	0	0	0	0	0	0.00	0.00
Pseudoscorpionida	0	0	0	0	0	0.00	0.00
Ianiropsis kincaidi	0	0	0	0	0	0.00	0.00
Paramoera sp. 1	0	0	0	0	0	0.00	0.00
Spinulogammarus subcarinatus	0	0	0	0	0	0.00	0.00
Gammaroporeia alaskensis	0	0	0	0	0	0.00	0.00
Insecta	0	0	0	0	0	0.00	0.00
Diptera	0	0	0	0	0	0.00	0.00
Chironomidae	3	0	0	1	0	0.80	1.30
Total Abundance (N)	9	10	6	80	8	22.60	32.12
Number of Species (S)	4	8	3	13	3	6.20	4.32
Diversity (H')	1.31	2.03	1.10	1.77	1.04	1.45	0.43

Table 12. Measurements of infaunal diversity, abundance, and number of taxa at the lower intertidal elevation of the Block Island site, 1990-1994.

Sample Year	Diversity H'	Abundance N	No. of Taxa S
1990	1.99	40.60	11.0
1991	2.27	103.60	14.4
1992	2.14	95.40	15.2
1993	2.10	66.60	12.4
1994	2.12	62.25	13.0

abundance from 1990 to 1992, and then showed a decline in 1993 and 1994. Other molluscs have demonstrated similar trends of sharp increases in 1991 and 1992, with marked declines in

1993 and 1994. *Macoma balthica* was one of the most abundant species present in 1990 and 1991, but declined in 1992 and was completely absent in 1993 and 1994. As noted previously, this species has been used as a “sentinel” organism for oil pollution, and laboratory studies (Shaw et al. 1976; Shaw et al. 1977) have yielded lethal concentrations of crude oil and sublethal behavioral effects from exposure. The polychaetes *Eteone longa* and *Pectinaria granulata* increased at the site in the first three of five years of the study, but appeared to stabilize in 1993 and 1994. In contrast, the polychaete *Armandia brevis* gradually decreased to negligible abundances in 1993 and 1994. Except for the cumacean *Cumella vulgaris*, crustaceans have occurred only infrequently in the “top ten” listing between 1990 and 1994.

Because the lower portions of the intertidal were not known to have been directly treated during cleanup operations, the trends in the primary infaunal taxa appear to reflect recovery of the assemblage from losses due to oiling toxicity or indirect effects of oiling and cleanup. However, the consistent, rapid increases in abundance and other parameters (Table 12) did not continue between 1992 and 1994 and may reflect oscillation or cycling of the infaunal system as the process of recovery continues.

The hardshelled clams *Protothaca staminea* (littleneck clam) and *Saxidomus giganteus* (butter clam) were collected from 0.25-m^2 excavations and from 0.009-m^2 cores at the lower elevation between 1990 and 1994. Both species exhibited similar patterns in abundance with a large increase in numbers in 1992 from the previous two years. However, these numbers declined in 1993 and 1994, consistent with the overall pattern for infauna at the site.

The Block Island lower intertidal zone has also been the focus of clam transplant studies to investigate the effects of oiling on growth and survival of the littleneck clam, *Protothaca staminea*. An in-depth discussion of this experiment follows later in this chapter and can also be found in Houghton et al. (1993).

Table 13. Ten most abundant infaunal species at Block Island lower mixed-soft station, 1990 to 1994.

1990

Species	Mean	SD
Macoma balthica	6.60	4.22
Protothaca staminea	3.40	2.61
Armandia brevis	3.00	2.74
Macoma spp.	2.20	4.92
Barantolla americana	1.80	1.30
Capitella capitata	1.20	1.79
Mysella tumida	0.60	0.89
Ophelina spp.	0.60	1.34
Pectinaria granulata	0.40	0.55
Fartulum spp.	0.20	0.45
Macoma obliqua	0.20	0.45
Mediomastus californiensis	0.20	0.45

1991

Species	Mean	SD
Macoma spp.	11.60	11.76
Macoma balthica	7.80	13.14
Protothaca staminea	6.40	5.22
Macoma inquinata	4.40	2.70
Alvania compacta	3.80	3.63
Laonice spp.	3.60	5.68
Syllis elongata	3.00	3.54
Mysella tumida	3.00	3.32
Armandia brevis	2.20	2.86
Eteone longa	1.60	1.52
Allorchestes spp.	1.60	1.82

1992

Species	Mean	SD
Mysella tumida	16.00	15.41
Protothaca staminea	13.00	8.09
Macoma inquinata	12.00	7.78
Eteone longa	9.60	8.91
Syllis elongata	6.80	13.01
Cumella vulgaris	5.00	7.68
Alvania compacta	4.00	6.75
Spio filicornis	3.60	3.51
Pectinaria granulata	3.60	3.91
Naineris quadricuspida	3.40	7.60

1993

Species	Mean	SD
Mysella tumida	14.00	11.47
Protothaca staminea	9.40	5.77
Macoma inquinata	8.20	7.95
Pectinaria granulata	6.40	4.62
Pholoe minuta	5.80	2.17
Eteone longa	3.40	2.70
Syllis elongata	2.40	4.28
Macoma spp.	2.00	2.45
Alvania compacta	1.80	1.79
Barantolla americana	1.80	2.39
Cumella vulgaris	1.40	2.07

1994

Species	Mean	SD
Mysella tumida	11.20	8.14
Macoma inquinata	9.40	5.13
Protothaca staminea	7.60	6.31
Pectinaria granulata	5.80	3.70
Pholoe minuta	4.40	4.16
Cumella vulgaris	4.20	6.69
Polydora quadrilobata	4.20	7.19
Eteone longa	3.40	5.94
Odostomia spp.	2.00	2.92
Alvania compacta	1.80	1.30

Tissue Chemistry

Mussel tissue has been the only tissue matrix consistently collected and analyzed each year of the NOAA biological monitoring program at Block Island. During the initial biological survey year of 1990, *Mytilus* (mussel) and *Nucella* (drill) tissues were collected and analyzed. Since 1991, we have analyzed *Mytilus* and *Protothaca* (clam). The *Protothaca* analyses have included both native clams and clams transplanted to the Block Island site from unoiled areas. The transplant experiments have constituted a major effort at Block Island to define the bioavailability of residual hydrocarbons, and will continue into the future. We will describe these experiments in greater detail below.

In 1990, the summed concentration of PAHs found in the drill *Nucella* was relatively low, 0.09 ppm dry weight. Of thirteen samples analyzed from the July 1990 collection at all sites, the Block Island sample ranked ninth. The mean and median values for the thirteen sites were 0.40 and 0.13 ppm, respectively.

MUSSELS

The first mussel tissue sample collected at Block Island in 1990 was a composite of individuals from both rocky substrate (the bedrock outcrop where the middle and upper intertidal rocky transects for biology are located) and from gravel substrate (the low-angle tidal flat where the middle and lower biological transects have been established). Summed PAH concentration for this sample was 2.7 ppm dry weight. In 1991, the mussel chemistry sample, collected below the rocky middle intertidal transect, measured 2.1 ppm. In 1992, to discern differences between mussels living on the two substrate types, discrete samples were collected from the rocky outcrop and from the cobble surface of the tidal flat. Respective concentrations were 2.2 and 8.9 ppm, suggesting a higher level of exposure to those mussels living on the flat.

In 1993, when discrete (as opposed to composited) samples were also collected, concentration of total PAHs were lower but consistent with the 1992 substrate pattern. Mussels from the outcrop contained 0.34 ppm, while those from the tidal flat contained 1.3 ppm. The relatively higher body burdens found in mussels collected from the flat might be attributed to any one or more of several causes, including proximity to higher PAH concentrations in the sediments or water, differences in tidal elevation that would result in longer *time* of exposure through filter-feeding or direct contact with hydrocarbons in the water, or inherent physiological or metabolic differences between the populations.

NATIVE CLAMS

Chemical analysis of clam (*Protothaca staminea*, littleneck clam) tissues in the monitoring program began with samples collected in May 1991. During this visit, we initiated an experiment to transplant clams at the Block Island site. *Protothaca* collected at an unoiled site on Bainbridge Pass were tagged with a UV fluorescing dye and moved to Block Island, where they were set into five 0.25-m^2 plots across the tidal flat. We moved any clams that lived in the plots, reserving them for chemical analysis. Native clams were found in four of the five designated transplant quadrats, but results are available for only two of those four plots (one sample was lost, the other was too small to analyze). Summed PAH concentrations for the two analyzed plots were 0.72 and 1.0 ppm dry weight.

In July 1991, a standard chemistry collection of *Protothaca* began at the site along the lower intertidal biological monitoring transect. The transect spanned a visible gradient of sediment contamination common to this elevation. The clam sample composited along the transect contained 6.4 ppm. In 1992, the standard collection from the same area along the transect measured 3.5 ppm. In 1993, a substantially lower level was found, at 0.19 ppm. While these results might suggest a decrease over time in the level of hydrocarbon exposure to clams collected near the lower intertidal transect, more spatially detailed chemistry results from the site reflect a high degree of variability in exposure and uptake for clams at Block Island. As has been noted, this site has an obvious gradient of sediment contamination across the flat, with relatively higher levels noted in the lee of the bedrock outcrop area on its southern side. While preparing transplant plots in 1992, we collected native clams found in fifteen 0.25-m^2 plots for chemical analysis. The concentrations found in the fifteen samples of native clams ranged from below detection to 15 ppm. The mean and median concentrations were 1.9 and 0.66 ppm, respectively, with a standard deviation of 3.8. Figure 18 shows a schematic of native clam samples collected with summed PAH concentrations as histograms. While the figure illustrates a higher level of exposure to the right on the figure (south), it also shows the variability found even in samples located next to each other. It is interesting to compare the summed PAHs in tissues (Figure 18) with those in sediments from the same plots in Figure 11, all for 1992. Sediment bioconcentration factors ranged very widely, from 0 to 180, suggesting multiple pathways of exposure.

TRANSPLANTED CLAMS

The oiling conditions encountered at the Block Island site provided a unique set of circumstances in which to study the effects of chronic hydrocarbon exposure. During its first visit to the site in 1990, the biological team noted but did not quantify the relatively high degree of variability in sediment oiling. In September 1990, to better define this variability, five discrete (i.e., not composited) sediment samples were collected along the lower intertidal transect (Table 6). The wide range in results for summed PAH concentrations (0.07 to 29 ppm; mean = 6.4, standard deviation = 12.8, median = 1.1) confirmed the observed conditions and the presence of a variable gradient in residual oiling across the lower tidal flat.

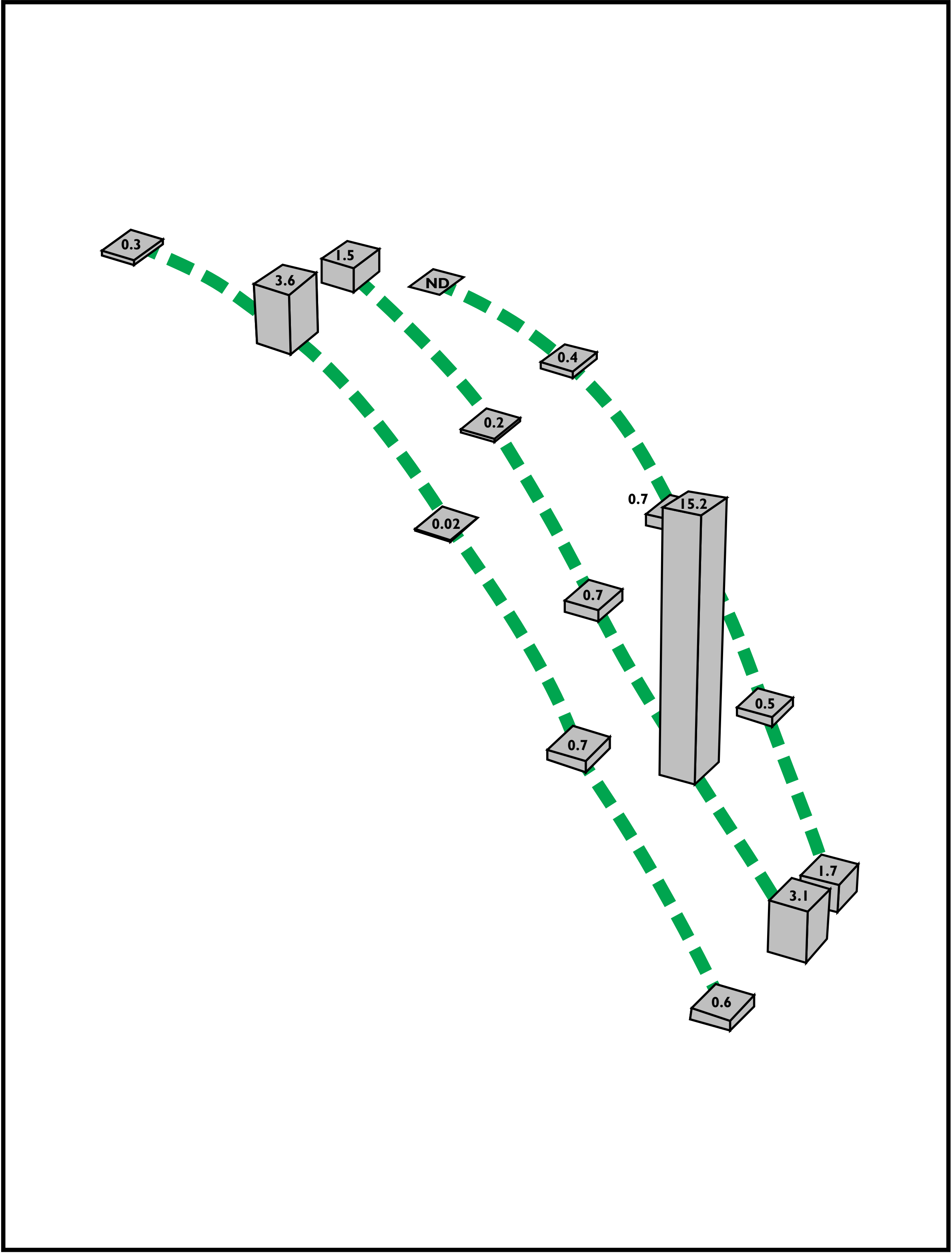

Figure 18. TPAH results for native *Protothaca staminea* clams from Block Island clam transplant plots in 1992. Values in ppm dry weight. Refer to Figure 10 for orientation within site.

As discussed previously, discrete samples of native clams collected across the face of the flat also reflected a high degree of variability. The residual contamination of the sediment and the continuing exposure to resident clams led to the staging of an experiment to more closely examine bioavailability of hydrocarbons at the site by transplanting clams.

In 1991, a modest experiment was established to examine spatial variability in the availability of residual PAHs to clams transplanted from an unoiled area. The source site for the clams was designated Bainbridge Bight, located on the northwest side of Bainbridge Pass in southwestern Prince William Sound. The clams from this site contained almost no detectable concentrations of target PAHs (0.009 ppm, dry weight). These clams were placed in calcein dye in order to mark the shells for growth studies, then—as described previously—placed in five plots at Block Island. At the time of the transplanting (May 1991), sediment samples were collected for chemical analysis from each transplant plot. Native clams found during plot excavation were reserved for chemical analysis. Approximately 100 marked clams from Bainbridge Bight were placed into each transplant plot. These were left in place until September 1991, when the transplants were recovered and another series of sediment samples were collected.

Table 14 summarizes results from the 1991 transplant experiment. The sediment chemistry results from both May and September showed a higher level of contamination on the south side of the Block Island site. This was also consistent with the discrete sediment chemistry results obtained in September of 1990. Fewer native clams were found in the oilier sediment material. Uncontaminated clams transplanted into the plots showed a substantial uptake of hydrocarbons over the four months they resided in Block Island sediments. Mortality over that time period appeared to be correlated with the chemistry results, with higher mortality found in plots with higher sediment oiling and tissue contamination. Growth of three-year-old clams (the dominant age class for clams used in the transplant experiment) also suggested a relationship with chemistry. We compared the measured growth rate in 1991 with that in 1990, expressing it as a percentage for each plot. The highest relative rate was found in the least oiled plot, while the lowest value was found in the most contaminated plot.

Figures 19 and 20 portray results of the 1991 transplant experiment. The mean survival of clams in four experimental plots from May to September 1991 ranged from 62 percent at the most heavily oiled plot to 88 percent at the least oiled plot. Aging of the clams collected from these plots suggested better growth of age 3 and age 4 clams with lower oiling, but little difference in growth of age 5 or age 6 clams with oil in the sediment (Figure 19). Figure 20 is a plot of one set of the variables from Table 14, the sediment PAH concentration when the experiment ended in September vs. age 3 clam growth and clam mortality. These limited results indicate a correlation between sediment PAH concentration and both clam growth and clam survival.Overall, the results from the 1991 Block Island transplant included the following observations:

- Sediment contamination appeared to be inversely correlated with survival of both native and transplanted clams. Sediment PAH levels between 0.6 and 1 ppm corresponded with substantially reduced numbers of clams found in the transplant plots.
- Sediment hydrocarbon measurements in May and September indicated a large reduction in levels of sediment contamination over that time period.
- However, mortality and growth among transplants were affected by and were strongly correlated with remaining levels of residual oiling.

Table 14. Summary of results from 1991 clam transplant experiment at Block Island.

PLOT #	SEDIMENT CHEM		NATIVE CLAMS		TRANSPLANTED CLAMS		
	∑ PAH ppm wet May-91	∑ PAH ppm wet Sep-91	Density # in plot May-91	∑ PAH ppm dry May-91	∑ PAH ppm dry Sep-91	Mortality % Sep-91	Growth 91 as % of 90 Sep-91
Plot 1	0.41	0.31	17	-	0.54	12	69%
Plot 2	0.33	-	10	0.72	-	-	-
Plot 3	0.62	1.09	4	1.05	2.76	18	51%
Plot 4	12.40	0.77	0	-	1.69	22	55%
Plot 5	25	1.38	1	-	14.60	38	44%

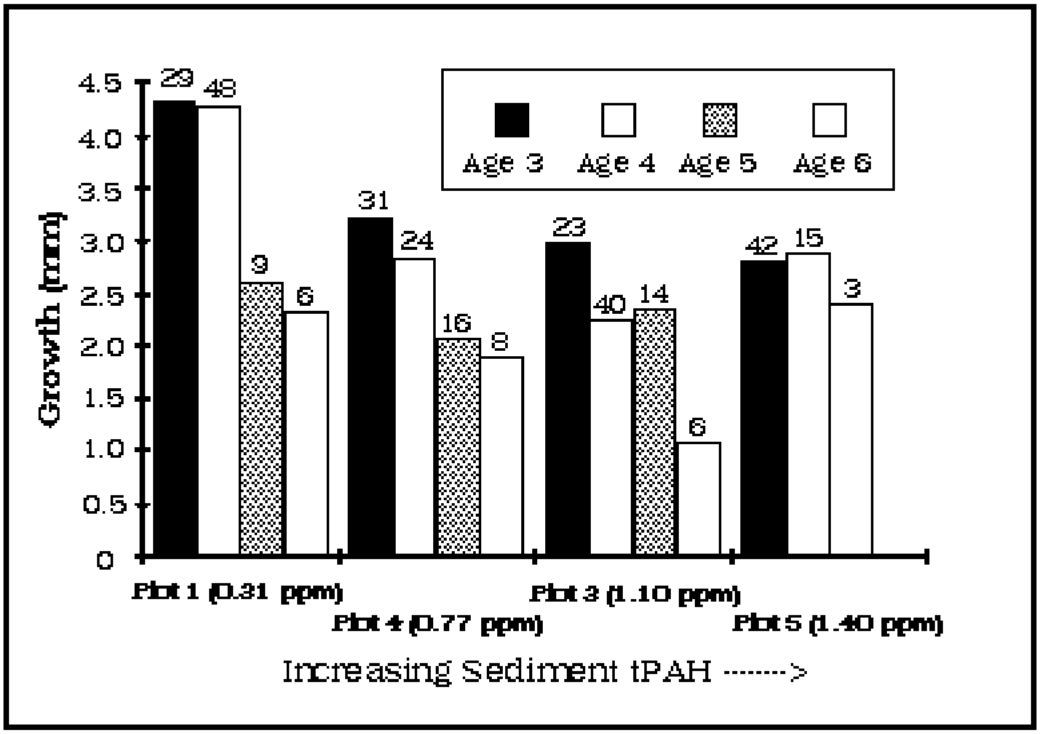

Figure 19. Mean growth of transplanted *Protothaca staminea* clams (age classes 3-6) under different oiling conditions at Block Island, May - September 1991. Number in each age class shown above each column.

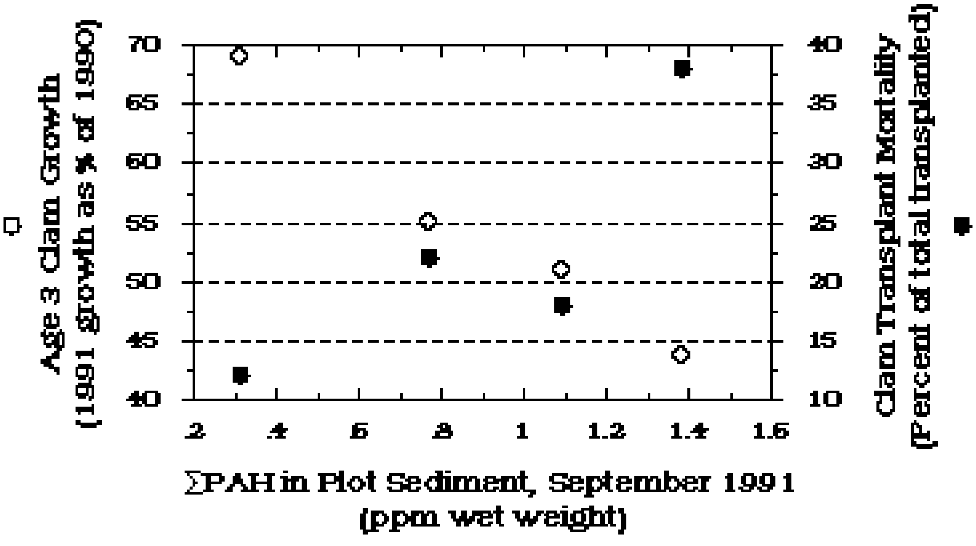

Figure 20. Plot of clam growth and mortality vs. sediment total PAH from 1991 clam transplant experiment at Block Island.

The results of the 1991 *Protothaca* transplant experiment provided the impetus for an expanded, longer-term investigation which was deployed in 1992 and recovered in 1993. In this effort, additional transplant plots were established and a greater number of clams were used. As in 1991, source clams were obtained at the Bainbridge Bight site, were exposed to calcein dye, then transplanted into the Block Island plots.

Figure 10 shows the orientation of the transplant transects that were established in July 1992. The three lines were oriented across the tidal flat parallel to the water line. About one hundred clams were placed into each of five plots spaced about 6 meters apart along the middle transect and, on the transects above and below, 25 clams were placed into each of five plots along each line. Sediment samples were collected from each plot, as were native clam tissue chemistry samples (where available). Results for the native clam tissue chemistry have been discussed previously (Figure 18), as have sediment chemistry results for the fifteen plots (Figure 11). Both sediment and clam tissue chemistry results reflected a higher level of oiling toward the south side of the study area, but both also showed a substantial degree of spatial variability in that oiling.

In contrast to 1991, when transplanted clams remained in place for about four months, the *Protothaca* transplanted in 1992 were not collected until one year later, in late June 1993. Tissue chemistry samples were collected for all fifteen plots. In plots 1-5 (i.e., the middle transplant transect), collections were also subsampled for histopathological examination.

Figure 21 shows chemistry results for PAH levels found in the transplanted clams. Comparison with Figure 19 shows a similar pattern of hydrocarbon uptake between the native clams removed in 1992 and the transplants that were exposed for one year and removed from the same plots in 1993. Summed PAH levels ranged from 0.09 to 9.5 ppm dry weight. As was the case in 1992, the highest concentrations in 1993 were encountered on the southern end of the middle transplant transect.

Although the range of values found along this transect was 0.21 to 9.5 ppm, the histological examination of clams from the plots showed no pathological disorders. However, an apparent offset in reproductive status was observed in the clams, similar to that observed in Smith Island mussels (discussed in the Smith Island chapter to follow), in which one sex was substantially advanced in its spawning cycle relative to the other sex. In the case of the Block Island clams from the central transplant transect at the time of collection in July 1993, many female clams had spawned or were spawning, while many males were still maturing. This occurrence could not be directly correlated to either sediment or tissue hydrocarbon concentrations. It is possible that if this offset does reflect an exposure effect, the threshold for it is so low that all clams at the Block Island site would show it. However, this is speculative and might best be addressed

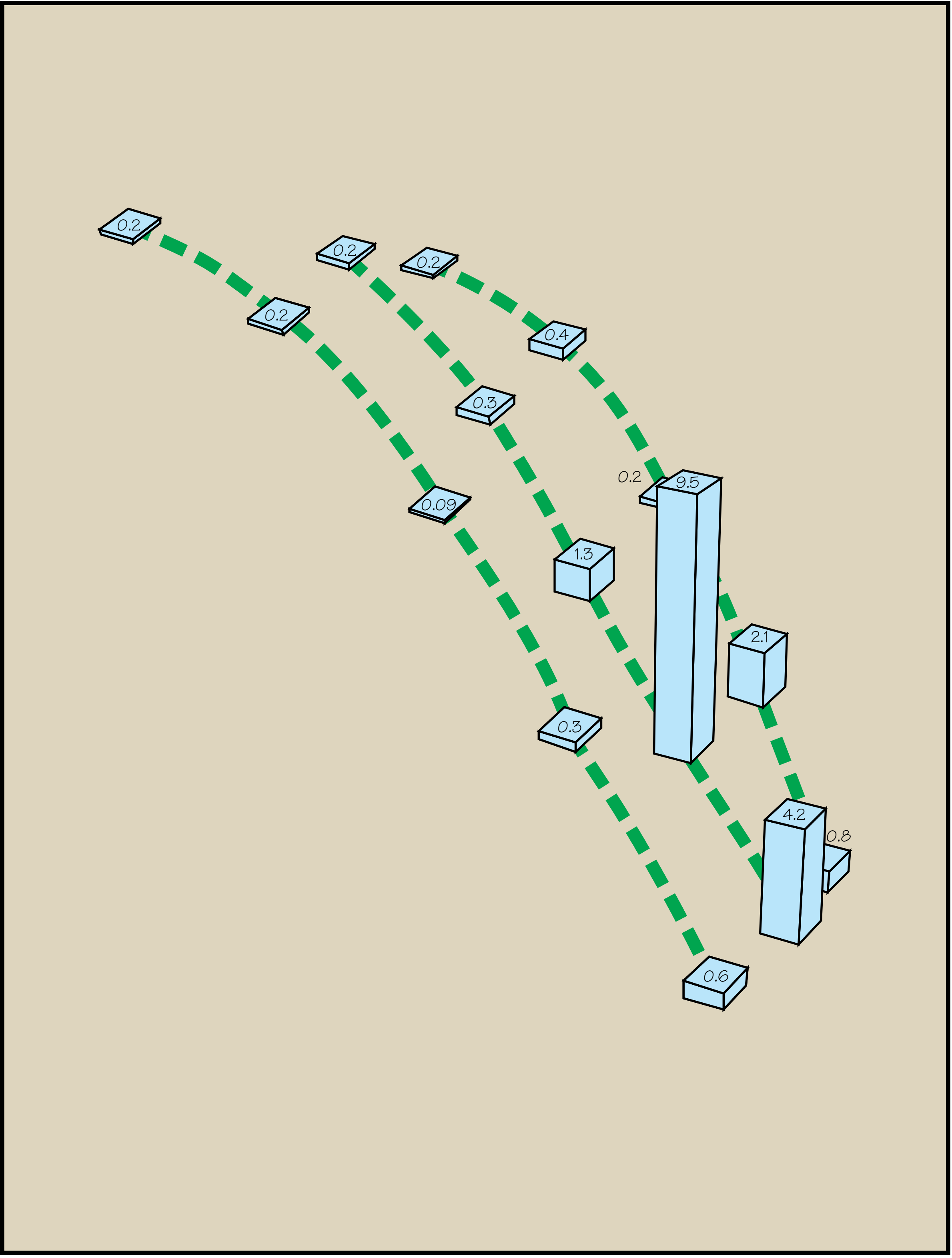

Figure 21. TPAH results for *Protothaca staminea* clams transplanted into Block Island plots in 1992 and collected in 1993. Values in ppm dry weight. Refer to Figure 10 for orientation within site.

through a laboratory exposure experiment. More extensive sampling and analysis is being planned for future cycles of the NOAA monitoring program to provide a more detailed picture of field conditions.

DISCUSSION

The physical characteristics of this site played an important role in determining the persistence of oil at the site. First, the site is relatively sheltered, both at a large scale (from wave fetch) and at a smaller scale (by the several intertidal and offshore bedrock outcrops). This would help to minimize exposure to the physical processes that would speed the removal or degradation of residual oil.

The vertical uplift of greater than one meter which occurred in 1964 during the Alaskan earthquake redefined the physical environment, shifted resident biological communities, and may have been at least partially responsible for substrate conditions observed at the site. The elevation of the tidal flat could have increased the water drainage through sediment material and hence, the penetration of oil into the substrate. At the same time, the peat layers that may be attributable to decomposition of pre-earthquake eelgrass beds appear to prevent oil penetration beyond them. Peat layers could have also acted as a localized source of organic carbon that would provide favorable habitat for opportunistic organisms, such as the polychaete *Capitella capitata,* and possibly increased the tolerance of other resident biological communities to organic carbon exposure through oiling. However, measurements of total organic carbon at Block Island since 1992 do not indicate extraordinary conditions there.

The penetration of oil at least into the upper layers of the Block Island site sediments and the absence of larger-scale physical processes for reworking of the sediments meant that removal of oil from the site, to the extent defined as necessary or desirable, would be effected primarily by human intervention and cleanup. Although substantial amounts of time and effort were invested in cleaning the site, considerable amounts of oil remained and persisted through 1993. This oil weathered, but was present at the site in relatively large quantities. In 1994, in response to these conditions, Trustee remediation crews removed bulk amounts of oiled sediment and replaced them with clean material. Although we don’t know the consequences of the short-term physical disruption of the tidal flat, this intervention may reduce the long-term consequences of sediment contamination.

The biological richness of this study site, despite its relatively heavy and persistent degree of oiling, was unexpected. The robust nature of the biological communities, particularly the infauna, may be attributed at least in part to the ability of resident organisms to tolerate, or possibly even utilize, the hydrocarbons deposited into the intertidal environment. It also could be that the relatively unique physical characteristics of this site (broad tidal flat, high organic loading, fine-grained sediment structure) provided a favorable habitat for a diverse and abundant infaunal community.

The physical characteristics of the Block Island site and its rich biological assemblage translated into operational difficulties during shoreline cleanup. As a rule during oil spills, tidal flats do not require oil removal because the stranded oil does not readily adhere to the surface of the substrate and generally is lifted off by subsequent tidal inundation. However, *Exxon Valdez* oil penetrated the substrate of the Block Island tidal flat to an initial depth of at least eight cm and persisted there for years. Aerial photographs taken shortly after the oil came ashore showed that the most effective tools for surface oil removal during cleanup operations—hot-water and high-pressure-washing—were disruptive to this sheltered tidal flat. In retrospect, however, the approach apparently taken here—i.e., hot-water washing in the middle and upper intertidal zones, where fewer organisms are present and where much of the oil originally stranded, and avoidance of any activity in the richer, more sensitive, and less oiled lower intertidal zone—may have represented the only viable strategy for oil removal with some accommodation of the biological habitat and resources there. The washing that did take place at the site may have resulted in adverse effects, such as the removal of fine-grained sediments important to many infaunal organisms, and possibly the washing of oil and oiled material into lower intertidal areas that were not initially oiled. However, analyses of both grain size structure and residual hydrocarbon chemistry at this site suggest that these impacts have not been long-term. Moreover, cleanup actions reduced the extent of gross oiling and may have lessened the degree of chronic exposure to residual oiling.

Indicators of infaunal community health such as abundance, diversity, and number of taxa show that after rapid increases that took place between 1990 and 1992, conditions either stabilized or declined in 1993 and 1994. We believe this reflects recovery of the infauna from the initial exposure to oil, followed by adjustment of the system with time.

Although many indicators of community health suggest that Block Island biota are in comparatively good condition, this should be tempered by other measurements suggesting adverse effects. These include bivalve hydrocarbon uptake, with potential impacts to both the resource and predators that feed upon it; the correlation of clam mortality with sediment oiling (although the Trustee operation in 1994 to remove gross oiling should reduce this concern); and indications of possible subtle biological problems like the reproductive offset in the bivalve populations. The long-term consequences of less obvious biological impacts may not manifest themselves for several years. If, in fact, more subtle biological effects attributable to oiling or cleanup have occurred or continue to occur, then these would ultimately be reflected at the organismal or population level and will be documented in the core monitoring parameters measured by the NOAA long-term program as well as other monitoring efforts ongoing in Prince William Sound.

NORTHWEST BAY WEST ARM (EL-52B)

BACKGROUND AND SITE DESCRIPTION

Northwest Bay is a large and complex bay on the northwest side of Eleanor Island. Three coves can be defined within Northwest Bay, the largest of which is called the West Arm. Study sites for the NOAA monitoring program are located at the head of the West Arm. Figure 22 is a 1:10,000-scale map of the study area, while Figure 23 is a 1:1,000-scale portrayal that shows the approximate locations of the biology and geomorphology transects.

This arm of the bay, generally oriented north-south, is about 2.3 km long. It has a very narrow entrance of less than 0.5 km. The entrance to this arm of Northwest Bay has an effective fetch of 27 km in a northerly direction, but the narrowness and length of the bay serve to dampen the storm waves entering from the north, the only possible entrance direction. Consequently, wave conditions are mostly mild at the head of the bay. This station has an EI of 64, moderately sheltered. Wind conditions, however, can be severe.

The West Arm has a sheltered pebble/granule beach at its head through which a small stream flows. As shown on Figure 23, the geomorphology transect was established just to the east of this stream; the biological study borders the stream to the west. Biological core samples were taken for infaunal analysis near the lower western edge of the beach, while transects were located about 50 m west of the stream in primarily cobble substrate. The quadrats are sited in a zone positioned between the fine-grained bayhead beach and the steep, rocky, rubble western shore, with the beach surface composed of a cobble armor on a relatively gentle slope.

Both the geomorphology and biology teams for the NOAA/HAZMAT monitoring project established study sites at the head of Northwest Bay West Arm in 1989. These site selections were independent, made before any collaboration between the two groups. As a result, the geomorphological and biological study areas are adjacent, but not strictly coincident. Direct comparisons, therefore, are probably not appropriate. Although both study areas are subject to similar physical processes, there are differences in substrate. These will be discussed in greater detail later.

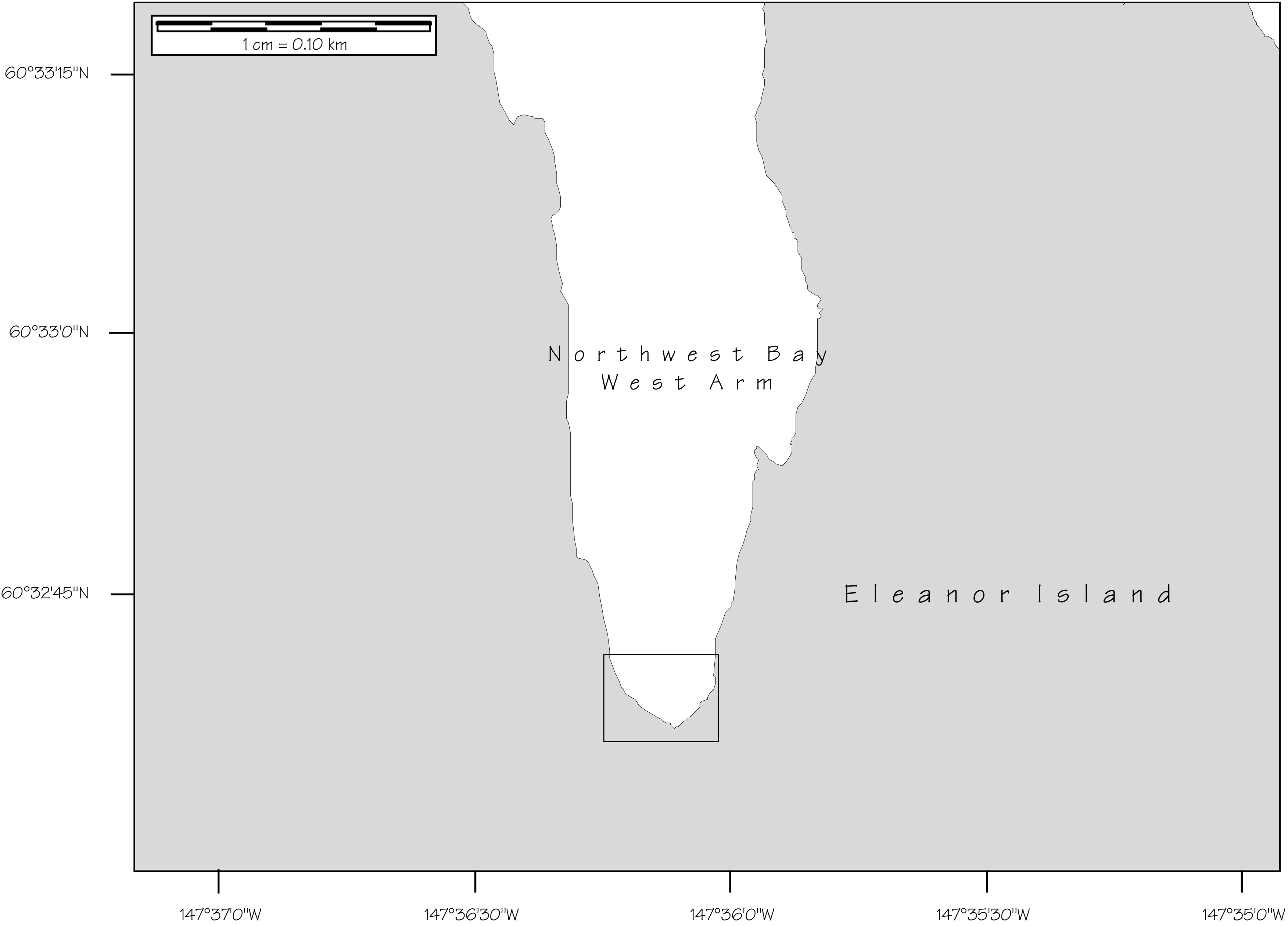

Figure 22. Map of Northwest Bay, West Arm vicinity, 1:10,000 scale. Rectangle denotes area shown in greater detail as Figure 23.

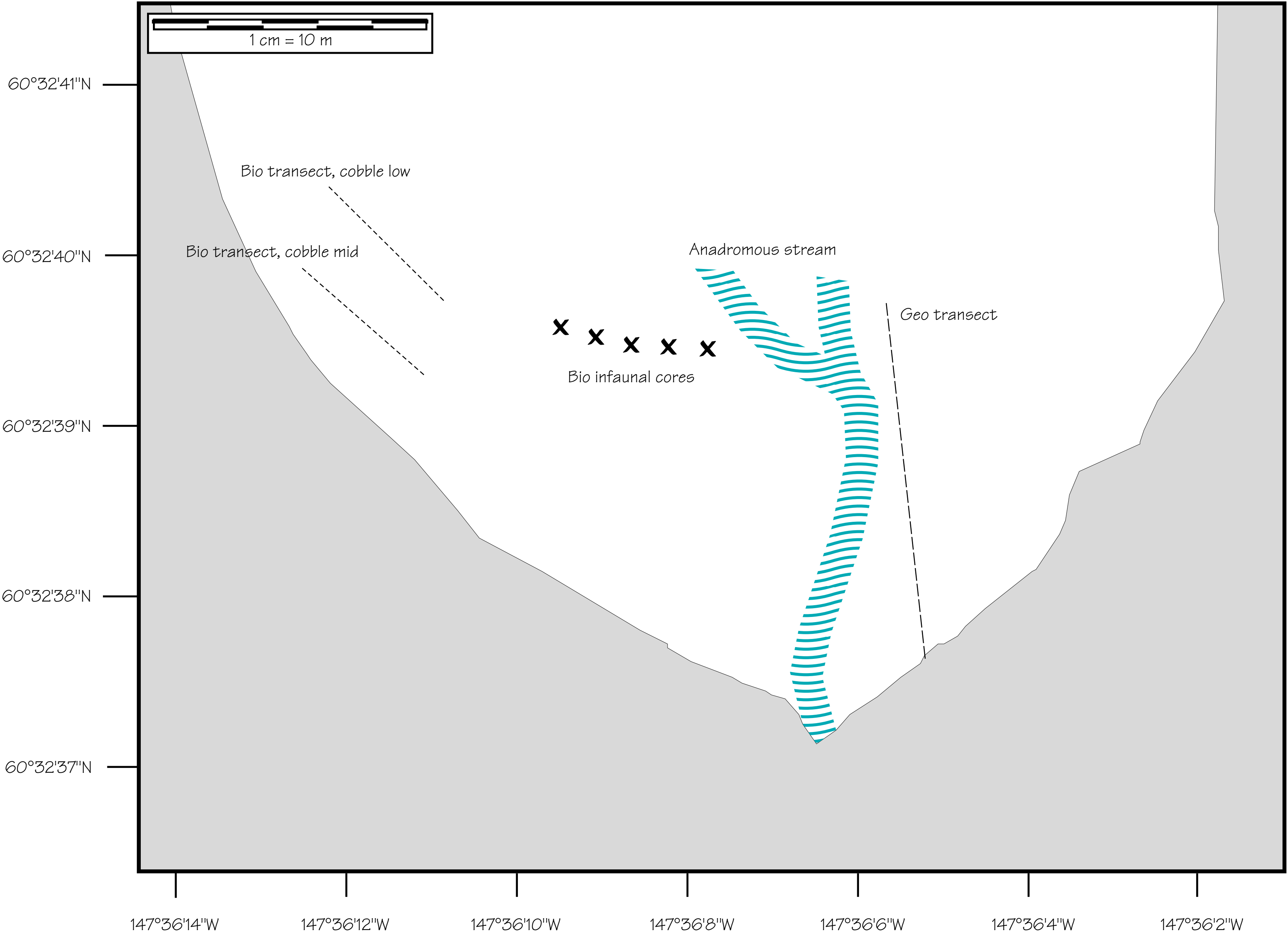

Figure 23. Detail map of Northwest Bay West Arm site, 1:1,000 scale, showing approximate location of study transects.

OILING AND TREATMENT HISTORY

Northwest Bay was extensively oiled during the early stages of the spill. Its location at the northern end of the Knight Island chain, and its orientation with the bay opening to the north, resulted in a large amount of *Exxon Valdez* oil entering and being retained within its shorelines as the slick moved from northeast to southwest in Prince William Sound. In the West Arm, most of the intertidal zone was surface-oiled, with oil penetration into the finer materials near the stream mouth at the head of the arm.

Northwest Bay was one of the first of the oiled areas to undergo widespread shoreline cleanup that relied largely on heated high-pressure water. In part, the bay served as a testing ground to fine-tune the technique. Much of this effort took place in May and June 1989. Figures 24 and 25 are aerial photographs of the West Arm and the site itself, respectively, taken on June 4, 1989, showing much of the cleanup equipment discussed in Appendix A. One of the biggest problems was the frequent escape of sheen under the containment booms and subsequent reoiling of treated shorelines. Therefore, many shorelines received multiple washing with landing craft vessel (LCV) systems. The smaller LCV systems were used because of the small size of the bay and the wide intertidal zone at the bay head. The LCVs were anchored at about mid-tide and allowed to rest on the tidal flat at low tide. There was also extensive flushing of oiled sediment into the lower intertidal and subtidal zones during the washing activities, especially at the bay head.

Manual cleanup operations and bioremediation also occurred between 1989 and 1991. In the NOAA monitoring program, this site was categorized as oiled and treated with high-pressure, hot water. Appendix A details shoreline oiling assessments and cleanup operations at the Northwest Bay West Arm site.

GEOMORPHOLOGY

The Northwest Bay site is classified as a bayhead gravel beach. A small, anadromous stream flows across the beach near the geomorphological profile, providing a source of pebbles and granules to the beach and influencing the sediment distribution patterns when the stream mouth changes direction. The lower part of the profile was usually host to slowly migrating pebble swash bars throughout most of the survey. This area was uplifted 1.2 m during the 1964 earthquake and, as a consequence, part of the substructure of the lower part of the intertidal zone is uplifted bay bottom. The geomorphology team surveyed this site nine times between 1989 and 1994. Field sketches drawn during site visits between 1990 and 1994 are reproduced here as Figures 26- 28.

Figure 24. Aerial photograph of Northwest Bay West Arm, June 4, 1989, showing study site at lower portion of figure. NOAA/HAZMAT photo.

Figure 25. Aerial photograph of Northwest Bay West Arm study site, June 4, 1989, in the midst of shoreline cleanup activities. Equipment shown discussed in Appendix. Photo by J. Michel, Research Planning, Inc.

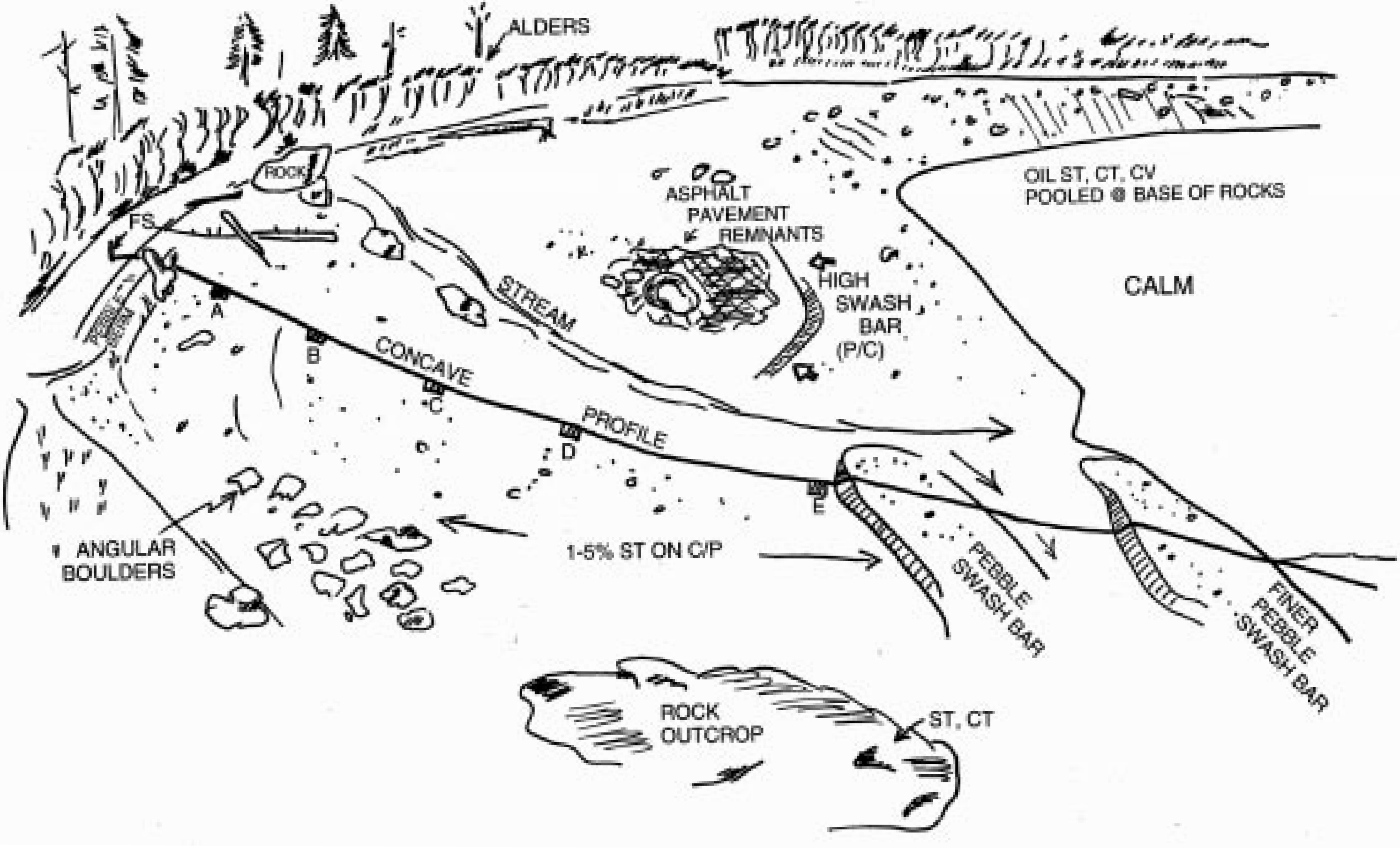

Figure 26. Field sketch showing observed geomorphological conditions at Northwest Bay West Arm site, May 23, 1990. Miles O. Hayes, Research Planning, Inc.

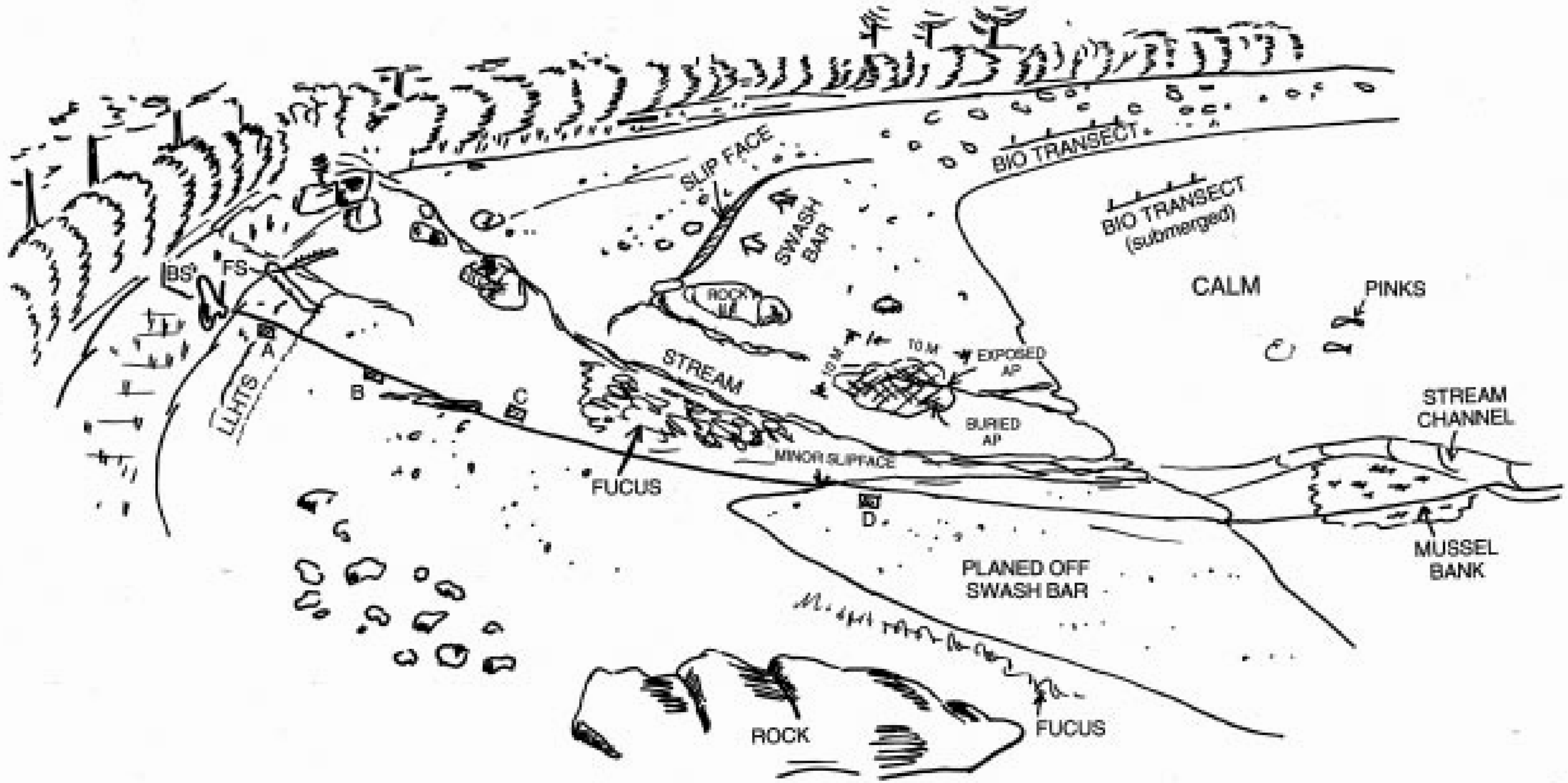

Figure 27. Field sketch showing observed geomorphological conditions at Northwest Bay West Arm site, August 11, 1992. Miles O. Hayes, Research Planning, Inc.

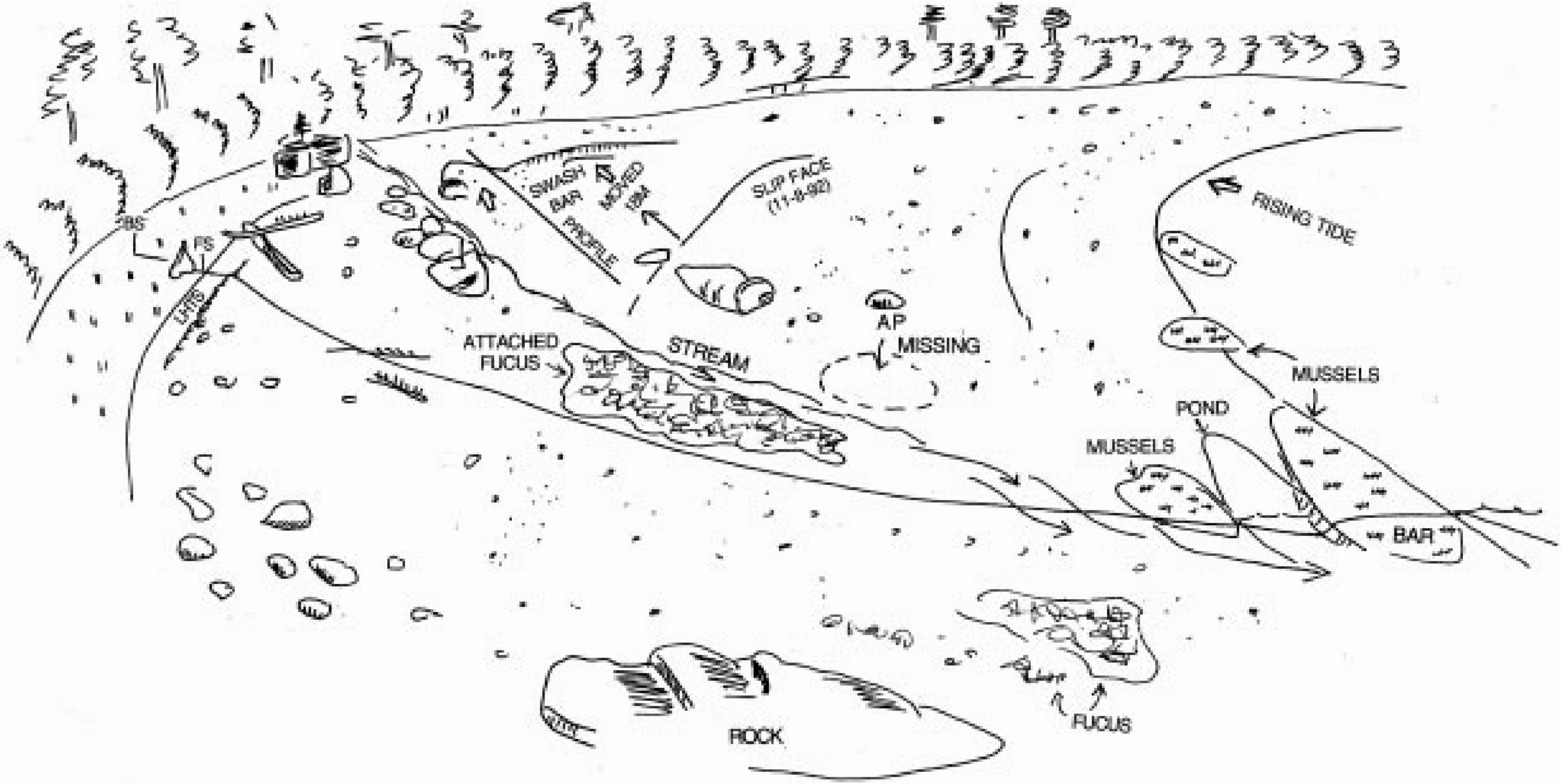

Figure 28. Field sketch showing observed geomorphological conditions at Northwest Bay West Arm site, July 21, 1994. Miles O. Hayes, Research Planning, Inc.

Morphology and Beach Dynamics

Three very distinct morphological components make up this station:

1. High-tide berms

Though they rarely achieved heights of more than a few centimeters, spring and/or neap-tide berms were nearly always present at the top of the beach. They were usually composed of pebbles and granules. The average beachface slope was 6 degrees.

2. Stable central ramp

This part of the profile, which is the coarsest-grained of the three components, even containing some boulders, has a distinct concave-upward shape, which signifies a historic erosional pattern. Changes were very slight during the survey period, however. Note the stability of this part of the beach profile in the sketches in Figures 26-28. The ramp slopes seaward at 2 degrees.

3. Low-tide bars

Swash bars were first observed on the lower reaches of the profile during the December 8, 1989 survey, and they were present up to the July 1994 survey. The surface of this part of the profile, in effect a low-tide delta surface, dips seaward at the comparatively flat angle of 1 degree.

As previously discussed, wave action at this site at the head of Northwest Bay West Arm is probably low to moderate during most storms because of the narrow entrance and length of the bay. However, even moderate waves generate currents strong enough to move the relatively fine-grained sediments at this station, particularly in the region of the low-tide bars. Comparing the location of the swash bars in Figures 26-28, one can see the migration of the sediments back up the beach face.

A formerly buried zone of asphalt pavement was exposed to the surface in August 1992 there as the swash bar that had buried it migrated up the profile. This same bar had migrated another 18 m up the profile by the time of the July 21, 1994 survey (Figure 28), and the asphalt had been removed, apparently by natural processes. It is hypothesized that the swash bars represent sediment washed from the beachface during the high-pressure flushing in 1989, and are being slowly returned by wave action. As shown in the comparison plot of beach profiles in Figure 29, the overall level of the beach along the profile was elevated even further during the time interval between the August 11, 1992, and July 21, 1994, surveys. This may be indirect evidence that a considerable amount of sediment was washed from this beach during the cleaning process and that, after five years, all of the displaced sediment had not yet returned to the upper beach.

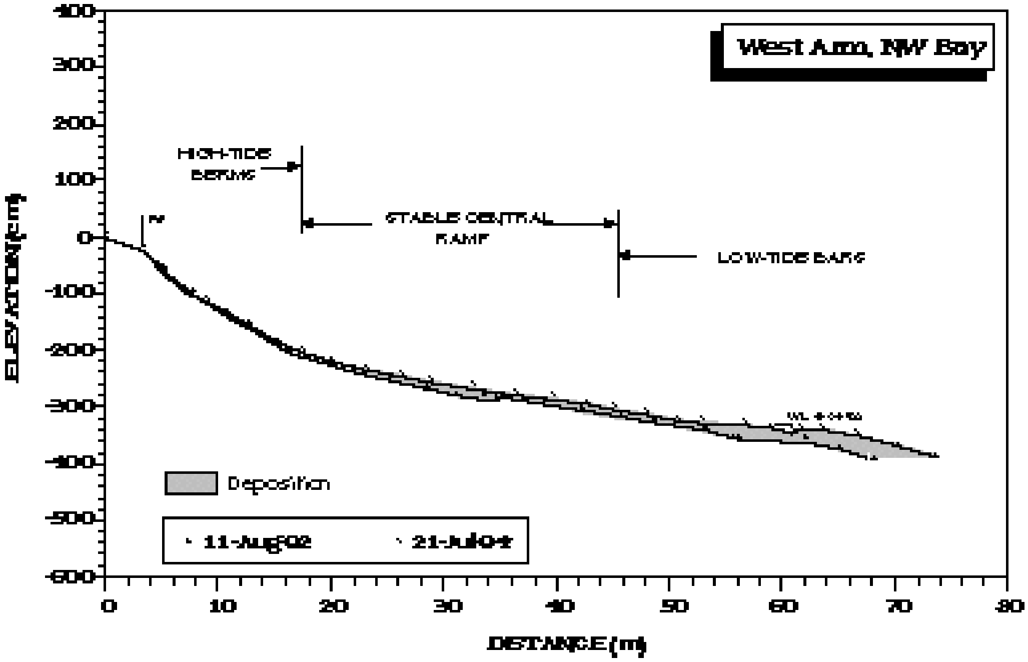

Figure 29. Comparison of August 11, 1992, and July 21, 1994, surveys, plotted at a 5:1 vertical exaggeration. Note the continued deposition along the profile .

Sediments

Sediments along this bay head are derived from the erosion of adjacent headlands by waves and from deposition by two streams, the primary source for most of the finer components of the sediment suite. The rocks of Eleanor Island are mostly basaltic lava flows and intrusives associated with sedimentary rocks, chiefly basalt and diabase (Moffit 1954).

Primarily pebbles and granule material (roughly half and half) covered the high-tide berms. Cobbles and boulders occurred almost exclusively on the slightly eroding central ramp, with boulders composing less than five percent. Pebbles dominated the surfaces of the low-tide bars, with granules averaging around 20 percent.

Oil Distribution Patterns

Surface oil. The surface sediments along the profile looked deceptively clean in September 1989, except in two areas. Oiled wrack covered the high-tide zone and there was a 5-m band of 100-percent oil cover about midway down the central ramp. However, surface sediment samples from all three zones contained over 1,000 ppm TPH. The surface oil on the central ramp decreased by half in October but persisted through December, with significant reduction thereafter. Most of the remaining surface oil occurred as a stain on the larger pebbles and cobbles, which occurred throughout the profile. Less than five-percent stain was reported in May 1990 and no surface oil was observed by September 1990.

Heavily oiled areas were observed next to the profile, most notably a large asphalt pavement to the west (Figure 26) that was manually removed in 1990. However, as discovered during the August 1992 survey (Figure 27), a 10-m^2 zone of asphalt pavement had been buried under the large, landward-migrating swash bar on that side of the stream. This mostly buried asphalt pavement was exposed in the channel of a small distributary of the stream that had cut across the eastern side of the bar. The geomorphology study team at the *Amoco Cadiz* and Gulf War spill sites has also observed this mechanism of oil burial by migration of intertidal swash bars.

The rocky shoreline on both sides of the bay was observed to be oiled in 1989 and 1990. At that time, sheens were commonly observed on the water table when large cobbles were turned over. It appeared that oil being released from these areas tended to adhere to the granule surface sediments, thus the measurement of 400 ppm TPH in a surface sample from the low-tide bars in February 1990. By 1992, there was little evidence of oiling along the rocky shorelines.

<u>Subsurface oil</u>. In October 1989, a discontinuous oiled layer at 5 to 10 cm below the spring berm was found to contain 6,500 ppm TPH, but the layer was never observed again. A sample taken at 40 to 45 cm in the same trench contained 20 ppm TPH. The only other highly oiled sample was taken 50 cm deep in September 1989 and contained 1,090 ppm TPH. This sample was below a discontinuous "peat" layer, so it probably represents the limit of sediment reworking during shoreline treatment activities. All other subsurface samples collected after September 1989 had less than 100 ppm TPH, with most containing 20 ppm or less. Therefore, the sediments were relatively clean with depth. However, in December 1989, sheens were observed in groundwater rills draining the area near the asphalt pavement, with silver sheens under the larger cobbles and boulders. Trace sheens were again reported in February 1990 but, thereafter, the sediments appeared to be clean.

The extensive washing of the sediments in the 1989 cleanup was very effective at removing the subsurface oil. The depth of oil penetration into the beach was obviously shallow enough to be mobilized during flushing, although this kind of treatment on granule beaches resulted in sediment transport into the lower intertidal and subtidal habitats. The sediments deposited on the lower intertidal zone are returning to the beach in the form of swash bars (Figures 26-28), but the fate and effect of the sediments deposited in deeper water are unknown.

SEDIMENT CHEMISTRY: TOTAL TARGET PAHs

Sediment PAH concentrations measured at the Northwest Bay West Arm site between 1990 and 1993 generally reflected low-level surface contamination. This was particularly evident at the lower intertidal elevation collections, where fifteen samples from the four years (including sediments sampled for the clam transplant experiment at the site, shown in Table 15) yielded an average of 0.02 ppm ± 0.016 ppm. These results indicated that the lower intertidal zone in the portion of the beach sampled for infauna did not show persistent contamination that might have been attributable to large quantities of oil being washed from upper to lower zones of the beach during shoreline cleanup.

Table 15. Summed target PAH concentrations measured in sediment samples collected from lower intertidal clam transplant plots at the Northwest Bay West Arm site in 1991. Results in ppm wet weight.

	Sta.1	Sta.2	Sta.3	Sta.4
5/91	0.03	0.05	0.02	0.04
9/91	0.02	0.01	0.03	0.02

Although there were fewer chemical measurements at the middle intertidal elevation, three results are available from samples collected in 1990 and 1991. These analyses, from July and September 1990, and July 1991, showed a large degree of variability. The measured concentrations were 0.33, 0.06, and 6.7 ppm, respectively.

SEDIMENT CHEMISTRY: PAH DISTRIBUTION AND WEATHERING PATTERNS

As previously noted, only low concentrations of oil were detected in the biology transects at the Northwest Bay West Arm site. The oil degradation patterns varied greatly from moderately to highly weathered. Figure 30 provides a temporal comparison of the PAH degradation pattern detected in 1990, 1991, and 1992. The lower intertidal results were highly variable, but reflected only low or trace levels of TPAH. Sediments collected from clam transplant plots in the lower intertidal zone also contained low levels of PAH contamination, but the hydrocarbon distribution patterns indicated moderately to heavily weathered residual oil. The middle transects reflected higher concentrations of less weathered oil.

Tissues

Mussels collected in Northwest Bay in 1991, 1992, and 1993 exhibited highly variable PAH patterns, as shown in Figure 31, but only the 1991 samples yielded a profile derived primarily from weathered crude oil. However, transplanted clams did accumulate petroleum hydrocarbons compositionally similar to the sediment samples removed from the same plots, as shown in Figure 32. The PAH profiles for both sediments and accumulated oil detected in transplanted clams were characteristic of moderately to heavily weathered oil.

OTHER PHYSICAL SITE CONDITIONS

Although results for other sites within Northwest Bay are available, no water temperature and salinity data were collected for this site at the head of the West Arm.

Samples for grain-size analysis were collected at the site beginning in 1991. Results for 1991-1994 are summarized in Table 16. The table shows that grain-size structure at Northwest Bay was dominated by larger-size fractions, with only minor percentages of sediments 125µ or smaller. The samples from this location have consistently ranked near the bottom in terms of finer grain size content, relative to other sites monitored in the NOAA program. While it is possible that this was a characteristic of the site before the spill and cleanup operations in 1989, the grain size fraction ≤125µ has proportionally increased each year that we have analyzed site sediments for size distribution (Figure 33).

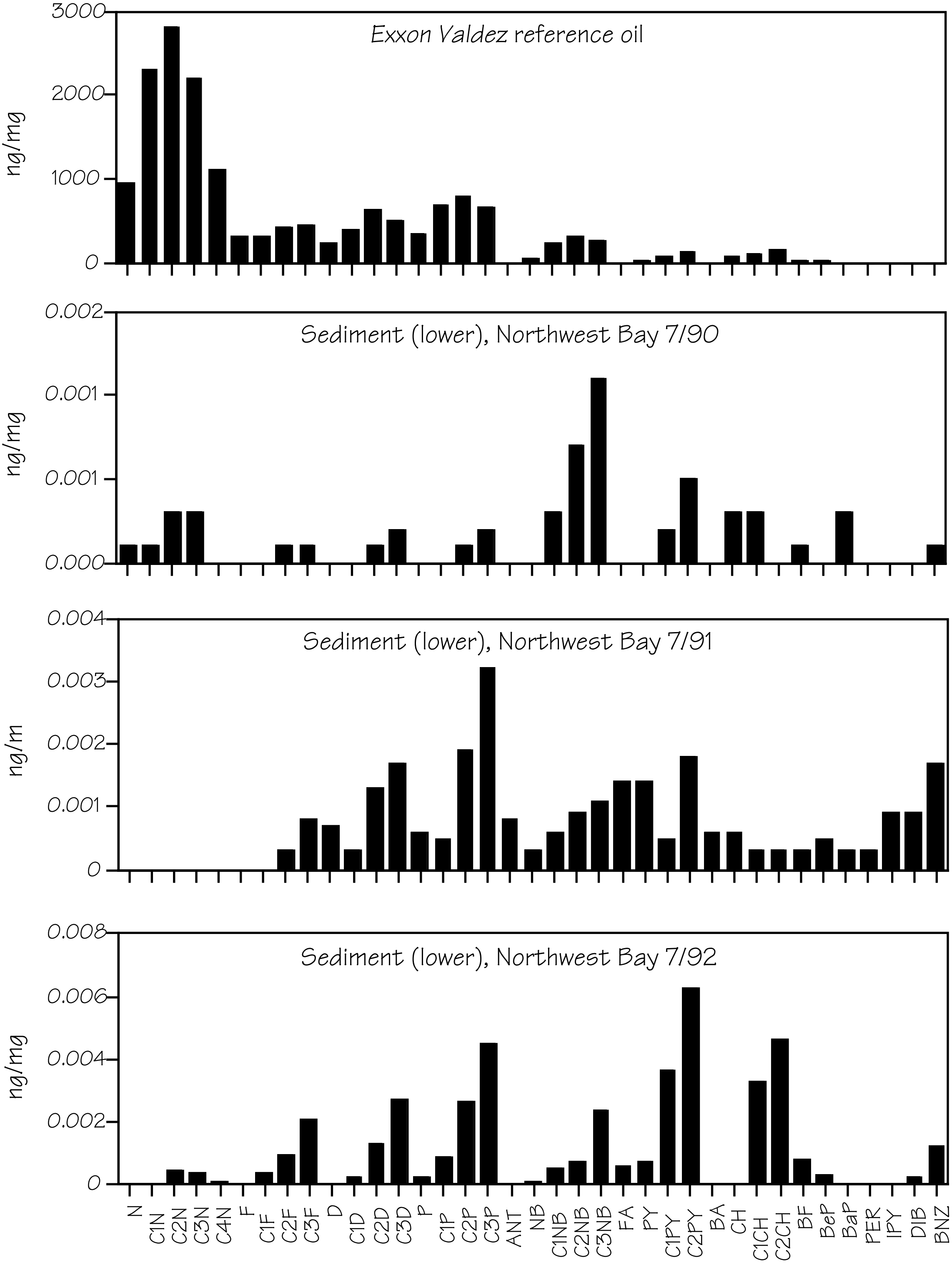

Figure 30. Comparison of PAH distributions in composite samples collected along the Northwest Bay West Arm lower intertidal transects in 1990, 1991, and 1992.

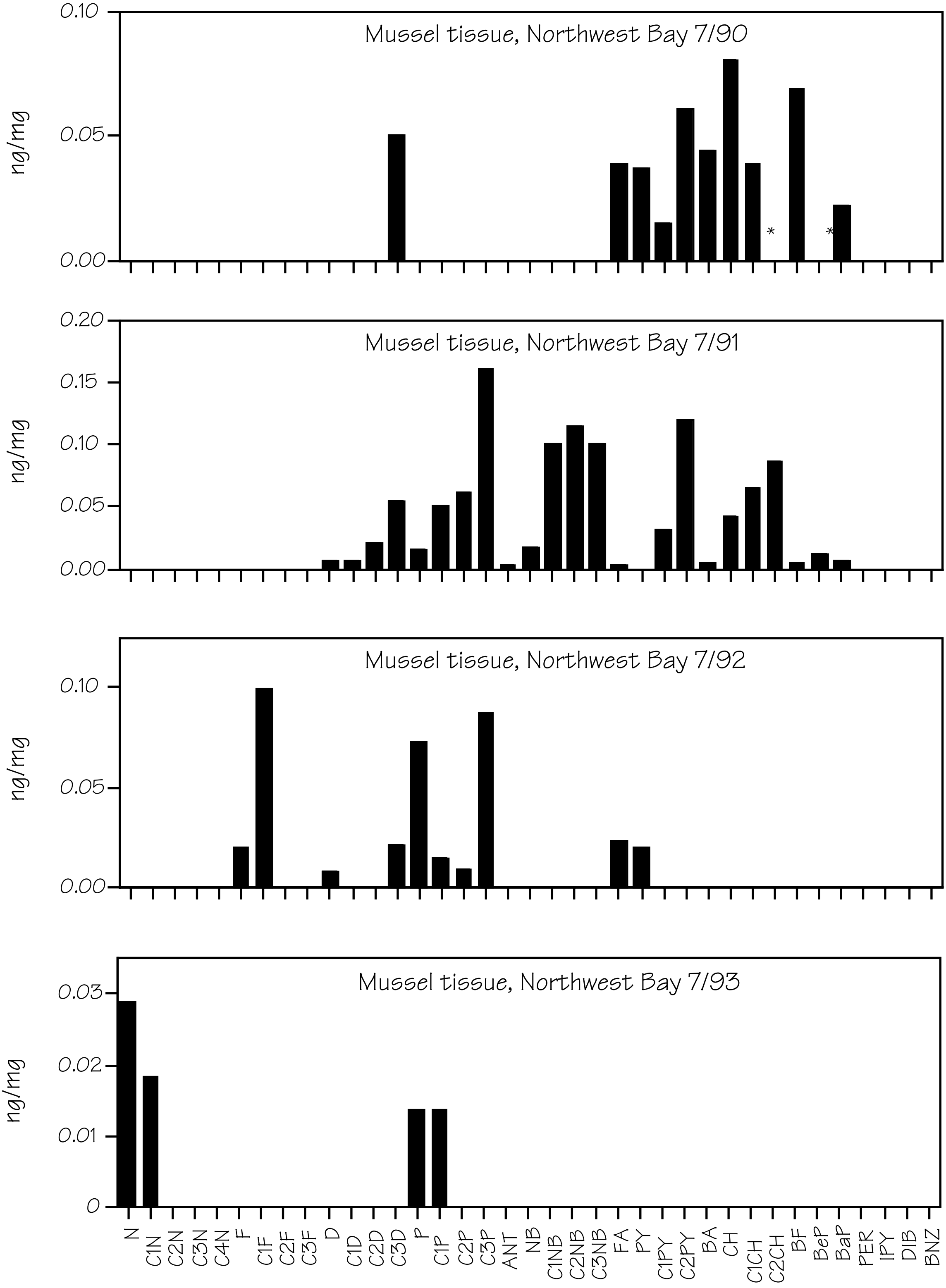

Figure 31. Comparison of PAH distributions in mussel tissue samples collected at the Northwest Bay West Arm site in 1990, 1991, 1992, and 1993. Asterisks signify compounds for which no data are available.

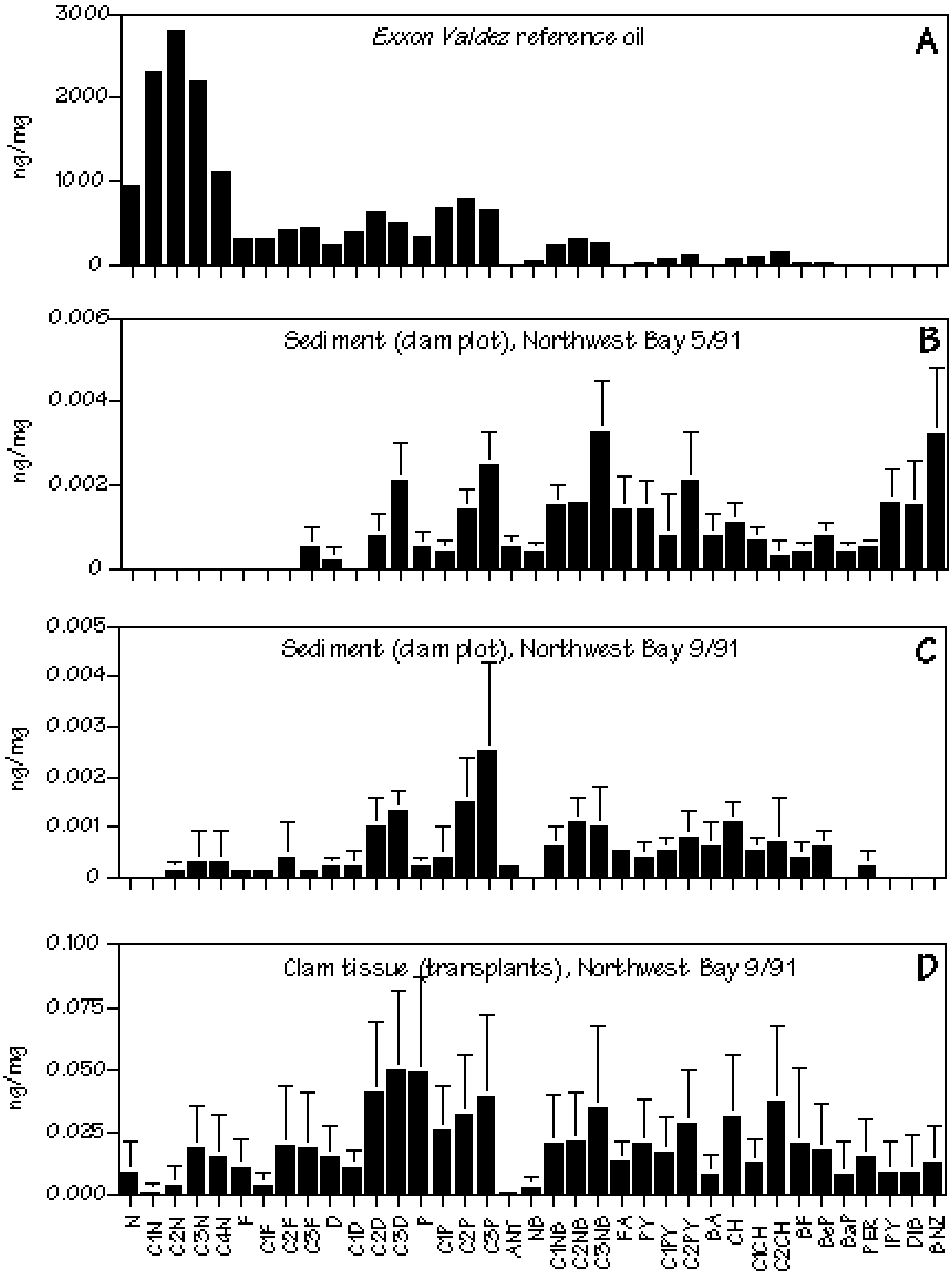

Figure 32. Comparison of PAH distribution patterns for *Exxon Valdez* reference oil (A), Northwest Bay sediments removed from clam transplant plots in May (B) and August (C) 1991, and in transplanted clams collected in August 1991 (D).

Table 16. 1991-1994 sediment grain-size analysis results for Northwest Bay West Arm site. Units = percent of total displacement volume for each size fraction.

	SAMPLE YEAR			
SIZE FRACTION	1991	1992	1993	1994
12.5 mm	20.65	25.21	33.87	33.81
6.3 mm	25.62	31.82	15.32	21.25
2.0 mm	27.15	33.05	18.55	29.72
1.0 mm	10.52	5.39	13.71	7.46
500 µ	9.75	1.71	12.10	2.15
250 µ	4.21	0.49	2.90	0.72
125 µ	0.76	0.49	0.48	1.74
63µ	0.67	0.37	0.81	1.33
Silt/clay	0.67	1.47	2.26	1.84

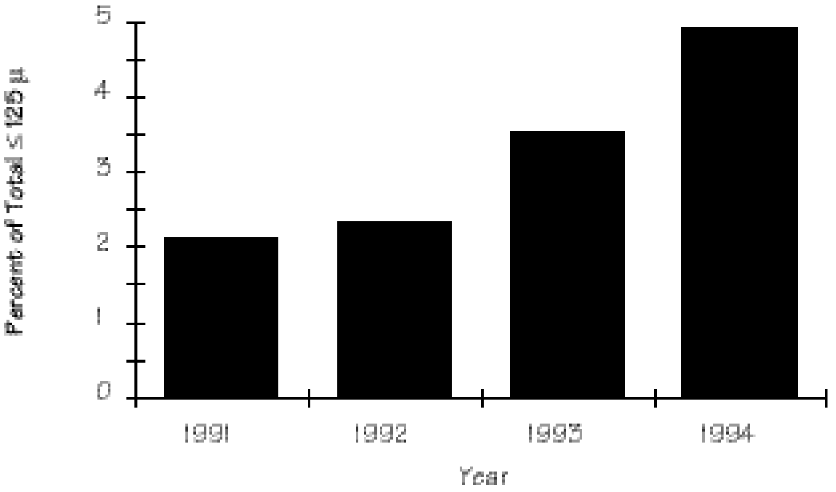

Figure 33. Proportion of fine-grain (≤ 125µ) sediments found at Northwest Bay West Arm site, 1991-1994.

As noted in the geomorphology discussion, the aggressive washing that took place in 1989 substantially altered this site. There was evidence of downslope movement of fine-grained material that would be expected to be restored at a slow rate due to the sheltered nature of the beach. If we assume that washing of the beach was responsible for depleting the smaller-fraction sediments, then the conditions observed at Northwest Bay West Arm are not surprising. Moreover, the results shown in Figure 33 are consistent with the notion that the ≤ 125 µ fractions were depleted and have subsequently steadily increased, from 2.1 percent in 1991 to 4.9 percent in 1994. However—we must once again inject a cautionary note—these are, of course, very limited data from a single analysis at the site each year. Although they seem to reflect physical recovery from beach treatment in 1989 and in this way are consistent with other observations by the geomorphology team, additional data from years to come as well as observations of biological trends will help to lend weight to or refute the hypothesis.

Results from 1992 and 1993 for TOC and TKN are shown in Table 17. The Northwest Bay West Arm is deficient in both parameters, relative to the other sites sampled in the broader monitoring program (thirteen total in 1992, eleven in 1993). In fact, in four of six cases, the Northwest Bay site represents the low end of the range for parameter and year.

Table 17. Sediment TOC and TKN from Northwest Bay West Arm lower intertidal station, 1992 and 1993. Results in ppm.

Date	TOC	Range, All Sites	TKN	Range, All Sites
7/92	*9,440*	*6,120 -47,929*	56	*56 - 2,190*
6/93	*7,330*	*7,330 -46,200*	122	*122 - 3,410*
6/94	*7,690*	*7,380 -21,400*	*99*	*99 - 518*

As was the case for the grain size distribution at Northwest Bay, the causes for the low TOC and TKN values are speculative at this time and remain the focus of further studies in the field. Unfortunately, pre-spill and pre-cleanup measurements are not available so it is not possible to compare the post-spill conditions with those existing before the incident. Nevertheless, it would be consistent with the grain-size observations to speculate that low values for sediment parameters like TOC and TKN reflect the lingering effects of the aggressive shoreline treatment that took place in 1989.

BIOLOGICAL CONDITIONS AND PROCESSES

One of the reasons that the Northwest Bay West Arm site was included in the suite of sites for this report is that, in addition to well-documented geological conditions, it has also been biologically well-characterized between 1989 and 1994. In particular, members of the biological study team were able to sample the site before and after treatment activities took place in 1989. Because of this rare opportunity, the short-term effects of oil-removal activities could be documented and referenced in the longer-term studies that are the focus of the NOAA program.

INFAUNA

Pre- and post-treatment observations in 1989

Infaunal sample collections from washed and unwashed sections of the beach at the Northwest Bay West Arm site indicated that hydraulic reworking of the sediment and exposure to high-temperature wash water substantially affected the infaunal communities there. The samples confirmed the lower density of mussels on the washed section vs. unwashed (means of 0.2/0.009 m^2 core vs. 18.6/core, respectively). Total macroinfaunal density was substantially less on the washed section of beach (2.6 vs. 49.4 organisms/ core, respectively). The higher abundance of the small polychaetes *Orbiniella nuda* and *Pholoe minuta* in the unwashed area primarily accounted for the reduction in density (Table 18). There were four infaunal taxa in the washed section of beach and eleven in the unwashed section. However, it is likely that densities of infauna recorded from these samples were underestimates of true density, because large amounts of oil in the samples impeded efficient sample washing and sorting.

Table 18. Lower intertidal infaunal abundance in washed and unwashed areas, Northwest Bay West Arm, April 27, 1989. Values in no./0.009-m^2 core sample.

Taxon	Unwashed				Washed				Percent difference
	Mean	SD	Min	Max	Mean	SD	Min	Max	
Decapoda, unid.	0	0	0	0	0.20	0.45	0	1	—
Eteone cf. *longa*	0.40	0.55	0	1	0	0	0	0	-100
Mollusca, unid.	0.20	0.45	0	1	0	0	0	0	-100
Mysella tumida	0.20	0.45	0	1	0	0	0	0	-100
Naineris quadricuspida	0.60	1.34	0	3	0.40	0.89	0	2	-33.3
Nemertea, unid.	0.20	0.45	0	1	0	0	0	0	-100
Nereis vexillosa	0.20	0.45	0	1	0	0	0	0	-100
Orbiniella nuda	37.60	25.04	7	62	0.60	0.89	0	2	-98.4
Pholoe minuta	9.40	8.17	2	21	1.40	1.52	0	4	-85.1
Polycladida, unid.	0.20	0.45	0	1	0	0	0	0	-100
Total Infauna (less meiofaunal taxa)	49.0				2.6				-94.7

To the west of the uniform pebble beach, in an area of boulders and cobbles set in a pebble/granule/sand matrix, epibiota and larger infauna were also sampled on April 27, 1989 (Lees et al. 1991). This area had not been washed, and at the time of sampling was oiled only. Densities of live hardshelled clams *Protothaca staminea* and *Saxidomus giganteus* at this lower station were 13.25/0.25 m^2 and 1.5/0.25 m^2, respectively. There were scattered dead or moribund clams visible on the sediment surface immediately below the area sampled, apparently reflecting the acute effects of oil exposure only.

When members of the biological team revisited this site in June 1989, the entire area had been hydraulically washed. On either side of the stream, pebbles had been reworked and washed downslope in large piles that were eroding in steep scarps cut by the stream. Substantial sheening was evident as the tide flooded the area or where materials sloughed into the stream. Over the next five years, the beach showed evidence of movement and sorting of materials as the pretreatment profile began to be re-established (see geomorphological discussion). In July 1991, the biological team observed a large boulder in the center of the beach with a sharp line about 15 cm above the sediment surface. Below this line, only young-of-the-year barnacles were found, suggesting that gravel movement had only recently exposed this lower area.

Table 19 shows that infaunal community parameters of diversity, abundance, and number of taxa present at the lower intertidal elevation have varied widely between 1989 and 1994. All three parameters were uniformly low in 1989, which is reasonable given the oiling conditions and cleanup activities there. Increases in the three parameters continued through 1991, and for diversity and number of taxa, through 1992 as well. However, all three markedly decreased in 1993, with some rebound in 1994.

Table 19. Measurements of diversity, abundance, and number of taxa at the lower intertidal elevation of the Northwest Bay West Arm site, 1989-1994.

	Diversity H'	Abundance N	No. of Taxa S
1989	0.44	3.60	2.00
1990	0.58	4.25	2.25
1991	1.16	18.60	5.80
1992	1.60	7.40	22.40
1993	0.81	4.60	2.80
1994	1.00	23.38	4.44

Examination of infaunal abundance by specific taxonomic classes also reflects this variability over time. Figure 34 portrays trends of mean abundances of polychaetes, bivalves, gastropods, and crustacean between 1989 and 1994. In 1992, considerable increases in abundance occurred for all four classes, followed by sharp drops in 1993, and rebound in 1994.

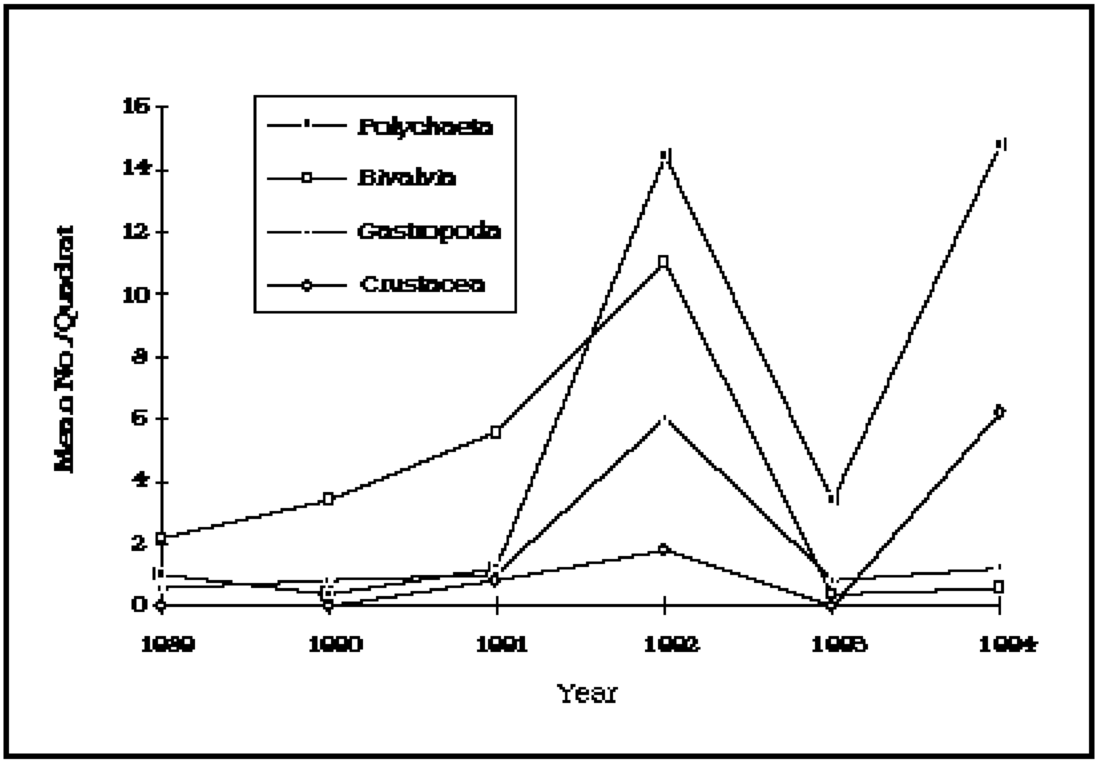

Figure 34. Lower intertidal infaunal abundance at Northwest Bay West Arm, by taxonomic class, 1989-1994.

Excavations conducted to assess clam populations in the cobble-armored beach to the west in June 1989 showed reduced densities of both species of hardshelled clams compared to April of the same year. The clams were found in two layers. A shallow group, buried only a few centimeters deep in the freshly deposited pebbles, apparently had been flushed downslope in the washing and had managed to rebury. A deeper group, about 20 to 25 cm below the surface, was likely the indigenous population at that elevation, which had been buried by the materials washed down from above. Many dead clam shells were also found at this elevation. Clams that were excavated were placed in clean seawater. Those from the upper group behaved normally, but many from the deeper group did not survive. Density of apparently live (shells intact and tightly closed) littleneck clams declined slightly from 13.25/0.25 m^2 quadrat in April, to 7.59/quadrat in June. In contrast, butter clam density declined to only 0.25/quadrat by June 1989. The density of littleneck clams at the lower station had declined further when sampled in July 1990 (to 0.75/quadrat) and had only partially recovered by July 1992 (2.5/quadrat). We have not found butter clams at this site since June 1989.

On the adjacent uniform pebble beach to the east, where infaunal cores were collected from 1990 on, recruitment of littlenecks has been very poor (Table 20), relative to both unoiled reference sites and sites that had been oiled but not washed. The low recruitment of clams to this site does not appear to be related to continued toxic or unfavorable conditions, however, as sediment chemistry results have not reflected contamination of the lower intertidal by residual oil (see Table 15 and related discussion), and clams transplanted to the lower station at the site in 1991 had excellent survival (97.5 percent) over five months. These suggest that some other factor or factors have inhibited successful recruitment. These may include unsuitable sediment characteristics (grain size, organic carbon content), lack of appropriate food items, or the lack of a viable reproductive population nearby.

Table 20. Numbers of recently recruited littleneck clams (*Protothaca staminea*) found in infaunal cores collected at the Northwest Bay West Arm study site. Mean values for unoiled sites and oiled/unwashed sites included for comparison. Values in no./0.009-m^2 core.

Year	N no. sites	Age 0 no./core	Age 1 no./core
Northwest Bay			
1990	-	0.4	0.0
1991	-	0.2	0.2
1992	-	0.0	0.0
1993	-	0.4	0.0
1994	-	0.0	0.0
Unoiled Sites			
1990	2	5.5	1.5
1991	2	4.0	1.5
1992	3	23.7	2.0
1993	3	6.3	11.3
1994	3	2.0	3.0
Oiled/Unwashed Sites			
1990	4	1.3	0.5
1991	4	9.5	0.3
1992	4	20.3	3.5
1993	4	3.0	4.8
1994	4	5.8	2.3

The relationship between infauna and the physical characteristics of sediments has been studied extensively (see, for example, Rhoads 1974, or Probert 1984). Much of the available literature suggests correlations between infaunal assemblages and parameters of grain size, organic carbon, stability, or microbial communities. However, a recent review by Snelgrove and Butman (1994) suggests that the physical and biological conditions of an area may simply reflect the hydrodynamic and sediment transport regime. In other words, flow characteristics determine both the sediment and infaunal community structure.

If this is the case, it will be more difficult to comprehensively understand infaunal recovery at impacted sites in Prince William Sound. Focused studies would be necessary to investigate the physical determinants most critical for the infauna; in fact, these are likely to vary among organisms. The results from the biological monitoring indicate that, for both portions of the Northwest Bay West Arm site (the uniform pebble-sand beach and the cobble-pebble-sand beach), physical changes resulting from the hydraulic treatments apparently continue to influence the infaunal assemblages. In 1994, experiments were deployed into the field to study the influence of physical sediment characteristics on infaunal recruitment. These may help to explain some of the observed results that suggest poor infaunal recovery.

EPIBIOTA

Beaches such as that at the head of Northwest Bay West Arm are typically characterized by a lower abundance and diversity of epibiota relative to rocky shorelines. This stems from the fact that rocky areas provide a more stable physical environment, allowing plants and animals to become established more easily. However, epibiota are found on gravel beaches, and in the case of the Northwest Bay West Arm site, they were described each year between 1990 and 1994 except for the 1993 sampling year. The available information permits us to make some general observations about the nature of recovery on the surface of this substrate.

Surface oiling was a relatively short-term phenomenon, and there is little doubt that the aggressive cleanup of the site in 1989 played an important role in reducing this contamination. However, as we've already discussed, the treatment physically changed the beach itself. As was the case with infauna, there were obvious indications that epibiota were adversely affected immediately afterward. For example, on the cobble-armored beach to the west, large quantities of pebbles and granules were flushed from the upper beach during the washing between late April and early June 1989. These sediments were deposited among the cobbles and boulders on the lower beach to depths of several centimeters. Many large cobbles had been turned over, burying the epiflora, which were then recorded as "inflora" during the biological surveys. The relatively healthy appearance of these plants in June 1989 (despite the disruption of the substrate) indicated that washing had been completed relatively recently and that these plants were not subjected to particularly high temperatures. Obviously, though, flora inverted in such a manner were not likely to survive over the longer-term.

Middle Station

Following the intensive washing activities during the spring and summer of 1989, the epibiota that typify the middle intertidal zone of this site showed a general trend of increasing abundance and diversity immediately following the oiling and treatment period, with some fallback in subsequent years. For example, rockweed cover was 0.1 percent in July 1990, was less than 2.0 percent in 1991, and in 1994 was 0.2 percent. Limpets were completely absent in July 1990, but were found at a density of 3.5/0.25 m^2 quadrat in July 1992. In 1994, limpets (*Lottia pelta* and unidentified Lottiidae) occurred at a density of 7.7/quadrat. Littorine snails (*L. sitkana* and *L. scutulata*) increased from 14.7/quadrat to over 700/quadrat by July 1992, and in 1994 occurred at a density of greater than 430/quadrat.

Lower Station

At the lower stations, oil cover that had been nearly 100 percent in April 1989 dropped to an estimated 7.3 percent after cleaning in June 1989, 1.0 percent in July 1990, and none in 1994. However, Figure 35 illustrates that rockweed cover that was 15.0 percent before treatment in April 1989, declined to 10.5 percent in July 1989 and 9.9 percent in July 1990. Between 1991 and 1994, rockweed cover has varied widely, possibly reflecting the influence and fluctuation in populations of grazers such as littorine snails. The measured densities of littorine snails in lower intertidal quadrats is co-plotted in Figure 35. The variability in rockweed cover suggests either a continuing adjustment of intertidal ecosystem components such as rockweed and its grazers, or perhaps the influence of some other controlling factor that may be related to the spill and subsequent recovery.

Tissue Chemistry

PAH concentrations measured in tissues of intertidal organisms sampled at the Northwest Bay site have been low relative to other oiled sites. Thirteen of fourteen samples of three species collected between 1990 and 1993 were found to be ≤ 0.6 ppm dry weight.

One sample of the grazing snail *Littorina sitkana* was analyzed in 1990. This was a composite collected in the middle intertidal zone along the length of the transect area. *Littorina* as a group did not show much evidence of uptake in 1990, with mean concentration for all 17 sites sampled in the overall monitoring effort at 0.67 ppm. The standard deviation associated with this mean, 1.4 ppm, reflects the range of 0.01 to 5.8 ppm. Median value for all sites sampled in 1990 was 0.04 ppm. The Northwest Bay West Arm sample in fact represented the median value for all *Littorina* analyzed, 0.04 ppm.

Figure 35. Temporal trend of rockweed (*Fucus gardneri*) and littorine snails (*Littorina scutulata* and *Littorina sitkana*) along the lower intertidal study transect at Northwest Bay West Arm, 1989-1994.

Summed PAH levels in tissue samples of *Mytilus* composited from along the middle transect were somewhat higher and variable between 1990 and 1993. In 1990, the dry weight concentration was 0.22 ppm; in 1991, 2.4 ppm; in 1992, 0.37 ppm; and in 1993, 0.11 ppm. Although the 1991 Northwest Bay value was considerably higher than those measured in other years, the concentration of 2.4 ppm still was an order of magnitude lower than the maximum levels found at other sites sampled in 1991 (e.g., Point Helen, Sleepy Bay). In other words, the degree of contamination measured at Northwest Bay was low relative to the contamination reflected in mussel tissue at other sites in 1991.

The clam *Protothaca staminea* showed consistently low tissue levels of PAHs between 1991 and 1993: 0.21 ppm in both July and September 1991, and 0.08 ppm in both 1992 and 1993. The range of values measured for native clams in 1991 at all monitoring sites where clams could be found was 0.01 to 6.4 ppm.

As part of the *Protothaca* clam transplant experiment in 1991 (see Block Island discussion), four plots of clams collected at the unoiled Bainbridge Bight site were placed at the Northwest Bay West Arm site in May 1991. Table 21 summarizes transplant results, and comparison with Table 14 (Block Island results) provides a useful point of reference. As was the case for the Block Island experiment, the Northwest Bay plots were relocated and the clams were collected in September of the same year. Recovery rates (i.e., number of transplanted clams found and removed from the plots) were high for all four plots: 102 percent for two (total exceeded 100 percent probably because of overlooked native clams in plot), and 100 percent for the other two, indicating that inherent survival rates were excellent. The clams showed some indication of hydrocarbon exposure and uptake relative to conditions at the Bainbridge Bight reference site: the Bainbridge transplant stock measured 0.01 ppm PAH, while the clams transplanted to Northwest Bay and collected four months later measured 0.21, 0.52, 0.12, and 0.12 ppm. On an absolute basis, and relative to other oiled sites in Prince William Sound (refer to the range of values for all sites, above), the latter represented low levels of contamination. In contrast, Bainbridge clams transplanted to the Block Island site measured as high as 14.6 ppm when collected in September 1991.

Table 21. **Summary of results from 1991 clam transplant experiment at Northwest Bay West Arm. Compare with Table 11, Block Island results.**

PLOT #	SEDIMENT CHEM		NATIVE CLAMS		TRANSPLANTED CLAMS		
	TPAH ppm wet May-91	TPAH ppm wet Sep-91	TPAH # in plot May-91	TPAH ppm dry May-91	TPAH ppm dry Sep-91	Mortality % Sep-91	Growth 91 as % of 90 Sep-91
Plot 1	0.03	0.02	(none)	-	0.21	0.0	85%
Plot 2	0.05	0.01	(none)	-	0.52	0.0	101%
Plot 3	0.02	0.03	(none)	-	0.12	0.0	83%
Plot 4	0.04	0.02	(none)	-	0.12	0.0	109%

Comparing Table 21 with Table 14 illustrates the differences in sediment and biological parameters for Northwest Bay and Block Island. At Northwest Bay, sediment contamination was lower, tissue concentrations of PAHs were lower, clam mortality was lower, and growth was greater than at the Block Island site. The good correlation of the biological parameters with sediment contamination at Block Island implies that the Northwest Bay West Arm site was relatively uncontaminated by residual oiling when this experiment took place in 1991.

In summary, the tissue chemistry results from the Northwest Bay West Arm site indicated a generally low level of exposure to and uptake by intertidal epibiota and infauna. Tissue concentrations were consistent with the measured low levels of sediment contamination at the site. Clam transplant experiments at the West Arm site did not indicate any acute or chronic biological effects from residual contamination, suggesting that the combination of beach washing and natural cleanup at the beach were effective in reducing environmental toxicity directly attributable to oil.

DISCUSSION

The sheltered nature of the beach at the head of Northwest Bay West Arm has in many ways defined the physical and biological conditions we have observed at the site. Constructional waves are rare at the head of the bay, and consequently any natural physical restoration of the beaches after disruption by cleanup activities there could be expected to be slow. Observations made by the geomorphological study team supported this, and showed that sediment moved downslope during 1989 treatment had, by 1992, moved to the level of swash bars, but not to that of the high-tide berms. By 1994, one intertidal bar had nearly reached the level of the high-tide berms.

Another important physical feature in the West Arm is the presence of the streams at the head of the bay. These are a continual source of sediment at the site, particularly finer-grained materials that may be a critical element for infaunal recruitment. In addition, the migration of the stream course over the beach face substantially affects the structure of the beach and provides some reworking and flushing of the sediment.

The physical framework for the Northwest Bay West site established by the geomorphologists is that of an initially (i.e., pre-spill) stable beach that would slowly respond to or recover from disruption. This would suggest that biotic recovery from the *Exxon Valdez* spill will be slow for those organisms for which substrate stability and structure are important. The biological study team's observations support this hypothesis: almost no recruitment of littleneck clams has been found at the site between 1989 and 1994, and butter clams have been completely absent since 1989. Biologists had observed acute toxicity effects to clams attributable to oiling alone during the first weeks of the spill: in April 1989, dead and moribund clams were observed (although not quantified) in an oiled but untreated portion of the beach.

However, by all indications, this toxicity was comparatively short-term. As we have discussed, the clam transplant results in 1991 showed that littleneck clams brought to the site from an unoiled region were not very affected (in terms of either mortality or bioaccumulation) by residual oiling, at least during a two-month exposure period. Yet recruitment of young clams into these sediments that had supported a substantial population before the spill has been negligible afterward. Conan (1982) noted a reduced recruitment in clam populations following the *Amoco Cadiz* spill in 1978, and attributed it to increased patchiness of parental stock and an unbalanced age distribution within the stock. At the Northwest Bay West Arm site, a more likely explanation could be that the extensive 1989 treatment removed much of the oil but substantially altered the physical composition of the substrate to the extent that clams cannot successfully recruit into it—even though adults may survive and grow when transplanted into it.

Substrate characteristics that may be important from the perspective of infaunal recruitment include the percent composition of fine-grained materials, and carbon and nitrogen content. Unfortunately, pre-spill or pre-treatment substrate characterizations are not available, so we cannot directly determine the changes that have occurred and correlate them with infaunal population changes. The limited (i.e., 1991-1994) grain-size data that are available for the site show that the finer grain-size fractions have been low relative to other sites sampled in the NOAA program, and have increased steadily in successive years. Measurements of organic carbon and nitrogen in sediment samples collected well after the spill and cleanup show that the site remains deficient in both parameters compared to the other sites in the program. These observations and those at the larger scale of geomorphological shoreline profiles are consistent with the idea that the site remains a dynamic place and is not the stable environment preferred by organisms like hardshelled clams. The importance of substrate stability was noted by Toba (1992), who found that grain-size composition was less critical for clam recruitment and growth than was overall stability.

There is ample evidence in the literature to support the notion that sediment characteristics influence how well clams and other infauna survive. Research in Puget Sound (Toba 1992) demonstrated that substrate modification (i.e., tilling to 10 cm deep and adding crushed oyster shell to gravel substrate) affected the recovery rate and growth of hardshell clams. Beal (1990) found that abiotic sediment characteristics (grain size and organic content) determined recruitment of soft-shelled clams to a greater degree than biotic ones (i.e., the nature of resident and colonizing infauna). Woodin and Marinelli (1991) determined that removing 1 to 2 cm of surface sediment caused juvenile nereid polychaetes to reject a site—although only for a period of a few hours.

However, suggesting that treatment-related changes in grain-size distribution or some other single factor are responsible for observed conditions at Northwest Bay may be an oversimplification of the complex relationship between the biological community and its physical environment. As mentioned earlier in this chapter, Snelgrove and Butman (1994) concluded that, although many studies in the last few decades have correlated sediment grain size with infaunal distribution and abundance, none have demonstrated that grain size alone is the critical determinant of infauna. Grain size covaries with other physical characteristics of sediments, including such factors as organic content, pore-water chemistry, and microbial community structure, all of which have been correlated with infaunal parameters. Snelgrove and Butman suggested that all of these factors reflect the hydrodynamic characteristics near the sediment-water interface, and that, ultimately, the flow regime structures the physical and biological aspects of an area.

In the case of Northwest Bay, we can ask if the oil spill and ensuing cleanup somehow changed the dynamic flow characteristics of the intertidal area. As the geomorphological studies of the site have shown, the beach was physically altered and it has slowly been shifting back to an approximation of (presumably) its original profile. Perhaps the most significant feature of the sediment -water interface in the midst of these dynamics is its instability as the profile of the beach returns. This, and the instability of the substrate itself, are potential causes for the observed biological conditions.

We can infer from the sum of these observations that cleanup of an oiled gravel beach supporting a healthy clam population involves distinct tradeoffs between reduction in the extent of initial oiling and its associated acute toxicity through shoreline cleanup, and longer-term effects attributable to physical disruption of habitat. The slowness with which the Northwest Bay site has physically and biologically recovered indicates that cleanup options on sheltered gravel beaches should be considered carefully and must take into account the natural restoration potential of the beach. For the West Arm site, pressure-washing appears to have delayed recovery of infaunal components that rely on certain substrate or flow characteristics. The tradeoff to this was the apparently rapid reduction in substrate oiling and the elimination of a long-term source of exposure to the intertidal community.

Because the stream at the head of the bay supports a run of wild pink salmon, a commercially important species in Prince William Sound, there were easily understood reasons for the expedient removal of oil. The inferred tradeoff, a delayed recovery of some infaunal members of the beach community, may well be acceptable in light of the symbolic and economic importance of salmon in the region. With the benefit of hindsight, the same beach treatment decisions may have been made, and the same methods may have been used for cleanup. However, with the insights gained from monitoring this site we should, in the future, be able to more accurately portray the tradeoffs to those involved with spill response decisions. With further and more directed research that builds on some of these initial findings, we may also gain a better understanding of the process of biological recovery.

SMITH ISLAND (SM-06B)

BACKGROUND AND SITE DESCRIPTION

The Smith Island site is on the northwest side of Smith Island, which is located at the northern end of Montague Strait (Figure 1). The island is northeast of Knight Island and northwest of Montague Island. The northern shoreline of Smith Island was very heavily oiled in March 1989, and received a great deal of treatment in both 1989 and 1990. Despite this cleanup activity, Smith Island has remained one of the more contaminated study sites in the NOAA monitoring program.

Figure 36 is a 1:10,000-scale map of the Smith Island shoreline that includes the NOAA study site. A prominent point one-quarter of the length of the island from its western tip helps to identify the location of the NOAA monitoring site. The point defines the western boundary of the study site. It is a highly exposed cobble/boulder beach, with bedrock outcrops in the middle and lower portions of the intertidal zone. There is a small puffin nesting area in the bluffs above the shoreline east of the site.

The geomorphological study team has monitored this site since 1989, while the biological team made its first visit in 1990. The geomorphological transect extends from the supratidal zone down to the lower intertidal. Three biological stations intersect the geomorphological line at right angles, at upper, middle, and lower intertidal elevations. Figure 37 is a 1:1,000-scale detail map that shows approximate locations of study transects and other experimental areas. Figure 38 is an aerial photograph looking back to the east across the study site on July 19, 1989, before treatment, showing a large amount of oil sheen bleeding off the beach. Figure 39 is a Spring 1990, aerial photograph facing to the west that shows the study area and its position relative to identifiable features of the shoreline. The prominent offshore outcrop seen in Figure 38 is also visible in Figure 39 at the upper edge of the boom as a low-tide feature attached to the shoreline.

OILING AND TREATMENT HISTORY SUMMARY

Because of the heavy oiling on Smith Island, a great deal of cleanup effort was invested there in both 1989 and 1990. In addition to the manual cleanup and high-pressure, hot water washing that was commonly used on much of the shoreline in western Prince William Sound, in late summer 1989, a new chemical shoreline cleaner was also extensively tested and monitored at Smith Island. Heavy equipment was also used to expose and move contaminated subsurface sediment into the surf zone in the summer of 1990 with a procedure called “berm relocation.”

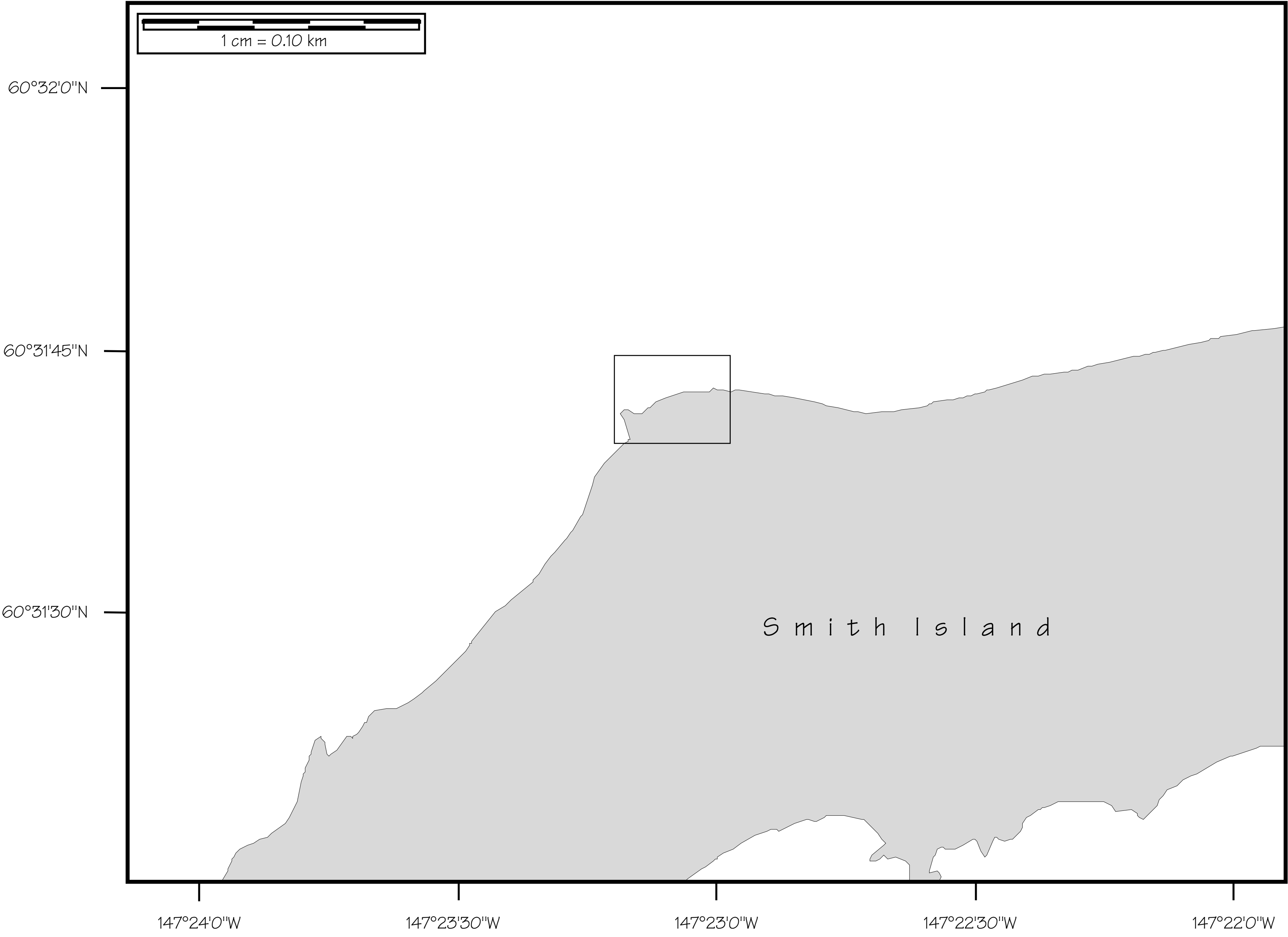

Figure 36. Map of Block Island vicinity, 1:10,000 scale. Rectangle denotes area shown in greater detail as Figure 37.

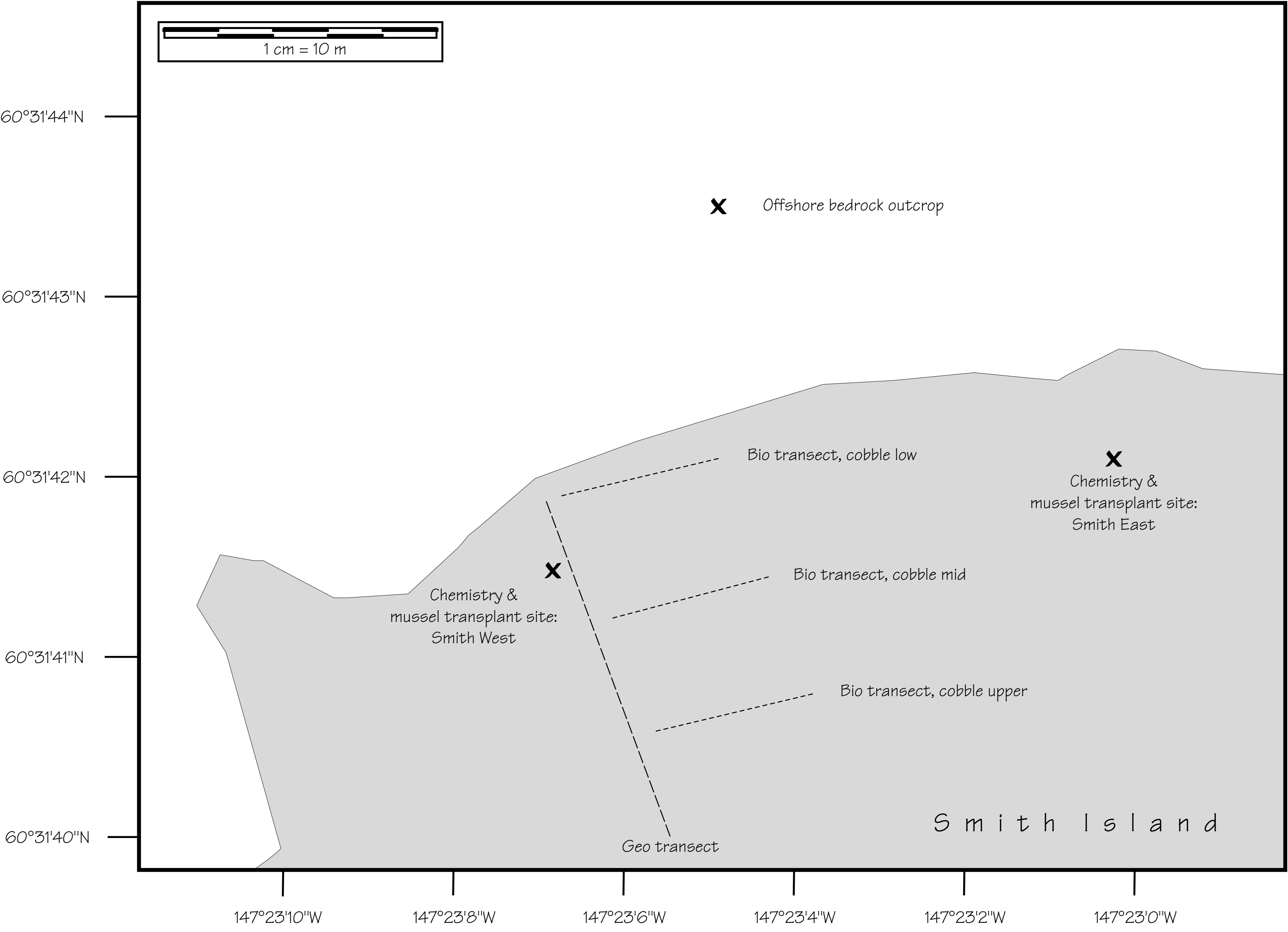

Figure 37. Detail map of Smith Island site, 1:1,000 scale, showing approximate location of study transects.

Figure 38. Eastward-facing aerial photograph of Smith Island study site on July 19, 1989, prior to cleanup operations. Note oil sheen bleeding from beach. Photo by L. Consiglieri, NOAA/HAZMAT.

Figure 39. Westward-facing aerial photograph of Smith Island study site in May 1990, with location of geomorphological transect shown in white. Note boom deployment to contain oil sheen. Photo by M. Hayes, Research Planning, Inc.

In the NOAA biological monitoring program, the Smith Island site was classified as oiled and treated with high-pressure, hot-water washing (Category 3, in the groupings defined in Lees et al. 1991). Details of shoreline oiling assessments and cleanup operations at the Smith Island site may be found in Appendix A.

GEOMORPHOLOGY

This station is located in a small indentation along the northwest side of Smith Island (Figure 36). The beach is oriented east-west, and is exposed in a due northerly direction. The intertidal zone contains abundant, abraded coarse material, which grades perceptibly from dominant pebbles to dominant boulders in an offshore direction. The effective fetch is around 10-12 km in a northerly direction. A large expanse of open water occurs to the north-northeast of the site, a straight-line distance of 45-50 km, making this one of the more exposed gravel beaches in Prince William Sound. The open-water fetch line intersects the beach at a 55° angle. The EI for this site is 730, highly exposed. Located 70 km from the epicenter, this station was uplifted 1.5 m during the 1964 earthquake, and a well-defined, vegetated, uplifted storm berm is clearly visible behind the present beach. The topographic beach profile comparison between 1992 and 1994, and the field sketch for the July 24, 1994 survey are shown as Figures 40 and 41, respectively.

This site has been visited by the geomorphological study team 12 times between 1989 and 1994. The dates of these visits are listed in Table 3.

Morphology and Beach Dynamics

The oblique aerial photograph (Figure 39) and field sketch (Figure 41) show two prominent bedrock outcrops west of the study area that create a natural groin effect, trapping sediment being transported to the west along the beach and allowing it to accumulate on the site. As a consequence, a relatively thick layer of gravel has been deposited on top of an underlying bedrock platform which had been uplifted during the earthquake.

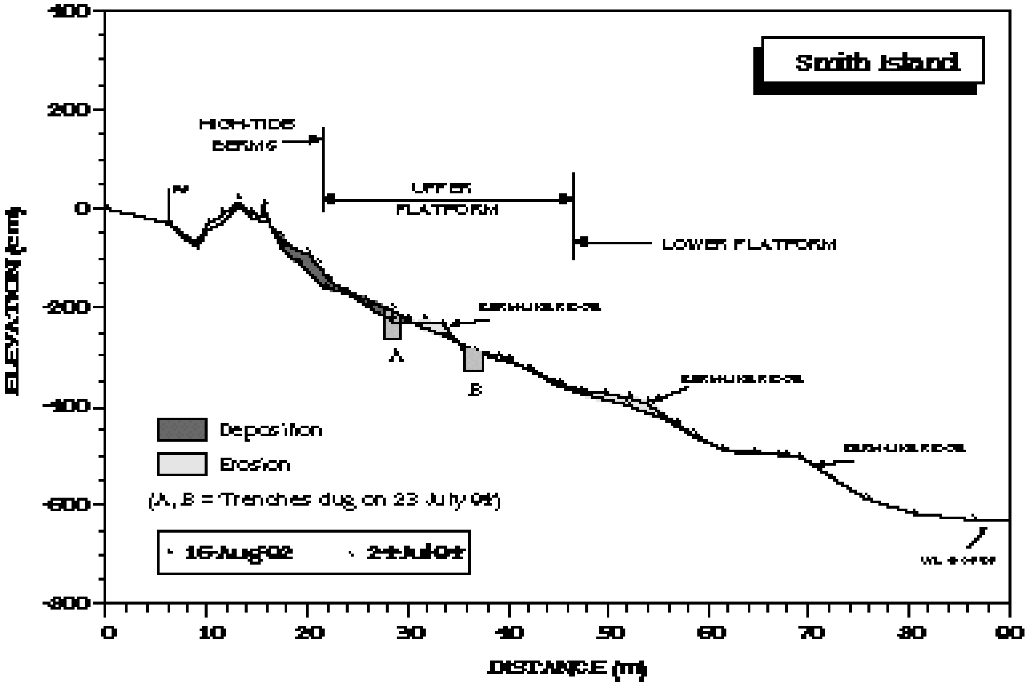

Figure 40. Topographic profiles run on August 16, 1992 and July 24, 1994, at the Smith Island site. Note that the upper two berm-like ridges present in 1992 had been eroded away at the time of the 1994 survey, and new deposition had occurred in the high-tide berm area.

As shown in Figure 40, the profile was divided into three morphological units:

1. High-tide berms

A well-defined storm berm was the dominant feature on this part of the profile. Minor spring- and neap-tide berms were usually present on the seaward face of the storm berm. Pebbles and cobbles made up more than 80 percent of the sediments on the berm surfaces. The average beachface slope was 12°, a typical value for gravel beaches.

2. Upper platform

The coarse-grained cobble/boulder platform, which sloped offshore at an average angle of 4.3°, has over the study period contained well-developed gravel ridges oriented parallel with the water line. Although these ridges have been regularly observed over the upper and lower platform of this beach, in general this part of the profile remained relatively flat. The surface sediments were mostly cobbles and boulders, and a well-defined surface armor was evident. Surface armoring on gravel beaches occurs when the finer-grained components of the surface sediments (i.e., pebbles, granules) are selectively transported away by wave-generated currents, leaving behind the coarser fractions (i.e., cobbles, boulders). This coarse surface layer overlies finer sediments below.

3. Lower platform

This part of the profile, similar to the upper platform described above, was also observed to include low-amplitude cobble/boulder ridges. It was covered by cobbles and boulders (half and half) and sloped seaward at 4°, a slope similar to that of the upper platform. The seaward portion of this zone contained abundant brown algae such as *Fucus* and *Alaria*. Rock outcrops were present.

Except for an erosional event between January 30 and March 4, 1990, that lowered the whole profile about 40 cm and a berm-relocation project carried out during the summer of 1990 (discussed below), the morphology of this beach has remained quite stable. At the time of the survey on August 16, 1992, there were three shore-parallel gravel ridges located on the platforms. These ridges, features observed by the NOAA geomorphology team only in Prince William Sound and here termed *berm-like ridges,* are thought to form near the lower three of the four mean levels of stillsand during the tidal cycle. The cycle in the Sound is marked by a strong diurnal inequality: 1) low-high tide; 2) high-low tide; and 3) low-low tide. At the time of the July 24, 1994 survey, the upper two berm-like ridges had been eroded away and the middle portion of the profile was extremely flat (see Figure 41). This flattening of the profile was indirect evidence of a period of high wave activity between the two surveys. However, the overlay of the two profiles measured during the 1992 and 1994 field seasons (Figure 40) shows little change except for the erosion of the two berm-like ridges in the middle of the profile and an addition of some gravel in the form of a high-tide berm on the seaward face of the storm berm. Thus, this station showed remarkable stability with respect to erosional/depositional trends.

Berm Relocation

A berm-relocation project was carried out at this site in mid-July 1990. During the berm-relocation process, the seaward face of the high-tide berm was excavated 0.5 to 1.0 m, and the excavated sediments were placed on top of the upper platform. The crest of the berm was not changed in the relocation process. By the time of the January 12, 1991 survey, the excavated area had been completely filled in, and the entire profile had returned to its original configuration. The August 26, 1991 survey revealed that the surface sediment distribution pattern had resumed the distribution it had before the berm-relocation project. The small amount of deposition observed in July 1994 (Figure 40) was part of the normal accretion and erosion pattern of berms at the high-tide level.

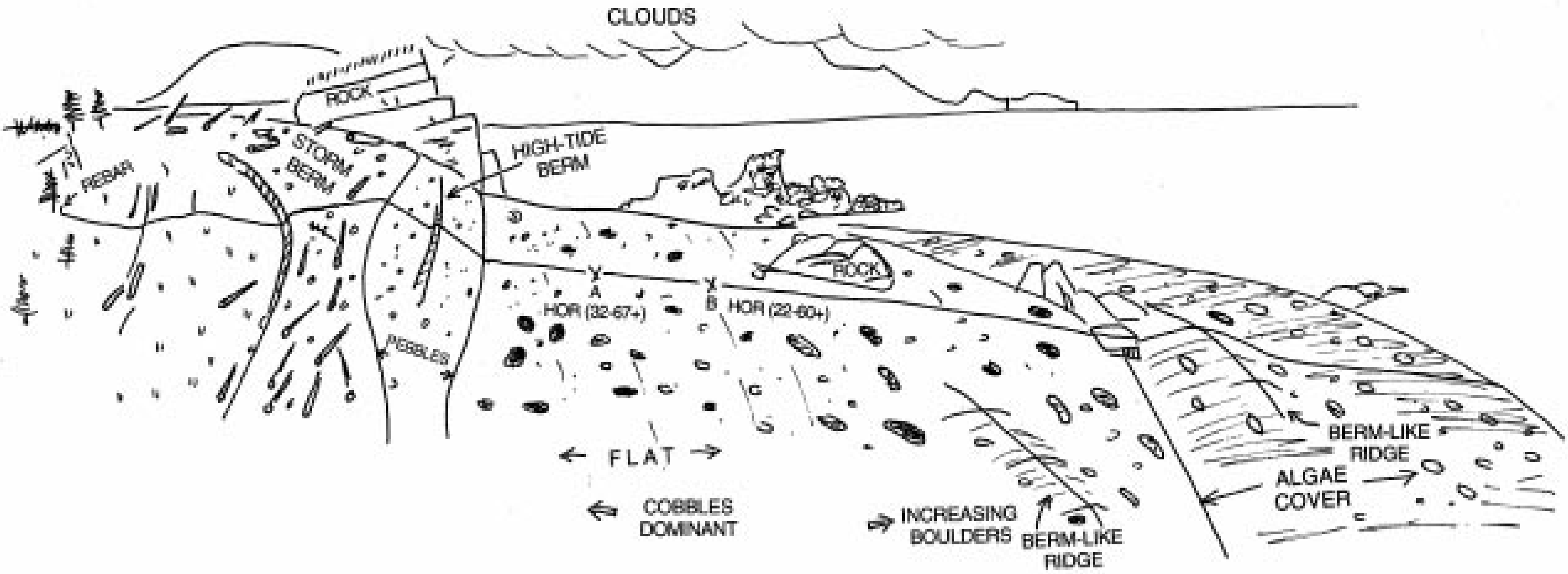

Figure 41. Field sketch of the Smith Island site on July 24, 1994. Sketch by M. Hayes, Research Planning, Inc.

Oil Distribution Patterns

Surface oil. This station has retained surface oil longer than any of the other sites classified as cobble/boulder platforms with berms, with the exception of a NOAA station at Point Helen. During the May 1990 survey, readings as high as 20-percent surface oil were recorded. The highest reading during the August 1991 survey was five percent. The reason for these relatively high numbers at such late dates is probably the fact that this was a very heavily oiled station with large amounts of subsurface oil that has continued to leach out, generating chronic sheens. Neither surficial oil nor sheens on surficial water were observed at the lower intertidal level, although the regularity with which sheens have been observed at higher intertidal elevations suggested a potential for exposure in the lower zones.

Subsurface oil. The historical summary on subsurface oiling at this station is shown in Table 22 and Figure 42. The first line of data in Table 22 is interpreted as follows: During the September 1989 survey, heavy oil residue (HOR[1]) was observed in a trench in the high-tide berm from the surface to 50 cm, but clean sediments were not reached in the bottom of the trench, thus the (+) symbol is shown. Heavy oiling of the subsurface sediments extended all the way to the lower platform to depths of 25 to 30 cm until January 1990. There was a major erosional event (probably a winter storm) between the January and March 1990 surveys, which removed 40 to 50 cm of the surface sediments from the profile. TPH values in subsurface sediments from the lower platform dropped from 13,450 ppm in January to 520 ppm in March. The oil in the lower platform was removed naturally during the January/March 1990 erosional event because it was less than 30 cm deep.

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[1] Subsurface oil was described using the following terms:

Heavy oil residue (HOR): Pore spaces partially filled with oil; oil usually not flowing out of sediments. For the July 1994 survey, five sediment samples were described as HOR, and the actual TPH concentrations ranged from 1,700-17,000 mg/kg.

Medium oil residue (MOR): Sediments heavily coated with oil; pore spaces are not filled with oil; pore spaces may be filled with water. Five sediment samples were described as HOR, and the actual TPH concentrations ranged from 800-4,700 mg/kg.

Light oil residue (LOR): Sediments lightly coated with oil. Five of the sediment samples were described as LOR, and the actual TPH concentrations ranged from 470-3,300 mg/kg.

Oil film (OF): Continuous layer of sheen or film on sediments; water may bead on sediments. Three of the sediment samples were described as OF, and the actual TPH concentrations ranged from 80-1,000 mg/kg.

Stain (ST): Oil less than 0.1 mm thick on surface of clast or rock (cannot be easily scratched off with fingernail). No oiling was described as ST at the Smith Island site in 1994. However, stained clasts were observed during the September 1990 and the two 1991 surveys, probably as a result of the berm relocation exercise carried out at the site in the summer of 1990.

Table 22A lists the TPH concentrations in subsurface sediments collected along the geological transect over the five-year period of study, grouped by geomorphic zones. Where multiple trenches were dug and sampled in a zone, each sample result is listed. Oil concentrations in coarse sediments are inherently highly variable, but distinct trends are apparent.

Table 22. Historical summary of the interval and degree of subsurface oil at the Smith Island study site. Results for different trenches separated by "/". Depths reported in centimeters.

Survey Date	High-Tide Berms	Upper Platform	Lower Platform
Sept. 1989	0-50+ (HOR)	0-60+ (HOR)	0-25 (HOR)
Dec. 1989	0-15 (LOR) 15-62+ (MOR)	0-52+ (HOR)	0-30+ (HOR)
Mar. 1990	0-25 (LOR) 25-60+ (MOR)	0-32+ (HOR)	No oil
May 1990 (Berm-relocation-July 1990)	7-35 (LOR)	5-25+ (HOR)	No oil
Sept. 1990	0-35+ (MOR)	0-44+ (ST)/0-38+ (HOR)	
Jan. 1991	0-40+ (ST)	0-42+ (HOR)	0-35 (LOR)
Aug. 1991	No oil	22-32 (MOR)/0-10 (OF) 32-45+ (HOR)/10-60+ (HOR)	
Aug. 1992	No oil	14-42+ (MOR)/3-32+ (MOR)	
July 1994	No oil	14-47+ (HOR)/4-40+ (HOR)	

Table 22A. TPH concentrations (in ppm) for coarse subsurface sediments from Smith Island by geomorphological zone.

Survey Date	High Tide Berms		Upper Platform		Lower Platform
	<25 cm	>25 cm	<25 cm	>25 cm	
Sept. 1989		8860/11430	14620	43500	23960/6430
Oct. 1989		4050		5200	
Dec. 1989		6900/3280	410	47820	14430
Jan. 1990		22690	3960	14530	13480
Feb. 1990	2650	5080	16300		520
March 1990	210	3540	7700	8260/5630	20
Sept. 1990		7640		10170	
Jan. 1991		350		4210/17400	
Aug. 1991				4670/12520/9210	
Aug. 1992			12420	8150	
July 1994			17000	16000	

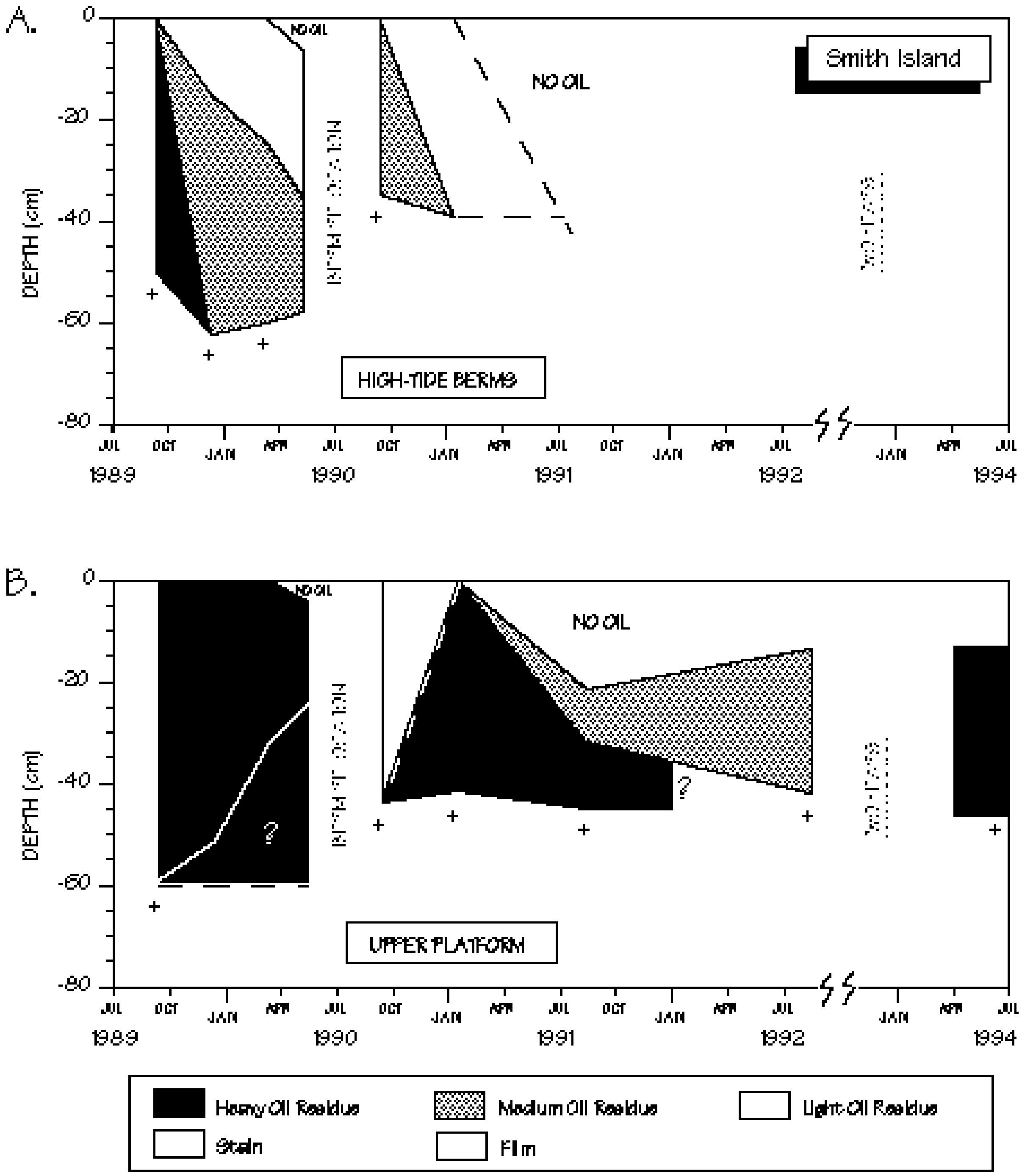


Figure 42. Time-series plot of the interval and degrees of subsurface oil at the Smith Island site, based on trench descriptions and chemical analyses for (A) high-tide berms, and (B) upper platform.

The degree of oiling in the high-tide berms decreased dramatically during the first non-summer storm period, decreasing from heavy, to moderate, to light over time in the top 25 cm (Figure 42A). Below that depth, however, oil concentrations ranged from 3,300 to 22,700 mg/kg through May 1990. The berm-relocation project in the summer of 1990 exposed the subsurface sediments classified as MOR. A sample taken from 25 to 30 cm in the excavation zone during the September 1990 survey contained over 7,600 mg/kg oil. By the time of the January 1991 survey, the excavated sediment had been pushed back up the beach by wave-generated currents, which resulted in the burial of the MOR sediments beneath at least 40 cm of oil-stained cobbles and pebbles. TPH concentrations dropped to 350 mg/kg. As shown in Figure 42A, however, the remaining oil in the subsurface sediments of the high-tide berm area was completely removed by natural processes by the time of the August 1991 survey, and, no oil was found during the 1992 and 1994 surveys.

The subsurface sediments of the upper platform were heavily oiled initially, containing up to 47,800 mg/kg TPH to depths greater than 60 cm in 1989. Through 1990, TPH concentrations ranged from 4,000 to 16,300 mg/kg, with little differences with depth of oil penetration in each trench. The 44 cm of stained sediments present in this zone in September 1990 (Figure 42B) is the result of the piling of excavated sediments on top of the original oiled subsurface sediments during the berm-relocation project in the summer of 1990. By the time of the January 1991 survey, the HOR sediments were exposed at the surface again, because the pile of stained sediments had been returned to their original position in the high-tide berm area. It was not until the August 1991 survey that significant reduction of the sediments classified as HOR was observed, with the top 22 cm of the sediment having been cleaned up by natural processes. Also, there was a 10 cm zone classified as MOR present on top of the HOR sediments below. One would deduce from these changes that significant storm action occurred at this station during the 1990-1991 non-summer months; however, we have no direct confirming data on this matter.

During the August 1992 survey, subsurface oil was still present at about the same depths on the upper platform, but it was classified as MOR in the field. TPH concentrations for the two samples collected were 8,100 and 12,400 mg/kg. A high water table prevented determination of the thickness of the entire oiled interval during that survey.

During the July 24, 1994 survey, subsurface sediments classified as HOR were once again observed in the upper platform at depths of 14-47+ cm in trench A and 4-40+ cm in trench B (see Figures 40, 41 and 43 for location of trenches and Figure 44 for trench descriptions). A sample from 15-25 cm in trench B contained TPH concentration of 17,000 mg/kg. A sample of HOR in trench A from 25-35 cm contained 16,000 mg/kg TPH. These levels were even higher than those measured in 1992, although the 1994 samples were from deeper intervals. Total targeted PAHs were 300 and 250 mg/kg in trenches A and B, respectively, reflecting the lesser degree of weathering this deeply penetrated oil has undergone. There essentially had been little change in the degree and extent of the zone of subsurface oil since 1991. The subsurface oil generated chronic sheening at this site, visible as silver sheens in the ground water draining from the beach during the falling tide.

The distribution of the subsurface oil is illustrated by the two trenches in Figure 44, and the oiled sediments in the bottom of trench B are pictured in the photograph in Figure 45. Note that the top 20 cm consisted of 40-60 percent boulder and the remaining was cobbles. Even with depth, the sediments were very coarse. However, there was enough pebble- and granule-sized sediments to slow removal by tidal and groundwater flushing.

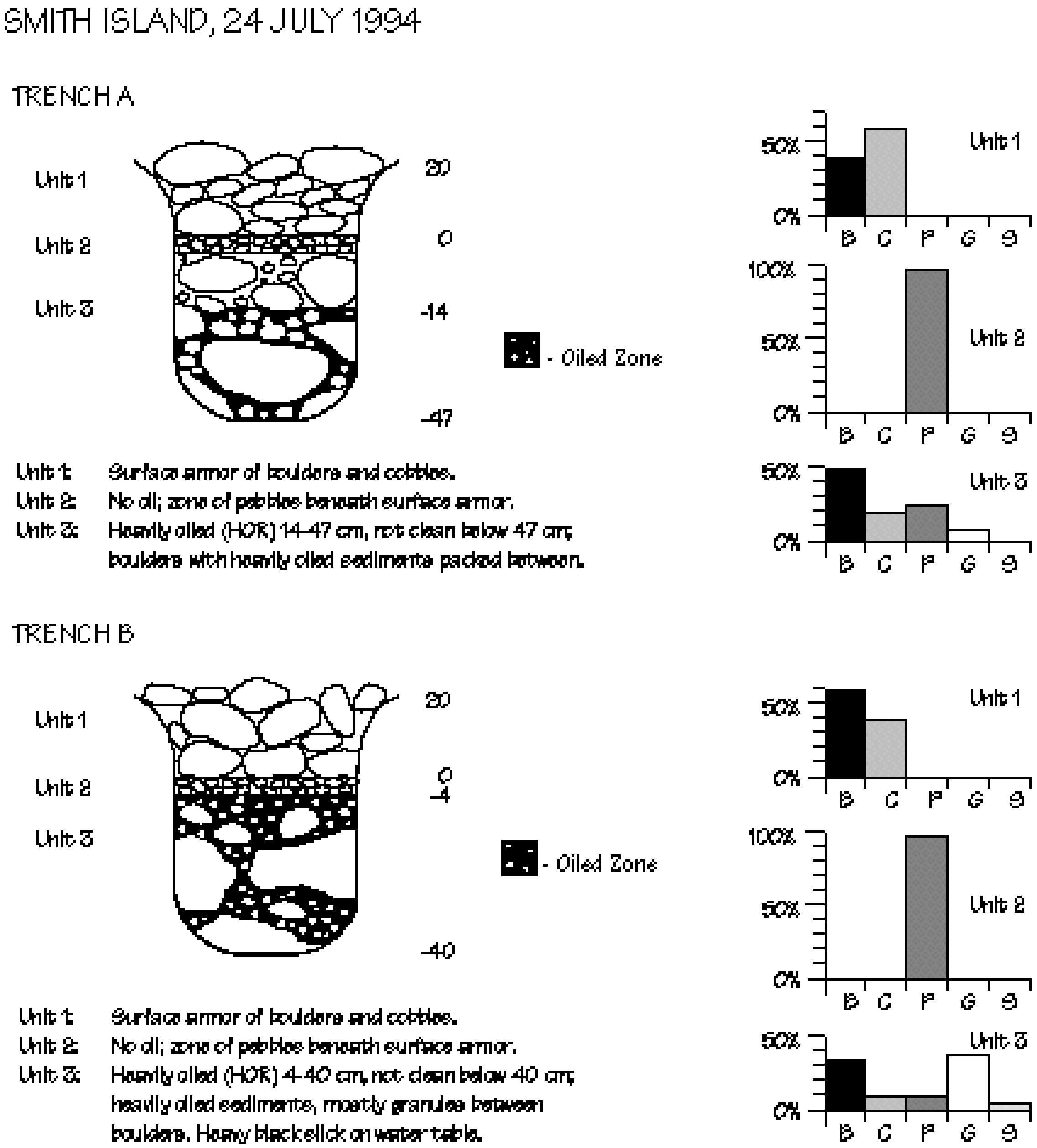
This station had retained the highest levels of subsurface oil for the longest period of time in the upper platform region of any of the stations classified as cobble/boulder platform with berms that we have studied. The probable reasons for this occurrence are:

1) The relatively deep surface sediments over the underlying uplifted rock platform as a result of the trapping of sediments by the rock outcrops to the west of the station. This allowed deep penetration of the oil and increased the depth to which tidal flushing must take place.

2) The well-developed armor of cobbles and boulders over the subsurface sediments (see Figures 44 and 45), which prevented wave action from reworking the deeper sediments. These deeper sediments had a large granule fraction which held the oil.

3) The relatively low angle of the slope of the rock platform (4.3 degrees), which partially explains why tidal flushing has been slower at this station than at those stations with steeper slopes.

4) The heavy initial oiling of the site.



Unit 1: Surface armor of boulders and cobbles.
Unit 2: No oil; zone of pebbles beneath surface armor.
Unit 3: Heavily oiled (HOR) 14-47 cm, not clean below 47 cm; boulders with heavily oiled sediments packed between.

Unit 1: Surface armor of boulders and cobbles.
Unit 2: No oil; zone of pebbles beneath surface armor.
Unit 3: Heavily oiled (HOR) 4-40 cm, not clean below 40 cm; heavily oiled sediments, mostly granules between boulders. Heavy black slick on water table.

Figure 44. Description of trenches a and b at the Smith Island site on July 24, 1994, showing presence of heavy subsurface oil under conspicuous surface armor. see Figures 41 and 42 for location of trenches.

SEDIMENT CHEMISTRY: TOTAL TARGET PAHs

The nature of the substrate at Smith Island necessitated modifications to the surficial sediment sampling protocols used during biological surveys. In order to collect sediments, the baseball- to bowling ball-sized armoring layer that constituted the "surface sediment" was removed, and underlying smaller-sized gravel was then collected for the chemistry sample (early attempts to extract oil residue from cobble and boulder material proved to be not only difficult, but also ludicrous).

In 1990, PAH concentrations in these surficial sediments (upper 5 cm below the armoring layer) from the vicinity of the biological stations were 0.13 ppm (wet weight basis) on the upper station, 0.76 ppm on the mid-level station, and 1.8 ppm on the lower station. Although this trend of increasing surface concentration with decreasing tidal elevation was consistent with the notion of oil washing from upper portions of the beach to the lower lower, there was no way to confirm this with the limited, post-treatment data available. Even if the concentrations in the Smith Island surficial sediments did, in fact, reflect a treatment-related phenomenon, July 1991 results would suggest that it was transient: concentrations at the upper, middle, and lower stations in the following year were 0.09, 0.09, and 0.02 ppm, respectively.

Sampling of subsurface sediments has not been a regular practice in the biological monitoring program, but a few samples have been collected, primarily for comparison purposes to the standard surficial composites. Concentrations of PAHs in July 1991 subsurface sediments were considerably higher than in surficial sediments at middle and upper intertidal levels, ranging from 32 ppm at the upper level to 110 ppm in the storm berm. These values for subsurface material were three orders of magnitude higher than those found for surficial sediments. The geomorphology team found even higher concentrations (120 and 900 ppm TPAH) in subsurface sediments collected in the same areas about a month later. In fact, the geomorphology team found TPAH levels in subsurface sediments in the same range (250 and 300 ppm) in the most recent sampling there in 1994 three years later. These confirm the persistence of large amounts of subsurface oil at the site.

Figure 45. Photograph of trench B at Smith Island, July 24, 1994. Note oil in sediments and on water table at bottom of trench. Photo by M. Hayes, Research Planning, Inc.

SEDIMENT CHEMISTRY: PAH DISTRIBUTION AND WEATHERING PATTERNS

Both the reductions in Smith Island sediment PAHs over the course of the program and the changes in relative abundances of the individual PAHs indicate that residual oil has weathered. Comparisons of the GC/MS patterns for compounds in 1990 and 1991 and comparisons of surficial and subsurficial oil in 1991, however, suggest that physical removal rather than chemical degradation has driven much of the reduction. PAH profiles showed relatively high proportions of the lighter fractions (i.e., naphthalenes and fluorenes) (Figures 46, 47). This similarity suggested that the subsurface oil in the upper and mid-intertidal zone was leaching upward, continually providing a fresh supply of hydrocarbons to the surficial sediments. It is unlikely that the surficial hydrocarbons in the mid- and upper intertidal will show significant evidence of weathering until subsurface reservoirs of hydrocarbons are exhausted.

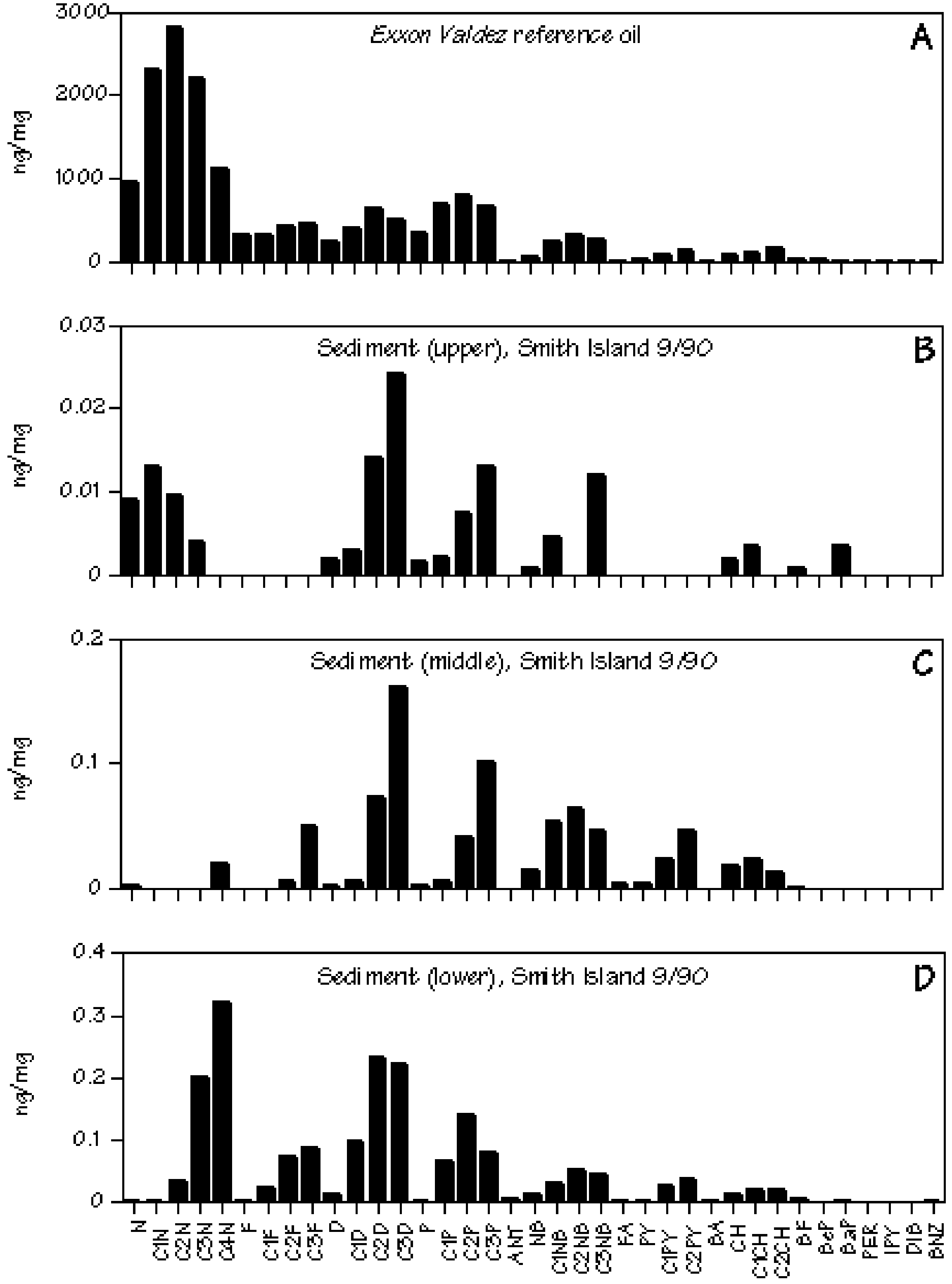


Figure 46. Comparison of PAH distrubitions for *Exxon Valdez* reference oil (A), and near-surface sediment samples collected along the upper (B), middle (C), and lower (D) intertidal transects in 1990.

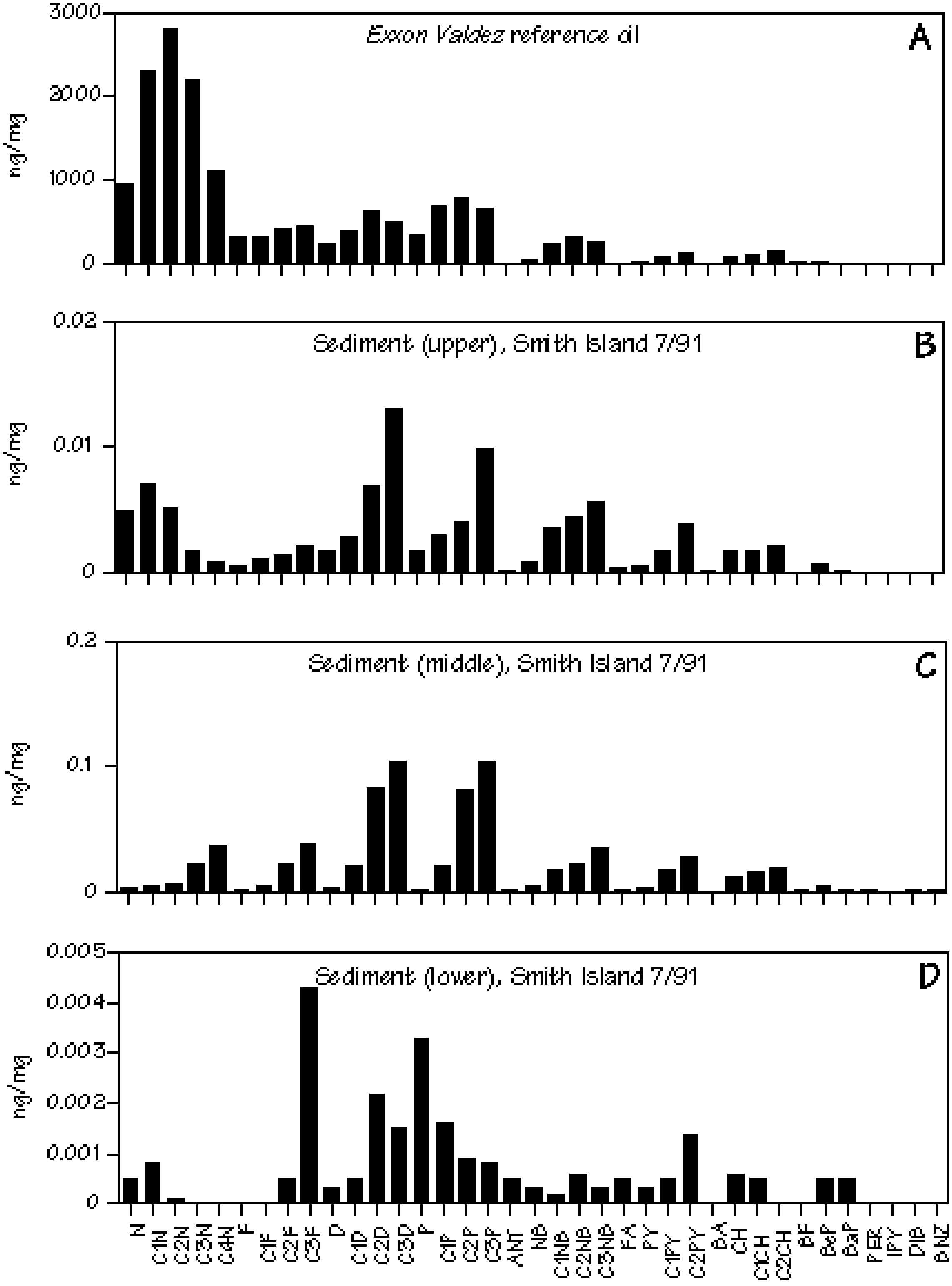


Figure 47. Comparison PAH distributions for *Exxon Valdez* reference oil (A) and near-surface sediment samples collected along the upper (B), middle (C), and lower (D) intertidal transects in 1991.

Sediment Chemistry: PAH Distribution and Weathering

Smith Island was typical of many of the boulder/cobble beaches in Prince William Sound with respect to the high degree of variability observed in both oil concentration and oil weathering. Composite sediments collected along the upper and middle biological study transects contained moderately weathered oil and, as previously stated, at relatively low TPAH concentrations. The lower transect contained oil that was classified as only slightly weathered. The lower intertidal transect contained the highest concentration of TPAH for the three 1990 transects, an observation that ran counter to what would have been predicted for high-energy beaches. Since the five field replicates were composited into a single sample submitted to the laboratory, it was not possible to determine whether the pattern exhibited by the 1990 lower transect sediment sample was representative of the transect or the result of an anomaly. Could a small amount of mousse or relatively fresh oil unseen by the naked eye been incorporated in the composite sample (a similar disparity was observed in the 1993 Block Island data and found to be attributable to only one of the five replicates—the other four were heavily weathered and at low concentration levels)?. Figure 47 shows 1991 data for the same three transects with relatively similar results, except for the lower transect composite sample that reflected trace levels of PAH apparently derived from a variety of sources—including heavily weathered Prudhoe Bay crude oil and combustion byproducts. Regardless of source, the overall PAH concentration observed at the lower transect was minor. An apparent enrichment of the C0-C4 naphthalene concentrations relative to the normal abundance and distribution patterns typical of moderately weathered Prudhoe Bay crude was observed in the upper transect for samples collected in both 1990 and 1991. While interesting, it does not appear in any subsequent samples and probably represented trace-level transient diesel pollution.

Although the intertidal transects exhibited relatively low levels of oil pollution, both the geomorphological study team and a mussel transplant study identified heavy oiling of portions of the upper- and supra-tidal zones. Mussels in the intertidal zone have continued to show uptake of oil. In 1992 and 1993, a wide series of samples was collected to further assess and characterize the oil pollution persisting at Smith Island and evidenced in the intertidal mussels. A mussel transplant experiment, which will be described in greater detail below, was also staged at the site in order to study bioavailability. Figures 48 and 49 are PAH profiles for 1992 and 1993 samples in different matrices.

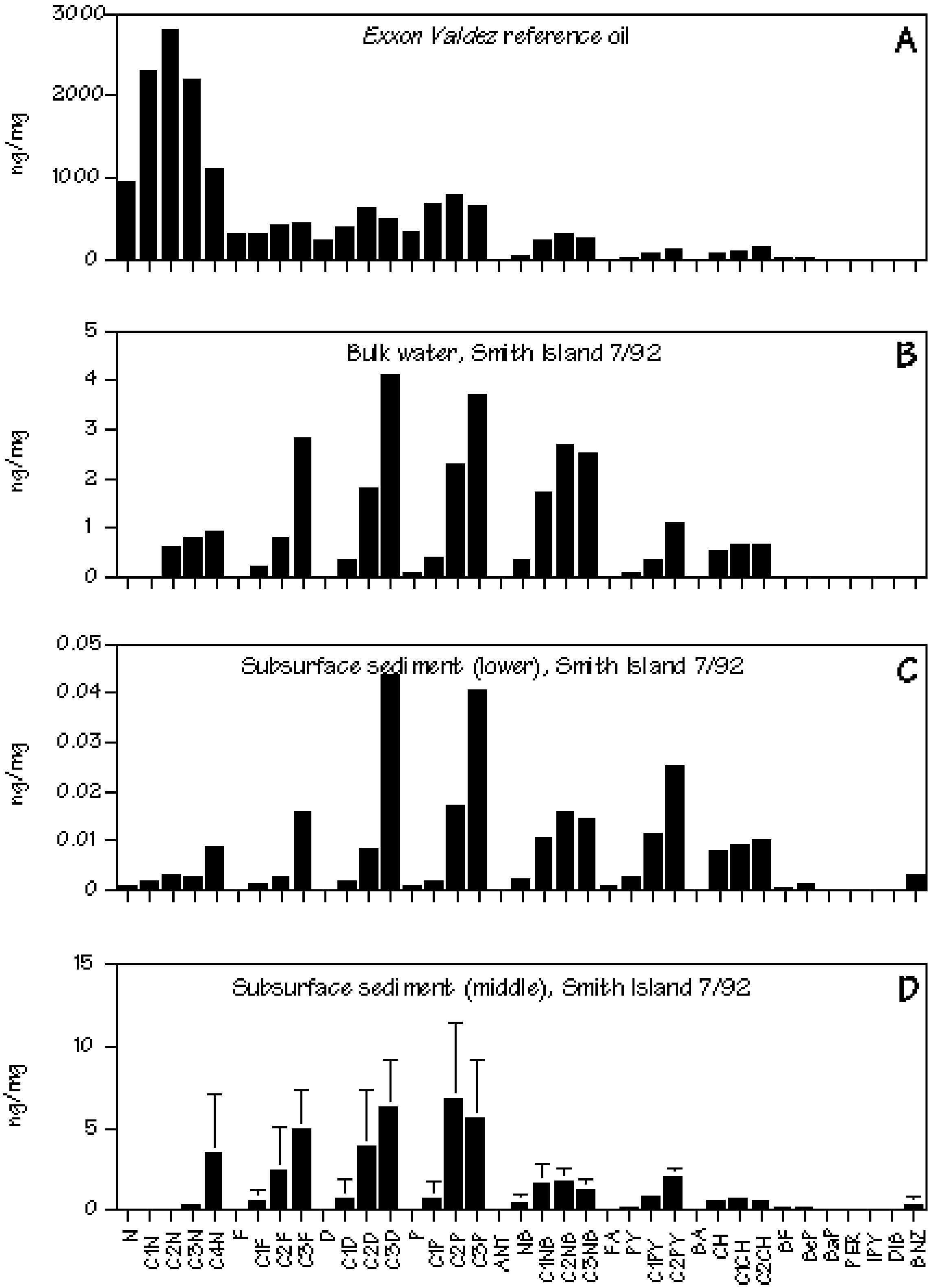


Figure 48. Comparison of PAH distributions for *Exxon Valdez* reference oil (A), bulk water collected in an intertidal pool (B), and subsurface sediment samples collected in the lower (C) and middle (D) intertidal zones during 1992.

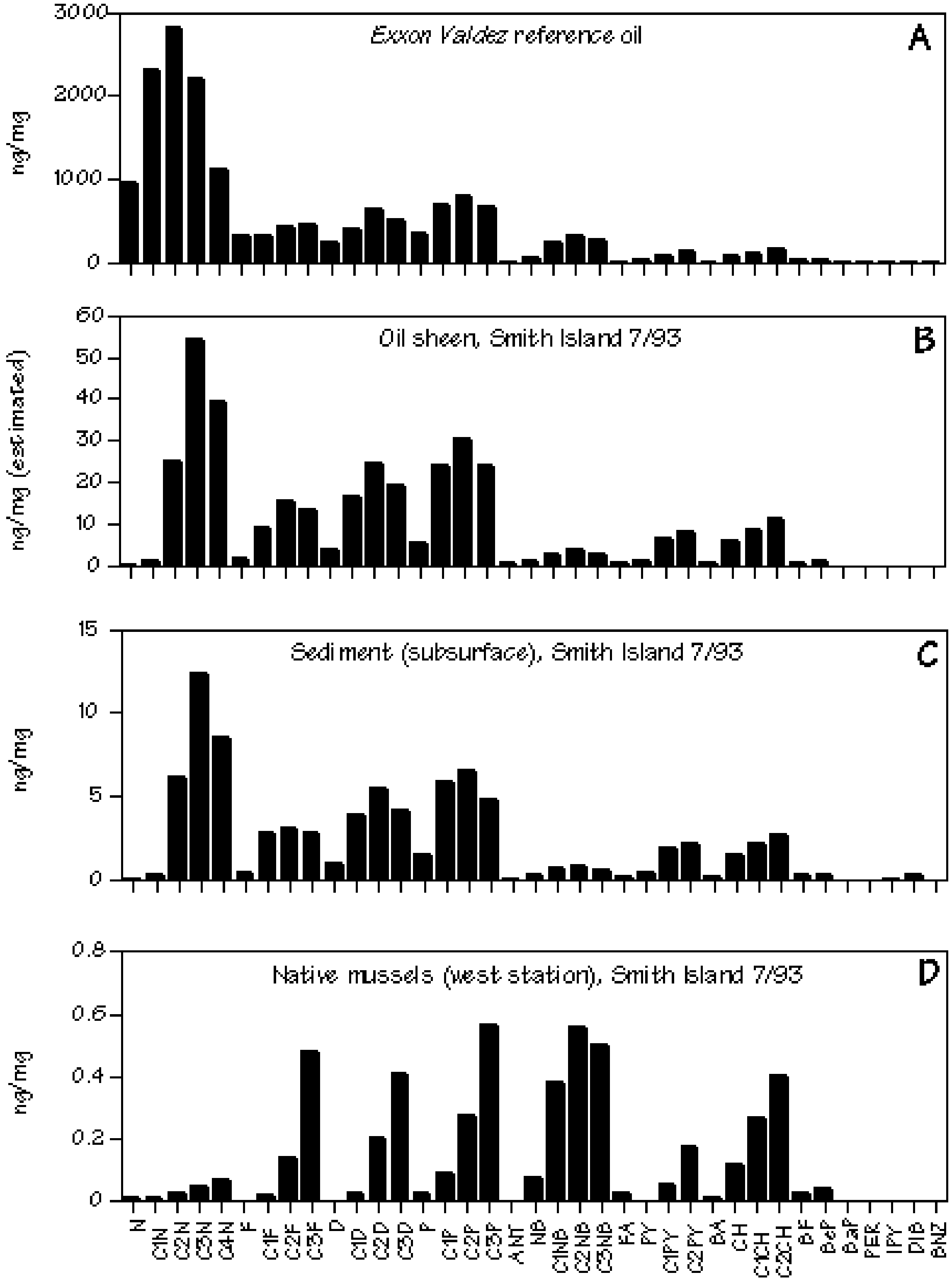


Figure 49. Comparison of PAH distributions for *Exxon Valdez* reference oil (A), surface oil sheen (B), subsurface sediment (C), and native mussels collected from the western side of the Smith Island study site (D) in 1993.

In 1992, a series of trenches was excavated in the middle and lower intertidal zone near the mussel transplant sit. The sediments were analyzed for qualitative comparison to the PAH profile detected in transplanted mussels. Four subsurface sediment samples were analyzed from the middle intertidal zone and two from the lower intertidal zone. A marked difference in concentration was observed between the middle and lower intertidal zone: 0.26 vs. 46 ng/mg. The middle intertidal samples appeared slightly less weathered, but both were classified as moderately weathered oil. A sample of silty water was also collected in a small tidal pool within the study area; the pool contained a visible sheen and the GC/MS results were remarkably similar to the subsurface sediment samples analyzed. We speculate that this sample result reflected the mechanism for the mussel contamination at Smith Island: adsorption to fine particulate material and flocculates. Such a transport mechanism in the form of oil-contaminated silts and flocculates is consistent with that described by Bragg and Yang (1995).

As late as 1993, subsurface samples composed of relatively fresh oil could be found at Smith Island. Surface sheens collected in small tidal pools were near-identical matches to pockets of relatively fresh oil as shown in Figure 49. In addition, mussel samples continued to show body burdens of PAH with distribution patterns within the range of samples collected in 1992 and 1993.

Mussels

Figure 50 compares the control mussels (deployed at an unoiled site on the south side of Smith Island), the intensive study site transplants collected in July and August 1992, and the sediment samples collected from the same study plots. Clearly, the PAH distribution pattern observed in transplanted mussels did not derive from the adjacent sediments alone. These sediments were relatively low in TPAH concentration and dominated by a weathering pattern significantly more degraded than that observed in the transplanted mussels. The PAH profile for the 1992 transplanted mussels and the native stock mussels collected in 1993 (Figure 49) were highly similar. By qualitatively comparing the wide spectrum of PAH distribution patterns observed at Smith Island between 1990 and 1993, it appeared plausible that particulate and sheens were the primary mechanisms of exposure to intertidal mussels at Smith Island. Although sheens were less weathered compositionally compared to the pattern of PAH detected in the mussels, it is feasible that adsorbed sheens would quickly lose the C0-C3 naphthalenes, C0-C2 fluorenes, and C0-C1 dibenzothiophenes and phenanthrenes through passive diffusion and dissolution. The resultant moderately weathered oil profile would be consistent with the chronic PAH pattern observed in mussels at Smith Island between 1990 and 1993.

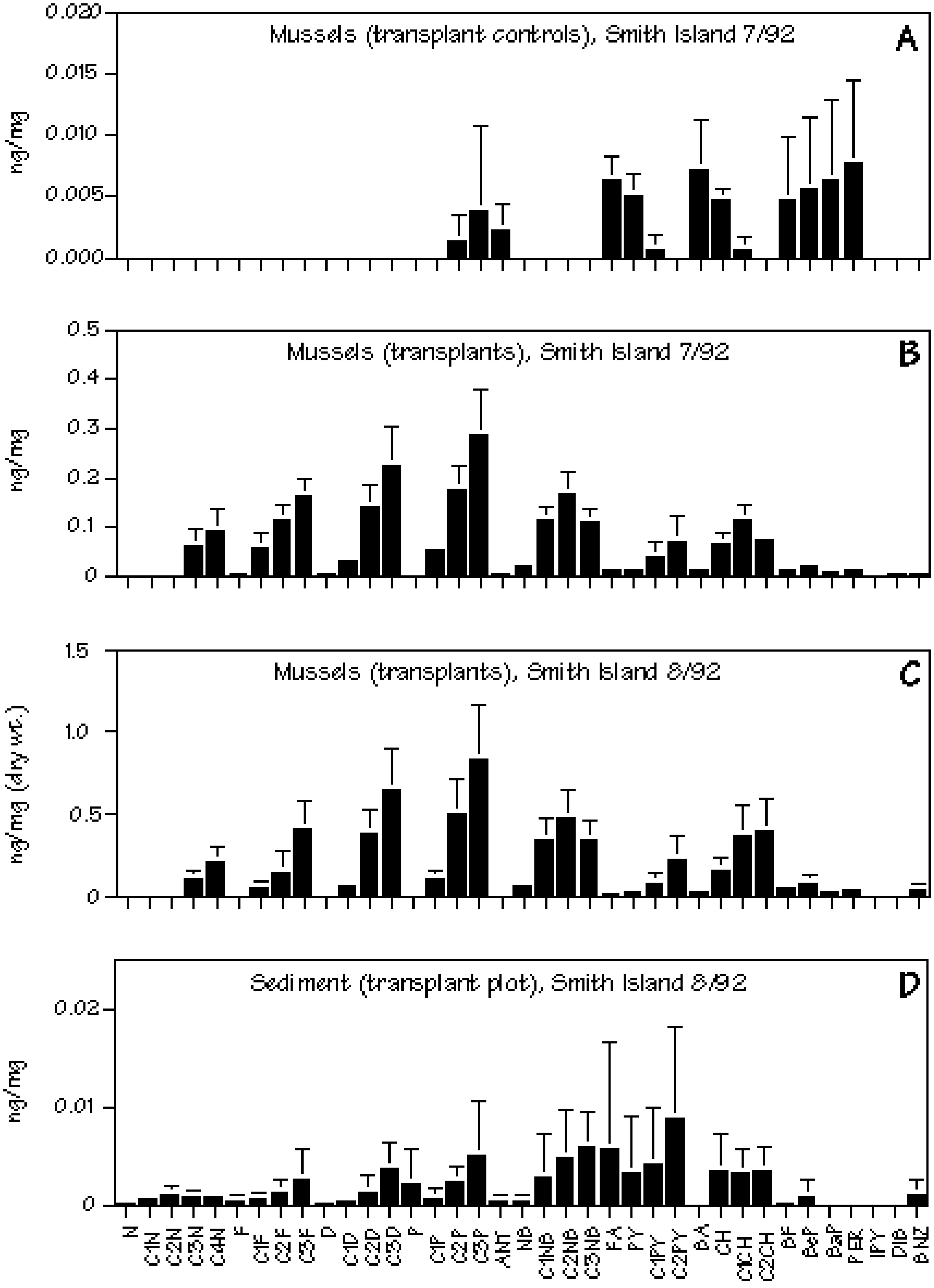


Figure 50. Comparison of PAH distributions for the control mussels deployed on the unoiled south side of Smith Island (A), the transplanted mussels harvested in July (B) and August (C) 1992, and sediments collected from the same plots in August 1992 (D).

BIOLOGICAL CONDITIONS AND PROCESSES

Biological studies were begun at this site in July 1990 to complement geomorphological surveys that had been ongoing since late 1989. The mid-tide quadrats were located at about the 37.5 m position on the geomorphological profile (Figure 40), and the low-tide quadrats were located at about 51 m. Both positions were in or just below the zone of the highest subsurface oil on the profile. The low quadrats were in the swale in front of the first ridge. It is likely that this low area was more protected from wave attack than were other parts of the beach. It is also possible that oil-contaminated water draining from the oiled sediments could have concentrated or even pooled in this shallow swale.

While the appearance of the biota indicated that the substratum in the lower intertidal was fairly stable most of the year, the substratum in the mid-intertidal was fairly disturbed. That is, there was a well-established community of algae and animals typical of the lower intertidal environment at exposed beaches, while biological communities in the middle intertidal were relatively sparse and occurred only in pockets protected from direct exposure in the surf zone. The high exposure index calculated by the geomorphology team (730) is consistent with the observed biological community here.

Based on the results from the NOAA core monitoring program, we considered the Smith Island site to be an interesting study location. Its biological communities reflected a lower abundance and diversity than many of the other sites monitored in the NOAA program, probably due to substrate dynamics. Yet, the chemistry results from sediment and tissue analyses flagged the area as having both high residual contamination and high hydrocarbon bioavailability. For these reasons, special studies were implemented at Smith Island to target more specific questions of interest arising from core monitoring results, while core measurements themselves were reduced in scope.

When core monitoring took place at Smith Island, only epibiota observations were collected (this was a standard procedure for boulder-cobble beaches because of the difficulty in accessing and collecting finer-grained sediment material using the infaunal coring device). Three elevations were sampled. The middle and lower intertidal stations at Smith Island were sampled three times (July and September 1990 and July 1991). The upper intertidal station was sampled twice (September 1990 and July 1991).

Upper Station Results

The upper intertidal station at Smith Island was sampled only twice, and very few biota were observed (Table 23). Only five taxa were documented: the barnacles *Chthamalus dalli* and *Semibalanus balanoides*; the periwinkle snails, *Littorina scutulata* and *L. sitkana*; and limpets (Lottiidae). Density of *Littorina sitkana*, the only taxon observed in both surveys, increased considerably in the second survey. *L. scutulata* was quite scarce in the first survey and limpets (Lottiidae) were rare in the second.

Table 23. Biota found at the Smith Island upper intertidal elevation, September 1990 and July 1991. Units are numbers of organisms/quadrat.

	Sept. 1990	July 1991
Littorina scutulata	0.2±0.4	0
Littorina sitkana	1.2±1.8	56±32
Chthamalus dalli	0.1±0.2	0
Semibalanus balanoides	0.2±0.3	0
Lottiidae, unidentified	0	0.2±0.4

The Smith Island upper elevation was the only upper boulder-cobble station sampled in the monitoring program in 1990. In 1991, two other boulder-cobble upper elevations were also visited (Bass Harbor and Point Helen). In contrast to the Smith Island site, where only two genera were counted in 1991, seven were found at both of the other two boulder-cobble upper stations.

The paucity of epibiota at this elevation during the sampling visits in 1990 and 1991 probably reflected both the inherently depauperate nature of the upper intertidal zone, especially on boulder-cobble beaches, as well as the lingering effects of oiling and aggressive treatment in 1989. Whereas the increase in *L. sitkana* in 1991 could be interpreted as a sign of recovery from the latter, the site has not been sampled intensively enough to confirm this.

Middle Station Results

Epibiota observations at Smith Island indicated that, similar to the upper intertidal, the middle elevation was biologically less diverse and organisms less abundant than other sites visited in the monitoring program. The fauna were generally similar to those observed on a similar boulder-cobble habitat in Bass Harbor, an unoiled site on Naked Island. Species richness at the Smith Island middle elevation was less than that at the two other oiled and treated boulder-cobble sites (Northeast Latouche and Point Helen) sampled in 1990 (see Table C-3 of Lees et al. 1991).

As was the case for the upper elevation, the biota at the middle intertidal transect were dominated by periwinkle snails during all surveys (Table 24). *L. scutulata* strongly dominated during the two surveys in 1990, but its density declined substantially in July 1991, when it was less abundant than *L. sitkana*. In contrast, density of *L. sitkana* was stable in the first two surveys, but increased by a factor of four by July 1991.

Table 24. **Abundance of selected biota at the Smith Island middle intertidal elevation, July and September 1990, and July 1991. Units for littorines and Lottiidae are numbers of organisms per quadrat; units for barnacles are percent cover per quadrat.**

	July 1990	Sept. 1990	July 1991
Littorina scutulata	124±34	164±99	56±24
Littorina sitkana	39±15	47±45	192±97
Lottiidae	0	2.2±4.0	6.1±5.8
Chthamalus dalli (%)	0.8±0.6	1.3±1.2	1.6±1.4
Balanus glandula (%)	0	0.3±0.3	0.7±0.8
Semibalanus balanoides (%)	0.6±0.4	1.8±1.6	6.4±7.7

Limpets (Lottiidae) were not observed in the first survey, but became progressively more common in subsequent surveys. Barnacle cover (represented in Table 24 above as percent cover of *C. dalli*, *B. glandula*, and *S. balanoides*) doubled in each subsequent survey. Abundance of *L. sitkana*, limpets, and barnacles increased steadily from the first survey and may be a sign of recovery from the oiling and subsequent shoreline treatment carried out on this beach. However, as we noted for the upper epibiota results, these data are not conclusive because the stations have not been sampled consistently.

Lower Station Results

Similar to results from the upper and middle intertidal surveys, epibiota observations from 1990 and 1991 indicated that the lower intertidal elevation was biologically less robust compared to many other rocky intertidal sites. The biota were fairly similar to those observed on similar habitat at the unoiled Bass Harbor unoiled site, and were dominated by algae—particularly rockweed (*Fucus gardneri*)—during all surveys. Abundance of rockweed (Table 25) was stable in 1990, but increased by nearly 50 percent by July 1991. Filamentous green algae were common in July 1990, but declined by an order of magnitude by September and remained sparse in July 1991. Overall, algal cover varied from a minimum of 57 percent in September 1990 to a maximum of 121 percent cover (cumulative summation of understory and overstory plant cover) in July 1991.

Table 25. **Abundance of selected biota at the Smith Island lower intertidal elevation, July and September 1990, and July 1991.**

	July 1990	Sept. 1990	July 1991
Fucus gardneri (% cover)	52±26	54±31	76±24
Palmaria hecatensis (% cover)	11±14	10±12	11±11
Ralfsia spp. (% cover)	0	17±14	10±15
Lottiidae	12±9.7	52±68	39±32
Pagurus hirsutiusculus	2.2±1.5	2.0±2.0	8.7±6.2

Limpets were the dominant invertebrates at the lower elevation, but there were no clear trends in abundance. Other invertebrates observed included the hermit crab (*Pagurus hirsutiusculus*), periwinkle snails, mussels, and barnacles. Abundance of the hermit crab was stable in 1990, but appeared to increase in 1991. Density of other invertebrates was low in all three surveys; many apparent changes were decreases. The limited number of data again restricts the conclusions that can be drawn about trends in abundances.

Qualitatively, however, comparison of the biota in the lower intertidal zones at Smith Island and Bass Harbor suggested that neither the initial oiling nor the subsequent shoreline treatment had a lasting effect on the lower elevation at Smith Island. Generally, the same taxa dominated at both sites and the abundance levels for the dominant taxa were fairly similar in each of the three surveys.

Epibiota on an Offshore Outcrop

The relative richness of the biota in the lower intertidal zone at Smith Island and the apparent age structure of the rockweed population raised questions about the severity of effect caused in the lower intertidal zone by the oil spill and shoreline treatment. A small rock outcrop about 50 m offshore from the lower station provided another opportunity to examine how the biota were affected by oil exposure and the shoreline treatment. The outcrop, shown in Figure 51, measured about 4 m long and 3 m wide and ranged in height from about -0.6 m mean lower low water (MLLW) to about the same elevation as the middle intertidal station at this site (about +1.5 to +1.8 m MLLW). However, the biota on the outcrop were very different than those on the shoreline.

Figure 51. Photograph of bedrock outcrop offshore from Smith Island study site, July 1991. Photo by A. Mearns, NOAA.

During the biological team's first visit to the site, the biota on the outcrop showed no evidence of oiling or shoreline treatment. The top of the outcrop was dominated by a mature population of the thatch barnacle (*Semibalanus cariosus*). Associated with this dense population of barnacles were mature populations of the predatory drill, *Nucella lamellosa*, three species of chiton, including the leather chiton (*Katharina tunicata*), several species of limpets, sea star, and sea anemones (*Urticina* spp.). All of these invertebrates require several years to attain the size (age) structure observed at this site and all were probably mature during the spill only one to two years earlier.

Algae formed several layers on the sides of the outcrop and dominated that biota. Red algae predominated on the upper half, whereas kelps formed a canopy over the layer of reds and a pavement of encrusting coralline algae on the lower half. The epibiotic assemblage on this outcrop, one of the richest observed during this study in the intertidal zone in central Prince William Sound, was particularly impressive since it occurred immediately adjacent to a shoreline among the most heavily oiled in Prince William Sound. This site had chronic sheening through 1994 and was subjected to extensive shoreline treatment.

Considering the observed sensitivity of several of these species (e.g., *Nucella*, chitons, limpets, and red algae) to oil contamination and/or hot-water washing, it seems unlikely that this outcrop was exposed to the heavy oiling described for the beach immediately shoreward, despite reports from early aerial surveys of Smith Island that a heavy band of crude oil extended approximately one-quarter mile offshore along most of the northern shore of the island for at least a week after the slick contacted the island. It is not entirely clear what physical circumstances would have permitted the outcrop to escape more severe effect, although it is possible that fortuitous tidal conditions minimized contact with the initial slick. Algal cover or wave action may have prevented oil that did contact the outcrop from adhering to the biota or substrate. Perhaps waves reflecting off the rock kept the oil from adhering to the rock surfaces long enough to cause impacts. Because the rock is completely submerged at high tide, oil coming into contact could have been lifted off (the outcrop did not have a shoreline against which oil would be held). Nevertheless, it is almost certain that, in the months that followed, the outcrop was exposed to surface slicks bleeding from the beaches, and to runoff from treatment activities taking place nearby. Biological effects attributable to these exposures would be difficult to discern at the level of study for our program, so for the time being, this outcrop remains an unexplained anomaly.

Tissue Chemistry

In 1990, tissue samples were collected for mussels (*Mytilus*), periwinkles (*Littorina*), drills (*Nucella*), and a sea star (*Pycnopodia*) to assess bioaccumulation and biomagnification in invertebrate food webs. These organisms represented, respectively, a filter feeder, a grazer, and two predators. The mussels, periwinkles, and drills were collected from the middle intertidal level, while the sea star was found in the lower intertidal.

Surface oiling of the beach at Smith Island was noticeable but appeared to be comparable to that found at many other sites during the first visit by the biological team in July 1990. However, the PAH concentration in mussel tissues from Smith Island in July 1990 was the highest observed at any site in the entire monitoring program: 84 ppm, on a dry weight basis (the next highest was that from a similar boulder/cobble habitat on Latouche Island, at 44 ppm). In contrast, the mean and median PAH concentrations for the 21 other mussel samples collected at all other monitoring sites in July 1990, were 2.1 and 1.1 ppm, respectively.

The tissue concentration of PAHs in littorines from the Smith Island site was two orders of magnitude less than that found in mussels, at 0.5 ppm. For the two predators, PAH concentrations were 2.4 ppm for the drill and below detection in the sea star. Although the Smith Island tissue concentration was the highest found in drills in 1990, it was an order of magnitude less than that found in the Smith Island mussels. Because higher concentrations occurred in the filter feeder (mussels) rather than the grazer (littorine snails), it appeared that PAHs were more biologically available in the water column and/or material filtered from the water than on the beach substrate. The occurrence of lower concentrations of PAHs in tissues of predators than in prey indicated that PAHs did not biomagnify in the invertebrate food webs, despite high levels of contamination in subsurface sediments and in mussel tissues.

In 1991, tissue concentrations of PAHs in mussels were much lower than those measured in 1990: the summed value for the target PAHs had declined by about an order of magnitude (from 84 and 13 ppm in July and September, 1990, respectively, to 4.9 and 3.7 ppm dry weight in July and September 1991). These results are for tissue collections made from a bedrock outcrop located on the western end of the site, at the western terminus of the middle intertidal biological monitoring transect (refer to Figure 37).

Although a substantial decline in PAH concentrations was noted between 1990 and 1991, the trend between 1991 and 1993 indicated no change in the level of exposure and uptake to mussels at Smith Island. No indigenous mussels were analyzed in 1992. However, the 4.9- and 3.7-ppm tissue burdens measured in July and September 1991 at the western outcrop suggested a slight increase by the July 1993 collection, when the tissue concentration was found to be 8.8 ppm.

A series of four mussel tissue collections made in 1993 across the face of the beach at the Smith Island site suggested a gradient of bioavailability to mussels. Mussel chemistry collections were made from east to west: at the eastern bedrock outcrop, in armored cobble on the eastern beach face, in armored cobble on the western beach face, and on the western bedrock outcrop. Measured concentrations increased steadily moving east to west with these samples: 2.5 to 3.2, to 4.1, to 8.8 ppm. It was not clear whether this gradient in tissue concentrations was attributable to a gradient in underlying subsurface concentrations, reflected physical patterns of drainage and nearshore circulation, or resulted from a combination of these or other factors. Although these mussel tissue concentrations were lower by an order of magnitude than those measured in 1990, they also represented the highest values measured in the monitoring program for 1993.

The unusually high mussel-tissue PAH levels prompted a more focused examination of the situation beginning in 1991. This included transplanting mussels, histological examination of mussel tissues, and using artificial surrogates to study PAH bioavailability. These are described in greater detail below.

Mussel Transplant Experiments

To further investigate the elevated concentrations found in mussels at the Smith Island site, in 1991 a transplant experiment was performed in which mussels from an unoiled reference site in Prince William Sound (Eshamy Bay) were moved to Smith Island. The mussels were deployed for a two-month period, after which they were collected and analyzed by GC/MS for tissue PAH levels. The reference mussels showed a significant uptake of PAHs over the two-month period: the Eshamy Bay transplants contained 0.8 ppm, while the same stock of mussels transplanted to the east and west ends of the beach site on the north side of Smith Island contained 20 and 4.8 ppm, respectively, upon collection two months later. Native (i.e., not transplanted) mussels collected at the same time from the west-end location contained a level of PAHs lower than, but comparable to, the transplant there, at 3.7 ppm.

In 1992, the transplant experiment at Smith Island was expanded to further investigate and define conditions there. In this experiment (discussed in entirety in Shigenaka and Henry 1995), mussels from another unoiled reference location in Prince William Sound (Barnes Cove, Drier Bay) were moved to Smith Island and deployed in cages along a transect established in the middle intertidal zone. A recently developed passive sampling tool, called semi-permeable membrane devices (SPMD), was paired with each mussel cage for comparison purposes. In addition to the standard monitoring site on the northwest side of Smith Island, the team also established a reference site on the unoiled south side of Smith Island. The cages containing mussels and SPMD were collected from the two beaches at 14- and 52-day intervals.

The Barnes Cove transplant stock contained low levels of PAHs, averaging 0.02 ppm. After 14 days at the Smith-north monitoring site, the transplants averaged 1.6 ppm, a two-order-of-magnitude increase; mussels transplanted to the unoiled south side of Smith Island averaged 0.03 ppm. After 52 days, Smith north mussels contained 4.9 ppm; the only remaining Smith south sample had been displaced from its original deployment position, but contained 0.06 ppm. SPMD PAH concentrations on the north side of the island increased from 0.35 ppm to 1.5 ppm after 14 days, while on the south side SPMD contained an average of 0.43 ppm.

The experiment confirmed that residual PAHs were biologically available to the mussels at the standard monitoring site, that there was a significant difference in that availability between the north (oiled) and south (unoiled) side sites, and that uptake was apparent in two weeks. Presuming that the level of exposure was relatively constant over the study period, it also appeared that mussels continued to accumulate PAHs after the 14-day collection. There was a significant correlation among sediment, mussel, and SPMD hydrocarbon levels, indicating that differences in bioavailability were discrete and localized. Particulate material and oil sheens were suggested as important pathways for exposure to the mussels. Analytical interferences prevented a direct comparison of PAH uptake patterns between mussels and SPMD, but the experiment indicated the potential utility of the membrane devices for monitoring hydrocarbon availability in the environment.

OTHER BIOLOGICAL STUDIES

Although the post-spill biological availability of residual hydrocarbons has been well-demonstrated at Smith Island, the biological *significance* of this availability and uptake is a more difficult question to address. That is, it has been relatively easy to demonstrate that mussels have been exposed to PAHs since the spill, and that they can subsequently bioaccumulate PAHs to tissue levels much higher than those found in the environment. The biological effects of the exposure and bioaccumulation, if any—the “so what?” question—have been much more difficult to determine. In theory, however, these effects should ultimately frame the rationale for response and cleanup actions—and can help to answer the “how clean is clean?” question that defines when cleanup is effectively over.

One approach commonly used in other pollution studies to link contamination and biological effects has been to examine the structure of tissues of exposed organisms to determine whether histological abnormalities can be correlated with contaminant exposure or body burden. A well-known example is the positive correlation between liver neoplasia in flatfish and elevated levels of high-molecular-weight PAHs in Puget Sound (Malins et al. 1988). With this in mind, field-preserved samples of mussel tissues from Smith Island and other monitoring sites were examined microscopically in 1993 to determine the occurrence of histopathological abnormalities. Although very few tissue abnormalities were observed in any of the Prince William Sound mussel samples, differences were noted in the reproductive status of the individuals from Smith Island.

In 1993, histopathological samples were collected at both the east and west bedrock outcrops at the Smith Island monitoring site. From the examination of tissue samples collected at a number of sites between 1990 and 1993, it appears that blue mussels in Prince William Sound spawn in July. The fact that the peak of spawning has coincided with the primary field sampling period for the monitoring program complicated assessment of changes in tissue condition, because spawning causes a marked loss in tissue mass and also can significantly change tissue lipid content (hydrocarbons like PAHs are often associated with high lipid-content tissues).

However, the coincident timing of sampling and spawning also resulted in a potentially important finding at Smith Island (excerpted from Brooks 1994):

> Mussels in the eastern (Smith) population were in generally fair to good condition. There was some evidence of kidney atrophy, and three parasites were observed. The population was in the late stages of spawning. In contrast, males in the Smith Island West population were in the early stages of spawning, while females were nearly spawned out or had very few ova, many of which were deformed. The Smith Island West population was in generally poor condition. These differences were so striking as to warrant further investigation with an attempt made to identify causal factors. There were, however, no significant, identifiable physiological lesions in either population.
>
> "…It appears that mussels from all sites did undergo gametogenesis. However, mussels from the western sample site on Smith Island…appear to have matured later and to have produced fewer gametes (particularly ova) than did the other sites. Females from the western Smith Island site were in very poor condition and produced very few normal ova.

It is intriguing that this apparent mistiming in male-female reproductive cycles coincided with the location where the highest tissue-PAH concentration was found. While it would be premature to attribute the phenomenon to chronic exposure to residual oiling, it has served to identify a topic for further research. Additional samples were collected in 1994, and biological conditions at the Smith Island site will continue to be studied in future cycles of monitoring.

The combined result of several methods of shoreline treatment, along with natural weathering processes, appears to have effectively removed a great proportion of the surficial oil. However, it was clear from the earliest assessments of oiling conditions at Smith Island that surface oil was only a minor part of the total amount present on the beach, and that the subsurface reservoir of oil resulting from the deep initial penetration would pose continuing problems. It was for this reason that the technique of berm relocation, previously discussed, was implemented on boulder-cobble beaches such as those on Smith Island in 1991. Berm relocation appeared to be effective on a localized basis for exposing contaminated sediments to natural weathering processes. However, large pockets of subsurface oiling were present under the armor of the upper platform. Berm-relocation work orders called for restricting those activities to the area of the high-tide berm. As a result, reservoirs of buried oil remained and apparently were sources of chronic hydrocarbon exposure to intertidal organisms such as mussels.

As we have no direct observations of conditions at the Smith Island site before either the oil spill or treatment, it is difficult to estimate how the spill affected intertidal communities. The task of doing so has also been complicated by the relatively low biological productivity of boulder/cobble beaches, especially at middle and upper intertidal elevations. Bass Harbor, an unoiled boulder/cobble beach on Naked Island, offers one comparison for Smith Island. Clast size and roundness at the two sites are similar, which would indicate some similarity in degree of exposure. Differences attributable to tidal elevation would be expected to be minimal, as the maximum difference in elevation between respective sampling elevations at the two sites is 0.3 m. However, orientation and effective wave fetch are different, and calculated exposure indices are very different: 730 for Smith Island, and 176 for Bass Harbor. Bearing in mind these differences, qualitatively comparing biological conditions at Smith and Bass in 1990 offers some insight into potential effects of oiling and treatment on biotic communities of boulder/cobble beaches.

Bass Harbor averaged nearly three times as many taxa as Smith Island in the upper intertidal level, and 1.5 times as many at the middle intertidal level, but averages at the two sites were equal in the lower intertidal zone. Biota at Bass Harbor averaged about 50 percent higher abundance than Smith Island at the upper intertidal level, while the two sites were similar in the middle intertidal. Smith Island averaged about 50 percent higher at the lower intertidal level. These 1990 comparisons suggest that the Smith Island site was depressed at the upper and middle intertidal levels relative to Bass Harbor, which would not be at all surprising given the aggressive treatment that took place over two seasons on Smith Island. Nevertheless, attributing these differences exclusively to treatment must be done cautiously and with qualification, since the difference in EI may have played a role in shaping the communities. There was a relative lack of difference in the lower intertidal zones of the two sites, but both treatment activities and wave exposure would have been less significant than in the middle zones.

Another way to evaluate the effects of the spill and the treatment is to examine trends in abundance for patterns that indicate recovery or random change. At the upper elevation, three taxa increased, one decreased, and four showed no change at Bass Harbor, whereas one taxon increased and four showed no change at Smith Island. Although the large number of taxa showing no change suggested that the biological community is stable at both sites, the one change in abundance at Smith Island was a 40-fold increase in *L. sitkana*, while remaining taxa were very uncommon.

At the middle elevation, five taxa increased, five decreased, and seven showed no change at Smith Island. Although most of the taxa showed no change and the number of increases and decreases was even, several major taxa (*L. sitkana*, barnacles, and limpets) increased substantially, suggesting that this site is recovering. Comparable middle intertidal data are not available for Bass Harbor.

At the lower elevation, patterns of increases and decreases in abundance between the two sites were comparable: eight taxa decreased, eight increased, and fourteen showed no change at Bass Harbor, whereas eight taxa decreased, eleven increased, and ten showed no appreciable change at Smith Island.

DISCUSSION

The geomorphological studies of the Smith Island site characterize it as an exposed and dynamic physical environment, which was confirmed by the personal experiences of the monitoring program study teams both in attempting to make landings in stormy conditions, and in their only moderately successful attempts to anchor in situ sampling gear there (see, for example, Shigenaka and Henry 1995). The regular occurrence of berm-like ridges over the profile, and the predominance of well-sorted and rounded clasts on the beach, suggest regular movement of the boulder/cobble surface material. As might be expected, the dynamic nature of the substrate translates into a difficult habitat for epibiota, and this has been reflected in the relative paucity of such organisms observed by the biological survey teams. However, it is also clear that a number of biota have been and continue to be resident at the site, particularly at those portions of the beach that are stable: bedrock outcrops, lower intertidal zones that are both less exposed to wave action and characterized by larger clast sizes, and in beach substrate underlying the well-developed armoring layer on the cobble/boulder platform.

These biota have reflected a high initial (1990) tissue concentration of spill-related hydrocarbons and a continuing exposure over time. This appears to result from the large amounts of oil that came ashore in 1989, and the deep penetration into the beach substrate where it became difficult to expose and remove oil either naturally or through shoreline cleanup. As a consequence, subsurface oil has persisted at this site, and sheening has been observed over the entire study period. The magnitude of this sheening has declined steadily and significantly over time, with booming necessary in 1990, continuous surface sheens observed on clasts during winter storms in 1991, and minor sheens seen in water draining from the beach face at low tide between 1992 and 1994.

Results of biological sampling from the Smith Island site indicate that abundance and diversity of communities typically found on exposed boulder/cobble beaches began to rebound from the effects of oiling and treatment rather quickly. The rich intertidal community present on the outcrop just offshore from the monitoring site indicates that even when large amounts of gross oiling, reoiling, sheening, and shoreline treatment took place nearby, biological effects of this exposure were difficult to discern after 1989. Understanding why this isolated outcrop escaped the impacts that were widely apparent nearly everywhere else in the oiled and treated areas may offer insights into response and cleanup strategies to minimize effects in the future—but for now explanations are purely speculative.

Despite the documented chronic exposure to residual oil that remains buried in the beach, biological effects to date were subtle—although not necessarily nonexistent. There has been some indication of offset reproductive timing in mussels resident at the site and, in particular, in the population showing the highest levels of PAHs in their tissue. These conditions will be examined during future cycles of the NOAA program, and will help to determine the status of recovery at the site.

Our monitoring results have suggested that, while armored boulder/cobble platforms like Smith Island are among the most problematic sites from the perspective of cleanup and removal of gross contamination, biological effects from oiling and cleanup were generally less severe than those recorded for other shoreline types. Although the middle and upper intertidal zones of boulder/cobble beaches are characteristically less productive than those of other shorelines, the fact that the organisms there are adapted to life under stressful physical conditions may also help them survive and recover from the additional impact from an oil spill.

In a broader ecological perspective, the lower biological abundance and diversity of boulder/cobble beaches relative to other coastlines in Prince William Sound suggest that any short-term impairment of biological communities at the former may be of lesser importance than would be the case at more ecologically sensitive or critical locations. The exposed nature of the shoreline at Smith Island, the well-protected locations into which the resident biota have settled (e.g., cracks, crevices, and interstitial spaces), and the localized nature of the pockets of oiling that still remain, minimize the availability of contaminated plants and animals to potential grazers and predators foraging for food. The Smith Island site, while relatively contaminated, is also relatively ecologically isolated and not heavily used for habitat. Thus, it may not represent significant sources of contamination to the larger Prince William Sound ecosystem.

Nevertheless, because mussels from the Smith Island site have consistently ranked among the highest in tissue concentrations of PAHs since the early days of the response and assessment activities, it will give us the opportunity to study how chronic contamination and biological availability affect exposed organisms. That is, we know that intertidal organisms continue to be exposed to residual hydrocarbons. One of our goals in the remainder of this monitoring program will be to ascertain the biological significance, if any, of this exposure.

SNUG HARBOR ROCKY SITE (KN-401A)

BACKGROUND AND SITE DESCRIPTION

Snug Harbor is a sinuous cove on the southeast side of Knight Island, well-protected on nearly all sides by high mountains. The EI for the site is 14, highly sheltered. Shorelines of the inner portion of the bay are steep and rocky except at its very head, where a gravel beach and a small tidal lagoon abut an anadromous fish stream. Figure 52 is a 1:10,000-scale map of the southeastern shoreline of Knight Island that includes Snug Harbor.

Snug Harbor was a heavily oiled sheltered embayment, which made it well-suited for spill research activities. Several of the shorelines around Snug Harbor were used as special research areas during the first three years of the spill. For example, the U.S. Environmental Protection Agency conducted a series of bioremediation experiments there in 1989 to evaluate that technique as a tool for oil spill cleanup. In addition, in 1989 an interagency process was initiated in which two “set aside” sites were designated in Snug Harbor. That is, oiled shorelines were not treated at these sites. It was recognized that set asides of this kind would provide an important basis for comparing recovery among sites with different substrate type, and different oiling and treatment histories.

The geomorphological and biological study sites were located in one of the two set-aside zones established in Snug Harbor, although they were separated by a lateral distance of about 300 m (the study areas were established in 1989 before the two study teams were consolidated). The physical and biological processes affecting both areas are presumed to be very similar for the purposes of this discussion. Figure 52 shows the location of the biological and geomorphological sites within the inner arm of the bay. Figure 53 is a 1:1,000-scale detail map of the shoreline section containing the geomorphological transect, while Figure 54 is a same scale map of the biological study area.

OILING AND TREATMENT HISTORY

The upper and middle intertidal shorelines of this portion of Snug Harbor were moderately oiled in 1989. As noted above, the shoreline segment containing the study transects is within a designated set-aside area. There are no records of the area having been treated in any substantive fashion, and the available treatment directives specifically stated that the designated set-aside areas were not to be cleaned. However, evidence that portions of it may have been bioremediated (Customblen pellets, a formulation of nutrients designed to release over a period of days or weeks) was observed on some of the visits by the biological team in 1990. Details of shoreline oiling assessments and cleanup operations at the Snug Harbor site may be found in Appendix A.

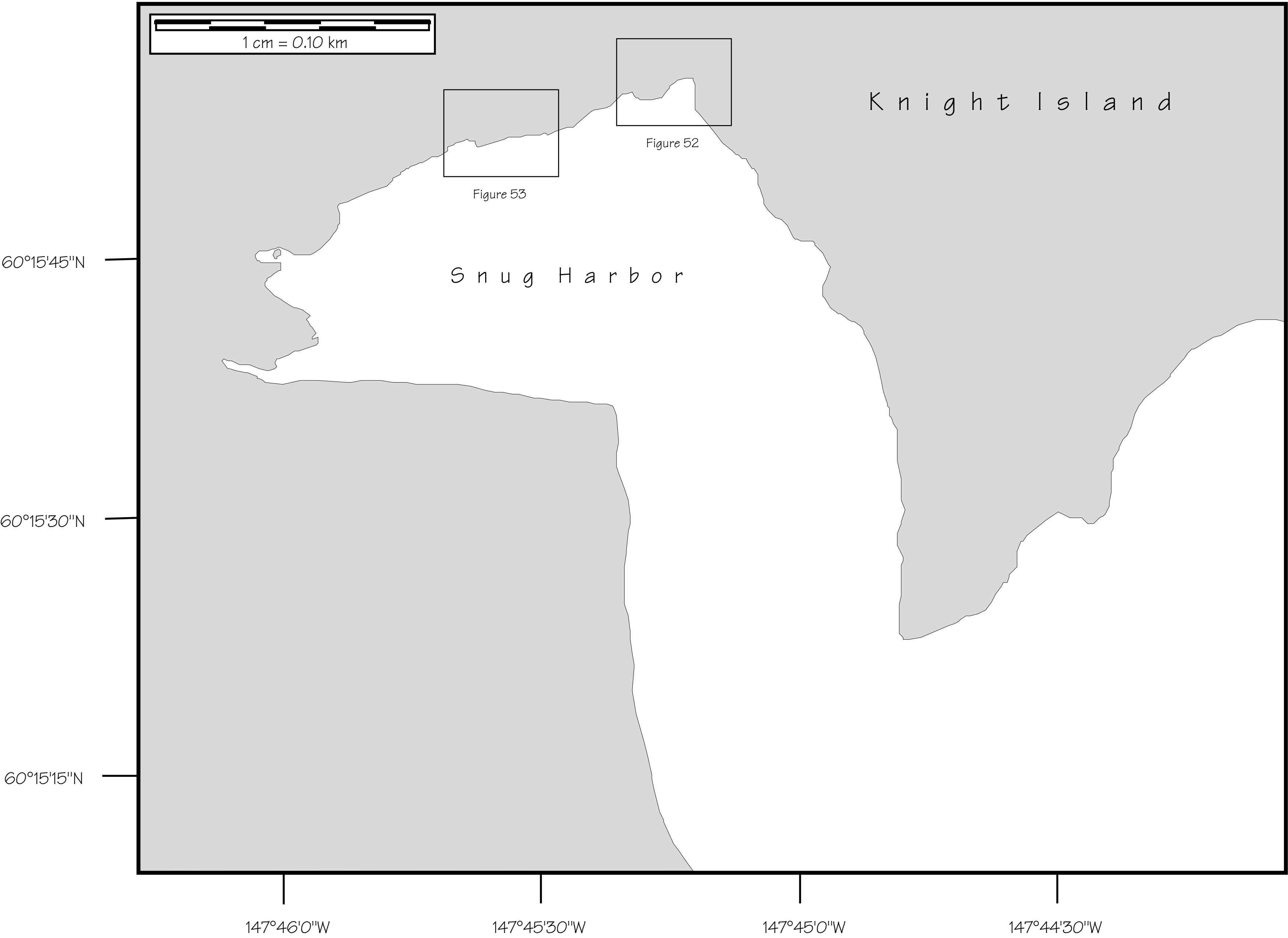


Figure 52. Map of Snug Harbor vicinity, 1:10,000 scale. Rectangles denote study areas shown in greater detail as Figures 53 and 54.

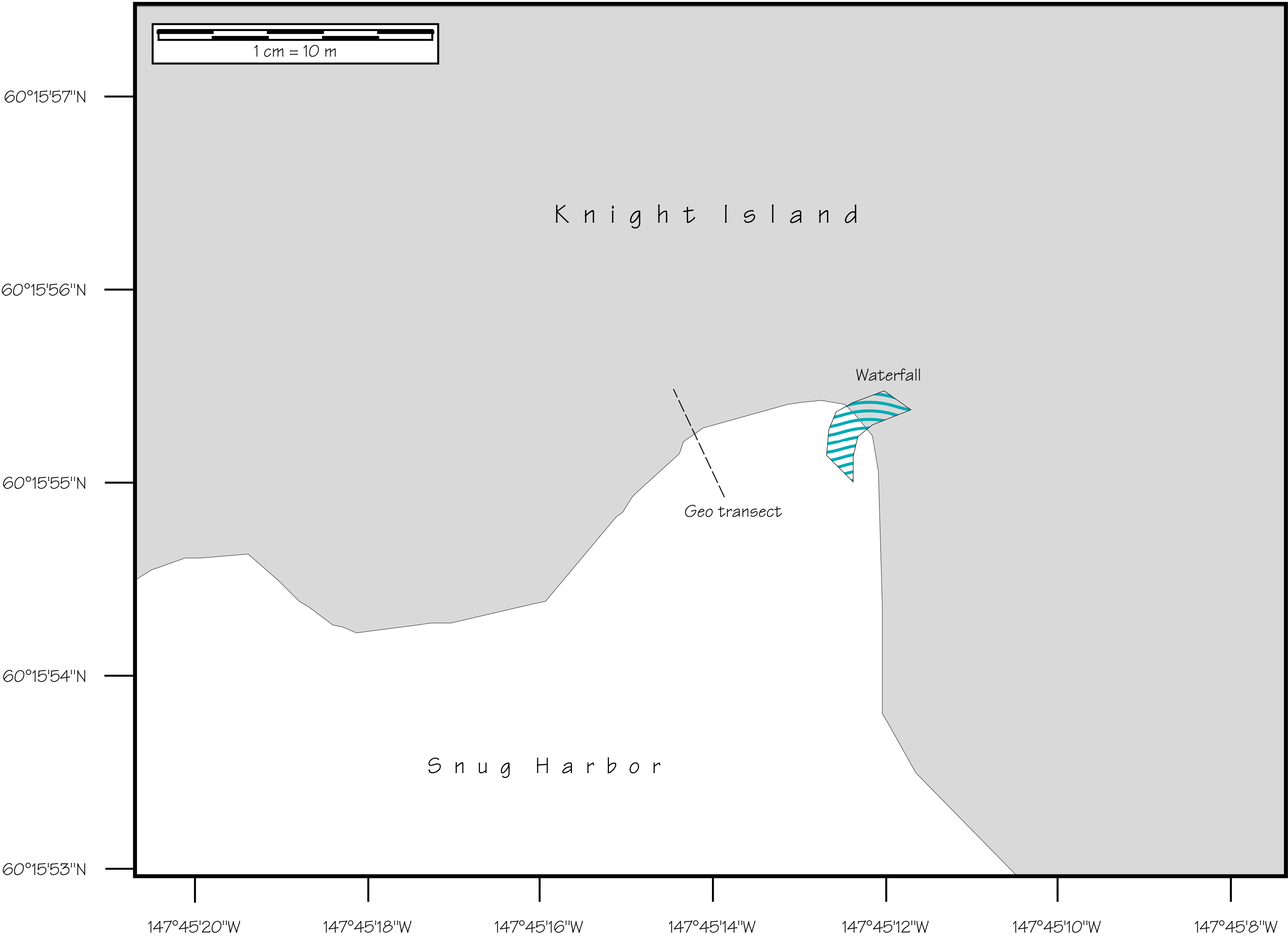


Figure 53. Detail map of Snug Harbor site, 1:1,000 scale, showing approximate location of geomorphological study transect. See Figure 52 for location relative to biological study area.

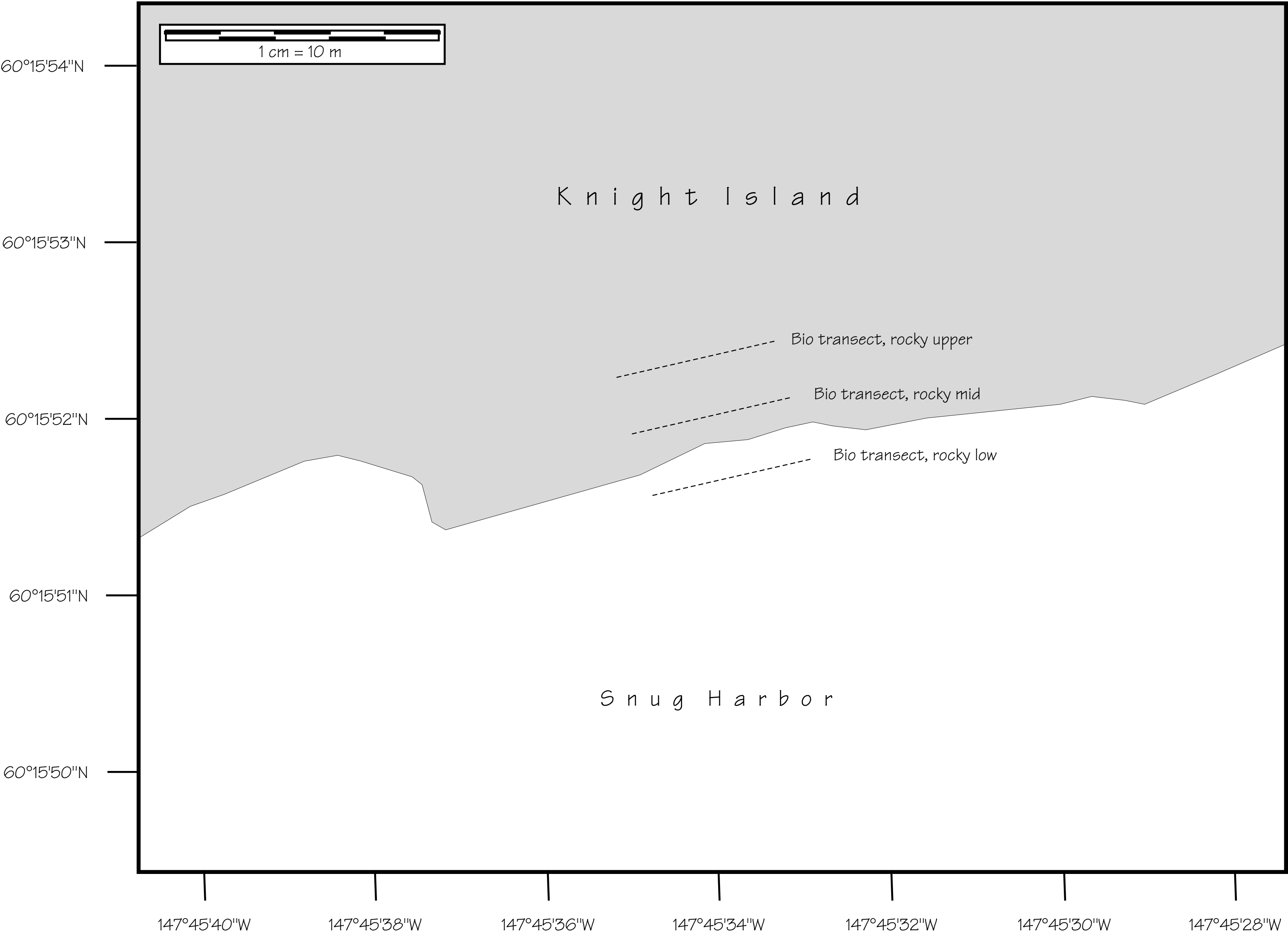


Figure 54. Detail map of Snug Harbor site, 1:1,000 scale, showing approximate location of biological study transects. See Figure 53 for location relative to geomorphological study area.

GEOMORPHOLOGY

This site is located well inside of Snug Harbor on Knight Island (Figure 52). On environmental sensitivity maps of the kind typically used for contingency planning, this shore would be classified as a sheltered rocky shoreline. The geomorphology profile originated on a bedrock ledge and passed down over coarse rubble debris in the upper intertidal zone to somewhat finer material on the lower intertidal zone. Clasts were angular to subangular and poorly sorted. Heavy growth of rockweed, barnacles, and mussels occurred at the lowest reaches of the intertidal zone. Figure 55 is a photograph taken on May 31, 1990, showing the typical characteristics of the substrate there.

This station was located on a curving shoreline that faces in a south-southeasterly direction down Snug Harbor, an effective fetch distance of 1.5 km. In order to reach the study site, waves entering Snug Harbor from the open Sound would have to travel 2 km into the Harbor and then bend at a right angle and travel another 1.5 km to the study site. Needless to say, this was a low-wave energy shoreline. This part of Knight Island was uplifted around 2 m during the 1964 earthquake. Photographs of this site from the July 22, 1994 survey are shown in Figures 56 and 57.

Figure 55. Photograph of Snug Harbor geomorphological site on May 31, 1990. View looking east from profile line. Tide was rising rapidly, covering the raised bay bottom. Photo by M. Hayes, Research Planning Inc.

Figure 56. Photograph of Snug Harbor geomorphological site on July 22, 1994. View across the profile showing the rocky rubble surface (where the two persons are standing) and the pebble/cobble surface of the raised bay bottom. Oil residues of 1-5 percent cover of asphalt pavements remained in the rubble zone as of 1994. Photo by M. Hayes, Research Planning Inc.

Figure 57. Photograph of Snug Harbor geomorphological site on July 22, 1994. Closeup of a patch of asphalt pavement. Note the oil on the edges of the angular pebbles pulled from between the crevices in the lower center of the photograph (arrow points to oil). Below the surface crust, the oil was soft, brown, and mousse-like. Photo by M. Hayes, Research Planning, Inc.

Morphology and Beach Dynamics

The intertidal part of the station, excluding the bedrock outcrop at the high-tide line, was classified into two units:

1. Rubble slope

This part of the profile was primarily a rubble-strewn bedrock surface that sloped steeply offshore (11 degrees). The rubble was mostly boulder-sized blocks that had fallen from the bedrock scarp behind the shore.

2. Raised bay bottom

This zone sloped offshore at a lower angle (8.5°) than the rubble slope, and the surface sediments were finer, <10 percent boulders with the rest being roughly equal amounts of pebbles and cobbles. Below this coarse surface layer, the sediments had a large sand and mud component, with a minor amount of shells. This surface was part of the subtidal zone before the 1964 earthquake raised it to an intertidal elevation.

The intertidal zone at the Snug Harbor site has been surveyed nine times during the study (Table 3). There were no significant changes of the topographic surface and no indication of sediment motion during the entire study.

Sediment Structure

The sediments at this station were derived from the local bedrock outcrops. The composition of 60 clasts was determined by the geomorphological study team, and it was found that all but two were greenstone (metamorphosed mafic igneous rocks). The grain size decreased significantly in an offshore direction. Boulders, which made up 20 to 30 percent of the surface sediments of the rubble slope, decreased to less than 10 percent of the total near the bottom of the raised bay bottom. Pebbles increased from 20 to 30 percent of the sediments on the slope surface to around 50 percent at the base of the raised bay bottom. Cobbles showed a uniform distribution throughout the profile. The coarse sediments at this site were rarely, if ever, moved by wave action, as reflected by the wide range of grain sizes present (the sediments are considered to be poorly sorted) and their angular shape (compare shape in Figure 57 with Smith Island sediments in Figure 43). Roundness and sorting of sediments correlate with exposure to wave action, an important natural cleansing mechanism. However, oil penetration is likely to be less in poorly sorted sediments.

The rubble slope overlaid a zone of angular pebbles and cobbles supplemented by a matrix of sand and mud. Pebbles, shell hash, sand, and mud were the dominant subsurface sediments of the raised bay bottom.

Oil Distribution Patterns and TPH measurements

The site was moderately oiled, and no treatment was conducted because it was a set-aside. Figure 58 shows the distribution of surface oil along the profile over the period of September 1989 to August 1991. There was a band of 100 percent coverage of black oil in September 1989 at the high-tide line, with no apparent oil elsewhere. The December 1989 and January 1990 observations were nearly identical, showing 10 to 30 percent oil coverage on the upper part of the raised bay bottom, indicating re-oiling. By May 1990, less than five percent oil was observed in this zone, mostly as scattered mousse patties. The oil band had weathered to a dull black stain and coat on the rock surface, with 5 to 20 percent coverage in September 1990 and 1 to 15 percent pavements in August 1991. By the time of the July 22, 1994 survey, oil residues consisted of 1 to 5 percent coverages of oil in crevices between the boulders in a band less than 2 m wide. The patches of oil were very small, occurring where angular pebbles were packed in finer sediments. The photograph in Figure 57 shows that the oil remained very soft and mousse-like in 1994, indicating that it had undergone limited weathering after five years. Total PAH were 330 mg/kg, relatively high for the TPH level of 32,500 mg/kg.

SEDIMENT CHEMISTRY: TOTAL TARGET PAHs

The biological monitoring site in Snug Harbor was characterized by large cobbles and boulders strewn over and between bedrock outcrops on a fairly steep (for intertidal habitats sampled in Prince William Sound) slope. At the lower station, a considerable amount of finer-grained material was found among the cobbles and boulders. Although acceptable sediment samples for chemistry at such rocky sites were difficult to locate and collect, small pockets of depositional material were found at the Snug Harbor biological study site, at the western margin of the set-aside segment. Consistently sampled between 1990 and 1993, these PAH analyses can be used to track weathering rates of the residual oil. Since surface oiling on boulders and cobbles, and oiling of depositional material are qualitatively different, there are limits to the extent to which the chemistry results(no photos for 1991). 175le, it is likely that both finer-grained depositional sediments and fresh oil would tend to settle into similar pockets. Sampling of the PAH contamination of these pockets, therefore, may have overstated the extent to which the site as a whole was oiled.

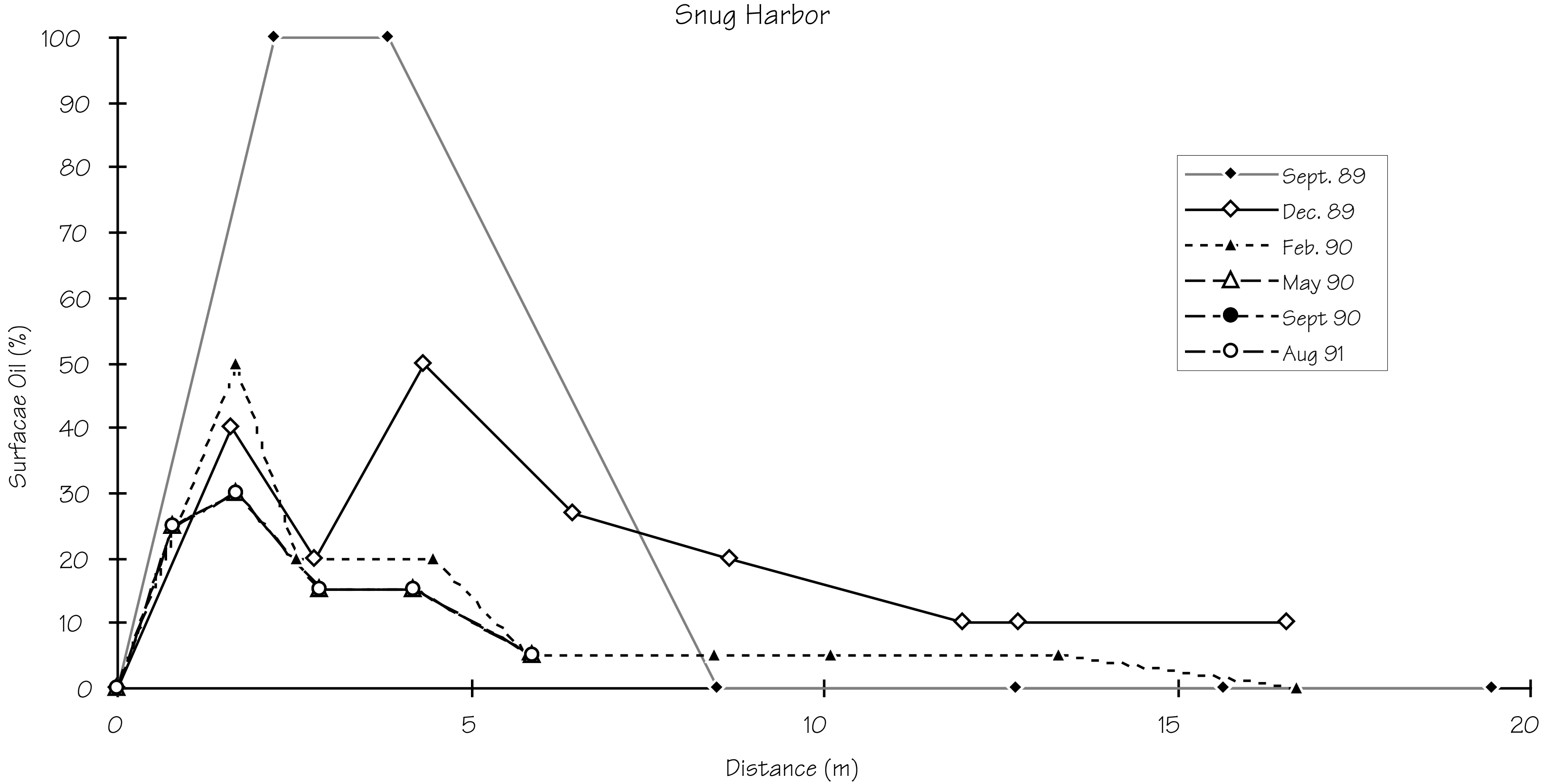


Figure 58. Distribution of surface oil observed along the geomorphology profile over the period from September 1989 to August 1991.

The reports from the Snug Harbor site in 1989 indicated heavy surface oiling concentrated in the upper and supratidal zones, with light to moderate oiling in the middle to lower intertidal zones. Not surprisingly, the GC/MS chemistry results for PAHs have reflected this gradation in oiling to a large degree. Table 26 summarizes total target PAH results at Snug Harbor by intertidal elevation and year (sediment samples were not collected in 1994). Figure 59 illustrates the July data for the 1990-1993 period graphically. Relatively high concentrations of residual oil were found at the upper and middle intertidal elevations in 1990 and 1991, with highest concentrations measured in 1990.

Table 26. Sediment hydrocarbon results for the Snug Harbor biological site, by intertidal level and sampling period. Values in ppm wet weight basis.

ELEVATION	TPAH ppm wet Jul-90	TPAH ppm wet Sep-90	TPAH ppm wet Jul-91	TPAH ppm wet Jul-92	TPAH ppm wet Jul-93
Upper	16.30	165	11.80	8.9	3.55
Middle	20.20	1.47	0.42	0.34	0.08
Lower	0.01	-	0.21	0.03	0.72
Below lower			0.24	0.01	0.11

Both Table 26 and Figure 59 show that PAH concentrations at the intertidal elevations that were the most heavily oiled in 1989—the middle and upper levels—declined substantially between 1990 and 1993 even though no active cleanup operations took place at the site. Residual hydrocarbons in lower intertidal sediments increased slightly in 1993, but it is not clear whether this reflected a real trend or was simply indicative of the inherent variability in the environment.

As a standard practice each time the biological survey team visited the study sites, the degree of surface oiling that occurred in the 0.25-m^2 quadrats at each elevation was visually estimated and recorded. The time series of results from these estimates at Snug Harbor permits a general overview of oiling conditions there that can be compared to the chemical analyses. As shown in Table 27, very little surface oiling was observed in the quadrats after 1990, and none was found after 1993.

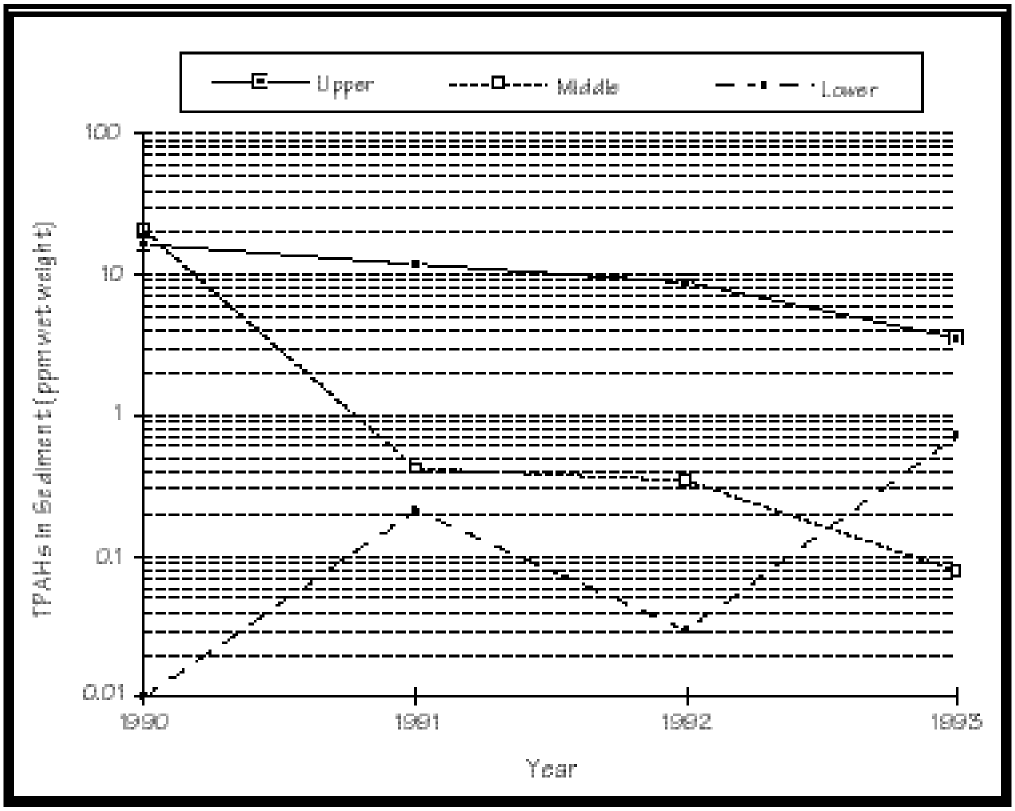


Figure 59. TPAHs measured in surficial sediments collected at the Snug Harbor biology site, 1990-1993. Note semi-logarhthmic scale. Values in ppm, wet weight basis.

Table 27. Estimated surface oil cover in Snug Harbor biological quadrats, 1989-1994.

ELEVATION	May-89	Jun-89	Sep-89	Jul-90	Jul-91	Jul-92	Jul-93	Jun-94
Upper	-	-	76±35	53±31	0.5±0	0.4±0.2	0.1±0.2	0
Middle	14±2.5	19±20	8.4±13	0.8±1.2	0.5±1.6	0	0	0
Lower	100±0	0	38±45	0	0	0	0	0

SEDIMENT CHEMISTRY: PAH DISTRIBUTION AND WEATHERING PATTERNS

Figure 60 identifies changes in the PAH distribution at the Snug Harbor middle intertidal biological transect for 1990, 1991, and 1993. By the summer of 1990 the oil had degraded significantly and could be classified as moderately weathered. This trend continued, and for 1991 and 1993 the PAH profiles were classified as heavily degraded.

Figures 61 and 62 contrast oil weathering with respect to beach elevation by plotting the PAH profiles obtained from composite samples collected in the upper, middle, lower, and below-lower intertidal transects for the years 1991 and 1993. For the 1991 collections, the oil degradation pattern appeared to correlate with oil concentration downslope. The upper intertidal zone contained the highest concentration of stranded oil and the least degradative changes relative to downslope transects (middle, lower, and “below lower”) where the degree of oiling was significantly less and the PAH profiles reflected greater oil degradation. The PAH profile for the 1991 “below lower” transect (essentially the low tide mark) at Snug Harbor exhibited an anomaly in the degradation profile. The three-ring dibenzothiophenes (C0-C3) and phenanthrenes (C0-C3) were highly degraded but appeared disproportional to the rest of the profile (Figure 61), relative to the distribution pattern exhibited by the lower and middle transects and other heavily degraded oil sites in Prince William Sound. The slight enrichment of the three-ring compounds at the “below lower” may have been due to some weathered diesel contamination—but, if so, the overall contribution was relatively low, since the TPAH value was only 0.24 ng/mg.

The PAH profile downslope for the 1993 samples had a similar pattern overall and showed a greater extent of biodegradation (as would be expected), but the lower intertidal transect was contaminated with only slightly weathered oil. The 1993 composite sample from the lower transect at Snug Harbor provided further evidence as to the patchy nature of the stranded oil. Unfortunately, the samples at Snug Harbor were all field composites, which did not allow an assessment of the variability within specific transects. The PAH profile presented in Figure 62 for the lower transect may be dominated by a single sample containing a small pocket of less degraded oil, and possibly was not representative of the middle transect as a whole. We observed something similar at Block Island where, fortunately, each individual replicate was analyzed, and we were able to confirm that the variability was contributed by a single sample. At the low overall TPAH concentrations observed at Snug Harbor, a small fragment of trapped, unweathered oil (barely visible to the naked eye) could be responsible for the TPAH concentration and profile observed. The PAH profile for both the middle intertidal and below low transect were characterized as heavily weathered.

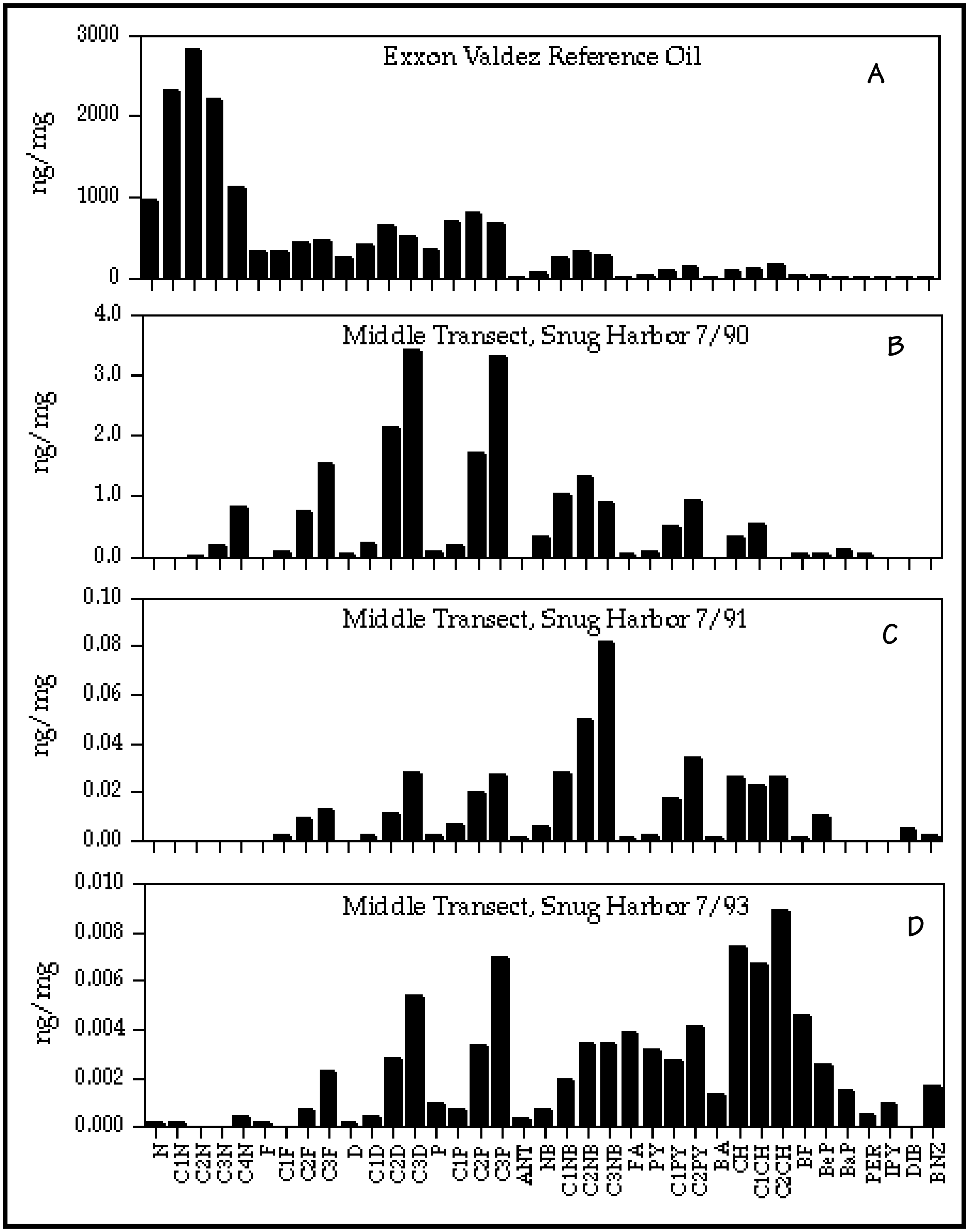


Figure 60. Comparison of PAH distributions for *Exxon Valdez* reference oil (A), and middle intertidal surficial sediment composites collected in 1990 (B), 1991 (C), and 1993 (D).

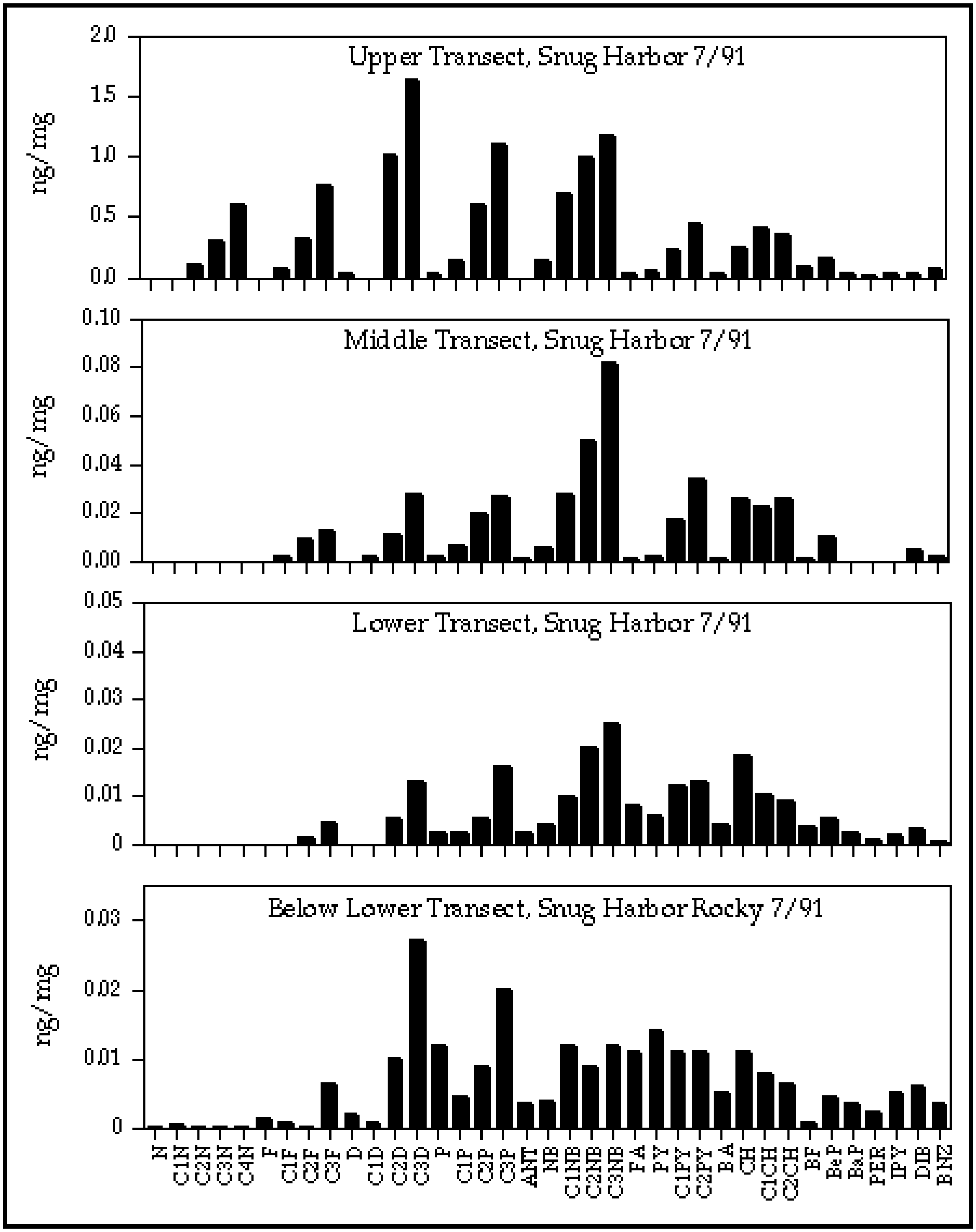


Figure 61. PAH profile plot of composite sediment samples collected at each intertidal transect during 1991. Data are normalized to the most abundant PAH constituent.

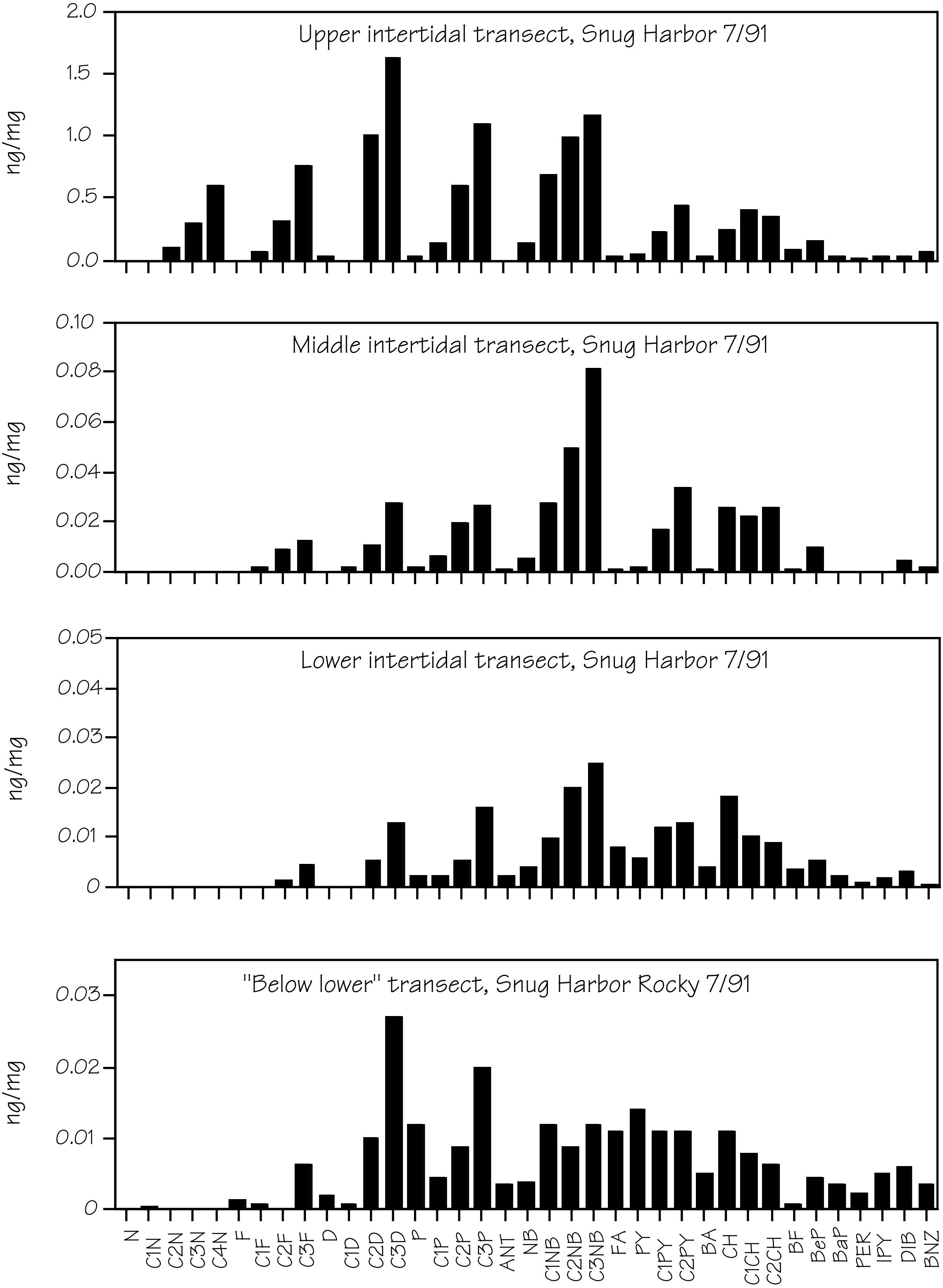


Figure 62. Comparison of PAH distributions for composite sediment samples collected at different intertidal elevations during 1991. Data are normalized to the most abundant PAH constituent .

Mussels

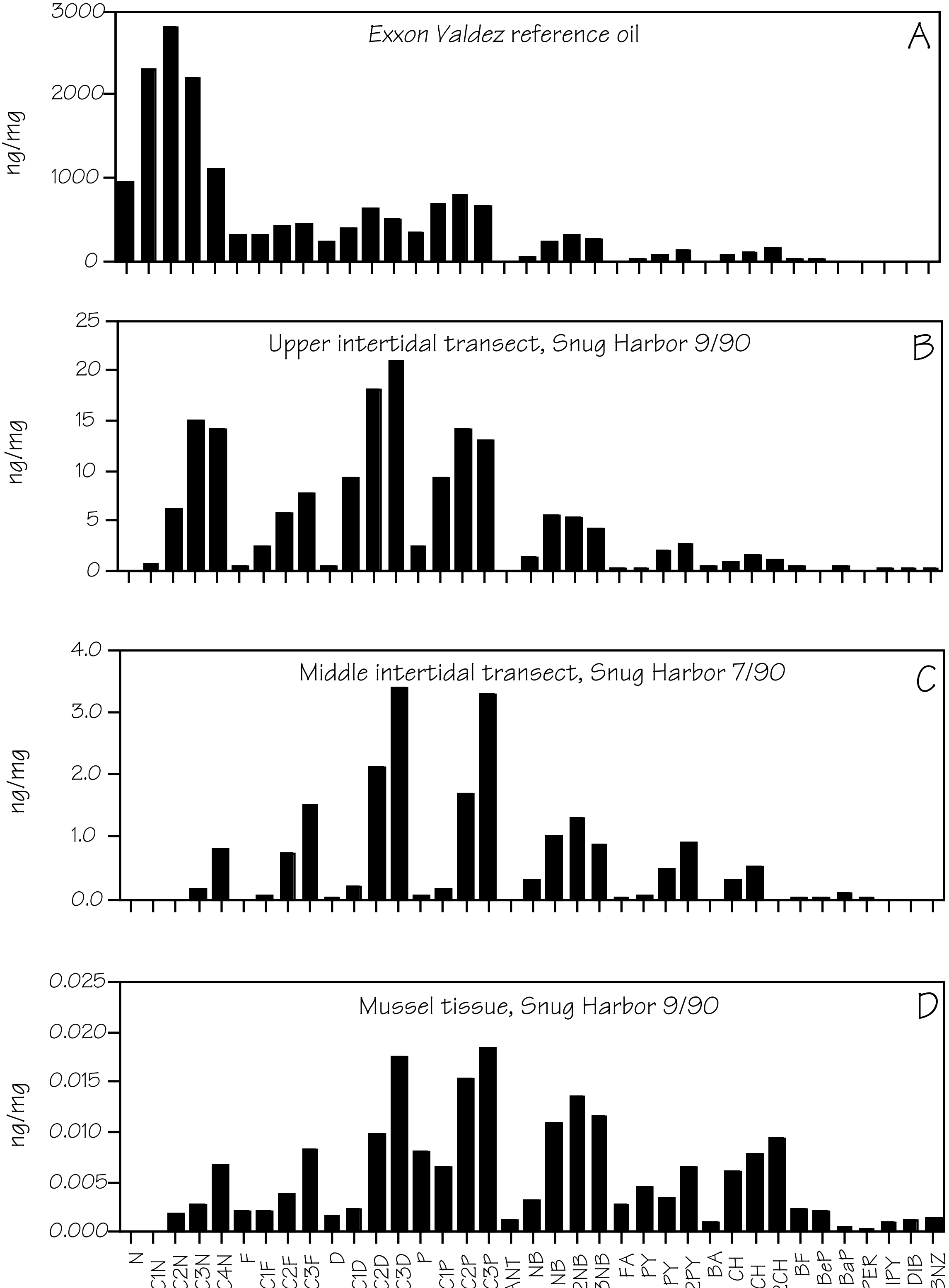
The PAH distribution pattern detected in the 1990 mussel collection at Snug Harbor was consistent with the PAH patterns observed for sediments adjacent to the intertidal mussels. Figure 63 is a histogram comparison of the PAH distribution pattern for sediments collected along the upper transect and middle transect in September 1990 and mussels collected at the same time. The distribution pattern detected in the mussels appeared to fall somewhere between the moderately degraded oil patterns observed at the upper and middle transects.

BIOLOGICAL CONDITIONS AND PROCESSES

Upper Station

We observed extensive surface oil cover at the upper elevation of the Snug Harbor biological site in 1989 and 1990 (Table 27), but saw a dramatic decline between 1990 and 1991. By June 1994, we could record no surface oil along the study transect.

The brown alga *Fucus gardneri*, or rockweed, commonly occurred throughout the intertidal zone of the Snug Harbor study site (Table 28). Along the upper intertidal transect, rockweed cover was estimated during surveys between September 1989 and June 1994. As shown in Table 28, percent cover in the upper intertidal remained fairly constant until 1992, when a substantial increase was noted (4.6 percent in 1991, increasing to 15 percent in 1992). The cover further increased in 1993 and appeared to plateau in 1994 at around 36 percent. .Periwinkle snails (*L. scutulata and L. sitkana*) and limpets (several species, see Table 29) along the upper intertidal transect showed patterns of increase similar to those discussed above for rockweed in 1993 and 1994. That is, variably low abundances occurred between through 1991 but, beginning in 1992 and 1993, we observed considerable increases. Both groups of organisms were most abundant in 1994.



Exxon Valdez reference oil

Upper intertidal transect, Snug Harbor 9/90

Middle intertidal transect, Snug Harbor 7/90

Mussel tissue, Snug Harbor 9/90

Figure 63. Comparison of PAH distributions for *Exxon Valdez* reference oil (A), upper intertidal surficial sediment composite (B), middle intertidal surficial sediment composite (C), and mussel tissue (D) collected in 1990 at the Snug Harbor biology site.

Table 28. Percent cover of rockweed, *Fucus gardneri*, recorded along study transects at Snug Harbor, 1989-1994.

Date	Upper	Middle	Lower
May 1989	-	16±16	20±14
June 1989	-	12±13	43±19
Sept. 1989	5.4±11	6.4±6.5	-
July 1990	8.4±18	6.5±4.9	14±11
Sept. 1990	4.3±8.8	4.7±3.0	13±11
May 1991	3.4±6.5	4.0±2.9	-
July 1991	4.6±8.6	17±14	-
July 1992	15±22	37±33	32±16
July 1993	37±33	46±23	47±17
June 1994	36±42	32±27	24±12

Middle Station

Initial oiling at the Snug Harbor middle rocky transect was moderate compared to that observed in the upper intertidal zone (Table 27). Oil was distributed mainly on the tops and sides of the rocks and was not observed under the large clasts. This resulted in refugia where motile organisms such as snails could temporarily avoid direct contamination. Oil cover estimated in the biological quadrats at this elevation averaged between 10 and 20 percent in mid-1989, but by July 1990, had declined to less than one percent. Remaining oil took the form of a thick mousse in patches between the boulders. By July 1992, we could record no oil at the middle intertidal station of the biological site, and observed none in 1993 or 1994. Although we still observed some oil at the nearby geomorphological site in 1994, the trends of rapid decrease in surface oiling were similar at the two sites.

Average cover of rockweed (*Fucus gardneri)* along the middle intertidal transect has been variable at the Snug Harbor site (Table 28, Figure 64). It declined from around 16 percent immediately after the spill to around five percent at the end of 1990. However, between 1991 and 1993, cover increased by an order of magnitude—from four to 46 percent—before declining slightly in 1994.

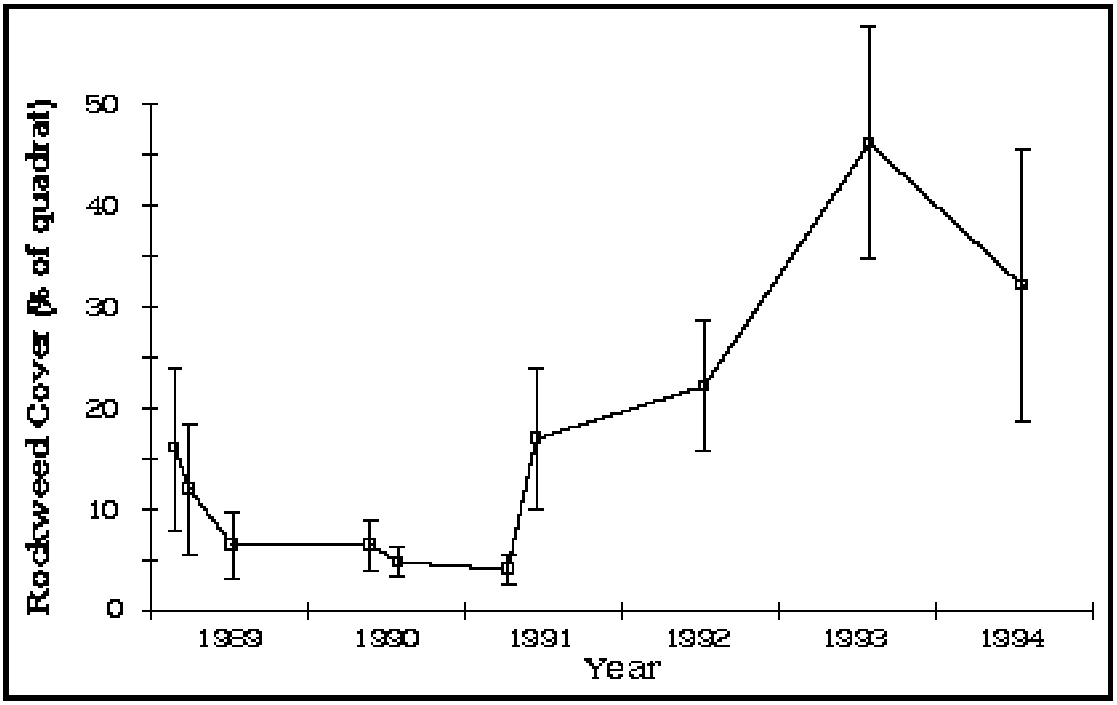


Figure 64. Percent cover of rockweed (*Fucus gardneri*) along the Snug Harbor biology site middle intertidal elevation, 1989-1994.

This variability in cover at the middle intertidal elevation can also be shown in a qualitative, powerful way by a series of photographs taken at the same location between 1990 and 1995 (Figures 65A-65F; photos for 1995 are included here, even though transect results are not, in order to affirm the changes observed). This series illustrates the magnitude of year-to-year changes in the epibiotic cover of one boulder, located just below the middle intertidal study transect (whose location relative to the boulder is shown in Figures 64B and 64C). Figure 65A shows young rockweed cover on the boulder which, by 1991 (Figure 65B), had continued to grow and cover the surface. However, between 1992 and 1994 (Figures 65C-65E), the rockweed cover steadily diminished and, by 1994, was limited to sparse germling plants. Cover in 1995 did not increase over that in 1994 (Figure 65F), although the germlings visible in 1994 appeared to have persisted and grown. Figures 65D and 65E (1993 and 1994) also show the marked decline in rockweed above the boulder near the middle elevation transect in the angular cobble rubble. Figures 66A through 66E provide another photographic time series at Snug Harbor between 1990 and 1994 (no photo was available for 1991). In this series, the increase in rockweed cover between 1990 and 1993 is evident, as is the substantial decline in 1994 that continued into 1995

A

B

Figure 65A,B. Time-series photos of a large boulder in the middle intertidal zone of the Snug Harbor biology study area. Photos A-F document conditions between 1990 and 1995. Photos by A. Mearns, NOAA/HAZMAT.

C

D

Figure 65C,D. Time-series photos of a large boulder in the middle intertidal zone of the Snug Harbor biology study area. Photos A-F document conditions between 1990 and 1995. Photos by A. Mearns, NOAA/HAZMAT.

E

F

Figure 65E,F. Time-series photos of a large boulder in the middle intertidal zone of the Snug Harbor biology study area. Photos A-F document conditions between 1990 and 1995. Photos by A. Mearns, NOAA/HAZMAT.

A

B

Figure 66A,B. Time-series photos of the middle intertidal zone of the Snug Harbor biology study area. Photos A-E document conditions between 1990 and 1995, respectively (no photo available for 1991). Photos by A. Mearns, NOAA/HAZMAT .

C

D

Figure 66C,D. Time-series photos of the middle intertidal zone of the Snug Harbor biology study area. Photos A-E document conditions between 1990 and 1995, respectively (no photo available for 1991). Photos by A. Mearns, NOAA/HAZMAT .

E

Figure 66E. Time-series photos of the middle intertidal zone of the Snug Harbor biology study area. Photos A-E document conditions between 1990 and 1995, respectively (no photo available for 1991). Photos by A. Mearns, NOAA/HAZMAT .

Table 29. Abundance of periwinkle snails and limpets recorded along the upper intertidal transect at Snug Harbor, 1989-1994.

SPECIES OR TAXON	Sep-89	Jul-90	Sep-90	May-91	Jul-91	Jul-92	Jul-93	Jun-94
L. scutulata	12±10	7.2±3.1	2.0±1.9	1.0±1.7	0.4±0.9	2.4±2.7	52±36	55±79
L. sitkana	19±19	14±13	12±4.3	0.4±0.6	1.2±1.1	18±14	119±20	152±178
Lottia pelta	-	-	0.4±0.6	0	0	0	0.2±0.4	0.2±0.4
Tectura persona	-	0	0.8±1.1	0	0	1.8±1.1	13±5.8	26±6.4
Tectura scutum	-	-	0.6±1.3	0	0	0	0	0
Lottiidae, unid.	1.8±4.0	1.6±2.3	0.4±0.6	0	0.2±0.4	0.2±0.4	0	2.0±2.8

- indicates specific species not enumerated in given month/year.

Table 30 summarizes results for abundance or density of common intertidal epifauna along the middle intertidal transect between 1989 and 1994. The results for these organisms were highly variable, both within-site in a given year and over the six-year time frame for which results were available. Abundance of the periwinkle snails *L. scutulata* and *L. sitkana*, which were not observed at all along the transect in May 1989, peaked in 1992 before declining in 1993 and 1994. Limpets (represented by *L. pelta*, *T. persona*, *T. scutum*, and Lottiidae) were found in the study quadrats during each visit except for the first, in May 1989. During the 1993 and 1994 enumerations, all four taxa of limpets were documented. Percent cover of mussels, *M.* cf. *trossulus*, has varied, with a peak measured in 1993.

The black patches on the boulder clearly shown in Figures 65D through 65F are mussel cover. Mussels were also present on the boulder between 1990 and 1992 (Figures 65A through 65C), but are less visible in the photographs. The figures indicate that mussel cover increased between 1993 and 1994, but showed a sharp decline in 1995 (Figure 65F).

At this point, the NOAA program can document the epibiotic changes that have occurred over time, but cannot definitively identify causes for the notable trends discussed above. However, Houghton et al. (1996) found that the decline in rockweed cover observed at Snug Harbor and other oiled sites was not found at the unoiled reference sites. For this reason, they suggested that the marked reduction in rockweed cover may reflect the natural culmination of the life cycle of the plant. That is, oiling and cleanup activities in 1989 wiped out the usually diverse mix of year classes for rockweed, and the plants that began growing in late 1989 and in 1990 reached the end of their life spans in 1994 and 1995. The reduction in plant cover, then, would reflect the natural dieback of rockweed in the intertidal zone. Absence of significant grazing pressure from herbivores, whose numbers were reduced immediately after the spill, would have contributed to the initially rapid increase in plant cover observed both in quadrat results and in photographs.

Predatory drills, *Nucella* spp., are common inhabitants of the rocky intertidal, but have been relatively scarce at the Snug Harbor site (Table 30). In May 1989, we observed unoiled but moribund specimens of the predatory drill *Nucella* spp. that had recently crawled from unoiled under-rock refugia onto oiled substrate. Of the ten visits made by biologists between 1989 and 1994, *N. lamellosa* has been observed along the middle intertidal transect only twice. *N. lima* has been observed more frequently (eight of ten times) but in relatively low numbers. *Nucella* were observed in highest numbers at Snug Harbor during the most recent two sampling visits, in 1993 and 1994.

Lower Station

At the lower intertidal transect in Snug Harbor, no surface oil has been reported since September 1989 (Table 27) despite the fact that in May 1989, oil coverage was recorded as being 100 percent. Rockweed cover followed a trend similar to that along the middle intertidal transect, where cover was high in 1989, declined and remained lower through 1990, showed steady increases 1991 through 1993, and declined slightly in 1994 (Table 28).

Other epibiotic taxa varied substantially over the five-year period (Table 31), and did not follow the same pattern of abundance as rockweed. With the exception of a few barnacles and an unidentified fish, no living animals were found at the lower intertidal elevation in May 1989. In contrast, over twenty taxa were enumerated in 1994.

Among the animals, limpets were completely absent from the lower transect in 1989, but have been found in variable numbers on each visit since. We have observed hermit crabs (*Pagurus hirsutiusculus*) in the lower intertidal since June 1989, but their numbers increased from around one animal per quadrat before September 1990 to between three and 12 individuals afterward.

Epifauna such as limpets and hermit crabs, living in intimate contact with the substrate and unable to seal themselves off from a contaminated habitat, would be expected to be vulnerable to oiling. The heavy initial oiling conditions and the near-absence of these animals along the lower transect at Snug Harbor through 1989 was consistent with this.

Table 30. Abundance of common epifauna recorded along the middle intertidal transect at Snug Harbor, 1989-1994.

SPECIES OR TAXON	May-89	Jun-89	Sep-89	Jul-90	Sep-90	May-91	Jul-91	Jul-92	Jul-93	Jun-94
L. scutulata	0	39±41	16±28	39±55	18±18	21±17	47±19	56±41	76±71	44±46
L. sitkana	0	6.2±12	1.0±1.9	25±31	9.8±8.4	9.2±7.7	17±7.6	91±85	38±39	44±36
Lottia pelta	-	-	-	0	0	0.2±0.5	0	1.3±2.0	1.3±2.0	0.6±1.3
Tectura persona	-	-	-	-	0.2±0.2	0	0	0	0.1±0.3	0.3±0.5
Tectura scutum	-	-	0.4±1.3	0	0.2±0.2	0.8±0.5	0.1±0.3	0	3.2±3.4	3.7±4.0
Lottiidae, unid.	0	7.2±8.9	10±13	7.3±5.6	13±16	4.8±4.4	7.4±6.9	4.8±10	1.2±3.2	1.6±4.4
Mytilus cf. trossulus (%)	3.5±3.7	0.9±0.2	1.0±0.8	6.0±11	2.1±3.6	2.9±3.5	2.9±3.7	5.2±6.0	9.5±8.3	5.2±4.1
Pagurus hirsutiusculus	0.4±0.6	0.2±0.4	5.7±9.1	2.4±4.3	5.4±4.4	0	2.4±3.6	8.5±18	26±28	5.8±6.0
Nucella lamellosa	0	0	0	0.4±1.1	0	0	0	0	3.5±7.0	0
Nucella lima	2.4±5.4	0	0.6±1.1	1.6±1.5	0.4±1.3	0.2±0.5	0	0.2±0.4	1.3±2.9	3.1±3.8

- indicates specific species not enumerated in given month/year.

Table 31. Abundance of common epibiota recorded along the lower intertidal transect at Snug Harbor, 1989-1994.

SPECIES OR TAXON	May-89	Jun-89	Jul-90	Sep-90	Jul-91	Jul-92	Jul-93	Jun-94
Neorhodomela oregona	42±31	0.3±0.4	31±20	26±23	24±19	28±22	22±11	13±10
Pilayella littoralis	9.0±11	0	5.9±16	0	16±14	28±20	20±13	48±27
Ulva/Ulvaria spp.	3.4±4.0	10±4.6	0	4.4±13	2.1±2.2	0	0	1.4±2.1
Filamentous green algae	0	41±24	58±33	77±20				
Blue-green algal crust	-	-	0	0.1±0.2	66±19		-	
S. balanoides	0	0	2.6±6.3	5.1±10	2.1±1.9	2.0±2.4	1.4±2.9	0.2±0.6
M. cf. trossulus	0	0	0.1±0.2	0.05±0.2	1.4±2.0	0.3±0.4	0.3±0.4	0.4±0.9
L. sitkana	0	0.2±0.4	0.5±1.6	0	1.2±1.1	1.0±1.0	0.7±1.5	0
L. scutulata	0	0	0	0.4±1.3	7.6±12	2.5±3.0	7.3±6.5	0.1±0.3
Nucella lima	0	0	0.7±1.9	1.5±2.6	0	0.7±1.2	0.7±1.9	0.7±1.2
Nucella lamellosa	0	0	0	0	0.1±0.3	0.2±0.4	0	0.1±0.3
Lottia pelta	-	0	-	-	0	0	0.1±0.4	0.6±1.3
Tectura persona	-	-	-	-		0	-	0.1±0.3
Tectura scutum	-	-	-	-		0	0.6±1.1	1.6±2.6
Lottiidae, unid.	0	0	8.5±11	10±17	9.1±14	4.8±10	0.3±0.8	0
Pagurus hirsutiusculus	0	1.0±1.7	0.6±1.1	3.6±3.5	3.1±3.0	12±12	5.7±4.6	3.9±6.0

- indicates specific species not enumerated in given month/year.

Tissue Chemistry

In 1990, when tissue samples were analyzed for all four organisms initially selected for chemical analysis (mussels, periwinkle snails, drills, and starfish), Snug Harbor samples yielded relatively higher concentrations for three of the four organisms targeted. Only concentrations in mussel samples were low relative to the other sites sampled. Even with these higher tissue concentrations in predatory species like *Nucella* and *Pycnopodia* found in Snug Harbor (relative to results in the same species at the other monitoring sites sampled), there was no indication that levels were being biomagnified in the food web. In other words, hydrocarbon concentrations did not appear to increase from prey to predator.

Tissue concentrations in littorine snails were analyzed in the monitoring program only in 1990. The July 1990 sample from the Snug Harbor rocky biological site contained an elevated PAH level for littorines. The soft tissue concentration of 2.0 ppm dry weight was the second highest measured in *Littorina*, behind the 5.4 ppm found in a sample collected at Shelter Bay on a heavily oiled boulder. Excluding these two values, the mean value of fifteen other sites where samples were collected in 1990 was an order of magnitude lower at 0.24 ppm. The Snug Harbor rocky site concentration in *Littorina* was an order of magnitude higher (2.0 ppm vs. 0.2) than that found in the same species at the nearby gravel beach site in the inner arm of the bay.

Between 1990 and 1992, tissue PAH concentrations in *Mytilus* samples were relatively constant and relatively low: six separate samples analyzed in that time frame averaged 1.1±0.5 ppm. By 1993, however, there was an indication that there was a reduced level of exposure to mussels, in that tissue concentrations at Snug Harbor had declined to 0.1 ppm.

In the predatory snail *Nucella lamellosa*, tissue concentrations of PAHs measured at Snug Harbor were relatively high. The 1.4 ppm found there was exceeded in 1990 only by the 2.4 ppm measured at Smith Island. The other ten sites for which samples were available averaged 0.1±0.1 ppm for PAHs in *Nucella*.

Similarly, for the sea star *Pycnopodia*, concentrations found in 1990 at Snug Harbor were elevated over those found elsewhere. The concentration of 0.4 ppm, while not high compared to concentrations measured in other organisms like mussels, nevertheless equaled the maximum found in sea stars in 1990 (the sample collected at Northwest Bay Islet also contained 0.4 ppm). The average for the other ten *Pycnopodia* samples collected and analyzed in 1990 was 0.06±0.07 ppm.

The results from 1990 indicated that compared to other sites monitored for the NOAA study, PAHs were biologically available at the Snug Harbor site—particularly to organisms other than filter feeders. Although chemical analyses for organisms other than mussels and clams were discontinued in the monitoring program after 1990, analyses of mussel tissue from the Snug Harbor site in 1993 indicated a decline in bioavailability to that organism.

DISCUSSION

The section of shoreline in Snug Harbor that included both the biological and geomorphological sites was among the few oiled locations in Prince William Sound that were excluded from aggressive cleanup in 1989. Results of monitoring at this Snug Harbor set-aside suggest that even when sheltered from wave action, oiled rocky areas tend to clean up fairly well on their own. The study sites for the NOAA monitoring program are stable, low-energy shorelines, located in a protected arm of Snug Harbor. Despite the apparent lack of exposure to significant wave action, both the geomorphological and biological study teams documented a substantial reduction in surface oiling at their respective sites in the first year after the spill. By 1992, the biological team noted only a fraction of a percent surface cover of oil where, in 1989, the cover had been described by shoreline survey teams as 95 percent. The geomorphologists recorded a similar decline, although small isolated patches of mousse were still found in 1994.

Because the wave energy level at this site is so low, the oil was reduced by mechanisms other than physical abrasion, such as desiccation and clay-oil flocculation. In May 1990, the thick oil coating was observed flaking from the top of the rocks, much like dry, chipping paint, at both the Snug Harbor set-aside site and another located in Herring Bay. The oil coating on the side of the rocks was much softer and more resistant to removal. The oil on the top of the rocks, in direct sunlight for the long summer days, was apparently weathering at a faster rate then oil on the sides. We did not see this flaking nature of the oil on treated shorelines, where the thickness of the oil had been reduced by washing with hot water. It appeared that only the thicker coating of oil was subject to such desiccation and ultimate flushing by the tides.

Bragg and Owens (1995) demonstrated in the laboratory that oil was removed from *Exxon Valdez*-contaminated sediment at seawater flow velocities below those resulting in sediment movement, precluding abrasion as a factor in the hydrocarbon reduction. This would suggest an alternative mechanism for oil removal from low energy shorelines such as the Snug Harbor site.

It is possible that flocculated oil removed from the rocky substrate would also increase the biological availability of oil by potentially exposing organisms in the water column and benthos, but results from chemical analyses performed for the NOAA monitoring program were not sufficient to evaluate this (water column and suspended particulate analyses were not performed). Although Table 26 and Figure 59 suggest a modest increase in surface sediment hydrocarbon concentrations with time in the lower intertidal while those in the middle and upper have steadily declined, the relatively low tissue hydrocarbon levels found in mussels indicated that exposure to such filter feeders was low. Bragg and Owens (1995) noted potential concerns about flocculated oil sinking and contaminating the benthos, but stated that the flocs which form are either positively or neutrally buoyant. This would promote their dispersion by currents and—according to the authors—explain why flocculated residues would not occur in offshore sediments above detection limits.

The higher concentrations found in 1990 in intertidal organisms besides mussels indicates that allowing the oil to remain on the surface of the substrate increases the likelihood of elevated tissue concentrations in some intertidal organisms, particularly in those organisms most intimately associated with that rock surface (i.e., the snails *Littorina* and *Nucella*). Biological observations from 1989 showed that organisms such as hermit crabs and limpets suffered mortalities when the oil came ashore, but these animals have since returned to the site in densities comparable to pre-spill conditions. While some biota (mussels, snails) were less acutely sensitive to the oil, others known to have been present on the pre-spill shoreline (some snail species, some algae) have not yet returned.

Comparing Results with Intertidal Ecological Models

There is a substantial literature on ecological succession and the recovery of intertidal communities from disturbance. These include studies of recovery from oil spill events, but a broader examination of the disturbance literature is relevant as well. For example, McCook and Chapman (1993) examined rocky community interactions following massive ice scour. Although the initial disturbance was very different in nature from an oil spill, the effect on biological communities was similar in that whole expanses of shoreline were effectively denuded.

Newey and Seed (1995) investigated the effects of the *Braer* oil spill on rocky intertidal communities in the Shetland Islands, and concluded that the major impact of that incident was to remove key grazing species such as limpets and littorinid snails. The absence of these species permitted opportunistic algal species to grow relatively unchecked. Newey and Seed, citing the work of Southward (1982), predicted the following progression as the affected areas recover:

> The breakdown in biotic interactions, particularly the loss of grazing herbivores from the community, results in a ’flush’ of ephemeral algae. In the absence of grazers, there may also be an upward extension of the lower shore algae, and heavy settlements of fucoids. This stage is then typically followed by the reappearance of grazing herbivores, often at greater densities than were previously present. The community may then proceed through a series of severe fluctuations of a few dominant interacting species, before diversity and equilibrium are restored.

At least at this descriptive level, there are distinct similarities to what we have seen in Prince William Sound.

Farrell‘s 1991 study of an intertidal community on the central Oregon coast presented a less functionally oriented picture of succession in a rocky intertidal environment, but nonetheless yielded interesting and consistent results. Farrell found that succession followed the same general sequence at three different sites where substrate plots were cleared. The barnacle *Chthamalus dalli* was the initial colonizer, later replaced by the barnacle *Balanus glandula*. Algal species such as *Pelvetiopsis limitata*, *Fucus distichus*, and *Endocladia muricata* colonized only after *B. glandula* had established itself.

These types of models of community succession following disturbance have been popular in the literature for many years. It is reasonable to ask, therefore, whether the observed conditions at Snug Harbor have been consistent with the models above, within the limits of extrapolation.

The recent decline in cover by the common rockweed, *Fucus gardneri*, was apparent both from middle intertidal transect enumerations (Figure 64) and the site photographs taken over most of the study period (Figures 64 and 66). Whether this decline can be attributed to oil or cleanup activities remains a question for further investigation. In studies examining a very similar intertidal community in Nova Scotia, McCook and Chapman (1993) investigated the relationships among different portions (or “guilds”) and the influences on recovery of rockweed cover following severe ice-scour. Ice conditions caused the same degree of disturbance as oil and subsequent cleanup. A number of previous studies cited by the authors suggested that persistence of fucoid canopies in the rocky intertidal was due to predation by *Nucella* snails on filter feeders (barnacles and mussels), and grazing by periwinkle snails on opportunistic and ephemeral algal species. However, they found that, in the absence of large numbers of these snails in their study area over their study period, the most significant factor affecting *Fucus* recruitment was the presence or absence of blue-green algal mats. The mats apparently provided a favorable surface for germlings to settle and ultimately penetrate, and may have helped to protect embryonic plants by sustaining moist conditions between periods of tidal submergence.

Although the roles and relative importance of predator-prey and grazer-algae interactions in structuring the Nova Scotian intertidal studied by McCook and Chapman was unclear, it seems reasonable to infer that these kinds of relationships have been important in Prince William Sound. Fluctuations in abundances support this: both *Nucella* and littorine snails were present and at times abundant at the Snug Harbor site. Increasing populations of *Nucella* would be expected to limit populations of barnacles and mussels, theoretically favoring greater recruitment of other epibiota like *Fucus* and opportunistic algal species. Herbivores like littorine snails (present in increasing numbers at Snug Harbor) would—again theoretically—graze on those opportunistic algae. By controlling the growth of ephemeral green algae, grazers would, on the one hand, favor increased cover of rockweed. On the other hand, the large community of littorines would have an inhibitory effect by feeding on the blue-green algae that McCook and Chapman found facilitated *Fucus* settlement and growth.

In April 1989, at another rocky site studied by the NOAA biology team in Northwest Bay, a rocky platform was documented after oiling but before washing as being completely covered with a *Fucus* canopy. This canopy was killed by the washing, leaving bare rock by June 1989. While a heavy growth of a blue-green alga was found two years later in May 1991 on the rock surface, a large population of *Littorina scutulata* was also observed on the mat (Figures 67 and 68). When the sampling team returned in July 1991, however, the blue-green mat was gone and the numbers of littorines substantially reduced. Regrowth of *Fucus* to the bedrock at this site has been very slow. Based on the findings of McCook and Chapman, the grazing of blue-green algal mats could have delayed recovery of *Fucus* canopy at this site. The large expanses of bare rock evident during recent visits were consistent with this. At the Snug Harbor site, the increases in numbers of *Littorina scutulata* and *L. sitkana* were observed over the same period when *Fucus* cover began to decline. The wide fluctuations in plant and animal cover may reflect the interactions between forage plants and grazers, which would affect rockweed cover both directly and indirectly.

In addition to providing important non-treatment comparison data for the overall monitoring program, results from the Snug Harbor sites identify some of the tradeoffs associated with not removing oil from a shoreline of this type: noticeable amounts of surface oiling of the upper intertidal zone for at least a year, but relatively effective natural removal after that time; some initial mortality to resident biota (likely to take place regardless of the treatment strategy chosen); short-term, relatively low-level bioaccumulation effects in grazers and predators; and possible longer-term absence of some species. Substantial changes continue at this site. Determination of whether these can be linked to the spill and its cleanup is a current and as yet unfulfilled goal. However, disruption of pre-existing relationships among predators, prey, grazers, and forage plants seems a likely factor in causing the results observed at Snug Harbor.

Figure 67. Photograph of blue-green algal mat observed at Northwest Bay Islet site by NOAA biological team in May 1991. Note *Littorina scutulata* grazers. Photograph by G. Shigenaka, NOAA/HAZMAT.

Figure 68. Photomicrograph of blue-green mat pictured in Figure 66. Photo by S. Lindstrom, University of British Columbia.

DISCUSSION, SUMMARY, AND CONCLUSIONS

By now, it should be apparent that this program has generated a tremendous amount of information about the study sites in Prince William Sound, information that will require substantial time and effort to analyze and interpret. In truth, this process has only begun. However, the need for relevant and useful guidance for spill response has not diminished, and this remains the overriding priority for the NOAA research effort. Although this program resembles other long-term environmental monitoring efforts, for spill responders, resource managers, and those with an interest in minimizing environmental harm during an incident like an oil spill, the focus for this study has been, "What lessons can we extract from the *Exxon Valdez* experience to enable us to do a better job next time?"

The objective of this report was to focus on trends in geomorphological, chemical, and biological conditions at four different sites in Prince William Sound that had been oiled by the *Exxon Valdez* spill. This site-oriented approach differs from that used in the core biological monitoring program (where analysis is based on changes among categories of sites grouped by oiling and treatment histories), but is similar to that used in the geomorphological studies. As time has passed and the differences among the arbitrarily defined categories of sites have diminished, focusing on temporal trends at the sites has become both more illuminating and more interesting. What has become most apparent is that the nature of recovery has differed at the study sites, but the reasons behind these differences are not always as apparent.

SUMMARY OF CONDITIONS AT THE SITES

The four sites described in this report represent very different physical settings, but all four were moderately to heavily oiled. With the exception of the Snug Harbor site, a designated set-aside that received no shoreline cleanup, the selected sites underwent aggressive treatment relying on warm- and hot-water pressure-washing. Other techniques, such as the use of chemical shoreline cleaners and movement of contaminated sediments into the surf zone, were also employed at some sites.

Oil has persisted at the four locations to varying degrees. At Smith Island and Block Island, oil can easily be found below the surface of the beaches in greater quantities and in a less weathered state than is the case for most other sites in the overall monitoring program. We believe that the physical characteristics of the shorelines that initially permitted the oil to penetrate deeply below the surface layers have also permitted it to remain in the environment, protected from important physical and biological degradation processes. The amounts and relative freshness of the residual oil at these two sites have also resulted in a greater availability to resident intertidal organisms. Nevertheless, this increased bioavailability has not necessarily translated into increased adverse biological effect: Block Island is home to one of the most robust infaunal assemblages described in the monitoring program. On the other hand, indications of more subtle effects at Block and Smith islands may reflect chronic exposure to elevated concentrations of hydrocarbons in bivalve species that are gender-offset in their reproductive timing.

The slow pace of recolonization or recruitment for macro-infaunal species such as hardshell clams at the aggressively washed coarse-sediment at Northwest Bay is notable because the effect does not appear to be related to oil contamination. Washing and removing residual oil from the beach at Northwest Bay West Arm may have prevented a long-term source of oil exposure for that site. Although the sediment chemistry results for the middle intertidal elevation are variable, they and selective trenching by survey teams have shown little evidence of the widespread subsurface contamination found at Block and Smith. Chemistry results for the lower intertidal region at this site have been uniformly low, and transplants of clams to the site have indicated low biological availability of oil. The washing activities at Northwest Bay, combined with natural processes, apparently quickly reduced the gross contamination at this site. In doing so, however, the attendant alteration of the sediment structure may have inhibited the recolonization of the site by the hardshell clams that were known to have been abundant before treatment. Although there is some indication that the Northwest Bay sediments are deficient in the smallest grain-size fractions and in organic carbon and nitrogen, additional studies and a longer-term record are necessary to more conclusively demonstrate a link between physical sediment characteristics and infaunal recruitment.

Because oil penetration issues are of much less importance for rocky shorelines such as Snug Harbor, the consequences of not cleaning (in terms of both oil persistence and biological effects) would be expected to have been less severe than shorelines where subsurface oil reservoirs developed and persisted. Observations from Snug Harbor support this, despite an initial mortality suffered by epibiota that came into contact with the oil when it washed ashore. Disappearance of surface oil has been surprisingly rapid for a site where cleanup did not occur, and the NOAA/HAZMAT geology team has documented qualitative differences in the nature of the oil on different faces of the rocks at the Snug Harbor site. Those observations and the relatively sheltered nature of the site support the idea that differential physical weathering, perhaps in concert with the recently described phenomenon of clay-oil flocculation, may be responsible for the bulk of oil removal from the untreated and sheltered site.

However, the biological survey data and the photographs showing general characteristics of plant and animal cover at the Snug Harbor site show wide fluctuations in abundances of some of the important epibiota. Specifically, we have noted substantial declines during our most recent visits to the site. Are these attributable to the oil spill, or do they reflect completely unrelated, Sound-wide phenomena? The literature on ecological recovery and succession suggests that community oscillations similar to those seen at the study sites are common responses to disturbance. Whether we will be able to confirm this for the sites we study remains to be seen.

Biological effects resulting from exposure to residual *Exxon Valdez* oil have not been easy to define, particularly after the obvious acute effects diminished: the intuitive relationship of increasing effect with increasing level of oil has not been a consistent observation at the sites studied for this report, particularly after a period of two to three years post-spill. It suggests that the biological effect of residual oil a few years old may be less than expected (due to weathering of the product, or differences in route of exposure), or perhaps occurring at a more subtle level than traditionally examined.

RESEARCH QUESTIONS

We will probably never fully understand the long-term effects of the *Exxon Valdez* oil spill. There are, however, areas of fundamental research that would help us to interpret the research results we have garnered thus far. Some of these are detailed below, and provide guidance for additional studies that we would like to pursue over the remaining course of the monitoring program.

ROUTES OF HYDROCARBON EXPOSURE FOR INTERTIDAL ORGANISMS

It is apparent that resident biota (primarily bivalve molluscs) are subject to a continuing chronic exposure to residual oil at some locations. While we can document the accumulation of oil in tissues, we have not been able to determine the route of exposure to the organisms. That is, does oil bind to particulate material in the nearshore zone as it leaches out from remaining reservoirs, subsequently resulting in ingestion by filter-feeding organisms? Are organisms exposed via their food sources? Is direct contact with sheens an important route of exposure? By understanding how organisms continue to be exposed, we may then understand how response and cleanup choices made shortly after a spill can influence or enhance longer-term resource recovery.

BIOLOGICAL SIGNIFICANCE OF REMAINING OIL

Is the oil that remains in the Prince William Sound environment significant for the indigenous resources? Is it biologically inert? We have inferred some insights indirectly, but direct assessment has not been a core objective. At this writing, there continues to be support for further remediation and oil removal activities in the Sound. Assessing whether these are *biologically* necessary (as opposed to political or aesthetic choices) would be helpful guidance. Ultimately, the question of biological effect feeds directly into the difficult-to-answer “how clean is clean?” question that spill responders face during the course of a cleanup. We intend to investigate this question within the context of the intertidal organisms that we study, but it must be noted that the large part of the ecosystem has been unaddressed, even within the body of research that has taken place under Trustee, Exxon, and other auspices.

FUNDAMENTAL RELATIONSHIPS IN THE INTERTIDAL COMMUNITY

It is stating the obvious to emphasize the importance of understanding how the Prince William Sound intertidal community functions, as a precursor to understanding the spill’s effects. This has become increasingly apparent as we garner enough information to portray longer-term trends in and among members of the intertidal communities that we have studied. We have documented the large fluctuations in abundances of certain representative taxa, and now want to ascertain what is driving these oscillations and whether they are related to oil exposure. To do so, however, some fundamental information is required that we’re not sure we have, or can extrapolate.

Much of this information is related to the seemingly simple questions of, Who is eating whom (or what)? and Is “top-down” predation the primary factor in structuring the Prince William Sound intertidal environment? For example, does direct grazing control cover of rockweed, or does competition with other epibiota (algae, mussels, barnacles)? Does predation limit littorinid snail populations, or is food availability the controlling factor? Some of this information can be inferred from the available ecological recovery and succession literature, and that continues to be a favored approach for the NOAA program. However, it is inevitable that gaps in knowledge will remain, and direct research may represent the only way to answer our questions.

REPRODUCTIVE STRATEGIES AND RECOVERY OF IMPACTED AREAS

It was apparent that the large amount of oil that washed ashore initially and the intrusive nature of the subsequent shoreline cleanup immediately killed large numbers of intertidal infauna and epibiota. The reproductive strategies used by the affected component organisms have undoubtedly influenced the course of recovery, but we can only speculate on the degree and mechanism of influence or extrapolate from similar systems.

For example, those animals that use direct larval development (on-site) would be expected to be more severely affected by an oil spill than animals that use planktotrophic development (dispersal of planktonic larvae). Recovery of the direct populations would depend upon migration of unimpacted animals into areas rendered depauperate by oiling or treatment, or alternately by floating or rafting into the impacted areas. In contrast, large numbers of planktonic larvae from remote locations could be carried into spill-affected areas relatively quickly, and when conditions became favorable for recolonization, successful recruitment could take place.

In contrast to the apparent recruitment advantage that might be conferred in a spill situation by a planktonic reproductive strategy *vis a vis* direct development on-site, the egg cases sometimes employed in direct development (as in the example of the drills *Nucella lamellosa* and *Nucella lima*, shown in Figures 69 and 70 below) may offer a degree of physical protection from toxic chemical exposure lacking in free-floating planktonic eggs. Research by Lord (1986) on another *Nucella* species indicated that egg cases were not necessary for successful development of embryos, but appeared to provide some level of antibiotic, antibacterial protection. It is possible—although not demonstrated—that egg cases could also provide additional protection in the early stages of an oil spill, while oil is still on/in the water.

While we can speculate about the role of reproductive strategies in shaping recovery from major disturbance, one of the fundamental difficulties in assessing the situation in Prince William Sound is the lack of knowledge about invertebrate life histories. Giangrande et al. (1994) noted that, in general, there is very little information on marine invertebrate life cycles. They point out that, for polychaetes, a relatively well-studied group often used in environmental assessment, only about five percent of species have a known life cycle. For other taxa, this percentage is much less.

Figure 69. Photograph of *Nucella lamellosa* and egg cases, taken at NOAA Crab Bay site in May 1991. Photo by G. Shigenaka, NOAA/HAZMAT.

Figure 70. Photograph of *Nucella lima* and egg cases, taken at NOAA Ingot Island site in May 1991. Photo by A. Mearns, NOAA/HAZMAT.

Complicating the situation is the fact that generalizations about reproductive strategy within taxa or even within genera are not possible. For example, in Prince William Sound, the periwinkle snails *Littorina scutulata* and *Littorina sitkana* employ different strategies: the former broadcast larvae planktonically, while the latter lay eggs on-site (Yamada 1989). Figure 71 shows *Littorina sitkana* and its egg mass photographed at one of the NOAA study sites in 1991. This kind of difference between species of the same genus has been observed elsewhere, e.g., with *Littorina saxatilis* and *Littorina littorea* in the North Atlantic (Johannesson 1988).

Figure 71. Photograph of *Littorina sitkana* and egg mass, taken at NOAA Bass Harbor study site in May 1991. Photo by G. Shigenaka, NOAA/HAZMAT.

The consequence of the overall lack of knowledge about how organisms are affected by the spill reproduce is that it presently will be difficult to conclude whether one reproductive strategy or the other has resulted in a recovery rate advantage. Nevertheless, it becomes more apparent that the hydrodynamic regime of a shoreline location is an important determinant of the kinds of organisms that readily recolonize a site, and the level of ease with which that recolonization can occur.

SEDIMENT CHARACTERISTICS AND INFAUNAL RECOVERY

One of the major conclusions we have inferred from our research results is that infaunal recovery remains delayed where the substrate was highly disturbed by washing in 1989. Is there a single most important factor responsible for facilitating infaunal recovery, or is it some combination of factors? What are they? How long will it take for comparable (to conditions before the spill) beach characteristics and infauna to return? Is there some way to accelerate the recovery through sediment modification (similar to what is practiced in clam-rearing areas of Puget Sound)?

Recent scientific reviews have suggested that it the hydrodynamic regime structures both the sediment characteristics and infaunal community of a given area. While it is a relatively straightforward process to collect information on sediment grain size, it is much more difficult to garner data on currents and waves. As Hall (1994) commented in a review of the relationship between physical disturbance and marine benthic communities, the equipment for making detailed measurements of such physical parameters is expensive and unavailable to biologists studying the benthos. Given this kind of limitation, Hall identified a research need that is relevant for our studies in Prince William Sound as well: simple summaries that would permit characterization of the physical regime for a given study site in a way that is ecologically meaningful. A significant component of these would be translations of sediment dynamicists' admittedly incomplete understanding into useful models that give ecologists a feel for the importance of physical processes at their sites, compared to areas studied previously.

Many questions remain about recruitment and recovery of infauna. Integrating what is known about nearshore physical processes with what is known about infaunal biology may yield a model much more relevant for interpreting Prince William Sound conditions.

PREDATOR-PREY AND GRAZER-ALGA RELATIONSHIPS

As we suggested in the Snug Harbor discussion, the wide fluctuations in certain components of the intertidal ecosystem suggest complex relationships that continue to adjust themselves with increasing temporal distance from the spill event. While we can infer the importance of one component or another in determining the synoptic composition of the biological community, it is almost certain that manipulative experiments—i.e., inclusion or exclusion studies—would be a much more elucidating means for quantifying relative roles. Invited scientific observers of the NOAA monitoring program (e.g., R. Paine, University of Washington, pers. comm.) have stressed the importance of predators and grazers in shaping the intertidal assemblage composition, especially at the spatial scales involved in the program.

It has been pointed out that there is an extensive, even enormous, body of ecological literature related to these considerations. It is possible and likely that further insights into the observed conditions at our Prince William Sound sites can be extrapolated from this literature. As previously noted, however, it is also possible and likely that some questions will be addressed most effectively by designing and implementing experimental work at the actual sites of interest.

PHYSICAL AND CHEMICAL CHANGES IN THE DISTRIBUTION OF OIL RESIDUES IN GRAVEL BEACHES

The 1994 geomorphological survey results were characterized by surprisingly little change in the oil residues between 1992 and 1994, in terms of the oil loading and degree of chemical weathering of the remaining oil. The most important oil persistence and weathering patterns are associated with the deeply penetrated and highly persistent oil in gravel beaches, and the factors controlling oil degradation in incipient surface pavements. Nearly one-third of the samples taken 5-1/2 years post-spill were characterized as only moderately weathered, and most of these were from deeply penetrated oil in gravel beaches. Thus, it is very important to continue tracking the physical and chemical fate of these persistent oil residues over time. Because the group of gravel beach stations that includes Smith Island has been consistently sampled since 1989, we have a detailed database on oil distribution with depth and oil weathering patterns.

As part of this work, the historical storm track pattern and intensity should be studied in order to correlate oil removal rates from gravel beaches with storm activity over the entire monitoring period. At the end of the 1989 shoreline cleanup period, the FOSC asked NOAA to predict when winter storms would remove the oil in gravel beaches. We now know that it takes longer than five years. However, the storm intensity over that five-year period should be related to the exposure index for each station, which is a key characterization of the stations that should increase the confidence of station groupings and comparisons. For the geomorphological stations, the EI has been well-correlated with field indicators of exposure, such as sediment grain size and roundness, and geomorphic features such as wave-built bars and berms. Similar field measurements are needed for the biological station at Bass Harbor (a reference site for Smith Island), which appears to be an anomaly in the calculated exposure values.

RECOVERY OF BEACH MORPHOLOGY AND SEDIMENT DISTRIBUTION AFTER BERM RELOCATION

In 1990 and 1991, Exxon conducted berm-relocation cleanup activities at over 25 sites, including the Smith Island site discussed here. In 1994, NOAA found that several of the berm-relocated sites still had not returned to their original profiles and/or sediment distribution patterns. Although the Smith Island site appeared to have recovered, we need to resurvey the site to track and correlate recovery from storm wave exposure. Ultimately, the objective would be to predict the conditions under which berm relocation should not be considered because of potentially long recovery periods.

THE QUESTION OF RECOVERY

We are often asked, because of our involvement with this long-term monitoring program, whether we believe Prince William Sound has recovered from the *Exxon Valdez* oil spill. For statistical reasons, we cannot extrapolate the results from the NOAA monitoring program to generalize about Prince William Sound. We can, however, speak to the universe that is represented by the sites we have studied for several years. With this in mind, the key word, as indicated in the introduction to this report, is “recovered.” Clearly, our sites have come a long way in the process of recovery since 1989, and at the level of the casual observer or occasional visitor to Prince William Sound, conditions have vastly improved. With notable exceptions, few overt signs of the oil spill and the massive cleanup remain. Does this translate into recovery?

Results from the analysis of conditions at four selected sites, as well as from the larger NOAA monitoring program (Houghton et al. in press), reflect a system that is still in physical and biological flux. We do not believe that the criteria specified in our chosen definition of recovery—original functional and structural conditions, return to comparable ranges of variability—have been satisfied. The physical setting, in terms of topographic beach profiles and certainly chemical loading, continue to change and converge on pre-disturbance and background conditions. The above summary of biological conditions at the sites studied for this analysis indicates that we continue to observe, for example, impaired infaunal recruitment and declines in important epibiota. While we are not prepared to directly attribute these to the spill or its cleanup activities, neither are we prepared to rule out the latter as causes.

Gilfillan et al. (1995), interpreting the results from a separate shoreline ecological monitoring program in Prince William Sound, predicted that “There is no reason that complete shoreline biological recovery will not have taken place within a few years following the 1991 survey.” They defined complete recovery as the point when spill impacts are no longer detectable. More specifically, they noted that recovery is not considered to be complete as long as an oiling effect on the biological community, *either increases or decreases* (emphasis added), can be detected. Recalling in particular the oscillations in abundance we have seen for some intertidal community components, our study sites have not yet recovered by this definition either.

THE BOTTOM LINE: IMPLICATIONS FOR RESPONSE

The NOAA monitoring program was not intended to be an esoteric exercise in ecological research. Rather, it was intended to provide research results that would serve as the basis for response guidance in the future. This, in a sense, is another level of "integration" that is a goal of this study: integrating a structured scientific effort into the very operationally oriented world of oil spill response.

Given these goals and mandates, what have we learned and what would we advise in the event of another spill in this kind of environment? The answer is not as simple as the "sound bites" rather prominently featured in the national news media during the first years of this program, which concluded that the cleanup "did more harm than good." While we have found that this was the case in specific instances, the finding needs to be considered within the larger context of the spill response and cleanup. We do continue to observe lasting impacts from the use of intrusive cleanup techniques that are not apparent at sites that did not receive the treatment. But does this imply we would not support the use of those techniques during comparable spills in the future? Probably not; the choice is not between use and non-use but, more likely, between non-use and a more carefully considered and judicious use of the most aggressive methods. As is clearly the case during spill response, the choices involve evaluating environmental tradeoffs to minimize the overall damage to affected resources. There have been—and will be in the future—appropriate circumstances for using even the most intrusive shoreline treatment techniques. Identifying those circumstances and choosing how the methods are used remains the difficult part of the equation.

A few of the specific lessons we have learned from examining trends and conditions at four sites of interest include:

- Aggressive surface oil removal activities do not necessarily ensure the removal of long-term sources of hydrocarbon contamination. If oil penetrates deeply into the beach substrate, it will continue to be biologically available for years, although the environmental consequences of such an exposure are not known.

- Although surface oil removal on oiled but untreated rocky shorelines appears to be fairly rapid, subsurface oil remains and is not very weathered after five years. One mechanism for surface oil removal may be the recently described clay-oil flocculation.

- Even though we do not yet understand the underlying factors, it seems apparent that hydraulic flushing of biologically rich, sheltered gravel beaches can alter previously favorable conditions and inhibit recolonization by infauna. However, the positive tradeoff involved with using the technique is the apparent reduction in hydrocarbon contamination that also can result from use of flushing, and reduction in attendant biological effects linked to hydrocarbon exposure.

- Boulder-cobble beaches generally reflect a higher degree of exposure and are a less stable habitat for biota than other more sheltered shorelines. As a result, they are typically less populated by biota except on that part of the shoreline offering some measure of stability. For example, the portion beneath the mobile armoring layer, on bedrock outcrops, or in the lower portion of the intertidal. This lack of a robust biological community and the high-energy dynamics of the setting make boulder-cobble beaches suitable candidates for aggressive cleanup methods that may not be appropriate or desirable elsewhere. These include such methods as berm relocation, mechanical excavation, substrate replacement, and high-pressure flushing.

- The presence of a coarse boulder armor will significantly slow natural removal of deeply penetrated subsurface oil. The importance of armoring to the persistence of subsurface oil has been one of the major lessons learned about oiled gravel beaches in Prince William Sound. The armor effectively immobilizes the subsurface sediments, except during extreme storm events, such as a ten-year storm. Heavy oil residues persist under the armor, such as at Smith Island, where TPH concentrations of nearly 17,000 mg/kg remained five years after the spill and extensive cleanup efforts. The oil deeply penetrated in these beaches was also the least weathered of all oil residues after five years. At Smith Island, the subsurface oil generated chronic sheens even five years later. Where heavy oil has penetrated gravel beaches with a large, stable armor, it may be necessary to trade off the physical disruptions to the beach profile and sediments associated with sediment reworking for more effective oil removal.

- Our experience in Prince William Sound has underscored the need for and the utility of control and set-aside reference areas. In an ideal world, marine ecosystem baseline studies would exist for an area before a spill occurs, permitting direct assessment of ensuing effects from the incident. In reality, of course, this is rarely the case. The next best point of reference in the study of spill effects are sites in the area that have not been subjected to the stresses of oiling and cleanup.

  If there is an interest in learning from spill events when they occur, we must establish and maintain such sites. Political and public realities often provide compelling reasons for not setting aside areas for comparison. However, this precludes a relatively direct means not only to assess the discrete effects of oil versus those from cleanup, but also to distinguish variability or changes attributable to the incident from those with other causes (e.g., El Niño, earthquakes, unusual climatic conditions, range expansion of introduced species).

- High residual oil contamination does not necessarily translate into an acutely toxic biological environment over the long term. One of the more noticeably oiled sites in this study is also one of the richest, from the perspective of the infaunal community there. Although this runs counter to intuition, it is consistent with what we know about oil weathering and the rapid loss of the most acutely toxic components of crude oil soon after it is released into the environment. A caveat, however, is required: the more persistent components of crude oil include those that have been associated with carcinogenicity and other long-term pathologies. For this reason, it will be interesting to continue to track trends in the intertidal community to elicit whether any chronic problems can be attributed to exposure at oiled sites.

- Our chemical results from the four target sites for this report as well as the other locations sampled for the broader monitoring program support the concept of a threshold concentration in sediments, above which physical processes of degradation are most important and below which biodegradation is the dominant natural removal process. In Prince William Sound on the gravel beaches which predominate, we believe this threshold falls in the range of 10-100 ppm TPAH, with an equivalent TPH value of about 1.5 percent. Although such values must be considered and applied with a great deal of qualification, confirmation of threshold concentrations would provide a reference or target for cleanup decision-makers when pondering the “how clean is clean?” question for ending shoreline treatment. For example, those in charge of shoreline cleanup may decide it would be a prudent use of limited resources to clean a beach only to the extent where natural biodegradation or assisted bioremediation could then take over to further reduce contamination.

- Finally, lessons learned from case studies of oil spills should be used as guidelines, not truths, because every site is different. Spill responders rely heavily on their prior experience to make judgments about the type and degree of cleanup appropriate for a section of oiled shoreline. The approach is necessary because there is not enough knowledge or site-specific data for accurate predictions of the impacts of cleanup or how effective natural removal will be. However, it is extremely important to observe and understand the unique conditions of a site, so that the differences among standard types of

> shorelines can be accounted for in the cleanup approach. The shoreline geomorphology offers many clues to those who will look carefully and see them. Understanding these clues allows the responder to optimize cleanup methods so that they are most effective and least damaging.

Those of us who have been intimately involved with this program from its early days continue to be impressed and, at times, frustrated and bewildered, by the enormous complexity of the Prince William Sound intertidal ecosystem. Returning once again to Sammarco's analogy of the Japanese garden with which we opened this discussion, we now have gained enough perspective to grasp the environmental lay of the land. What remains is to learn more about the forces that have driven the physics, chemistry, and biology of the area toward this result.

It is a daunting task to document the changes taking place over time in this recovering system, and it has been even more challenging to attempt to explain those changes. As the NOAA program moves into the future, we intend to continue the monitoring activities initiated shortly after the spill occurred. Based on the results of that monitoring, however, we hope to explore those conditions and questions that will help us to understand how and why the ecosystem has responded as it has. Ultimately, we may be able to construct a rudimentary model of fate and effects for an environment like Prince William Sound that would provide one level of guidance for spill response in the future. Presently, however, we do not have the information necessary for that task, but are now beginning to understand the questions we need to answer.

As Sammarco (1994) concluded,

> One (scientific) team is not enough. As should become evident through the chapters in this book, more than one team is required to solve one problem, for each team will have its own approach and contribute its own set of pieces to the puzzle. Although we may never have enough pieces to make up a complete and accurate picture of the problem, through this approach, we should acquire enough groups of pieces to gain greater insight into the problem and adjust our own individual and team view accordingly.

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ACRONYMS

AP	asphalt pavement
cc	cubic centimeters
cm	centimeter
CT	coat
FL	film
FOSC	Federal On-Scene Coordinator
GC/MS	gas chromatography-mass spectrometry
GPS	Global Positioning System
HAZMAT	Hazardous Materials Response and Assessment Division (NOAA)
HOR	heavy oil residue
LCV	landing craft vehicle
LOR	light oil residue
LSU	Louisiana State University
m	meter
ml	milliliter
mm	millimeter
MOR	medium oil residue
NOAA	National Oceanic and Atmospheric Adminition
NSC	North Slope Crude
OF	oil film
ppm	parts per million
ppt	parts per thousand
RPI	Research Planning Incorporated
SPMD	semi-permeable membrane devices
ST	stain
TPAH	total polynuclear aromatic hydrocarbons
TPH	total polynuclear hydrocarbons
USCG	United States Goast Guard

APPENDIX

OILING & TREATMENT HISTORIES

APPENDIX

OILING & TREATMENT HISTORIES

BLOCK ISLAND OILING AND TREATMENT HISTORY

Assessment of initial oiling, as recorded in the Shoreline Oil Evaluation form for the shoreline segment was prepared by G. Sergy and dated April 15, 1989. This documented a continuous 15-m band of oiling over the splash, upper, and middle intertidal zones. Both pooled and free oil were noted as being present, at thicknesses less than 0.5 cm. Penetration into the substrate was estimated at 8 cm.

Two interagency Shoreline Cleanup Program forms, which guided treatment activities in 1989, were available for the Block Island site. The first, dated April 15, 1989, recommended the use of the Vikovak vacuum system as a test, flood-wash, steam cleaning, and medium to high-pressure washing. The following was included under "ecological constraints": "None except do not dislodge rockweed holdfasts or mussels." A subsequent form, dated April 21, 1989, recommended the following cleanup activities: washing/flooding, warm water at moderate-/ high-pressure, low-/high-pressure washing. The crews were again directed (under the "ecological constraints" section) not to dislodge rockweed holdfasts or mussels, reiterating a level of concern for middle intertidal elevation plant and animal communities.

The field notes of Alaska Department of Environmental Conservation (ADEC) monitor Scott Menzies documented some of the early cleanup activities that took place on this shoreline segment, between May 20-22, 1989. Excerpts from these are presented here because they suggest the scale of the oiling and cleanup effort as well as problems inherent in the process, especially early in the cleanup operations:

> "…We went across to site 1 of EL-11 on Block Island. They had 4 steam cleaners going by 9:00 a.m., but no 2" hose or header were going yet. This is a very large beach, about 150 yards by 20-50 yards in spots while the tide is out. The drainage of the beach at low tide goes in all different directions. This, plus the size of the cleanup area makes for problems with the positioning of the primary boom. So this morning they have the primary boom strung across the beach with sorbent pads and pom-poms lining it to catch runoff before the tide comes in.
>
> This site had a total of 44 workers plus 8 support personnel.
>
> The site was divided into 2 areas, each with 1 landing craft, 8 2" hoses, one six inch header flushing the entire work area and 2-3 steam cleaners. There was one additional work area on the site north of the first 2 areas. This was a smaller crew of about 10 workers. They had 3 steam cleaners and the rest were hand scrubbing with sorbent pads or pom-poms. The shoreline here was much more rugged than the first two areas, so they were trying to minimize the volume of water, by using only steam cleaners, so that they could collect the oil

> in the pools between the rocks with the pom-poms and sorbents. At low tide they also had an uncontaminated area at the lower level which would get re-oiled with high volumes of water flow."

May 22, 1989:

> "At site 1 EL-11 Mr. Ellison said that they collected 30 barrels of oil and 77 bags yesterday.
>
> At 9:30 a.m. they had 41 workers and 8 support workers, 8 2" hoses, 100' of header, 3 landing craft, 1 skimmer (Egmopol). On this site is a rocky knoll, most of which is below water at high tide. This morning they have a cold water header flushing it, 2 steam cleaners, and 11 people hand-scrubbing. For this knoll, there is basically no primary boom or containment and a lot of sheen is getting into the secondary containment. I brought this to Mr. Ellison's attention and the USCG's attention. Mr. Ellison said he's trying to get a boom, but they're very hard to find now…
>
> At 2:20 on site 1, EL-11 the header pipe was shut down, but flushing with the 2" hoses continued until the header came back on about 10 minutes later.
>
> At 2:40 the tide had been high enough for about 1 1/2 hours that they have all the booms floating and a lot of oil flushed into the water."

Figure 72 is a digitized diagram taken directly from the field notes of another ADEC beach monitor, Alison Woodings. This figure illustrates the configuration of equipment deployed at the study site on July 15, 1989.

Figure 8 shows the upper slope above the tidal flat at this site being hydraulically cleaned by a group of workers on July 17, 1989. In this NOAA aerial photo, a 15-person crew is shown washing oil off the beach. A large pool of oil can be seen contained within a boom, and a large sediment plume is visible in nearby waters offshore. This photo can be compared to the layout portrayed by Ms. Woodings on July 15.

The activities documented in Figure 8 apparently represented a final 1989 cleanup effort for the site, as the Segment Inspection Record dated July 18, 1989, documented that hot-water wash, warm-water wash, water deluge, mechanical, and nonmechanical methods had been completed on the segment.

In 1990, according to ADEC records, the site was located outside of designated work areas, although treatment did occur in the vicinity and there are anecdotal reports of manual removal at the site (M. Hayes, pers. comm., February 23, 1995). The available documentation indicates that the substantive portion of the remedial effort at the Block Island site occurred in 1989.

Figure 72. Diagram based on the field sketch of ADEC beach monitor Alison Woodings illustrating the configuration of equipment deployed at the Block Island study site on July 15, 1989.

To confirm and summarize the nature of the treatments determined for Block Island, both the state of Alaska and Exxon were independently queried as to the nature of the shoreline cleanup techniques that were used at the Block Island site. Treatments from 1989 listed by ADEC (J. Bauer, pers. comm., November 23, 1990) at the specified segment were:

1. Header-hose flood.
2. Warm-/hot-water moderate-pressure wash.
3. Hot-/steam-water high-pressure wash
4. Cold-water high-pressure wash.
5. Omni boom.

6. Maxi barge.

Similarly, treatments in 1989 listed by Exxon (R. Coulter, pers. comm., October 19, 1990) for segment EL-11 were:

1. Hot-water wash.
2. Warm-water wash.
3. Water deluge.
4. Bioremediation.

A more focused examination of site-specific ADEC records requested by NOAA in early 1991 (J. Bauer, pers. comm., January 7, 1991) indicated hot- and cold-water wash, header-hose flood, steam wands, and Omni boom were potential treatments between May 21, 1989, and July 19, 1989. However, use of Omni-boom units was generally restricted to rocky shorelines that were difficult to access by other means, so it is unlikely that such barges were deployed at the study site.

In summary, the direct photographic record, as well as written documentation by field monitors who observed cleanup activities, recorded that this site was heavily oiled and extensively cleaned between May and July 1989. While it is clear that the upper and middle intertidal portions of the tidal flat and rock outcrops were repeatedly treated during this period, the nature of cleanup activities in the lower intertidal is less certain. However, ADEC field notes suggest that although some indirect oiling took place in lower intertidal area (i.e., oil flushed from above), those areas were spared any direct impacts from cleanup. In the biological studies at this site, the middle and upper intertidal transects, and all of the adjacent rock outcrops, are classified as having been oiled and high-pressure, hot-water washed. Because of the wide physical separation between the middle and lower intertidal zones and the low slope of the site, the lower mixed-soft tide flat is considered to have been oiled but not directly treated.

NORTHWEST BAY WEST ARM OILING AND TREATMENT HISTORY

There were two independent Shoreline Oil Evaluations performed for the designated shoreline segment containing the study sites. The first, prepared by C. Dillon and dated April 22, 1989, documented a continuous band of oil across upper/middle/lower intertidal zones in a 3- to 10-m width. Oil thickness was estimated as greater than 0.5 cm, with a penetration of greater than 1 cm. Under comments, Dillon noted "Light oiling on most of innermost cove area becoming moderate with larger size sediment/rocks along eastern stretch of segment."

The other Shoreline Oil Evaluation is somewhat illegible in the archived copy, but it is believed to have been filled out by G. Robilliard and dated April 22, 1989. The general estimate of oil coverage agreed with that by Dillon on the same date: a 20- to 30-m continuous band of oil over the upper/middle/lower intertidal, with 2-cm penetration into substrate. Although an Ecological Evaluation form was included with Robilliard's report, it too is largely illegible.

The Shoreline Cleanup Program record for segment EL-52, dated April 26, 1989, recommended the following: warm-/cold-water washing and flooding, warm water at moderate/high pressure, and low-/high-pressure washing. The "ecological constraints" section noted "Fucus (rockweed) in local, dense patches on rocks at medium/low tide. Use low pressure if practical and minimize walking on, or dragging hoses over large boulders. Avoid streams across beach."

Field notes taken by ADEC monitors documented that a substantial amount of effort was directed toward the cleanup of this site. On June 3, 1989, Dianne Munson described the work force and equipment on location at two work areas at the head of the West Arm. The first, on the eastern half of the beach and roughly corresponding to the NOAA geomorphological study-site location, was classified as 100 percent gravel and measured 50 x 30 m. Fifteen workers were cleaning this location using four high-pressure cold-water units, one landing craft vessel (LCV), and one skiff, with primary and secondary booms and pompoms to contain the oil. The second work area, on the western side and including the area that would be studied by the NOAA biological study team, was classified as 10 percent rock and 90 percent gravel, and measured 80 x 40 m. Twenty workers were deployed here and used one LCV, four high-pressure cold-water units, a header hose. a skiff, with primary and secondary booms for containment.

On the next day, June 4, John Hayes of ADEC documented a similar level of effort at what he called and diagrammed (Figure 73) as sites 1 and 2 of segment EL-52. Hayes counted 27 workers and one security person on scene. Equipment was noted as including two LCVs, one mop skimmer, cold-water header, seven 2" high-pressure cold water hose, one high-pressure hot-water steamer, with a teardrop container for recovered oil.

Figure 73. **Diagram based on the field sketch of ADEC beach monitor John Hayes illustrating the deployment of equipment at the Northwest Bay West Arm site on June 4, 1989.**

Figures 26 and 27 are aerial photographs of the cleanup activities that took place on June 4, described above by Hayes. Figure 24 shows the entire West Arm and the flotilla of vessels deployed to clean the shoreline, while Figure 25 shows cleanup activities at the head of the bay where the NOAA study sites were eventually located.

Members of the NOAA biological studies team (who in 1989 were in Northwest Bay conducting intertidal surveys for Exxon) have noted that from late March or early April 1989 until late May or early June, the pebble beach at the head of Northwest Bay West Arm was heavily oiled throughout the tidal range. By April 27, test washings of portions of this beach had been conducted. On the northeast shoreline, a 5- to 10-m section of cobble/pebble beach had been hydraulically flushed. This dislodged numerous epibiota from the substrate, flushed considerable quantities of pebbles and granules downslope (an estimated 15 cm of sand and gravel were deposited over the substrate at lower elevations), and inverted many larger cobbles such that attached plants were buried. In addition, a small patch of the uniform pebble beach at the head of the arm, just above mean lower low water, had been hydraulically flushed, resulting in a much lighter appearance on the surface than that of the adjacent, unwashed beach. Mussels (*Mytilus* cf. *trossulus*) were embedded abundantly in the surface pebbles of the oily unwashed section, but were not evident in the washed section.

The Segment Inspection Record dated June 14, 1989, documented that warm-water wash, water deluge, and hand wiping took place on segment EL-52. A later record, from August 22, 1989, showed that bioremediation was completed on the segment.

Examination of site-specific records by ADEC in early 1991 (J. Bauer, pers. comm., January 7, 1991) listed hot- and cold-water wash, flood, steam wands, and Maxi Barge as potential treatments between May 23, 1989, and June 20, 1989. Steam wands were used without flooder hoses on some days. Manual raking and manual removal took place on May 22, 1990, with both debris and sediments removed. Both Customblen and Inipol were applied on June 28, 1990, August 21, 1990, and September 4, 1990. It was noted that no Inipol was sprayed near the anadromous stream. This summary is consistent with the field observations from Dianne Munson and John Hayes referenced previously.

A treatment history summary for EL-52B produced by Exxon for a field tour by media representatives detailed the following activities:

- May 20 to June 14, 1989: Warm-water washing and deluge using LCVs, manual cleaning with absorbents.
- August 21, 1989: Inipol.

- May 22, 1990: Manual pickup and tarmat removal.
- June 28, 1990: Inipol and Customblen.
- August 21, 1990: Customblen.
- May 28, 1991: Manual pickup, tilling, and raking.

There has been some disagreement among cleanup and monitoring personnel who worked in Northwest Bay in 1989 as to the precise nature of the equipment used, and more specifically, whether Omni-barge units were deployed as part of the task force assigned to the area. Contractors overseeing shoreline cleanup operations for Exxon in Northwest Bay were interviewed in 1993 (B. Hartley Sr., B. Hartley Jr., pers. comm. July 8, 1993) and could recall no Omni barges in Northwest Bay, only maxi-barges. However, the ADEC field monitor stationed in Northwest Bay in 1989 was also interviewed in 1991, and recalled Omni-barge units present and working in the bay. Available documentation mentions only maxi-barges, so it seems likely that Omni barges were not used. Ultimately, this question is relevant only in determining the degree of intensive shoreline cleanup used in Northwest Bay. However, it does serve to emphasize the difficulties in determining details of field operations.

In summary, the oiling and treatment information reviewed by NOAA has been consistent, and portrays the study site areas as moderately oiled, and treated with ambient- and elevated-temperature pressure washing, with header flooding to carry recovered oil into booms.

SMITH ISLAND OILING AND TREATMENT HISTORY

Smith Island was very heavily oiled by relatively fresh oil on March 26, 1989, when greater than 70 knot winds first blew the slick ashore. This site caught and held a large amount of oil, and it was a chronic source of sheens throughout 1989 (see Figure 38) and 1990 (Figure 39, note the sorbent boom deployed). Cleanup crews worked on this section of Smith Island several times during 1989, using cold-, warm-, and hot-water flushing. In 1989, a shoreline cleaning agent, Corexit 9580, was tested on Smith Island. The bioremediation agents Inipol and Customblen were used in both 1989 and 1990. In late August 1990, the berm was "relocated" (i.e., moved with heavy equipment into the upper and middle intertidal zones, where exposure to wave action sped the reduction of sediment oiling), and the exposed subsurface sediments treated with Inipol and Customblen; during the geomorphological survey in September 1990, Inipol was very visible at depths down to 40 cm.

Early visits to Smith Island for assessment purposes were documented in comments on standard shoreline forms. The Shoreline Oil Evaluation form, prepared by Dane Hardin and dated April 1 through 4, 1989, documented a continuous band of heavy oiling 10 to 20 m wide over the splash, upper, and middle intertidal zones. Estimated thickness of pooled oil was greater than 3 cm, with penetration into the substrate greater than 25 cm. Notes by Hardin included: "Pools are moussy. Extensive pools leaching into the water near western point on north side of island." (This point borders the NOAA study site to the west) "Boulder areas will be very difficult to clean because of dangerous footing." These early observations of the heavy oiling conditions and the deep penetration into the substrate at the site would be reflected throughout the NOAA shoreline monitoring study.

A Cleanup Assessment Report form prepared by Dane Hardin, dated April 14, 1989, contained brief notes for ecological considerations: "None for cobble/boulder beaches. On vegetated rocks do not dislodge plants or animals." The lack of specific guidance or directives for cleanup crews reflects the lower biological abundance and diversity of cobble/boulder beaches relative to other habitat types in Prince William Sound.

The Shoreline Cleanup Program record for the segment containing the Smith Island site, dated April 19, 1989, recommended the following activities: flood-flush; warm and cold washing; and high-/low-pressure washing. The "ecological constraints" listed on this form were vague in nature and presumably again reflected a lack of observed biological resources: "Avoid living ecological species. Avoid high-pressure washing where invertebrates/seaweed present."

In late August, 1989, near the end of the first treatment season, the Site Inspection Record documented that hot-water wash, warm-water wash, water deluge, pom-poms, and snare booms in isolated areas had been used on the segment.

During the same month, Exxon received permission from the advisory Interagency Shoreline Research and Development Committee for a full-scale test of the chemical shoreline cleaner Corexit 9580. The goals of the test were to determine whether use of the product would speed the removal of the weathering residual oil, and to elicit any ecological drawbacks to that use. The north side of Smith Island was selected for the test because "…the beaches had low biological sensitivity and, although washed earlier in the summer, were still considered to be heavily oiled" (Exxon Research and Engineering 1990). The treatment process was to be extensively observed and monitored.

Although a number of sites on the north side of Smith were treated using Corexit 9580, what was to become the study location for the NOAA monitoring program was worked on August 11 and 13. Figure 74 is adapted from an Exxon report on the treatment and shows the equipment deployed in relation to the beach, and sampling stations for treatment monitoring. A description of the treatment process, given by the Exxon-sponsored monitoring team from America North, Inc, follows:

> "PRETREATMENT OBSERVATIONS. In general, this site was very heavily oiled. All large rocks and cobble had a uniform coating of oil with small pockets of mousse observed at some spots on the site.
>
> TREATMENT. The site was treated on 11 August with Corexit 9580. The beach cleaner was applied in two sections above the clean low intertidal zone. Within 45 minutes of application, each section was treated by beach crews using high-pressure, hot water hoses and a cold water deluge system. The crews used the spray setting on the hose nozzles, rather than the usual high-pressue jet. A rope-mop skimmer and absorbant material was operated to collect the oil. The treatment lasted less than 4 hours.
>
> DURING TREATMENT OBSERVATIONS. At approximately an hour after the Corexit/wash treatment started on the first section the water at the tideline appeared dark and murky. The water at 3 m outside the primary boom along the shoreline was also brown and murky with no visibility of water depth. At two hours after the start of treatment a water sample was taken at T1 for time series 1 and visual observations indicated a presence of oil in the sample. At the time washing of the first section was finished, there was a distinct visual difference between the first section and the yet unwashed second section on SM2. A water sample was collected at T1 for time series 2 and the water appeared turbid. At ~1 hour after the Corexit/wash treatment began, small streams or 'slickettes' of oil were observed escaping the secondary boom at the west end near the shore. The water was turbid just a short distance outside the secondary boom"
>
> (Exxon Research and Engineering 1990).

Figure 74. Diagram based on Exxon figure showing equipment deployment at the Smith Island study site during the Corexit 9580 trial application, August 11 and 13, 1989.

In 1990, shoreline treatment activities in general were scaled back. However, at some boulder-cobble beaches, including Smith Island, the physically intrusive technique of "berm relocation" was used, and portions of the heavily oiled tidal and storm berm were pushed into the surf zone with heavy equipment. On July 18 and 19, 1990, manual vegetation removal occurred at the study site, along with manual tilling, berm relocation, and application of Customblen. A total of three supersacks of oiled vegetation was removed. On September 5, 1990, both Inipol and Customblen were applied at the site.

SNUG HARBOR OILING AND TREATMENT HISTORY

This site was first visited and sampled by the NOAA biological team (at that time employed by Exxon) on May 2 and 3, 1989. At that time, there was a gradient in oiling from the upper to lower intertidal zones: the upper station (not quantitatively sampled until September 1989) was heavily coated with dark mousse and oil that was especially thick in pockets between and under cobbles and boulders. Oil on south-facing rock faces had weathered to a somewhat tacky consistency. The middle station was less heavily oiled, and the oil had a lighter, moister appearance, but percent cover was still high. The lower station had only light sheens of oil in pooled water and on wet surfaces in May 1989.

The standardized Shoreline Oil Evaluation form, dated June 11, 1989, documented continuous oiling from the splash zone down to the lower intertidal zone, over 95 percent of the segment length of 1,400 m. A map accompanying the form noted that the area near the study site consisted of "boulders/cobble/rock generally light to locally moderate oiling throughout the intertidal zone." Eelgrass beds were shown offshore. At around the same time, members of the NOAA biological study team observed that oil on the rocky shoreline at the Snug Harbor site had weathered to a heavy tar.

In August 1989, Exxon described oiling conditions at the site when requesting that it be included in a group of shorelines that would remain uncleaned by work crews:

> "The site is heavily oiled in the upper intertidal to supra intertidal zone. The area of the protected shoreline, within the intertidal, is approximately 1000 m^2 (approximately 10m x 100m), light to moderate oiling in the mid- to low-intertidal zone. This beach is unlikely to have release of oil to adjacent coasts due to its low wave energy levels in the sheltered bay. The oil will likely weather and degrade in situ."

The Ecological Evaluation form dated June 11, 1989, noted under "Cleanup Precautions" that it was recommended that cleanup crews "use precautions to avoid oiling uncontaminated eelgrass beds."

The Shoreline Cleanup Program record dated June 13, 1989, recommended a number of treatment activities, including: manual removal of contaminated drift material, flood/flush with warm to hot water (up to 140˚F) on low-angle beaches, moderate- to high-pressure washing on rock, other approved methods as appropriate. Under "Ecological Constraints", crews were directed to "Take appropriate measures to protect uncontaminated eelgrass beds."

In July, 1989, Exxon field assessment personnel began suggesting to Exxon Environmental and shoreline cleanup supervisors that some oiled shoreline segments be exempted from treatment in order to evaluate cleanup effects as a discrete entity from oiling effects. For example, in a memorandum dated July 2, 1989, Perry Campbell of Dames and Moore, an Exxon contractor, made the following arguments to Al Maki of Exxon Environmental:

> "To enable us to evaluate the impact of the oil spill on the intertidal and subtidal environment of Prince William Sound, it is essential that we protect some sites from cleaning. We have requested <u>much</u> less than 1% of the oiled areas to be reserved as study areas where we can evaluate the impacts and observe the natural recovery process. If these sites are not protected we will never be able to tell whether the damage was done as a result of the oil spill or the cleanup…
>
> Further to this, there is every indication that the cleanup process is damaging the nearshore environment. The following items are among the many reports received from field investigators:
>
> - Oil washed into subtidal environments as deep as 90 feet in cleaned areas…,but not in uncleaned areas.
> - Mussel beds steam cleaned, i.e., cooked in place.
> - Alders above the tide line singed by the steam cleaning.
> - Mussel beds trampled to remove oil…
>
> While these reports are anecdotal in nature, they are likely to be indicative of <u>some</u> of the types of environmental damage which may be produced by a cleanup effort. Certainly the cleanup effort has great momentum and thousands of people moving in one direction are hard to stop, but we must ask ourselves 'why are we doing this?' If an 'environmentally stabilized' beach is one in which the biotic communities have been altered dramatically by the cleanup process, I don't think there's a good answer to that question."

In August, 1989, Al Maki and Andy Teal of Exxon made a formal request to the Interagency Shoreline Cleanup Committee and to land managers to defer seven sites from shoreline treatment. The reason for this request was given as follows:

> Exxon's environmental program is currently developing data on shoreline impacts and long-term recovery at a total of 43 specific study locations. To complete the full study objectives it is essntial that 7 of these sites be deferred from cleaning…The purpose of the site protection portion of the study is to investigate how the oil weathering and shoreline recovery rates vary between cleaned beaches and uncleaned beaches…

It was not until January of 1990 that the formal agreement among the Federal On-Scene Coordinator, Exxon, and the State of Alaska creating a group of nine set-aside sites was signed and implemented. The nine agreed-upon sites included four in Snug Harbor. Two of the four were Environmental Protection Agency bioremediation study sites located in the outer portion of Snug Harbor. The other two were in the inner arm of the embayment. One of these was a rocky shoreline, the other a gravel beach. The NOAA long-term monitoring program maintains study sites in both of these set-aside areas, but the present discussion focuses on the rocky shoreline setaside.

The available site treatment records indicate that in fact little or no cleanup took place within the designated setaside areas. The Site Inspection record dated August 20, 1989, documented the use of only nonmechanical treatment ("wiping, pompoms, picking up oiled debris per RAT Team") within the shoreline segment that included the setaside.

However, a more site specific examination of state records by ADEC in early 1991 (J. Bauer, pers. comm., January 7, 1991) determined that the site was not disturbed, due to its inclusion in a posted set-aside area. J. Michel (pers. comm., January 9, 1991) of Research Planning, Inc., a NOAA contractor, believed treatment at the site was minimal, if it was treated at all. Members of the NOAA biological monitoring team noted the presence of bioremediation pellets on the shoreline in 1989 and 1990, but it is possible that these were refloated from other non-set-aside areas. Regardless, it can be stated with some certainty that the shoreline of interest was not treated with the high-pressure hot-water washing techniques that were so widely used in 1989.

Based on this information, we consider the Snug Harbor rocky site to have been moderately oiled, and untreated.

APPENDIX REFERENCE

Exxon Research and Engineering Co. 1990. Large-scale field test of Corexit 9580, Smith Island, August 8-14, 1989. Report No. EE.2DM.90, 63 pp. + appendices.